INSTRUMENTATION
AND
CONTROL SYSTEMS

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Dedicated to

Shri Shirdi Saibaba

Contents

Preface

From pneumatic instrumentation to computer-controlled smart instrumentation and systems, there has been a large change in the Instrumentation industry related to the technology use cases, affordability, and dependency on the plant operations. Instrumentation systems have nowadays become an integral part of plant designing, operations, safety, and maintenance.

Target Audience

This book is primarily designed for fifth and sixth semester students of E&IE, I&CE, EEE, Chemical Engineering at various universities in the country. Apart from this, postgraduate students and entry-level engineers will also find this book helpful. The content has been presented in an organized manner which helps the students understand the basic principles of measurement along with analyzing the measurement techniques used in various conditions with their relative advantages and disadvantages. This will help the engineers critically examine the situation at hand and develop techniques and best practices for the industry.

Objective

The primary objective of the book is to familiarize the students with the fundamentals of instrumentation alongside preparing them for work in the industry as instrumentation professionals. In order to achieve this objective, basic operating principles have been explained in detail and are supplemented with adequate diagrams and equations. At several places within the text, real-time industrial photographs and video links have been provided to bridge the gap between theory and practice, and help the student visualize the procedures followed in industrial scenarios. Checkpoints implanted after each learning objective and extensive chapter-end exercises are focused on strengthening the critical-thinking, reasoning and analytical abilities of the students.

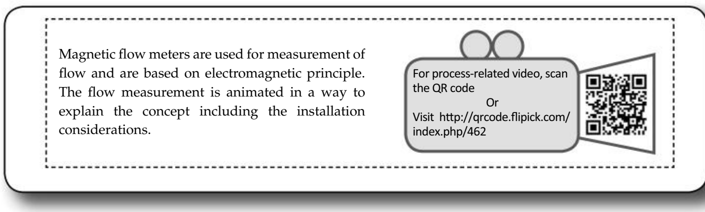
Learning and Assessment Tools

In designing this book, we have focused on the Learning Objective (LO) oriented approach. This is an educational process that emphasizes on developing engineering skill in the student and testing the outcomes of the study of a course, as opposed to rote learning. We believe it is not *what is being taught* rather it is *what is being learnt* that is the key to a student's overall development. This approach creates an ability to acquire knowledge and apply fundamental principles to analytical problems and applications.

Use of Technology

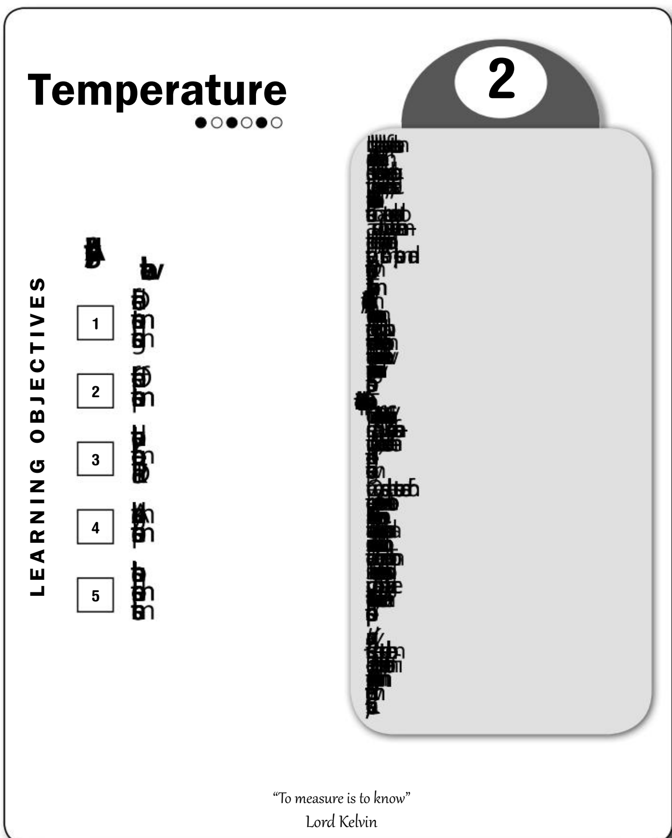
In bringing out this edition, we have taken advantage of recent technological developments to create a wealth of useful information to be supplemented with the physical book. For students using smartphones and tablets, scanning **QR codes** located within the chapters gives them immediate access to resources such as:

- Answers to Checkpoint
- Industrial process-related videos
- Interactive quizzes



Learning Objectives

Each chapter is organized into multiple learning objectives. These help students better anticipate and plan their study, and help instructors measure a student's understanding. The sections of the chapters are structured in a modular way, which help in systematic concept development.



Checkpoint

Each learning objective is followed by a set of questions for the self-assessment of students. This offers great retention through looping mechanism.

For answers to checkpoint, scan the QR code

Or

Visit http://qrcode.flipick.com/index.php/404

Checkpoint

✦✦	1.	List the type of level measurement encountered in process applications.
✦	2.	How point level process measurement is accomplished?
✦✦	3.	Give an example of point level process indication.
✦✦	4.	How many switches are required to achieve point level process control?
✦✦	5.	In a continuous level process measurement, a level measurement is provided with height of the process material surface in which representation?
✦	6.	Give an example of continuous level process indication.
✦✦	7.	What is the objective of automatic tank gauging system?
✦✦	8.	What is an interface level?
✦✦	9.	If the level is inferred from a pressure measurement, what are the units of measurement for water column?

Note: ✦ Level 1 & Level 2 category
✦✦ Level 3 & Level 4 category
✦✦✦ Level 5 & Level 6 category

Pedagogical Classification

The pedagogy is arranged as per levels of difficulty—all checkpoint problems are linked with Learning Objectives (LOs) and marked with Levels of Difficulty (LOD), to help assess the student's learning. This assessment of Levels of difficulty is derived as per Bloom's Taxonomy.

✦ indicates Level 1 and Level 2 i.e. Knowledge and Comprehension based easy-to-solve problems.

✦✦ indicates Level 3 and Level 4 i.e. Application and Analysis based medium-difficulty problems.

✦✦✦ indicates Level 5 and Level 6 i.e. Synthesis and Evaluation based high-difficulty problems.

Summary

Summary points specific to each LO are provided at the end of each chapter. It helps in recapitulating the ideas initiated with the outcomes achieved.

Summary

LO 1: Describe and classify control valves

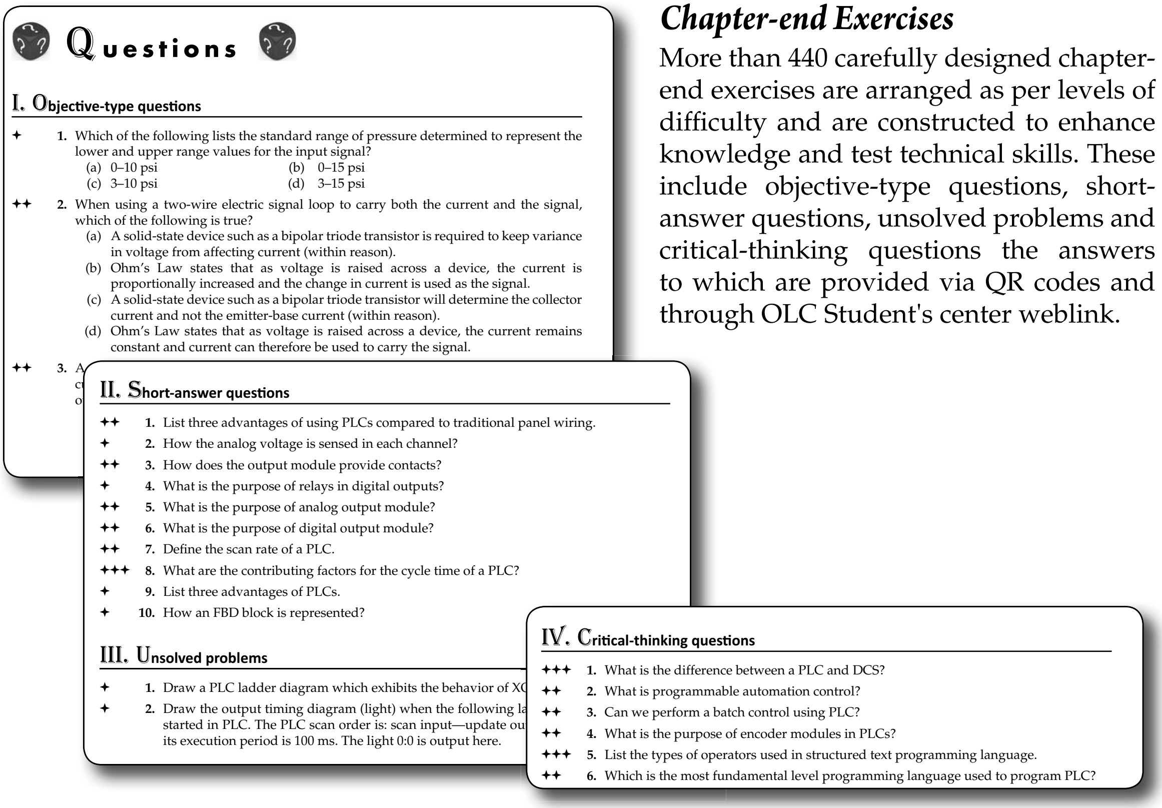
- The combination of valve and actuator is called an automatic control valve or simply a control valve.
- The control valve, or final control element, is the last device in a control loop. It takes signal from the process instruments and acts directly to control the process fluid.
- Control valves maintain process variables such as pressure, flow, temperature, or level at their desired value, despite changes in process dynamics and load.

LO 2: Analyze the parameters to evaluate the performance of control valves

- Dead band is the range through which an input can be varied without initiating an observable response.
- Control valve assemblies can be a primary source of dead band in an instrumentation loop. It is usually expressed as a percentage of diaphragm pressure spans.
- An actuator is the final part of control element that converts the control signal into action of the final control device. Cylinders, motors, and solenoids are some of the examples.
- The microprocessor-based positioners have performance equivalent to the conventional two-stage pneumatic positioners. They also provide diagnostic capabilities and valve monitoring that ensures initial good performance does not deteriorate with use.
- If a control valve assembly can quickly respond to these small changes, process variability is improved. This is a function of the volume of air that is required to produce any desired pressure on the diaphragm of a valve actuator.
- For a given increase of valve travel, an oversized valve usually produces a disproportionate flow change. This phenomenon in turn produces friction and exaggerates the process variability associated with dead band.
- Control valve assemblies play an important role in loop/unit/plant performance.

LO 3: Outline control valves' capabilities and capacities

- Installed flow characteristic is the flow characteristic that is obtained when pressure drop ΔP across the valve varies as dictated by flow and related conditions in the system in which the valve is installed.
- Linear describes an inherent flow characteristic that can be represented ideally by a straight line on a rectangular plot of flow versus percentage of rated valve stem travel. A linear valve gives approximately equal increments of flow per increment of valve stem travel at a constant pressure drop. Equal-percentage describes an inherent flow characteristic that for equal increments of rated travel will ideally give equal-percentage changes of the existing flow.
- Quick-opening describes an inherent flow characteristic in which there is maximum flow with minimum travel.



Questions

I. Objective-type questions

✦ 1. Which of the following lists the standard range of pressure determined to represent the lower and upper range values for the input signal?
(a) 0–10 psi (b) 0–15 psi
(c) 3–10 psi (d) 3–15 psi

✦✦ 2. When using a two-wire electric signal loop to carry both the current and the signal, which of the following is true?
(a) A solid-state device such as a bipolar triode transistor is required to keep variance in voltage from affecting current (within reason).
(b) Ohm's Law states that as voltage is raised across a device, the current is proportionally increased and the change in current is used as the signal.
(c) A solid-state device such as a bipolar triode transistor will determine the collector current and not the emitter-base current (within reason).
(d) Ohm's Law states that as voltage is raised across a device, the current remains constant and current can therefore be used to carry the signal.

✦✦ 3. A

II. Short-answer questions

✦✦ 1. List three advantages of using PLCs compared to traditional panel wiring.
✦ 2. How the analog voltage is sensed in each channel?
✦✦ 3. How does the output module provide contacts?
✦ 4. What is the purpose of relays in digital outputs?
✦✦ 5. What is the purpose of analog output module?
✦✦ 6. What is the purpose of digital output module?
✦✦ 7. Define the scan rate of a PLC.
✦✦✦ 8. What are the contributing factors for the cycle time of a PLC?
✦ 9. List three advantages of PLCs.
✦ 10. How an FBD block is represented?

III. Unsolved problems

✦ 1. Draw a PLC ladder diagram which exhibits the behavior of X
✦ 2. Draw the output timing diagram (light) when the following l started in PLC. The PLC scan order is: scan input—update ou its execution period is 100 ms. The light 0:0 is output here.

IV. Critical-thinking questions

✦✦✦ 1. What is the difference between a PLC and DCS?
✦✦ 2. What is programmable automation control?
✦✦ 3. Can we perform a batch control using PLC?
✦✦ 4. What is the purpose of encoder modules in PLCs?
✦✦✦ 5. List the types of operators used in structured text programming language.
✦✦ 6. Which is the most fundamental level programming language used to program PLC?

Chapter-end Exercises

More than 440 carefully designed chapter-end exercises are arranged as per levels of difficulty and are constructed to enhance knowledge and test technical skills. These include objective-type questions, short-answer questions, unsolved problems and critical-thinking questions the answers to which are provided via QR codes and through OLC Student's center weblink.

Organization of the Book

The book is meticulously organized into various chapters based on the automation framework model. Each chapter is clearly defined into set learning objectives which lead to a description of multiple sections. Each learning objective is completed with Checkpoint, real installation pictures and representation for the videos by the means of QR codes. The checkpoints are tagged with levels of difficulty. At the end of each chapter, well-defined summary and extensive questions are provided. The answers to these questions can be accessed through the provided QR codes and OLC weblink.

Chapter 1 begins with an introduction to the field of automation from a historical perspective to the latest happenings. In the introduction itself, the evolution of instrumentation, communications, signals and systems are discussed briefly. **Chapter 2** is dedicated for the discussion on temperature, measurement concepts, RTD, thermocouples and so on. The smart instrumentation and calibration techniques are discussed in detail. The application of various measurement techniques to different application scenarios are also discussed.

Pressure measurement comprises **Chapter 3** and is the second most important subject of the instrumentation industry. The discussion ranges from the mechanical and electromechanical and electronic sensors, their evaluation to the smart measurement area and their application suitability to various scenarios are discussed. **Chapters 4** discusses level measurement while **Chapter 5** focuses on flow measurement. These topics are discussed at length with different measurement techniques, applications, installation considerations, selection guidelines, criteria for the selection of different applications and the comparisons of different techniques. These two chapters also cover additional situations such as custody transfer measurements and interface level measurements. The discussion on these two topics makes students appreciate the real-time situations in which an instrument engineers play a key role in defining the safety, quality and productivity of the process industries.

Chapter 6 elaborates on control valves and the different types of valves, actuators, positioners used in the industry. The selection of valves is critical for proper operation of control loop and hence the different selection criteria and parameters are discussed. The real images of the control valves in operation and a video animation of the valve operation make it simpler to understand. **Chapter 7** deals with process control and discussion on various types of processes and controls is provided. The basic definition of the controllers such as PID and variants in the same are discussed. The topic continues with various types of control methodologies such as cascade, feedforward, ratio, etc. The discussion continues to the latest model predictive controllers and their tuning methods.

The data acquisition systems are discussed with their basic architecture and different subsystems in **Chapter 8**. Programmable logic controllers form the basis of **Chapter 9** in which the basic concept, different subsystems, programming languages, applications and examples of some of the applications are discussed. **Chapter 10** elaborates on Supervisory Control and Data Acquisition Systems (SCADA). The SCADA systems have been discussed from the historical perspective to their current evolution in architecture. The current architectural offerings are provided with different subsystems and features found in most of such systems. **Chapter 11** elucidates the most critical part of the control systems—distributed control systems (DCS). The DCS is used in many process industries and is also explained from the historical perspective to the latest offering with different hardware and software subsystems. The hardware subsystems are divided into controllers and IOs and are discussed in detail while the software subsystems are discussed in terms of the features and functionalities.

Get More on the Web

A number of supplementary resources related to the text, industry photographs can be accessed from the following web link: http://www.mhhe.com/padma_raju/ics1

For Instructors

- Solutions Manual
- Powerpoint Lecture Slides

For Students

- Answers to Short-answer questions and Critical-thinking questions
- Answer key to unsolved problems
- Colored industry installation photographs can be accessed from http://highered.mheducation.com/sites/9385880527/student_view0/index.html

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Piracy-related issues may also be reported.

List of Abbreviations

A/D	Analog-to-digital
ALU	Arithmetic and logic unit
AMS	Asset management system
ASIC	Application-specific integrated circuit
ATG	Automatic tank gauging
ATV	Auto tune variation
BASEEFA	British Approvals Service for Electrical Equipment in Flammable Atmospheres
BPD	Barrels per day
BPH	Barrels per hour
CCS	Constant current source
CCS	Computer control systems
CIM	Computer-integrated manufacturing
COTS	Commercial off-the-shelf
CPU	Central processing unit
CSA	Canadian Standards Association
CSTR	Continuous-flow stirred tank reactor
CTFE	Chlortrifluorethylene
D/A	Digital-to-analog
DAS	Data acquisition system
DC	Dynamic compensation
DCS	Distributed control system
DDC	Direct digital control
DDCS	Distributed digital control system
DMC	Dynamic matrix control
DP	Differential pressure
DTF	Double-ended tuning fork
DTM	Device type manager
EDDL	Enhanced device description language
EEPROM	Electrically erasable programmable read-only memory
EMF	Electromotive force
ESD	Emergency Shutdown Systems
FBD	Function block diagram
FDT	Field device technology
FM	Factory mutual
FMCW	Frequency modulated continuous wave
FOPDT	First-order plus dead time
FSK	Frequency shift keying
GC	Gas chromatograph
GOSP	Gas oil separation plant
GPM	Gallons per minute
GWR	Guided wave radar
HART	Highway addressable remote transducer
HCF	HART communication foundation
HF	High frequency
HIU	Hydrostatic interface unit
HMI	Human machine interface
HP	High pressure
HSE	High speed ethernet
HTG	Hydrostatic tank gauging
I&C	Instrumentation and control
I/O	Input/output
IC	Integrated circuit
ICS	Instrumentation and control system
ID	Inside diameter
IEC	International Electrotechnical Commission
IL	Instruction list
IP	Internet protocol
IPTS	International practical temperature scale
IS	Intrinsic safety

ISA	International Society of Automation
ISO	International Organization for Standardization
LAL	Less than alarm limit
LAN	Local area network
Lb/h	Pounds per hour
LC	Level controller
LCU	Local control units
LD	Ladder logic diagram
LNG	Liquified natural gas
LP	Linear program
LP	Low pressure
LPG	Liquefied petroleum gas
LRL	Lower range limit
LRV	Lower range value
LS	Low select
LSI	Large scale integration
MAC	Media access control
MIS	Management information system
MiTDR	Microimpulse time domain reflectometry
MMI	Man machine interface
MMS	Maintenance management systems
MMSCFD	Millions of standard cubic feet per day
MPC	Model predictive control
MSI	Medium scale integration
MTBF	Mean time between failures
MTTR	Mean time to repair
MTU	Master termination unit
NACE	National Association of Corrosion Engineers
NC	Normally closed
ND	Nominal diameter
NO	Normally open
NPS	Normal pipe size
NPT	National pipe threads
NPTF	National pipe thread, female connection
NTC	Negative temperature coefficient
OSI	Open systems interconnection
P&ID	Process and instrument drawing
PC	Personal computer
PD	Positive displacement
PI	Proportional integral
PID	Proportional integral derivative
PIT	Pressure to current transmitter
PLC	Programmable logic controller
PMMC	Permanent magnet moving coil
PTC	Positive temperature coefficient
PTFE	Polytetrafluoroethylene
PTOF	Pulse time of flight
QAD	Quarter amplitude damping
RAM	Random access memory
RLL	Relay ladder logic
RMS	Root mean square
ROM	Read only memory
RSS	Root sum of the squares
RTD	Resistance temperature detector
RTG	Radar tank gauging
RTJ	Ring type joint
RTU	Remote terminal units
S/H	Sample hold
SCADA	Supervisory control and data acquisition
SCFD	Standard cubic feet per day
SCFH	Standard cubic feet per hour
SFC	Sequential function chart
SI	System International d'Unites
SSC	Sulfide stress cracking
ST	Structured text
STG	Servo tank gauges
TC	Thermocouples
TL	Tyreus and Luyben
TPE	Total probable error
TTL	Transistor-transistor logic
UL	Underwriters Laboratories
URL	Upper range limit
URV	Upper range value
ZN	Ziegler-Nichols

Introduction

1

General introduction to the industrial automation, history of various subsystems, and inventions that have contributed to the field of Instrumentation and automation Systems Engineering are presented in this chapter. The evolution of automation systems from the users needs perspective, contemporary technology perspective, and various applications perspectives are discussed in detail. This chapter also covers the evolution of such subsystems such as controllers, communication protocols, layers of automation and process control networks.

The chapter highlights various units of measurement and their conversions to different units is described. Units of measurement are a key concept for the instrumentation engineers and hence enough descriptions are provided with examples.

Field communications are discussed from the traditional pneumatic communication phase to modern day digital communication phase. Instrumentation and control systems are organized in the form of layers based on their role in the overall objectives of the plant. The layered architecture has evolved as standard by various organization and it is important for the students to know the layers and their roles and systems in each layer. The layers contributes to the topologies of the systems and hence the topologies are also discussed for a better understanding of the system.

Keywords:
Automation, industrial, control, layers, level, functional, architecture, process

LEARNING OBJECTIVES

After reading this chapter, you will be able to:

1. Outline the history of instrumentation and control
2. Describe the units of measurement
3. Explain the communication protocols
4. Discuss the objectives and topologies of instrumentation and systems

"When you measure, what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind"

William Thomson, Lord Kelvin

1.1 HISTORY OF INSTRUMENTATION AND CONTROL

LO 1
Outline the history of instrumentation and control

From pneumatic instrumentation to computer-controlled smart instrumentation and systems there is a large change in the technology, use cases, affordability, and dependency on the plant operations. Instrumentation systems are becoming an integral and indispensable part of plant design, operations, safety, and maintenance. Today the plant operators see the value of instrumentation in day-to-day operations of the plants for ease of activities, improvements in the efficiency, and safe operations. Instrumentation and control systems (ICS) have a long history and following is a synopsis of its evolution.

1.1.1 Process Control

During *1930s*, process control consisted of operator adjustments by hand valves based on direct readings of local gauges. Control room instrumentation has taken some dramatic turns along the way from large-scale pneumatic recorders to miniature analog electronic controllers to microprocessor-based digital systems.

Chemical and petroleum plants were amongst the first to use control systems for their processes owing to the complexity of operations and pressure to improve the efficiency, and by the regulations thereby meeting the safety standards.

Pneumatic instrumentation became the leader in automatic control because of its safety. In the late 1930s and early 1940s, operators relied on local instrument gauges to monitor production processes. Control panels were located in the field near the process sensing points. Typically, only a handful of indicators, recorders, and controllers are mounted on a local panel. Often, the process fluids are piped directly into control panels.

In general, wherever fill fluids were needed, mercury was commonly used. Control panels served as a convenient means for improving control coordination by allowing operators to adjust valves in response to visual instrument readings.

In *1940s*, the use of pneumatic proportional controllers increased. New words such as integral, derivative, sensor, and final control element were added to their vocabularies. By the late 1940s, a trend toward the concentration of controls in centralized locations had begun.

In *1950s*, unit control rooms were built to centralize operations and to accommodate operators assigned to monitor control boards on a full-time basis. With the growing numbers and complexities of the indicators, recorders, controllers, and the need to operate the plant remotely from these panels, instrument mechanics were recruited who specialized in maintaining the pneumatic control systems.

By *mid-1950s*, electronic analog instrumentation had been formally introduced but it did not win industry acceptance until the late 1950s and early 1960s. With the exception of chemical and petroleum plants, most new plants used electronic analog instrumentation because of the greater cost of tubing work between pneumatic transmitters and controllers, and the expensive pneumatic auxiliaries, such as air compressors, filters, and dryers. So for this, instrument engineers needed to know electronics and electricity in addition to pneumatics. Larger plants formed groups namely, Electrical and Instruments (E&I), Instrument and Electronics (I&E), or Electrical and Control (E&C) while some plants formed an Instrument and Control (I&C) group that had both instrument mechanics and instrument technicians.

In *1960s*, digital computers began to appear in control rooms. The computer's initial role was essentially that of a data logging device from which paper printouts could be obtained. The concept of direct digital control (DDC) gained popularity in the 1960s but by mid-1970s the drawbacks had become apparent.

The central computer approach was dependant on the availability of a single large computer. Highly trained computer personnel were needed to maintain the computer hardware and to deal with high-level software languages.

Single-loop analog control continued to flourish during the *early 1970s*. Thousands of electronic signal wires crisscrossed central control rooms, adding complexity to the pursuit of improved coordination. Recognizing multiple functions inherent in panel instruments, split architecture systems were introduced. Analog display stations were segregated from rack-mounted printed circuit cards in the quest for functional modularity.

Instrument and control groups flourished, everyone was retrofitting and updating plants, and new plants provided more and more instrumentation requirements.

Instrumentation vendors were training the instrument mechanics and electricians to maintain their equipment. Standards for instrumentation were being developed, and manufacturers started following the guidelines of ISA (International Society for Automation) while developing new instruments.

A combination between single-loop electronic analog control and pneumatic control developed because of the need for powerful control valve actuators. Current-to-pneumatic converters and pneumatic-to-current converters linked electronic instruments to pneumatic instruments, sensors, and actuators. Chemical plants used pneumatic instruments in the hazardous areas along with signal wires to transmit the signals to central control rooms in safe areas.

Most plants built after *mid-1970s* used electronic rather than pneumatic instrumentation. Pneumatic valves, however, are still used almost exclusively for throttling control and even on-off control. About the same time in this period, Honeywell® introduced the first distributed digital control system (DDCS), now called the distributed control system (DCS). Multiple mini computers, geographically, and functionally distributed, performed monitoring and control tasks that had been previously handled by the central DDCS computer.

Each microprocessor-based controller was shared by up to eight control loops. Serial bit communication over coaxial cable linked individual system devices. As these distributed control systems became the standard for newer chemical and petroleum plants and the older single-loop pneumatic and electronic controllers were replaced, the I&C groups were trained on the new DCS.

This was the first introduction of computers to the I&C technicians, and DCS manufacturers designed their systems to be configured and maintained by I&C groups—not highly trained computer personnel. As a technological breakthrough, the microprocessor accelerated advances in control system design. At the operator interface level, distributed control contributed to an unforeseen development. For the first time, CRT display consoles gained acceptance as the primary operator interface, and conventional single-loop analog stations were reduced to an emergency backup role at many early-distributed control system installation sites. Long, floor-to-ceiling panel boards were replaced with CRT workstation consoles. Keyboards, CRTs, and printers served as modern tools for seated control room operators.

By the *end of 1970s*, control system innovations had advanced beyond industry's capacity to keep pace. Most plant sites contained an assortment of control technologies that spanned three decades. Instrumentation and control specialists (mechanics, technicians, and engineers) were commonplace in industry.

Distributed control system operator interfaces were further refined in the *1980s*. Intelligent CRT stations utilized multiple-display formats to condense and organize extensive operating information. Hierarchical arrangements of plant, area, group, and loop-level displays simplified on-screen database presentation. Real-time color graphics added further comprehensive overviews of unit operations. Most microprocessor-based control systems had a vast array of alarms and diagnostics to help operators and maintenance personnel determine if there were any problems. Distributed control systems had many online and offline diagnostics, including process and input alarms, reportable events, error messages, and hardware and software failure reporting.

Trends for the *1990s* were computer-integrated manufacturing (CIM) and management information systems (MIS). These interfaced the real-time devices (field devices at the machinery/process level) through distributed controllers to multiple-station coordination, then on to scheduling, production, and management information to the plant level for overall planning, execution, and control. Further development of artificial intelligence and expert systems gave advanced control new meaning.

With the introduction of computers and databases, maintenance management systems (MMS) [or asset management systems (AMS)] helped maintenance and management personnel determine repair frequency and spare parts availability and made decisions on when to replace obsolete equipment.

Distributed control systems, programmable logic controllers (PLC), computer control systems (CCS), supervisory control and data acquisition (SCADA) and smart field devices were the norm.

A digital signal is superimposed on the 4–20 mA signals for ranging and calibrating field devices. The International Organization for Standardization (ISO), open systems interconnection (OSI) model, and interconnection of devices made by different manufactures has opened systems architecture, replacing proprietary communications among devices.

Most part of the year *2000* constituted advancement with data being the center from plant floor to boardrooms, an advanced workflow system was developed. A large data generated is formatted for meaningful information for the decision makers.

The advanced communication technologies have begun their presence in the plants. The complete digital field communication protocols, wireless technologies, mobile systems, and video systems have been commissioned.

In the year 2010, the trend is toward consolidation of the systems that are vertical specific, more productive, and easy to maintain. Larger improvements have been done in the areas of instrument maintenance diagnostics, preventive maintenance technologies, etc. A lot of emphasis is given to human factors in the design of the systems, mobile work force related tools and remote diagnostics are in fashion.

1.2 UNITS OF MEASUREMENT

LO 2

Describe the units of measurement

In this section, the concept of SI unit system is explained along with the introduction to concepts like coherent units, base units, and derived units. The naming and symbol conventions associated with these units are also explained in this section. The standard definition of certain units have undergone the following changes:

- Mass, length, time and temperature
- Non-standard usage is looked at in the context of volume, temperature, and gravity-dependent pressure units
- The effects of gravity are considered and gravity-independent units of force and pressure outlined.

1.2.1 SI Units

There are a large number of units used in the industry. Few instrument engineers have not, at one time or the other confused a conversion and disordered equipment as a result. One has to not only deal with metric and imperial units but also with hogsheads, barrels, degrees, Brix, degrees, Twaddle, Imperial and U.S. gallons, torr, centipoise, centistokes, and pound per foot hour. Thus, the time taken for calculations is greatly increased and the necessary application of correction factors increases the likelihood of error. Hence, the need for rationalization has led to the development of System International d'Unites (SI) from a base of seven defined units from which all other quantities are defined. SI is a coherent system which means that the product of any two-unit quantities in the system is the unit of the resultant quantity.

Example

$$\text{Force} = \text{Mass} \times \text{Acceleration}$$

$$\text{Force} = \frac{\text{Mass} \times \text{Velocity}}{\text{Time}}$$

$$= \frac{\text{Mass} \times \text{Distance/Time}}{\text{Time}}$$

$$= \frac{\text{kg} \times \text{m}}{\text{s} \times \text{s}}$$

Therefore, unit of force is

$$\text{Force} \rightarrow \frac{\text{kg} \cdot \text{m}}{\text{s}^2} \rightarrow \text{Newton}$$

Units such as meter per hour are not coherent because seconds is the standard usage. Base SI units are given in Table 1.1 while the supplementary SI units are given in Table 1.2.

Table 1.1: Base SI units

Measurement Quantity	*Unit*	*Symbol*
Length or distance	Meter	m
Mass or weight	Kilogram	kg
Time	Second	s
Current	Ampere	A
Temperature	Kelvin	K
Luminous	Candela	cd
Amount of substance	Mole	mol

Table 1.2: Supplementary SI units

Measurement Quantity	*Unit*	*Symbol*
Plane angle	Radian	rad
Solid angle	Steradian	sr

A unit, which is the combination of two or more other units, is called a *derived unit*. Velocity is a derived unit because velocity = distance/time. Various derived units formed from the base and supplementary SI units are given in Table 1.3. Some of the units are named after their inventors/significant contributors to the field and have a capital letter as their symbol. These are given in Table 1.4.

Table 1.3: Derived SI units formed from base and supplementary SI units

Measurement Quantity	*Unit*	*Symbol*
Acceleration	Meter per second squared	m/s^2
Angular acceleration	Radian per second squared	rad/s^2
Angular momentum	Kilogram meter squared per second	$kg\ m^2/s$
Angular velocity	Radian per second	rad/s
Area	Square meter	m^2
Coefficient of linear expansion	1 per Kelvin	1/K
Concentration (of amount of substance)	Mole per cubic meter	mol/m^3
Current density/Electric current density	Ampere per meter squared	A/m^2
Density	Kilogram per cubic meter	kg/m^3
Kinematic viscosity	Meter squared per second	m^2/s

(*Contd.*)

Luminance	Candela per square meter	cd/m^2
Magnetic field strength	Ampere per meter	A/m
Magnetic moment	Ampere meter squared	$A\ m^2$
Mass flow rate	Kilogram per second	kg/s
Mass per unit area	Kilogram per meter squared	kg/m^2
Mass per unit length	Kilogram per meter	kg/m
Molarity	Mole per kilogram	mol/kg
Molar mass	Kilogram per mole	kg/mol
Molar volume	Cubic meter per mole	m^3/mol
Moment of inertia	Kilogram meter squared	$kg\ m^2$
Moment of momentum	Kilogram meter squared per second	$kg\ m^2/s$
Momentum	Kilogram meter per second	kg m/s
Rotational frequency	1 per second	1/s, r/s
Specific volume	Cubic meter per kilogram	m^3/kg
Speed/Velocity	Meter per second	m/s
Volume	Cubic meter	m^3
Wave number	1 per meter	1/m

Table 1.4: Derived SI units having special names

Measurement Quantity	*Unit*	*Symbol*	*Derivation*
Frequency	Hertz	Hz	s^{-1}
Force	Newton	N	$Kg\ m/s^2$
Pressure (and Stress)	Pascal	Pa	N/m^2
Work, energy quantity of heat	Joule	J	Nm
Power	Watt	W	J/s
Electric charge	Coulomb	C	As
Electric potential	Volt	V	W/A
Electric capacitance	Farad	F	C/V
Electric resistance	Ohm	Ω	V/A
Electric conductance	Siemens	S	Ω^{-1}
Magnetic flux	Weber	Wb	Vs
Magnetic flux density	Tesla	T	Wb/m^2
Inductance	Henry	H	Vs/A
Temperature	Degree celsius	°C	1°C = 1 K
Luminous flux	Lumen	lm	cd sr
Illumination	Lux	lx	$1m/m^2$

1.2.2 Definitions of Length, Time, and Mass

1.2.2.1 Length

In different forms, a meter is defined as:

- 10^{-7} of the distance from the equator to the North Pole along a Meridian passing through Paris
- 1889: Distance between two finely scribed lines on a platinum-iridium bar.
- 1961: 16650763.73 wavelengths of a particular orange radiation from a krypton atom.

1.2.2.2 Time

The SI unit of time, second, is defined as:

- 1/86,400 (of a mean solar day)
- 1967: 1 second is the time required for 9,192,631,770 complete vibrations of the Cesium atom.

1.2.2.3 Mass

Mass is a property of a physical body. It is a measure of an object's resistance to change of state of motion when force is applied. The standard SI unit of mass is kilogram (kg). There are various definitions of kilogram and is constantly getting revised.

1.2.2.4 Preferred Multiples and Submultiples

Metric prefixes are used to denote powers of ten. These prefixes along with their symbols are listed in Table 1.5. Multiples and submultiples for special use are listed in Table 1.6.

Table 1.5: Notation and symbols of multiples and submultiples

Factors by which the Unit is Multiplied	*Prefix*	*Symbol*
10^{12}	Tera	T
10^{9}	Giga	G
10^{6}	Mega	M
10^{3}	Kilo	K
10^{-3}	Milli	m
10^{-6}	Micro	µ
10^{-9}	Nano	n
10^{-12}	Pico	p
10^{-15}	Femto	f
10^{-18}	Atto	a

Table 1.6: Multiples and submultiples for special use		
Factors by which the Unit is Multiplied	*Prefix*	*Symbol*
10^2	Hector	h
10	Deca	da
10^{-1}	Deci	d
10^{-2}	Centi	c
Factors by which the Unit is Multiplied	*Prefix*	*Symbol*
12,000	N	12 kN
0.00394	m	3.94 mm
14,010	N/m^2	14.01 kN/m^2
0~0003	s	0.3 ms

1.2.3 Volume Measurement

The SI unit for volume is cubic meters (m^3). Liter is an acceptable unit but it should only be used for small quantities of liquids and should not be used for gases.

1.2.4 Temperature Measurement

In this section the definition of Kelvin and the relationship between Kelvin scale and Celsius scale is explained. The basic temperature is the thermodynamic temperature (T), unit of which is Kelvin (K). One Kelvin is defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water at 0.01°C.

The triple point is that combination of pressure and temperature at which ice, water vapor, and liquid water all exist in equilibrium. It is of fundamental importance in standard laboratories as it is relatively easy to reproduce triple point equipment with stability for long periods of time. The Celsius scale is now referenced to the Kelvin scale.

The consequences are that although the boiling point of water is considered a fixed point in the old Celsius system, it is not often used by standards laboratories because of the difficulties in reproducing the temperature. It is no longer a fixed point in the new scales, and water will henceforth boil at about 99.975°C. The Kelvin scale assigns the values of temperature to seventeen fixed points. These consist of six triple points, seven freezing points, one melting point, and three boiling points.

1.2.4.1 Understanding Gravity Effects

The standard gravity acceleration is 9.806650 m/s^2. However, variations of ± 0.1% are found around the world. These variations occur with height above sea level and attitude. Some values of gravity are represented in Table 1.7.

Table 1.7: Values of gravity at different places	
Physical Location	*Value of Gravity (g) (m/s²)*
Melbourne	9.79987
Wellington	9.80292
Hong Kong	9.78771
Pole	9.83216
Sydney	9.79683
Auckland	9.79962
Equator	9.78030

Transmitters if produced with rated accuracies of $\pm$0.05% then significant error can be introduced if a transmitter is calibrated and manufactured in the United States and used in Melbourne without a recalibration.

1.2.4.2 Gravity-dependent Units

Units such as psi, kg/cm^2, in Wc (inches of water column) and in Hg are all gravity dependent. The imperial unit of psi, is the pressure generated when the force generated by gravity acting on a mass of one pound is distributed over one square inch.

The same applies to units such as in wg (inch of water gauge) and in Hg (inch of mercury). The force at the bottom of each column is proportional to the height, density, and gravitational acceleration.

1.2.4.3 Gravity-independent Units

Gravity plays no part in the definition of Pascal. It has the same value wherever it is measured. Units such as pounds-force per square inch and kilogram force per square centimeter are also independent of gravity. The definition of pound-force is the force required to accelerate a mass of one pound by $9.806650 m/s^2$.

Under standard gravity conditions, the pound-weight and pound-force are numerically equal (which is the cause of considerable confusion). Under non-standard gravity conditions, correction factors are required to compensate for the departure from standard.

1.2.5 Pressure Measurement and Use of Pascal

1.2.5.1 Bar

After the introduction of SI units, the use of bar (100 kPa) gained favor, especially in European industry where it closely resembled the mks unit of kg/cm^2. At that time the SI unit was called the "Newton per squared meter". As well as being quite a large word, it was thought to be inconveniently small. The use of the millibar in meteorology lent weight to the acceptance of the bar.

1.2.5.2 PSI

In the English system, pressure was generally measured in pounds per square inch (lb/in^2) psi. The Standard Atmosphere was expressed as equal to the pressure exerted by a column of mercury 29.92 inches high at 32°F. The density of mercury at this temperature is 0.4913 lb per cubic inch and this determines "atmosphere" at 14.7 psi.

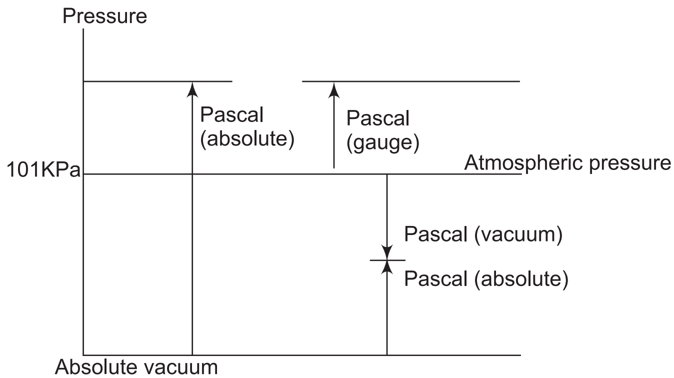

Figure 1.1: Use of Pascal in pressure measurement

Figure 1.1 represents various forms of expression of pressure at different conditions. The representation of the pressure as gauge and absolute is very common in the industrial measurement. Similarly, Table 1.8 represents different forms of expression of pressure as used in pneumatic communication of the industrial instrumentation systems.

Table 1.8: Units for pneumatic transmission

Output 20 kPa–100 kPa		
In Percentage	*In Kilopascal*	*In Pound per square inch*
0	20	2.902
10	28	4.063
20	36	5.225
25	40	5.805
30	44	6.386
40	53	7.547
50	60	8.788
60	68	9.869
70	76	11.030
75	80	11.611
80	84	12.191
90	92	13.353
100	100	14.514

For answers to checkpoint, scan the QR code

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Checkpoint

✦✦ **1.** The Treeby is a coherent unit such that, Treeby = (k.force.time)/temperature. If "*k*" is a constant, what are the SI units of Treeby?

✦✦ **2.** Convert these quantities:

Fathoms per Fortnight	*SI Equivalents*
24,250 Newton	Kilonewtons
10^{-9} picometer	Meters
12 dalx	Lm/m^2
2×10^{-7} Tzh	MHz
0.01°C	Kelvin
150 kPa (gauge)	kPa (absolute)
10 psi	kPa

✦✦✦ **3.** Using the information provided for Mercury in the Section 1.2.5.2, show how the 14.7 psi value for atmospheric pressure is determined. Justify your working using physical principles.

✦✦ **4.** A range of 3–15 psi corresponds to how much of kPa?

1.3 COMMUNICATION PROTOCOLS

LO 3

Explain the communication protocols

In this section, we shall understand the definition of a *signal*, leading into an analysis and comparison of pneumatic, analog, electrical, and digital protocols.

In analog electrical signals, the importance of power supply and the relative merits of a current, or voltage standard are considered. Digital communication standards are viewed from the perspective of Pure and Hybrid (Smart) systems. Comparisons are made between competing network topologies for a future field standard.

1.3.1 Signal

Information in the form of a pneumatic pressure, an electric current or mechanical position that carries from one control loop component to another is termed as a signal.

Note:
✦ Level 1 & Level 2 category
✦✦ Level 3 & Level 4 category
✦✦✦ Level 5 & Level 6 category

1.3.1.1 Pneumatic Signaling

The basic pneumatic mechanism converts a small motion or force into an equivalent (proportional) pneumatic signal. Most systems use 3–15 psig/20–100 kPa span which corresponds to 0–100% of scale. Using the traditional flapper nozzle control element, it may be seen that the scale movement is not linear. Electronics can correct for this non-linearity. Figure 1.2 depicts the characteristics of such a signal.

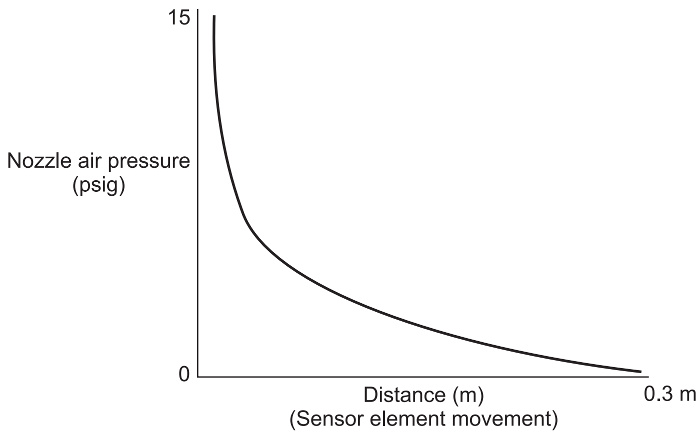


Figure 1.2: Sensor element movement

Advantages

- Sufficient power levels for positive valve actuation.
- Safe in hazardous area.

Disadvantages

- Longer the run of tubing, more significant the errors due to lag and temperature.
- Dirty air can clog orifices in those sensors using traditional technologies.

In common practice, a 0–100% input signal to a current to pneumatic converter (I/P) can be calibrated to a 1–17 psig (7–115 kPa) output to ensure from opening and closing of the control valves. Some times larger non-standard pressures (for example, 500 kPa) are used to reduce actuator sizing and save money.

1.3.1.2 Analog Electrical Signals

In the past, a competition for the analog field standard was in the range 0–20 mA, 10–50 mA, and 4–20 mA. The latter emerged as the preformed option, in practice it is better to have a "live zero" input to a device. Otherwise a 0 mA input could be ambiguously related to either zero output or a complete loss of signal due to power supply failure. As per the standards, 4 mA corresponds to zero input and 0 mA to complete loss. Using the analog standard gives rise to considerations best appreciated in the case of two wire transmitters in series with a power supply and various control room indications. The typical connection diagrams are represented as shown in Figure 1.3.

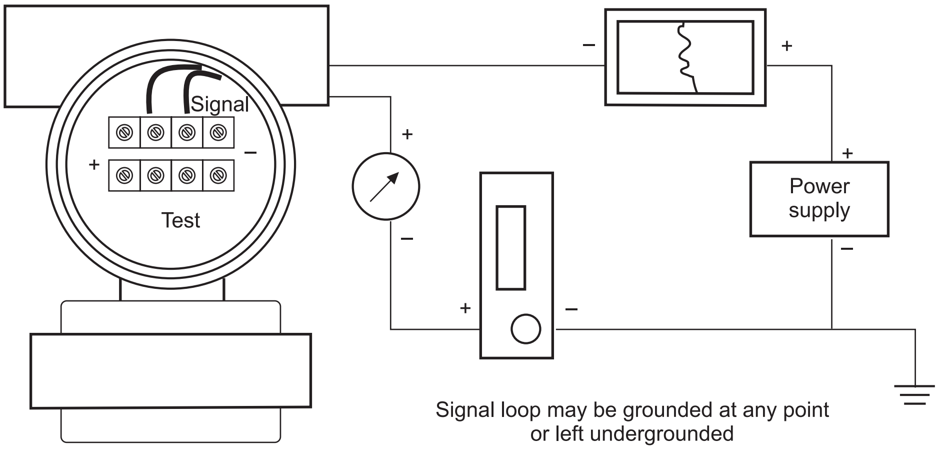


Figure 1.3: Representative analog signal loop

The transmitter acts as a variable load. To enable the meter to register the full 4–20 mA deflection, the combined effects of the transmitter and control room instrumentation load cannot exceed a value determined as per Figure 1.4. As shown in the figure, the combined load cannot exceed about 800 ohm for a 30 V dc supply. In reverse, a given load demands a minimum driving voltage.

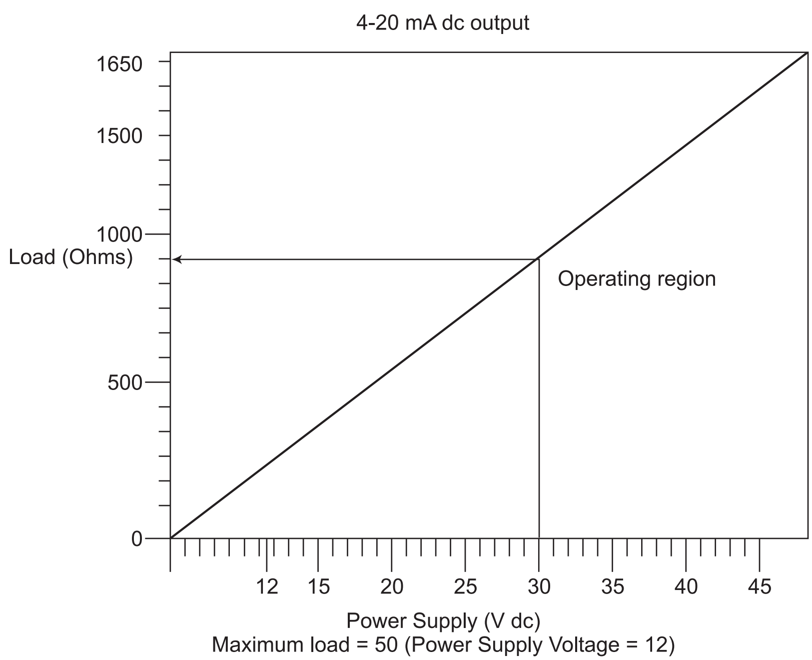


Figure 1.4: Operating resistance range of analog loop

If power supply should fall below this minimum, the effects on output are as shown in Figure 1.5.

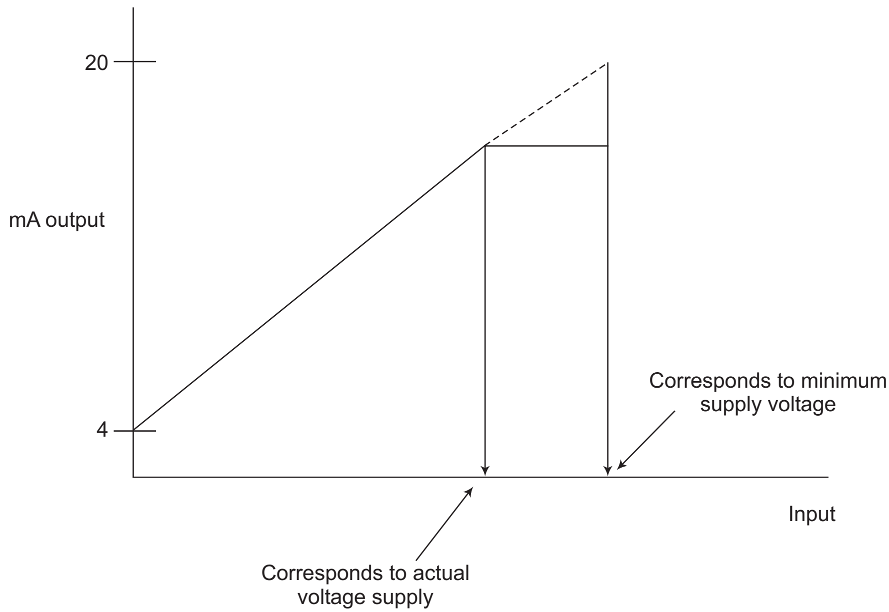


Figure 1.5: Operating voltage range of analog loop

It can be seen to be some ways preferable to have a voltage field standard. In this way indicators would be in parallel with the instrument. However, current based standards are less noise susceptible and are no subject to "voltage drop" on long cable runs.

1.3.1.3 Pure Digital Systems

The OSI model is used to delineate various parts of the digital standard as follows:

- Layer 1: Physical layer—physical transfer bits
- Layer 2: Data link layer—manages access control
- Layer 3: Network layer—performs routing functions between nodes
- Layer 4: Transport layer—provides reliable data transfer
- Layer 5: Session layer—synchronizes and manages data
- Layer 6: Presentation layer—restructures data to/from standard format
- Layer 7: Application layer—provide service to user application

This model modularizes the components of the networking hardware and software based on functionality. Each module takes the form of a layer in the model and is responsible for providing service to the layer above. A service is an abstract capability provided at the boundary between any two layers of the model. Services are provided by either hardware, software, or through the service availability from the layer below.

1.4 HYBRID SYSTEM

LO 3

In this system, two-wire transmitters are employed. The analog signal is so modulated that it carries digital control communication simultaneously with process measurement. A smart instrument employs simultaneous analog and digital communications.

The standard of smart instrument is the HART (highway addressable remote transducer) protocol, and is supported by more than 175 manufactures.

1.4.1 HART Communication

1.4.1.1 Definition of HART

Highway Addressable Remote Transducer (HART) is the open, standards based communication protocol to exchange digital information over analog wires between smart transmitters and control system. It is a widely adopted bidirectional digital communication protocol designed for industrial process measurement systems. HART superimposes digital signal over a traditional 4–20 mA analog loop, which allows a simultaneous analog signal with a continuous digital communication signal that has no effect on the quality and quantity of analog signal (process measurement) (Figure 1.6).

HART facilitates data access between intelligent field measurement transmitters and control, monitoring (host) systems. A host system can be any software application such as a handheld configurator or laptop-based system, control system, field device management application, etc.

HART was originally developed by Rosemount Inc. in 1980s. Later the standard has been made completely open, by sharing the technology with the partners and providing the rights to the independent HART Communication Foundation (HCF). HCF is an international, not-for-profit, membership-based organization, which owns technology and provides leadership, authority and control on the HART Protocol. HCF manages and controls the standard with new technologies and upgradations. HCF was founded in 1993 with the primary focus to improve the adaptation of HART communication protocols, standardize its position across the global plants, and maximize the value of HART instrumentation investments in the plants.

A maximum of four measurements can be transmitted in a single message using digital HART communication. Multivariable HART-based instruments have been developed to take advantage of single instrument with multiple measurement parameters. In addition, HART technology provided with a multidrop capability, where in all the HART enabled instruments can be connected to the traditional two wires in bus like connection, where in its legacy counterpart used to be connected to the system in a one-to-one mode, with pair of wires for each measurement. In a multidrop mode, each HART enabled instrument carries an address which is used for the communication by the control and host systems.

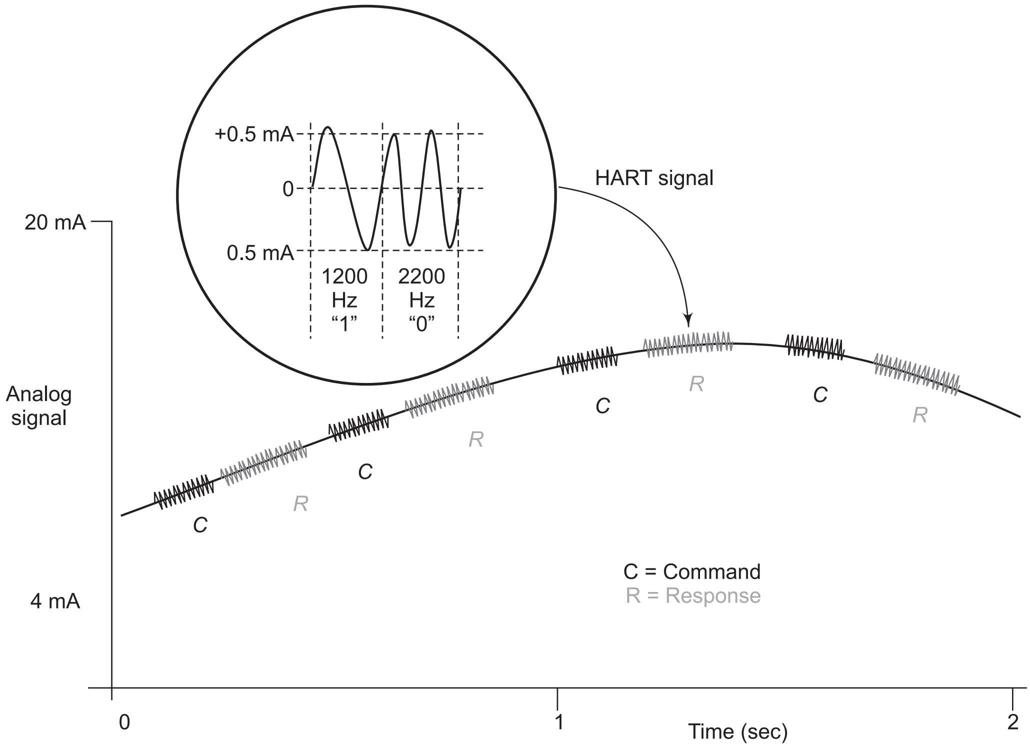


Figure 1.6: Digital over analog (frequency shift keying)

1.4.2 Basic Principle of HART

The following section explains the basic principles behind the operation of HART instruments and networks.

1.4.2.1 Frequency Shift Keying

Frequency shift keying (FSK) technique is the operating principle of the HART communication protocol which was developed using the Bell 202 telephone communication standards. The digital signal comprises of two frequencies—1,200 Hz and 2,200 Hz where the 1,200 Hz frequency represents "1" while the 2,200 Hz frequency represents "0". Sine waves of these two frequencies are superimposed on the direct current (dc) analog signal to achieve simultaneous analog and digital communication. This concept is represented in Figure 1.7. Even though there are two signals carried simultaneously on a common pair of wire, the average value of the FSK signal is always zero. Due to the average value being always "zero" the 4–20 mA analog signal which is a process measurement value is not affected. In general digital communication signals such as HART request and response codes have a response time of approximately 2–3 data updates per second without interrupting the continuous analog signal.

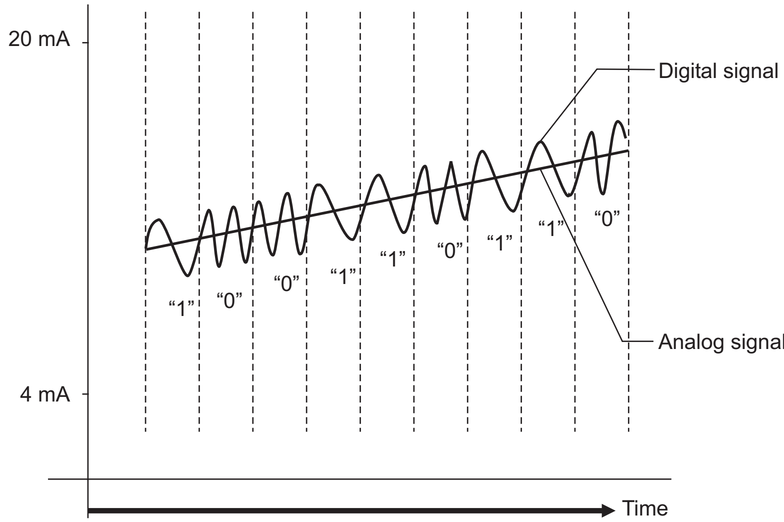


Figure 1.7: Example phase-continuous frequency shift keying

1.4.2.2 HART Communication Models

HART protocol supports two types of communications:

1. **Master-slave mode**: HART is a master-slave communication protocol. A master communication device initiates all slave (field device) communication during normal operation. In general, two HART master equipment/devices can be connected to each HART loop at any point of time. The primary master equipment is generally a DCS, PLC, or a personal computer (PC) while the secondary master equipments is a handheld configurator, PC or another laptop. Slave devices are process transmitters, valve actuators, and monitoring equipment that respond to commands from the primary or secondary master.
2. **Burst mode**: In burst mode, the master instructs the slave device (process transmitters, valve actuators) to continuously generate a standard HART response message (e.g. the value of the process variable). The slave device generates the message at a higher rate which is received by the master device until the time the master device instructs the slave to stop broadcasting the message. Burst mode in HART communication enables faster communication (3–4 data updates per second) with the master device or equipment.

1.4.2.3 HART Networks

The two basic network configurations in which the HART devices operate are listed as follows:

- **Point-to-point**: In this mode, one process variable is communicated via the traditional 4–20 mA signal whereas the additional process variables, configuration parameters, and other device data are transferred via the HART protocol digitally as shown in Figure 1.8. The digital signal—HART communication signal—gives access to secondary variables and other data that can be used for operations, commissioning, maintenance, and diagnostic purposes. The analog signal, 4–20 mA signal, can be used for normal control as they are not affected by the HART signal.

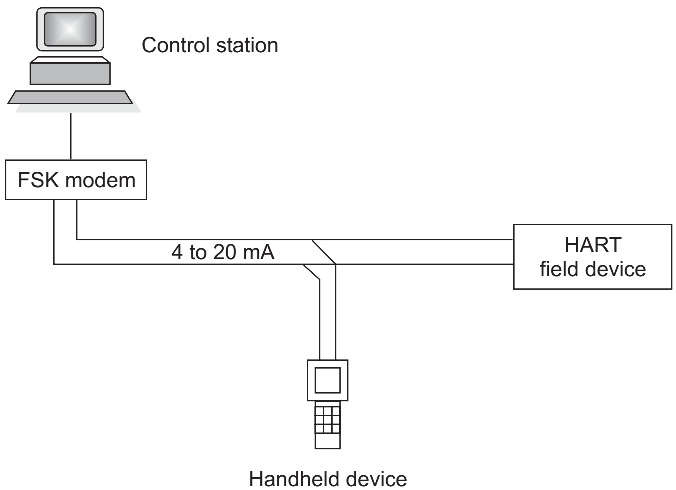


Figure 1.8: Point-to-point communication

- **Multidrop**: The multidrop mode of communication needs a single pair of wires, associated safety barriers, and power supply for up to 15 field devices as shown in Figure 1.9. In this mode, all the process values (variables) are digitally transmitted and all the field device-polling addresses are more than zero while the current through each device is fixed to a minimum value of 4 mA.

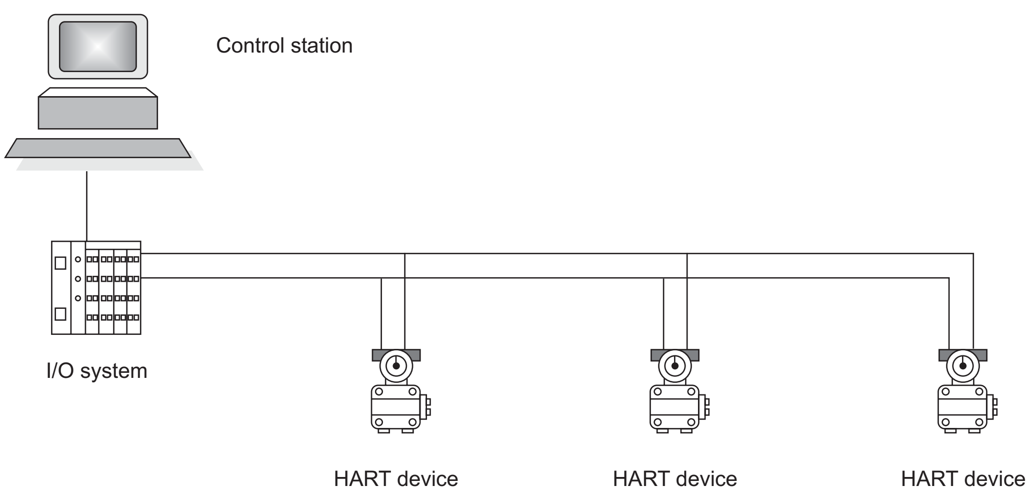


Figure 1.9: Multidrop mode of communication

1.4.2.4 HART Commands

The set of commands under the HART protocol are divided into three categories—universal, common practice, and device specific. These set of commands provide uniform and consistent communication for all kinds of field devices. Depending on the kind of applications, the host can implement the respective valid set of command.

- **Universal commands (0–30):** This command set must be supported by all HART devices and must be implemented exactly as specified by the HART foundation specifications. Universal commands provide normal operations related information such as read primary variable, units, etc.
- **Common practice commands (32–121)**: This is a set of commands applicable to a wide range of devices. This set of commands must be supported by devices whenever possible. Although the function of each command is well defined by the HART foundation specification, the actual meaning of the response data may require the interpretation of vendor DD files.
- **Device-specific commands (128–253)**: This command set is completely defined by the device vendor and each command performs a function specific to the particular device type and model. The use of these commands requires full interpretation of the vendor DD files.

1.4.3 HART Technology

HART communicating devices signal with either current or voltage, and all signaling appears as voltage when sensed across low impedance. For convenience, communicating devices are described in terms of data link and physical layers according to the OSI 7-layer communication model. Figure 1.10 represents the OSI layers and their corresponding equivalents in HART communications.

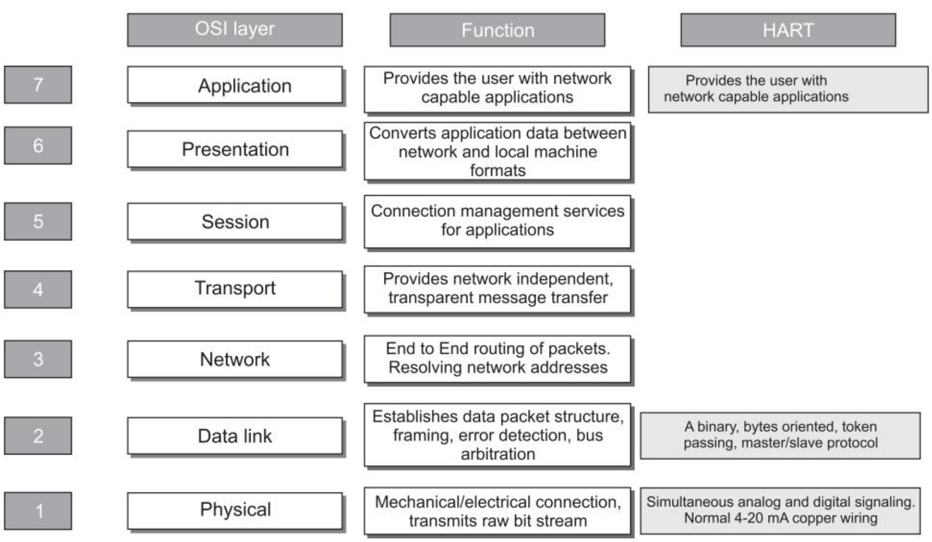


Figure 1.10: OSI 7-layer model

The HART protocol specifications maps to three layers in the OSI model: physical layer, data link layer and application layer.

1.4.3.1 Physical Layer

The physical layer is an abstraction for connecting process transmitters together and communicates the data in an electrical format (such as voltage, current, frequency) from one device to another. Physical layer describes the mechanical and electrical properties of the connection and the medium (the copper wire cable) connecting the process transmitters and valve actuators. Signal characteristics are defined to achieve reliability in communication and data transportation. The physical layer specifications specify the physical device types, network configuration rules, sample topologies and common characteristics of all devices, which include analog signaling requirements, device impedance, test requirements, cable characteristics, etc.

The physical layer commonly uses twisted-pair copper cable as its medium and provides solely digital or simultaneous digital and analog communication. Maximum communication distances vary depending on network construction and environmental conditions. A representation of the relationship between the HART protocol communications layers (including firmware and hardware) is given in Figure 1.11.

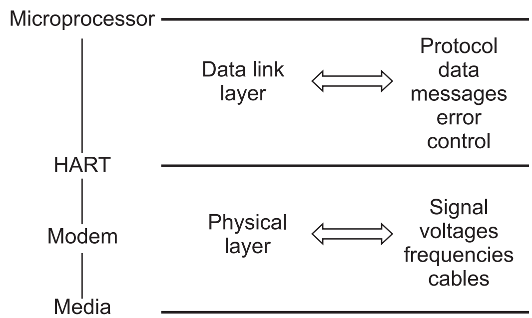


Figure 1.11: Data link layer and physical layer relationship

1.4.3.2 Data Link Layer

The data link layer is responsible for reliably transferring the data in the channel. In order to ensure proper access to the communication channel, this layer packages the raw bit stream into packets (framing) along with addition of error detection codes to the data packet and then performs a media access control (MAC). The concept is applicable at both sides of the communications such as master and slave process transmitters.

The bit stream is arranged into 8-bit bytes that are further organized into messages. In general, a HART transaction means a command from the master and a response from the slave. In this case, MAC constitutes of passing token between the process transmitters and valve actuators connected to the channel. The token pass is implied by the HART message transmitted. Timers are used to maintain the period between transactions. Once the timer expires, the owner of the token releases the control of the channel.

1.4.3.3 Features

- The analog signal can drive local devices, such as remote indicators, while re-ranging (say) is accomplished from the control room as shown in Figure 1.12.
- These devices may accommodate multiple masters for example a control system, handheld communicator, process computer, or in some cases, a combination of the three as represented in Figure 1.13.

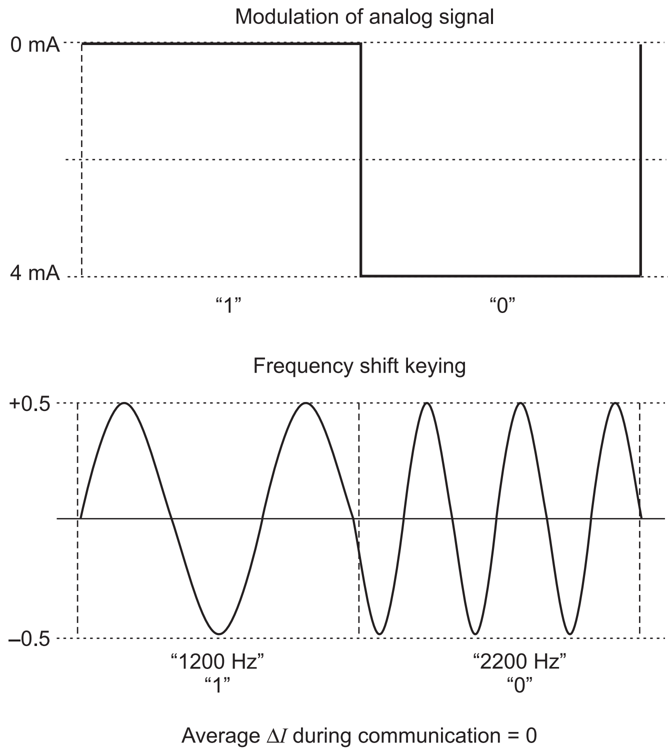


Figure 1.12: Two basic signaling mechanisms

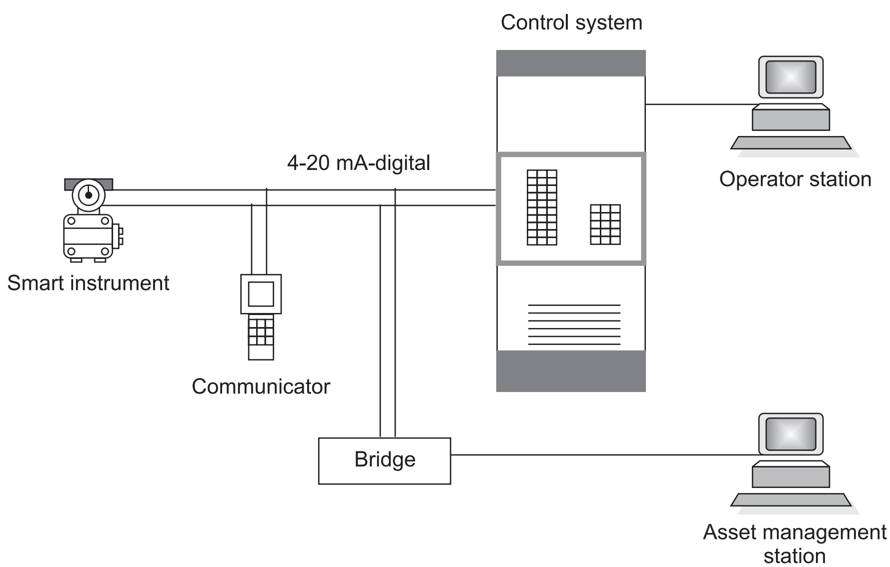


Figure 1.13: Smart transmitter linked to control

- Multidropping is possible with digital communications as shown in Figure 1.14.

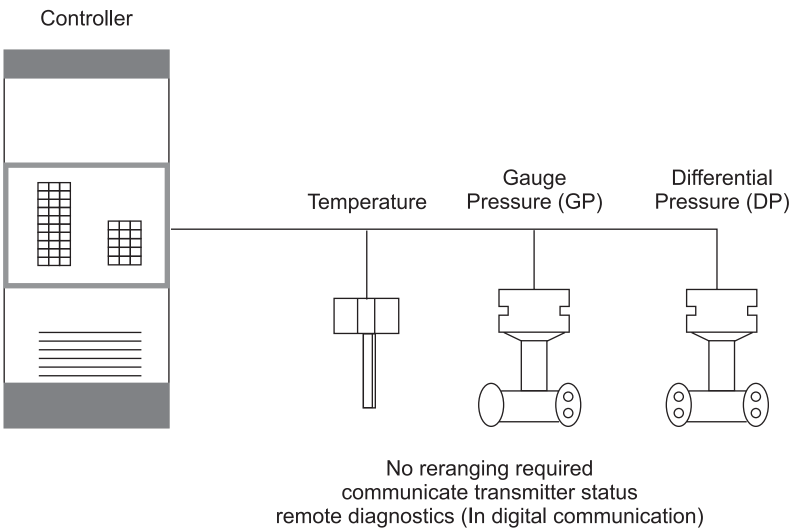


Figure 1.14: Multi-drop or bus network

- However, no common standard exists for a purely digital system. If additional instruments are connected in the same loop, the speed of the link gets reduced and reliability of the overall loop gets reduced. A vast amount of information can flow between the device and the control system. For example, process variable, transmitter status, configuration data, device panel layout, maintenance, construction information, temperature compensation data, alarm units, diagnostics, and loop checks. Communication can be managed remotely as shown in Figure 1.15 and 1.16.

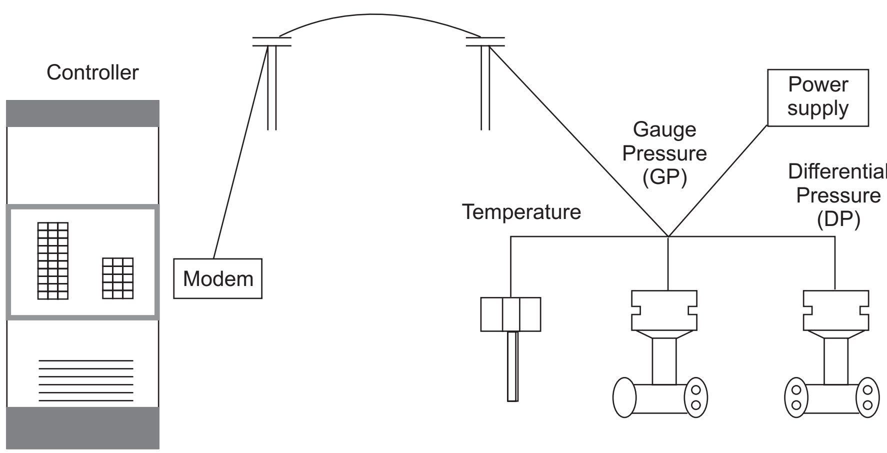


Figure 1.15: Leased telephone line communication

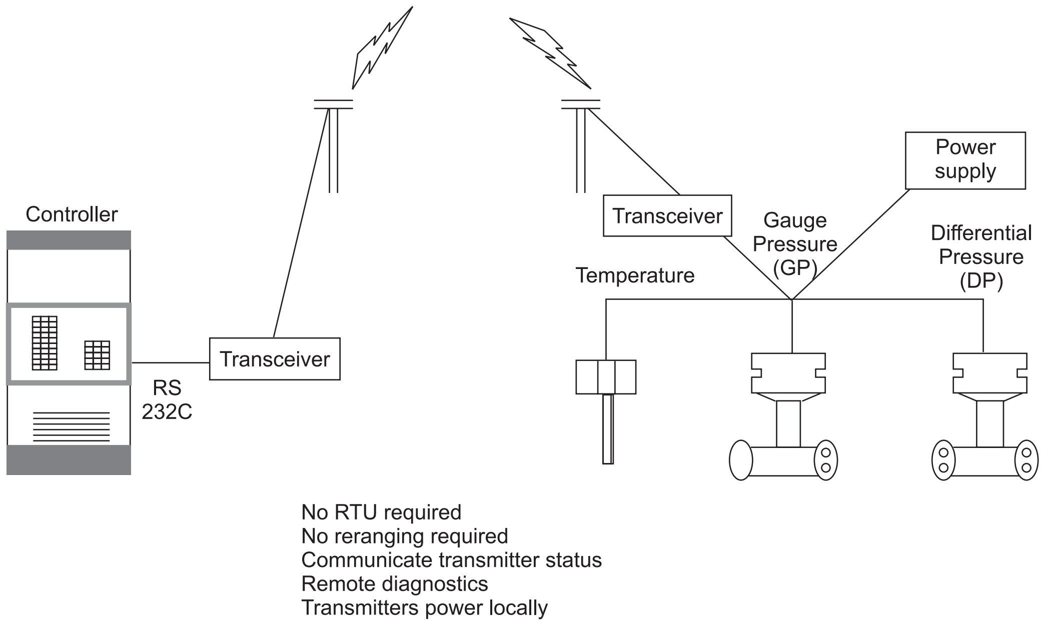


Figure 1.16: Radio communication

1.5 FOUNDATION FIELDBUS

LO 3

With the merging of world FIP and ISP (interoperable system project) into fieldbus foundation, progress towards an international agreed standard of digital communication took a leap forward and beta testing of software is now complete.

1.5.1 Introduction to Foundation Fieldbus

When process control first came into existence, it was only pneumatic and analog (4–20 mA) communication between field devices and the controller. These signals carried minimum information to the controllers. It was followed by hybrid communication, HART protocol, which has been discussed in the previous section. In addition to analog transmission capabilities, it provides remote communication to field devices.

1970 saw the emergence of DCS and with its introduction, process industries were able to distribute intelligent control systems across various levels.

In early 1990s, foundation fieldbus emerged in the market. Two parallel supplier consortiums, ISP and World FIP North America merged to form the Fieldbus Foundation Organization. The new organization immediately brought critical mass to achieve an internationally acceptable fieldbus protocol. The foundation organized development programs, conducted field trials for end users to drive foundation fieldbus technology in industrial applications.

Foundation fieldbus is a communication protocol which is all-digital, serial, two-way multidrop communication system and interconnects fieldbus devices with the control system.

It runs at a speed of 31.25 kbit/s that is used to connect intelligent field equipment such as process transmitters, valve actuators, and logic controllers. It serves as a local area network (LAN) for the instrumentation used within process plants and facilities. The intelligent network provides built in capability for distributed control applications and intelligent monitoring equipment across the network.

1.5.1.1 Overview of a Foundation Fieldbus System

Foundation fieldbus system is a DCS composed of field devices such as process transmitters and valve actuators and control/monitoring equipment such as DCS, PLCs, recorders, single/multiloop controllers integrated into the physical environment of a plant. Foundation fieldbus enabled devices communicate together to provide input/output and control for industrial process measurement and automation. Foundation fieldbus systems also operate in process controlled environments which require intrinsic safety. The process transmitters and actuators typically operate with limited memory and processing power and with networks that have low bandwidth constrained by the environment in which they operate.

1.5.1.2 Features

The foundation fieldbus retains the legacy functionality of the 4–20 mA analog system such as:

- Single-loop integrity from the sensing to the transmitters, barriers, junction boxes and marshalling panels to the control system.
- Standardized physical signals in the wire, where any transmitter with the 4–20 mA can communicate with any control system.
- Bus-powered devices on a single wire pair, where a single pair of wires carries the power to the process transmitter, while simultaneously transmitting the signal to the control system.
- Wide options for intrinsic safety and proven safety features with current and voltage limiting equipment.

In addition, foundation fieldbus enables:

- Better features due to full digital communication, reduced cabling and cable terminations due to many process transmitters on a single wire.
- Better options in selection of the suppliers due to interoperable standard.
- Less control room equipment due to distribution of functionality to the field.
- Provisions for connectivity with the high speed ethernet (HSE) backbone for larger systems and complex integrations.

The advantages of the foundation fieldbus over the legacy systems are as follows:

- Signals being digital are immune to noise.
- The need for damping to filter out noise is no more required as this is handled by the processor with advanced algorithms.
- Process transmitters and valve actuators are automatically detected by the host and all the connected devices are listed as a live list.
- Each of the process transmitter or devise carries an address and the host systems assign the address automatically. This automated address assignment eliminates

any possibility of duplicate addressing and enhances the mistake proofing in system configuration.

- Legacy input and output cards are 8, 16 or 32 channels and the density of the channels is decided based on criticality and cost. Generally these are costly and become a single point of failure. Module failures can generally cause all associated loops to fail. In case of foundation fieldbus, there is no input and output module concept and failure of single equipment does not cause the entire control loop to fail. The same is applicable in the case of accidental module removal or during troubleshooting.
- Minimizes the failure probability of the equipment due to reduced components in the overall control loops. In general, any loop with less equipment has a better reliability.
- The traditional systems are configured for the alarm limits, critical diagnostics such as cable failures, etc., whereas in a foundation fieldbus enabled system, there is no such need as such features are built in automatically as safety functions.
- The traditional systems use the scaled ranges. This implies that the engineer needs to configure in the system to indicate what it means by 4 mA and what it means by 20 mA. Foundation fieldbus uses engineering units, not scaled ranges—this eliminates the need for engineering the units in the system and hence provides a mistake proofing in engineering where there is a conflict in the ranges by human errors.
- In traditional systems, the actual sensor measures the signal in an analog mode, converts to the digital for processing and then is converted to analog for communication purpose. In case of foundation fieldbus—since there is no analog communication, associated conversions are not required. A direct digital processing and communication improves the accuracy and reliability of the overall system.
- Unlike the traditional systems, the foundation enabled smart process transmitters can measure multiple parameters from a single instrument. For example, a traditional differential pressure transmitter can provide the delta pressure wherein a multi variable differential pressure transmitter can provide temperature, delta pressure, gauge pressure and absolute pressure.
- The process transmitters are built with intelligence required to provide information which enables proactive maintenance.

1.5.1.3 Benefits

Foundation fieldbus enables increased capabilities due to full digital communications; reduced loading on control room equipment; input and output functions being migrated to filed devices and reduced wiring and terminations; multiple devices on one wire besides providing vast amount additional information from each field device that can be utilized for asset management and health maintenance. In fieldbus, multiple process variables as well as other information can be transmitted along a single wire pair. This is quite different from the traditional approach of connecting 4–20 mA devices to a DCS system using dedicated pairs of wires for each device. This means all the process transmitters and segments of these transmitters becomes a part of DCS. This shall require an integrated workflow based approach for network design, field device configuration, data rendering and storage. In addition, some design activities are to be performed earlier in the project cycle. Complex functions can be achieved within the foundation fieldbus devices that shall have significant cost designs and appreciably reduces the commissioning and start up time.

Foundation fieldbus can be utilized for majority of the process control applications, including the field instruments connected to the DCS. This shall include control valves, motor operated valves, transmitters and local indicators.

1.5.2 Fieldbus Network Classification

Foundation fieldbus has two types of network as depicted in the Figure 1.17. One is the foundation fieldbus H1 running on 31.25 kbits/s which is used to interconnect the field equipment like sensors, actuators and I/O. The other one is HSE running at 100 Mbits/s which provides integration of high-speed controllers (PLCs), H1 subsystems (via a linking device), data servers, and workstations.

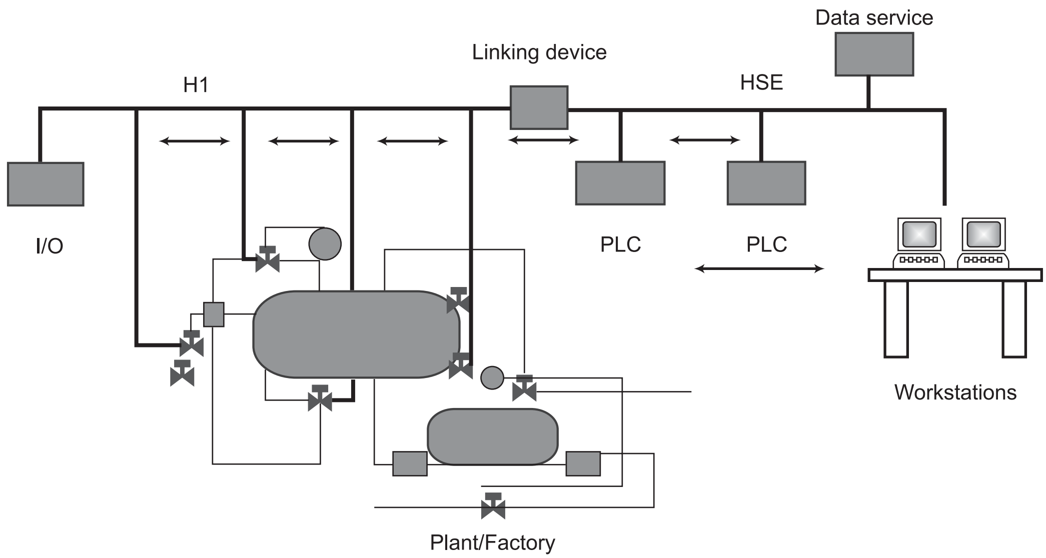


Figure 1.17: Fieldbus network classification

1.5.2.1 Foundation Fieldbus Topology

Foundation fieldbus network consists of fieldbus device, spur, trunk, device coupler, and fieldbus power supply as illustrated in Figure 1.18.

- **Link**: A link is the logical entity in which H1 fieldbus devices such as process transmitters and valve actuators are interconnected. Typically a link consists of one or more physical segments interconnected by bus, repeaters, or couplers.
- **Segment**: A segment is a section of a foundation fieldbus that is terminated in its characteristic impedance, meaning a cable and devices installed between pair of terminators. Repeaters are used to link segments to form a longer fieldbus.

- **Trunk**: Trunk is the cable between the control room and the junction box in the field. This is the longest cable path on the fieldbus network. This is the main fieldbus communication cable.
- **Spur**: Spur is a cable between the trunk cable and a fieldbus device, usually connected to the trunk via a device coupler. Spur is the cable that connects a device to the trunk.
- **Device coupler**: Foundation fieldbus device coupler is located where the trunk is connected to various device spurs. The device couplers have built in protection for short circuit. These features minimize the impact of a short circuit at one field device affecting the whole segment.
- **Fieldbus power supply**: Fieldbus requires special kind of power supply. The commonly available power supplies which were used to power the fieldbus would absorb signals on the cable in order to maintain a constant voltage level. A conditioned power supply for fieldbus is a way to isolate the fieldbus signal from the low impedance of the bulk supply. The inductor lets the dc power on the wiring but prevents signals from going into the power supply.

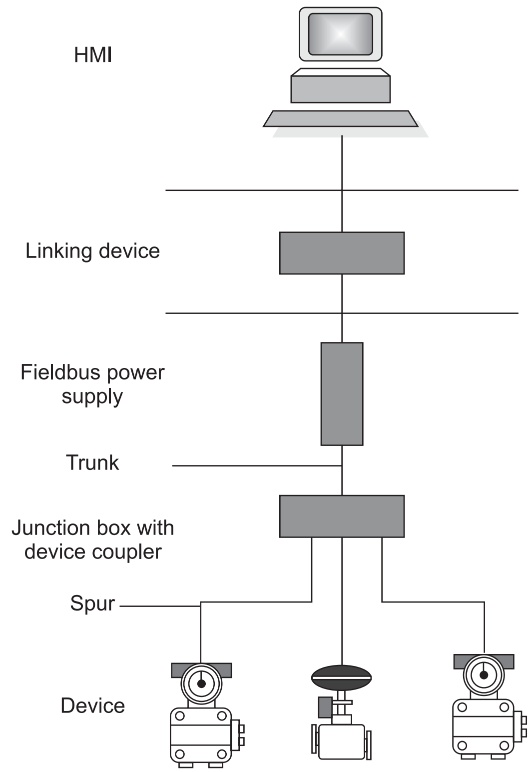


Figure 1.18: Foundation fieldbus network overview

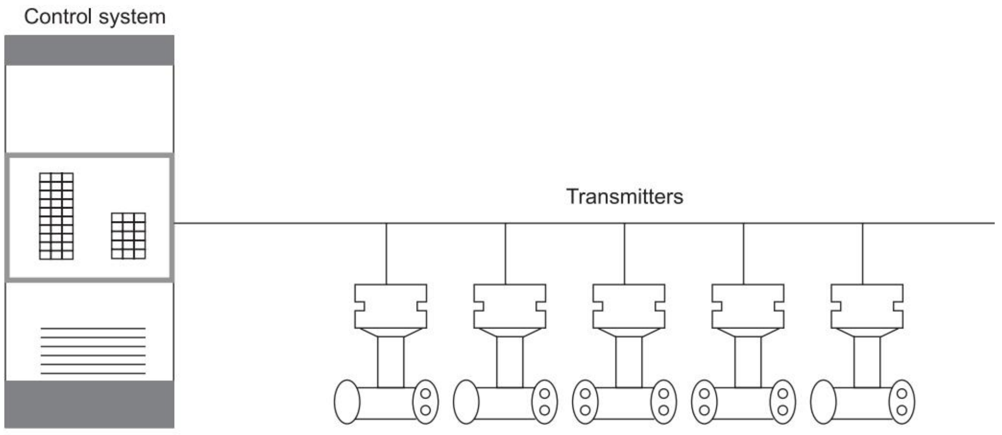
- **Fieldbus device**: In a conventional 4–20 mA DCS, two wires are used to connect to a device and in this case the data acquisition and control lies with the controller. With the introduction of foundation fieldbus, data acquisition and the control lie in the fieldbus device itself.

1.5.2.2 Foundation Fieldbus Connection Topologies

There are several possible topologies for fieldbus networks. This section illustrates some of the possible topologies and characteristics of each.

Topologies There are several types of topologies that are considered for a fieldbus network during the design and implementation phases of the projects.

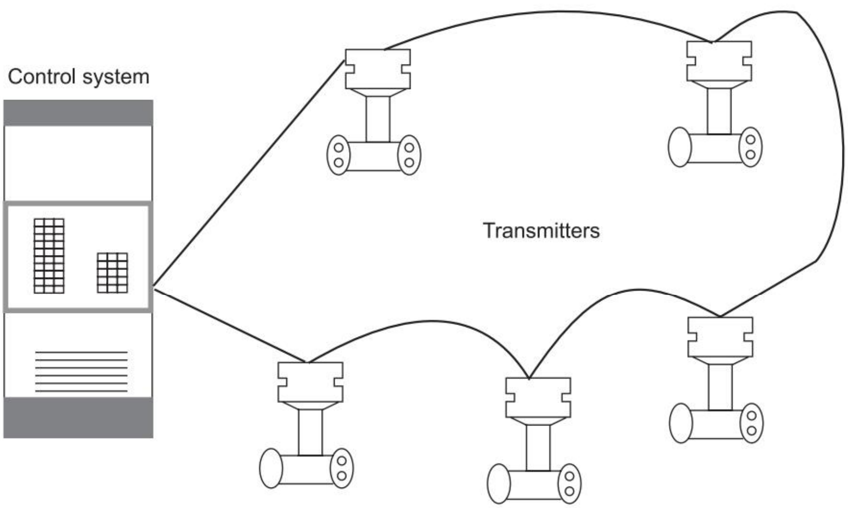
Bus topology provides a wide separation of devices in the field because each drop on the network is independent of the rest. Devices are not required to be operational to complete communications to other devices. Refer to Figure 1.19 for the typical bus topology of a network.



Design Attributes: Efficient wiring for wide separation of devices, potential for simpler protocols. Single device failure cannot cause a catastrophic network failure.
Design Liabilities: Greater installed cost due to the number of taps. Spacing and length of drop are critical. Maintenance complexity. Upfront engineering to plan for device connection.

Figure 1.19: Bus topology

Ring topology shown in Figure 1.20 indicate two possible communication paths, thereby increasing the reliability of the foundation fieldbus network. In this topology, each device acts as a repeater, so a fiber optic implementation can be easily accomplished. This type of topology is more expensive because of the complex nature of the electronics involved.



Design Attributes: Potential for simple point to point connections. Lends itself to fiber optics. Enhanced reliability.
Design Liabilities: Increased planning for wiring, increased hardware for complexity, each device is active and/or reporter of information.

Figure 1.20: Ring topology

Tree topology, also known as chicken foot topology, is an alternate type of bus configuration in foundation fieldbus network design. It consists of a single fieldbus segment connected to a common junction box to form a network. In this type, the junction box can be either active or passive and is consistent with current wiring practices. It also allows field wiring to be done different to that of the "home-run" cabling from the junction box back to the controller. Figure 1.21 depicts the physical connectivity of the devices in this type of topology.

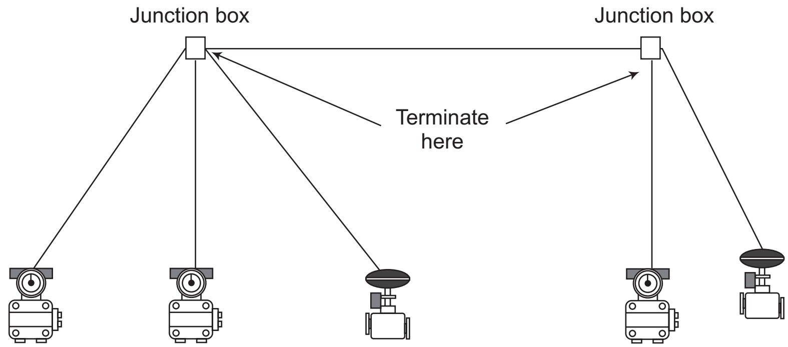


Figure 1.21: Tree topology

Point-to-point topology consists of a segment having two devices only. It could be a field device like a transmitter connected to a host system for monitoring or a slave and host device operating independently like a transmitter and valve with no connection beyond the two. Refer to Figure 1.22 for the physical connectivity of the devices in this type of topology.

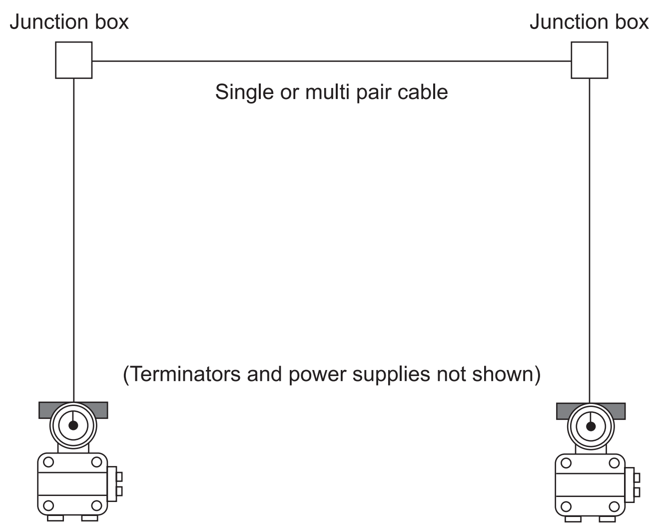


Figure 1.22: Point-to-point topology

Spur topology consists of foundation fieldbus devices interconnected to a multidrop bus. The bus segment through a length of cable up to the field device is called a spur. A spur can vary in length from 1 m to 120 m. Refer to Figure 1.23 for the physical connectivity of the devices in this type of topology.

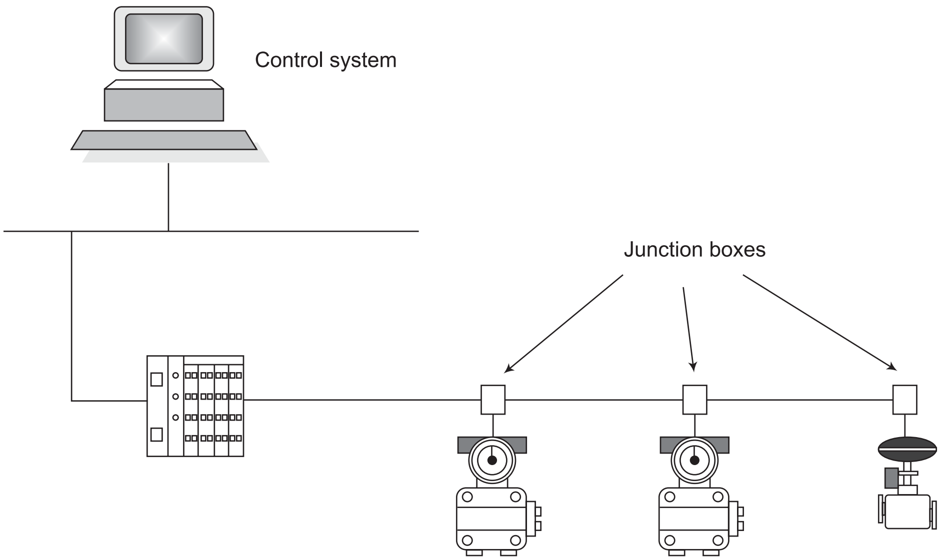


Figure 1.23: Spur topology

In daisy chain topology, the fieldbus cable is arranged from device to device on this segment and is interconnected at the terminals of each foundation fieldbus device. Refer to Figure 1.24 for the physical connectivity of the devices in this type of topology.

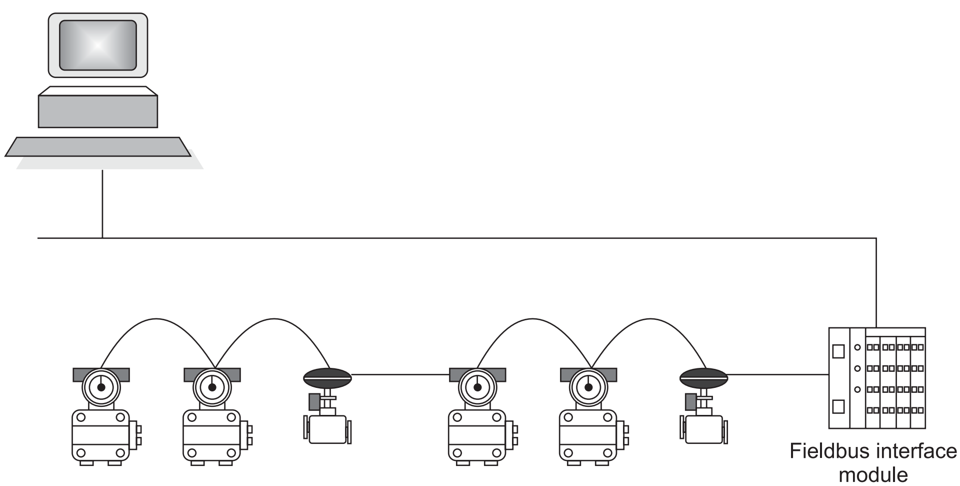


Figure 1.24: Daisy chain topology

One is the H1 running on 31.25 kbits/s, which is used to interconnect the field equipment like sensors, actuators and I/Os. The other one is High (HSE) running at 100 Mbits/s, which provides integration of high-speed controllers (PLCs), H1 subsystems (via a linking device), data servers, and workstations.

For answers to checkpoint, scan the QR code

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Checkpoint

✦✦✦ 1. What are the different topologies in foundation fieldbus network?

✦ 2. Explain the meaning of a signal.

✦ 3. Explain the 7 layers in the OSI framework.

✦✦ 4. Explain the reason for HART being called as hybrid system.

✦✦ 5. Name the different HOSTs that can use the HART enabled process data.

✦✦ 6. Explain the common practice commands in HART and their range of commands.

✦✦✦ 7. What are the different classes of the HART Commands?

1.6 OBJECTIVES AND TOPOLOGIES

LO 4
Discuss the objectives and topologies of instrumentation and systems

1.6.1 Objectives of Instrumentation and Systems

In an instrumentation and control system, measuring instruments acquire data and transmit it to a controller—typically, a computer or any microprocessor-based embedded intelligent system. The controller then transmits data (or control signals) to control devices, which act upon a given process. Quick and efficient data transfer between different systems in a plant along with a data communication links for integration of a system. A network-based communication between the systems in an automation system eliminates expensive wiring and multiple termination points. Safety, productivity and quality are the major objectives of any production facility. Production management can be improved by collecting data accurately and timely. An ICS can help the plant management to achieve safety, quality and productivity. The main purpose of an ICS, in an industrial environment, is to provide the following:

- **Control processes**: Traditionally, analog controllers communicating on standard 4–20 mA loops were used to control processes such as level and pressure. It is a common practice in industry to mix and use equipments from various systems in the same control system. The 4–20 mA standards are utilized by instruments and controllers from different suppliers. Nowadays, such controllers and instruments have been replaced by integrated systems such as DCS.
- **Control sequencing, interlocking:** In earlier times, control of sequencing, interlocking and alarms were provided by timers, relays and other components that were hardwired

into motor control centers and control panels. These requirements have now been replaced by PLCs.

- **Operator interface for display and control**: Traditionally, several operators, each responsible for a portion of the overall process, operated process plants from local control panels. Modern control systems tend to use a central control room to monitor the entire plant. The control room is equipped with computer-based operator workstations that gather data from the field instrumentation and use it for graphical display, to control processes, to monitor alarms, to control sequencing and for interlocking. Most of the operator interfaces and modern control rooms are designed for human factors such that operations are controlled in stress-free environments.
- **Management information**: Earlier management information was collected by taking readings from panel meters, recorders, annunciators, counters, and process transmitters. The information is also collected from the labs, which are samples taken from the production process. Management information data helps in monitoring the overall performance of a process/plant and provides the data needed to manage the process. Data acquisition systems in the modern day automation systems are integrated into the overall control system. This eliminates the collection of information from multiple sources at multiple frequencies and reduces the time required to correlate and use the information.

The ability of control equipment to fulfill the above needs has been met by recent the technological advancements in the fields of data communication, microprocessors, and integrated electronics.

Four types of systems that have made the most significant impact on how plants are controlled are:

- Smart instrumentation systems (SIs)
- Data acquisition systems
- SCADA Systems
- PLCs
- DCS

1.6.2 Smart Instrumentation Systems

By 1960s, most of the instrumentation systems had migrated from pneumatic instruments to the 4–20 mA analog interfaces. The 4–20 mA based systems were established as the standard for instrumentation technology. As a result, the suppliers of instrumentation devices had a standard communication interface on which to communicate with other control products. Users had an option to select the best instruments and sensors for their specific applications, from a wide range of suppliers. Any instrument, from any supplier has the ability to be integrated into their control systems. With the advent of microprocessors and the development of digital technology, the demands of the production from instrumentation have changed. Most users realized and started appreciating the advantages of digital instruments compared to the legacy analog instruments. These include more available information from the same device, local and remote display, reliability, cost, diagnostic capability. Owing to technical advancements, there has been a gradual shift from analog to digital technology. Numerous digital process transmitters together with their digital communication capability have taken over most traditional process control applications. Some of the examples include process transmitters for measuring temperature, pressure, level, flow, mass (weight), density, and power system parameters. These new and intelligent digital transmitters together make up the "smart" instrumentation. Vital features that can be attributed to a "smart" instrument are digital data communication capability; digital sensors, and the ability to be multidropped and interconnected with other devices.

There is also an emerging range of intelligent, communicating, digital devices that could be called "smart" actuators. Examples of some of these devices are protection relays, soft starters, variable speed drives and switchgear control with digital communication facilities.

1.6.2.1 Impact of the Microprocessor

The microprocessor has had an enormous impact on instrumentation and control systems. Traditionally, an instrument had a single dedicated function. Controllers were localized and, although commonly computerized, they were designed for a specific purpose. A microprocessor, as a general-purpose device, can replace localized and highly site-specific controllers. Microprocessors that can analyze and display data as well as calculate and transmit control signals are capable of greater efficiency, productivity, and quality gains.

Currently, a microprocessor connected directly to sensors and a controller, requires an interface card. This implements the hardware layer of the protocol stack and in conjunction with appropriate software, allows the microprocessor to communicate with other devices in the system. There are many instrumentation and control software and hardware packages; some are designed for particular proprietary systems and others are more general-purpose. Interface hardware and software now available for microprocessors cover virtually all the communication requirements for instrumentation and control. As microprocessors are relatively low cost, they can be upgraded easily as newer and faster models become available, thereby improving the performance and capacity of the instrumentation and control system. It means more features, less power and more reliability for the same cost. A comprehensive coverage of smart instrumentation is dealt as separate chapter in this book.

1.6.3 Data Acquisition Systems

DAQs were developed for applications where data collection and storage is the only requirement. The simplest of the DAQ systems have INPUT modules arranged in some modular racks and connected to the PC and software applications in the PC render/archive the information. The information from these systems is typically used for analysis, storage purposes. Chapter 8 covers more details on data acquisition systems.

1.6.4 Supervisory Control and Data Acquisition (SCADA)

Supervisory control and data acquisition systems are an enhanced version of the DAQ systems with some supervisory control. The typical application of the SCADA is in large, geographically distributed systems, where in the data collection occurs and supervisory control is provided from remote and central systems. The applications in which SCADA is used are utilities like electrical, gas and water monitoring applications. Chapter 10 covers more details on SCADA systems.

1.6.5 Programmable Logic Controllers

Programmable logic controllers were developed in the late sixties to replace huge sets of electromagnetic relays and associated complex wiring. Electromagnetic relays were particularly used in the automobile manufacturing industry for sequence control and interlocking with racks of on/off inputs and outputs. A central processor using programs such as ladder logic, sequence control, function blocks, etc., controls them. Modern PLCs now include analog and digital I/O modules and sophisticated programming capabilities similar to DCS, e.g. PID loops programming. High-speed inter-PLC (peer-to-peer) links are also available, such as 10 Mbps and 100 Mbps Ethernet (Chapter 9).

1.6.6 Distributed Control Systems (DCS)

A distributed control system is a digital hardware and software-based process control system that also functions as a data acquisition system. This system has a distributed and integrated architecture of modules each of which performs a specific task (operator interface, analog or loop control and/or digital control, etc.). The DCS system is based on a data highway and an interface unit is also available on the data highway through which other devices such as PLCs and other supervisory computer devices can be easily connected (Chapter 11).

The subsystems mentioned above typically constitute the instrumentation and control systems used in a plant. Through the list above is not complete, but provides an overview of the essential part. The details of each of these subsystems are dealt in the subsequent chapters.

1.6.7 Conceptual/Functional Topology of an Automation System

In the previous section, various levels of an automation system and the primary duties performed at each level are discussed. In this section, we shall discuss the conceptual topology of a system in relation to the reference model. We already know that there are five layers/levels of an automation system. The physical realization of such a system will be discussed now.

The conceptual topology diagram and functional areas are shown in Figure 1.25. The level 1 of the reference model can be mapped to the transmitters, control valves, solenoid valves, and limit switches, etc. The level 1 device functionally is meant to sense process, manipulate process, sense events, manipulate equipment, etc. The level 1 device communicates with the level 2 system using a communication mechanism. The communication mechanisms differ from system-to-system and they start from a base current based 4–20 mA to a digital communication technology.

The level 2 contains the controllers like DCS, PLC, safety systems, batch controllers, and single-loop controllers. The functional responsibility of the level 2 controllers is on/off control, programmed control, continuous control, phase control, interlock and safety control. The level 2 controllers will communicate with the level 2 systems using the plant communication network. The level 2 systems constitute HMI systems, SCADA systems, etc. Functionally the level 2 systems are responsible for alarm management, operator visibility, operator control, supervisory control, and recipe control, etc.

Level 2 and level 3 are connected by a network called plant information network and systems from various vendors are interfaced using the standards based interfaces. The level 3 systems contains MES, LIMS, etc., and are functionally expected to perform detailed scheduling, production execution, production analysis, etc.

Level 3 and level 4 are connected using a plant network and standard based interfaces. The level 4 devices contain ERP, SAP, etc., and functionally are expected to provide MIS, decision support system.

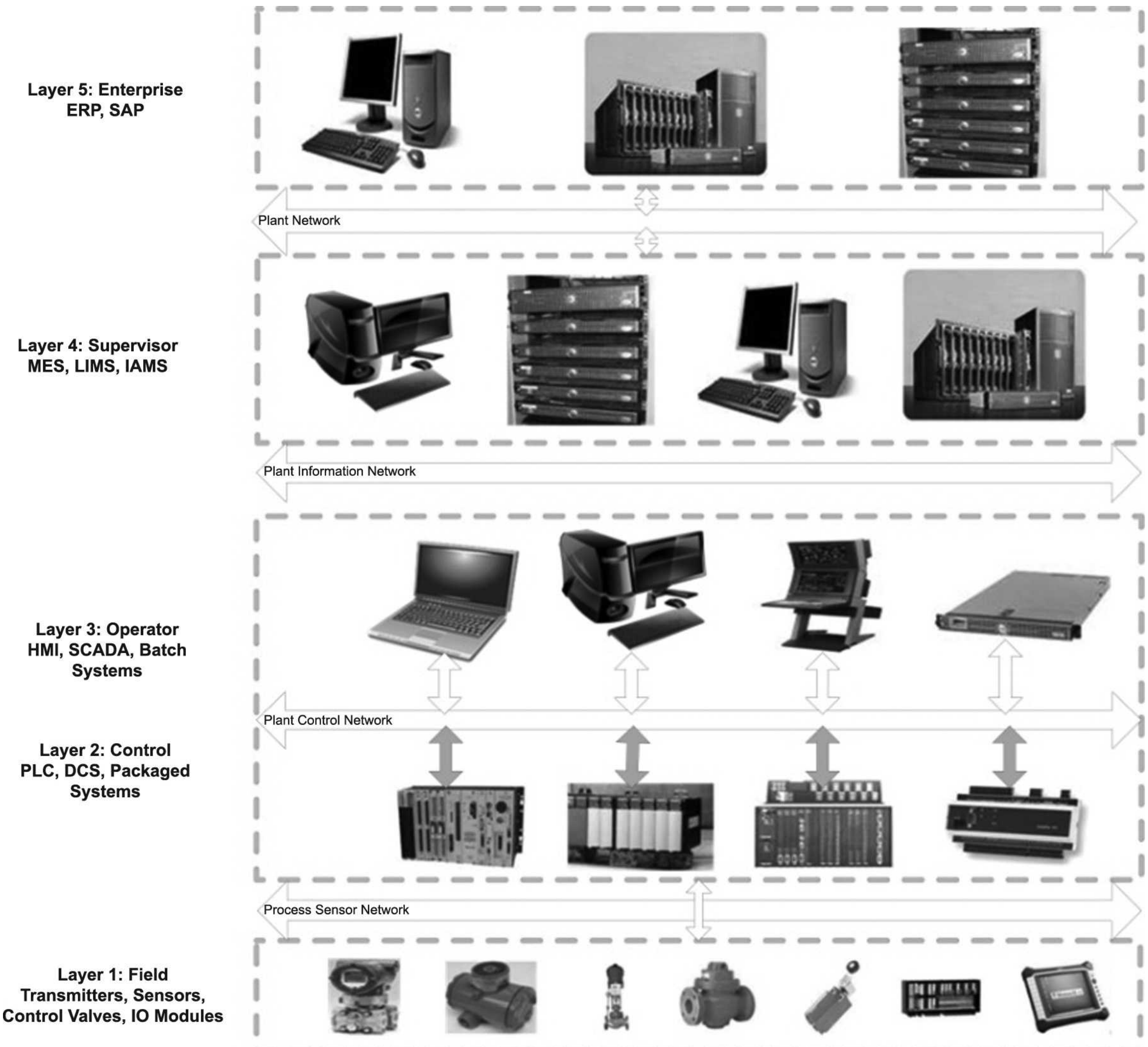

Figure 1.25: Conceptual topology of an automation system

Summary

LO 1: Outline the history of instrumentation and control

- From a safety point of view, pneumatic instrumentation is considered better compared to the electrical and electronic counterparts.
- Instrumentation and control skills in the plants increased over a period of time with the increased deployment of instruments and hence new departments were created with instrument engineers, technicians and mechanics, etc.
- The central, computer-based control having many advantages has a major disadvantage in terms of becoming a single point of failure. That means, if the computer fails for any reason, the entire operations of the plant comes to a halt.
- International Society of Automation has evolved as a nonprofit organization for developing standards in instrumentation for manufacturers and suppliers of the systems.
- The current to pneumatic and pneumatic to current (I/P) converters provide an interface between electronic instruments to pneumatic instruments, sensors and actuators.
- Introduction of the microprocessors in the instrumentation systems accelerated the deployment of the instruments due to availability of features at an affordable price.
- Most microprocessor-based control systems had a vast array of alarms and diagnostics to help plant operators and maintenance personnel to determine if there were any problems in the plant.
- The computer-integrated manufacturing (CIM) and management information systems (MIS) interfaced the real time devices through distributed controllers to multiple station coordination, then on to scheduling, production and management information to the plants levels. This helps in overall planning, execution and control.

LO 2: Describe the units of measurement

- The needs for the rationalization of many units lead to SI system of units (System International d'unites).
- The triple point is that combination of pressure and temperature at which ice, water vapor, and liquid water all exist in equilibrium.
- Gravity has an impact on the calibration of some varieties of the transmitters. If a transmitter is produced with a rated accuracy of $\pm$0.05% then significant error can be introduced if the same transmitter is calibrated and manufactured in the United States.

LO 3: Explain the communication protocols

- Signal is the information in the form of a pneumatic pressure, an electric current or mechanical position that carries from one control loop component to another.
- Pneumatic communication uses a flapper-nozzle control element and is nonlinear in nature. The electronic units can correct the nonlinearity.
- Analog communication standard had ranges of 0–20 mA, 10–50 mA and 4–20 mA. The later emerged as the preferred option; in practice it is better to have a "live zero" into to a device. Otherwise a zero milliampere input could be ambiguously related to either zero output or a complete loss of signal due to power supply failure.
- The transmitter acts as a variable load in electrical analog communication. To enable the meter to register the full 4–20 mA deflection, the combined effects of the transmitter and control room instrumentation load cannot exceed a value determined from the characteristics of the load.
- The analog signal is so modulated that it carries digital control communication simultaneously with process measurement. A smart instrument employs simultaneous analog and digital communications.

- HART is an open, global, standards-based communication protocol to exchange digital information over analog wires between smart transmitters and control systems.
- HART provides data access between intelligent field instruments and host systems.
- A maximum of four measurements can be transmitted in a single message using digital HART communication.
- A master communication device initiates all slave (field device) communication during normal operation.
- Burst mode enables faster communication (3–4 data updates per second).
- The 4–20 mA analog signals are not affected by the HART signal and can be used for normal control.
- The command set includes three classes: universal, common practice, and device specific.
- Physical layer in HART communication is an abstraction for connecting the mechanical and electrical properties of the connection and the medium (the copper wire cable) connecting the devices.
- The physical layer commonly uses twisted-pair copper cable as its medium and provides solely digital or simultaneous digital and analog communication.
- The data link layer is responsible for reliably transferring the data in the channel. In order to ensure proper access to the communication channel, this layer packages the raw bit stream into packets (framing) along with addition of error detection codes to the data packet and then performs a media access control (MAC).
- The bus topology lends itself to a wide separation of devices because each drop on the network is independent of the rest.
- Tree topology is an alternate type of bus configuration in foundation fieldbus network design. It consists of a single fieldbus segment connected to a common junction box to form a network. In this type, the junction box can be either active or passive and is consistent with current wiring practices. It also allows field wiring to be done different to that of the "home-run" cabling from the junction box back to the controller.
- Foundation fieldbus is a communication protocol, which is digital, serial, two-way multidrop communication system which interconnects fieldbus devices with the control system.
- Foundation fieldbus runs at 31.25 kbits/s and connects intelligent field equipment such as sensors, actuators, and controllers.
- The two kinds of foundation fieldbus networks are—foundation fieldbus H1 network and HSE network. Foundation fieldbus H1 network runs on 31.25 kbits/s and is used to interconnect the field equipment like sensors, actuators and I/Os. High speed ethernet network runs at 100 Mbits/s and provides integration of high-speed controllers (PLCs), H1 subsystems (via a linking device), data servers, and workstations.

LO 4: Discuss the objectives and topologies of instrumentation and systems

- DCS is based on a data highway and has a modular, distributed, but integrated architecture.
- The level 1 device functionally is meant to sense process, manipulate process, sense events, manipulate equipment, etc.
- The level 2 contains the controllers like DCS, PLC, safety systems, batch controllers, single loop controllers. The functional responsibility of the level 2 controllers is on/off control, programmed control, continuous control, phase control, interlock and safety control.
- Level 2 and level 3 are connected by a network called plant information network and systems from the various vendors are interfaced using the standards based interfaces.

Questions

I. Objective-type questions

✦ **1.** What is the current accepted international standard system of units?
(a) MKSA (b) SI
(c) CGPM (d) CGS

✦✦ **2.** What is the accepted base unit for temperature measurement?
(a) Celsius (b) Kelvin
(c) Rankine (d) Centigrade
(e) Fahrenheit

✦✦✦ **3.** Which pressure unit or units are not dependent on the effect of gravity?
(a) Kg/cm^2 (b) Pascal
(c) Inches water gauge (d) Inches mercury

✦✦✦ **4.** What is the basic unit of volumetric flow?
(a) Liters per minute (L/min)
(b) Cubic meter per hour (m^3/h)
(c) Cubic meters per second (m^3/sec)
(d) Megaliters per hour (ML/h)

✦✦ **5.** Circle the SI unit in each of the following groups:
(a) Gram, kilogram, milligram, pound
(b) psi, kg/cm^2, kilopascal, Pascal
(c) Degrees Celsius, Kelvin, degree centigrade, degree Kelvin

✦✦✦ **6.** Provide the correct symbol for each of the following units (make sure to use the correct case):
(a) Newton __________ (b) Kilopascal __________
(c) Hertz __________ (d) Meter __________
(e) Millimeter __________ (f) Milliampere __________
(g) Kilogram __________ (h) Second __________
(i) Megavolt __________ (j) Megameter __________
(k) Megawatt __________ (l) Gigahertz __________

✦✦✦ **7.** Which are the seven basic units?
(a) Pascal (b) Kilometers
(c) Bars (d) m^3/s
(e) Celsius (f) Ampere
(g) Meter (h) Kelvin
(i) Gram (j) Candela
(k) Hour (l) Kilogram
(m) Weber (n) Second
(o) Mole

✦✦✦ **8.** DCS system provides user to:

(a) Control (b) Monitor
(c) Archive process data (d) All of the above

✦✦✦ **9.** Which of the following is true of centralized computer control?

(a) Supervisory control used PLCs that were designed to be standalone and had little need for communication networks.
(b) Centralized computer control was more reliable than using many single loop controllers.
(c) Wiring and design cost was less and were more scalable than with decentralized controls.
(d) Redundant control often required analog instruments that make control strategy changes more difficult.
(e) All of the above

✦✦✦ **10.** Which of the following was employed in the first third of the 20th century to bring the meter face readings into a centralized control room?

(a) Pneumatic signaling transmitter
(b) Radio signaling transmitter
(c) Manual control
(d) Hydraulic signaling transmitter

✦✦✦ **11.** Which of the following correctly indicates how direct digital control system elements are specified?

(a) Unique numbers for hardware points and reusable software points identified by type code only
(b) Reusable identifiers for each type of hardware and software point
(c) Unique numbers for software points and reusable identifiers for each type of hardware point
(d) Unique number for each hardware and software point

✦ **12.** Which body defines the standards for instrumentation?

(a) IEEE (b) NEMA
(c) ISA (d) Local government body

✦✦✦ **13.** DAQ system provides user to:

(a) Control
(b) Monitor
(c) Archive process data
(d) Perform safe shut down operations

✦ **14.** The SI units of flow are:

(a) m^3/h (b) kg/s
(c) km/h (d) m^3/s

✦✦ **15.** Pressure = force/area, Force = mass x acceleration, Acceleration = length/time^2. How would the derived units of pressure, the Pascal be expressed in base SI units?

(a) kgm/s^2 (b) kg/ms^2
(c) m/s^2 (d) g/s^2m

✦✦ **16.** Standard signal used by transmitters is:

(a) 4–20 mA (b) 0–230 V

(c) 0–110 V dc (d) 0–16 mA

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II. Short-answer questions

✦ **1.** Which are the standard units in SI systems?

✦✦ **2.** Explain the triple point of water.

✦✦✦ **3.** Which type of cable and medium used in HART physical layer communications?

✦✦ **4.** Name the types of the bus topologies in HART communication based field devices.

✦✦✦ **5.** What is the throughput of the HI network in foundation fieldbus?

✦✦ **6.** Explain the additional capabilities added with digital communications such as foundation fieldbus.

✦✦ **7.** List the different parts of the foundation fieldbus topology.

✦✦ **8.** Explain HSE and the throughput of the network.

✦ **9.** Explain how a dirty air can create a traditional sensor to malfunction.

✦✦✦ **10.** Explain the impact of loop resistance on the functionality of the process transmitter.

III. Unsolved problems

✦ **1.** The lift off (operating) voltage of a 4–20 mA transmitter is specified as 12–30V, if the PLC measuring the current has an input resistance (impedance) of 250 ohm, the drop due to the transmission line measured to be around 2V. Calculate the minimum power supply voltage that should be applied on the transmitter.

IV. Critical-thinking questions

✦✦ **1.** Explain a unit that is a combination of two or more units.

✦✦✦ **2.** Explain the concept of calibration.

✦ **3.** Explain the meaning of media access control.

✦✦ **4.** Are local gravity variations important in any part of your plant measurement process? Does your past work experience provided an example of where it became important?

✦✦ **5.** Are there nonstandard units in your industry? Why are they retained? Does it create any problems?

✦✦✦ **6.** Why are very precisely defined standards be considered as both important and unimportant?

✦ **7.** What is World FIP?

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Temperature

2

LEARNING OBJECTIVES

After reading this chapter, you will be able to:

1 Describe the need for temperature measurement and measuring units

2 Outline different principles in temperature measurement

3 Illustrate the theory and application of thermocouple and RTD

4 Analyze analog and smart temperature transmitters

5 Illustrate the calibration methods for temperature transmitter

In this chapter, the history of temperature scales and the current International Practical Temperature Scales (IPTS) standards are overviewed, together with conversion formulae for Fahrenheit, Celsius, Kelvin, and Rankine. A consideration of the desirable characteristics of a temperature sensor leads to a discussion of various thermometry elements—bimetallic, filled thermal, quartz, crystal, radiation pyrometers, thermistors, thermocouples, and resistance temperature detectors (RTDs).

The theory of thermocouples involves examination of the Peltier, Thomson, and Seebeck effects. In addition, the importance of thermoelectric inversion, junction configurations, reference junctions, cold junction's compensation, and laws of thermocouple behavior are also explained. Distinctions are drawn between various thermocouple types, wiring conventions and applications.

The principles of RTD operation involve the introduction of R zero (Ro), alpha coefficient and Callendar Van Dusen equation, RTD types—immersion, surface mount (especially thin film)—are examined in the context of appropriate electrical connections and lead wire compensation bridges.

Over many decades, the constant demand for temperature sensors, transmitters and controllers has shown that temperature is the principal process variable of the plant comparted to others and is a serious concern to the process industries to control temperature of the process. Temperature control is critical to process operations such as distillation, drying, evaporation, absorbing, crystallizing, etc. Temperature control also plays a critical role in the safe operation of process plant facilities.

Keywords:
Resistance temperature detectors, thermocouple, Seebeck effect, platinum, temperature coefficient, pyrometers, mercury-filled thermometers, Thomson effect, Peltier effect, calibration, thermowell, bimetal-lic, Kelvin, Celsius

"To measure is to know"

Lord Kelvin

2.1 TEMPERATURE MEASUREMENT AND MEASURING UNITS

LO 1

Describe the need for temperature measurement and measuring units

2.1.1 Measuring Temperature

The physical variable in science to which humans are most sensitive is temperature. In earlier days human was able to differentiate between hot and cold sense organs. What is temperature? Webster's define temperature as "The degree of hotness or coldness measured on a defined scale". It is sometimes more convenient to think of temperature as the level of thermal energy just like voltage is a measure of electrical energy. Temperature is the driving force for heat flow as the voltage is the driving force for the flow of electricity.

By definition, temperature is a physical property of matter that quantitatively represents the common notions of hot and cold. It is perhaps the most fundamental physical parameter to be measured in a process plant. It is a good indicator of the intrinsic relationship of physical, chemical, and biological processes at the molecular and the complete system level. A variety of products and techniques have been developed to measure temperature in different situations and over a wide range of values. Such measurements are often used in various applications, to avoid unwarranted influences of temperature.

Galileo is credited with the invention of first thermometer around 1592. The thermoscope, as it was called, consisted of a glass tube with entrapped air that expanded or contracted by changes in barometric pressure.

Developments in the thermometer design continued until 1654, when the first hermitically sealed devices were made. The measurement of temperature difference could then be made independent of atmospheric pressure. In 1664, Robert Hooke placed a "Zero" on his thermometer at the point where the liquid in the thermometer stood when the bulb was placed in freezing distilled water. There was, however no universal agreement on the scales applied to these early thermometers.

Isaac Newton defined a temperature scale based on two "fixed" points in 1701. In 1706, Daniel Fahrenheit used the freezing point of water and salt and the blood temperature of a healthy man as reference points. Anders Celsius proposed a scale in 1742 that had zero at the melting point of water and 100 at the boiling point of water that eventually resulted in the Celsius scale.

Temperature, in case of ideal gases primarily relates to the kinetic energy of the molecules of a substance (as described in the definition of the absolute, thermodynamic, or Kelvin temperature scale). On a less academic note, temperature may be defined as "the condition of a body which determines the transfer of heat to or from other bodies," or even more practically, as "the degree of 'hotness' or 'coldness' as referenced to a specific scale of temperature measurement."

2.1.2 Scales of Measurement

Temperature is a critical measurement because it affects so many things such as the rate of reaction, viscosity, state of matter, strength of materials, quality, taste of food, safety of processes and so on. Following are the scales of temperature used in the industry.

2.1.2.1 Thermodynamic Kelvin Scale

From thermodynamic point of view, zeroth law of thermodynamics states, "if two bodies are in thermal equilibrium with third body then they are in thermal equilibrium mutually". In continuation to this theory, second law of thermodynamics is used to define a temperature scale based on this thermal equilibrium, if different bodies are brought into connection thermally. It is a scale that is derived on basis of a perfectly reversible Carnot's engine. In addition, the scale that is derived for this unit is called as Kelvin that is 1/273.16 of temperature of triple point of water. These temperatures are identified through Ideal Gas equation.

The triple point is achieved when ice, water, and water vapor are in equilibrium. It is the defined fixed point of the thermodynamic Kelvin scale and has the assigned value of 273.16 K. Constant volume gas thermometers are designed on this principle.

2.1.2.2 Celsius (Centigrade) Scale

Celsius is a scale and unit of measurement for temperature. In 1742, Anders Celsius of Uppsala University in Sweden, reported the use of thermometers where ice point to steam point was 100° which was the fundamental interval. Celsius marked the ice point at 0° and the steam point at 100°. It was known as the centigrade scale for many years prior to 1948. Later by an international agreement, it was renamed the Celsius scale, in honor of its inventor. Used worldwide, temperatures are denoted as degrees Celsius (°C).

2.1.2.3 Fahrenheit Scale

Fahrenheit scale was defined in 1724 by Daniel Gabriel Fahrenheit using the using the ice point (32°) and the human body temperature (96°) as the fixed points of the scale. Therefore, the fundamental interval, from ice point to steam point, was calculated to be 180 degrees (212 - 32 = 180). The Celsius scale in most countries replaced the Fahrenheit scale during the mid-to-late 20th century though it still remains the official scale of the United States and some other countries. Scientific and engineering books have largely converted to the Celsius scale, but because the conversion is still not complete, many technical books provide a value in °C followed by the equivalent value in °F.

2.1.2.4 Réaumur Scale

The Réaumur scale of measuring temperature was invented by René Antoine Ferchalt de Réaumur in 1730. The scale is used in brewing and liquor industries. The fundamental temperature interval is defined by the ice point (0°) and a steam-point designation of 80°. The symbol is °R.

2.1.2.5 Rankine Scale

Rankine scale is the equivalent of the thermodynamic Kelvin scale but is represented in terms of Fahrenheit degrees. Thus, the temperature of the triple point of water on the Rankine scale corresponding to 273.16 K is nearly 491.69° Rankine.

2.1.2.6 *International Practical Temperature Scale*

International Practical Temperature Scale is a precision calibration standard with fixed reference points in addition to the ice point and the steam point. The last revisions to this scale occurred with the publication of the fixed points for the IPTS of 1968. This scale is not frequently used in the normal temperature measurements. Some of the intermediate reference points on the scale include the triple-point of equilibrium of hydrogen, the boiling point of neon, the triple point of oxygen, and the freezing points of zinc, silver, and gold.

2.1.3 Units and Conversions

Various temperature scales are defined by the assignment of numerical values of the temperatures to the list of additional calibration points (Table 2.1). Essentially, the scales differ in two respects:

- The location of the zero temperature
- The size of one unit of measure. The average thermal energy per molecule represented by one unit of the scale. The SI definition of the Kelvin unit of temperature is in terms of the triple point of the water. This is the state at which equilibrium exists between the liquids, solids, and gaseous state of water maintained in a closed vessel. The system has a temperature of 273.16 K.

Table 2.1: Various calibration points

Calibration Point	*Temperature*			
	K	*°R*	*°F*	*°C*
Zero thermal energy	0	0	–459.6	–273.15
Oxygen: Liquid/gas	90.18	162.3	–297.3	–182.97
Water: Solid/liquid	273.15	491.6	32	0
Water: Liquid/gas	373.15	671.6	212	100
Gold: Solid/liquid	1336.15	2405	1945.5	1063

2.1.3.1 *Absolute Temperature Scales*

An absolute temperature scale is one that assigns a zero temperature to a material that has no thermal energy, i.e. no molecules vibration. There are two such scales in common use: the Kelvin scale in Kelvin (K) and Rankine scale in degrees R (°R). These temperature scales differ only by the quantity of energy represented by one unit of measure. Hence, a simple proportionality relates the temperature in °R to the temperature in K. Table 2.1 shows the values of the temperature in the Kelvin and degrees Rankine at the calibration points. From this table we can determine that the transformation of temperature near the water liquid/solid points and water liquid/gas point is 100 K and 180°R. As these two numbers represent the same difference of thermal energy, it is clear that 1K must be larger than 1°R by the ratio of the two numbers (Equation 2.1):

$$(1\ \text{K}) = 180/100\ (1°\text{R}) = 9/5\ (1°\text{R})$$

Thus, the transformation between scales is given by

$$T(\mathrm{K}) = 5/9T\ (°\mathrm{R}) \tag{2.1}$$

where, T(K) = temperature in K, T(°R) = temperature in °R

2.1.3.2 Relative Temperature Scales

The relative temperature scales differ from the absolute scales only in a shift of the zero axis. Thus, when these scales indicate a zero of the temperature, the thermal energy of the sample is not zero. These two scales are the Celsius and the Fahrenheit with the temperature indicated by °C and °F. The quantity of the energy represented by 1°C is the same as that indicated by 1K, but the zero has been shifted in the Celsius scale. Similarly, the size of the 1°F is the same as the size of 1°R but with a scale shift (Equation 2.2):

To transform from the Celsius to Fahrenheit, we simply note that the two scales differ by the size:

$$\left.\begin{aligned} T(°\mathrm{C}) &= T(\mathrm{K}) - 273.15 \\ T(°\mathrm{F}) &= T(°\mathrm{R}) - 459.6 \\ T(°\mathrm{F}) &= 9/5T(°\mathrm{C}) + 32 \end{aligned}\right\} \tag{2.2}$$

Of the degree, just as in K and °R, and a scale shift of 32 separates the two.

2.1.3.3 Point-to-point Temperature Conversion

Conversion from one scale to another is a matter of simple algebra using the following formulae (Equation 2.3):

$$\left.\begin{aligned} °\mathrm{C} &= 5/9(°\mathrm{F} - 32) \\ °\mathrm{F} &= 9/5(°\mathrm{C}) + 32 \\ °\mathrm{K} &= 273 + °\mathrm{C} \\ °\mathrm{R} &= 460 + °\mathrm{F} \end{aligned}\right\} \tag{2.3}$$

Figure 2.1 shows the relationship between these different scales.

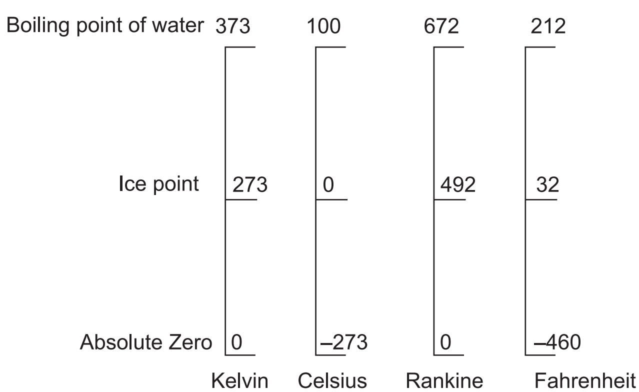

Figure 2.1: Relationship between different temperature scales

Interconversion of differential temperature requires special formulae as per Equation 2.4:

$$\left.\begin{aligned} °C &= 5/9°F \\ °F &= 9/5°C \\ °K &= °C \\ °R &= °F \end{aligned}\right\} \tag{2.4}$$

Note

If two points in a process differ in temperature by 100°C, the same two points differ by 180°F [i.e. 180 = 9/5 (100)] and they also differ by 100 K.

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Checkpoint

✦✦✦ 1. Define temperature.

✦✦✦ 2. What is the correlation between temperature and voltage?

✦✦✦ 3. What is Celsius scale?

✦✦ 4. What is the fixed point in thermodynamic Kelvin scale?

✦ 5. What is the fundamental interval in Celsius scale?

2.2 DIFFERENT PRINCIPLES IN TEMPERATURE MEASUREMENT

LO 2

Outline different principles in temperature measurement

Most of the sensors started their journey as mechanical sensors. Temperature sensors are no different to mechanical sensors, and below mentioned techniques are used to design them. Temperature has an impact on the physical properties of all materials. It is because of this feature, different measurement techniques have been developed for measuring temperature. The traditional measurement techniques of thermometers were based on the volumetric change in liquids and gases with change in temperature. This technique was used in a different way in bimetallic strips made of certain metals. Subsequently, temperature measurement techniques were developed based on thermoelectric methods for thermocouples, i.e. changes in the resistance of the material for the RTDs, thermistors, etc. Thermal radiation of the hot bodies served as the basis for radiation pyrometers.

Note: ✦ Level 1 & Level 2 category
✦✦ Level 3 & Level 4 category
✦✦✦ Level 5 & Level 6 category

The following sections of this chapter explain the above principles and their application in different situations. On a broader picture the sensors can be classified as mechanical sensors, passive electrical transducers and electrical transducers.

2.2.1 Quality Temperature Measurement

Every temperature-measuring device is made up of the following parts—sensing element, interpretation and display device, and a method of connecting the two together. The characteristics of these parts will vary based on the application to the device. For example, anybody can read a thermometer but it has no readable output for control purposes.

The following characteristics can be considered desirable in a sensing element:

- A clear and unambiguous response to temperature. Obviously a linear response would be easier to interpret and is most desirable for control applications.
- High sensitivity at all temperatures. The output of the sensor must change enough so that an accurate measurement can be made. Sensitivity can be described as the slope of the temperature measurement function—steeper the slope, more sensitive the device. If the slope is too flat, the sensing element will be unable to detect subtle changes in temperature.
- Stability is required if a reparable measurement is to be made. Many devices used to measure temperature may be adversely affected by the very medium in which the measurement must be made. For this reason, care must be taken to protect the sensing element from its environment. It is for this reason that RTDs and thermocouples are encased in a stainless steel sheath. The response time is lengthened but the tradeoff is a more durable sensing element.
- Low cost would obviously be a desirable characteristic of the ideal sensing element. In reality, the cost can vary from a few rupees for a disposable thermocouple to thousands of rupees for the most sophisticated pyrometers.
- Ideally, the sensing element would be capable of measuring a wide range of temperatures thereby reducing the instrumentation requirements.
- Small size is important in many applications.
- The thermal mass of the sensor must be low enough to make it possible to measure a change in temperature. In other words, if a great deal of heat is required to raise the temperature of the sensing element, the sensor would act as a heat sink and a small change would not be detected.
- Rapid response: the sensing element must be able to track accurately the changes in temperature of the medium being measured.
- Finally, the output of the sensing element must be useable for the intended purpose. A liquid in glass thermometer has a visual output that is ideal for many applications but is useless in unattended applications.

It should come as no surprise that the interpretation and display of temperature is as equally important as the sensor. The stability and sensitivity of the display must be at least as good as the sensing element. However, the display instrument can, in no way, improve the resolution of the temperature beyond that of the sensing element. It is also desirable that the readout instrument be capable of an output that is useable for recording or control.

2.3 THERMOMETERS

LO 2

Galileo is credited with the invention of first thermometer around 1592. The thermometer, then called the thermoscope consisted of a glass tube with entrapped air. It expanded or contracted as the temperature of the surrounding air changed. The first hermetically sealed devices were made in 1654.

2.3.1 Bimetallic Thermometers

The bimetallic thermometer is based on two simple principles. First point to know is that metals change in volume in response to a change in temperature and second is that the coefficient of change is different for all metals. If two dissimilar metal strips are bonded/joined together and then heated, the resultant strip tends to bend in the direction of the metal with the lower coefficient of linear expansion. The degree of deflection is directly proportional to the change in temperature. The bimetallic thermometer offers the advantage of being much more resistant to breakage than the glass thermometer; however, it is subject to change in calibration when handled roughly and the overall accuracy is not as good as the glass thermometer. Figure 2.2 represents a bimetallic thermometer.

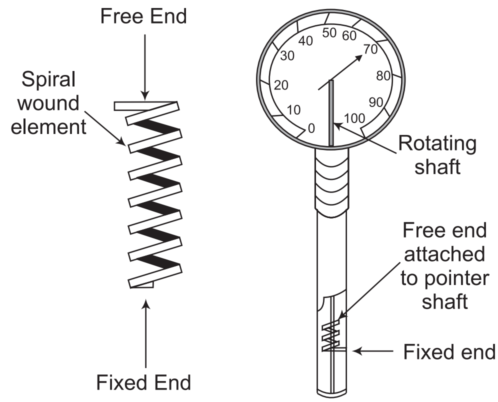

Figure 2.2: Bimetallic thermometers

2.3.2 Filled Thermal Elements

Filled thermal elements consist of a bulb connected to a small-bore capillary that is connected to an appropriate indicating device. The system acts as a transducer that converts pressure at nearly constant volume to a mechanical movement that in turn is converted to temperature by using an appropriate indicating scale. The entire mechanism is gas tight and filled with gas or liquid under pressure.

The fluid or gas inside the device expands and contracts with a change in temperature causing a bourdon gauge to move. The response time and accuracy provided by the filled thermal element are sufficient for many industrial-monitoring applications. Most of the industrial gauges are of type with filled thermal elements. Figure 2.3 provides a representative filled thermal system based temperature gauge.

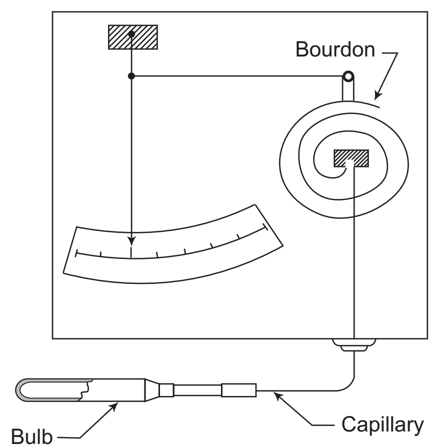

Figure 2.3: Filled thermal element based thermometer

2.3.3 Quartz Crystal Thermometers

Temperature measurements using a quartz crystal are based on the resonant frequency of a given crystal changing in response to change in temperature. This technology is capable of sensitivities of the order of 0.0003°F in laboratory conditions.

The quartz crystal is typically hermetically sealed in a stainless steel cylinder similar to a thermocouple or RTD sheath although somewhat larger. Since the quartz crystal converts temperature into a frequency, there are no lead resistances or noise problems to deal with. They provide good accuracy and response time and excellent stability. The quartz crystal technology is expensive as compared to other methods and accuracy is not quite like that of an RTD.

2.4 THERMISTOR

LO 2

Thermistors are semiconductors made from specific mixtures of pure oxides of nickel, manganese, copper, cobalt, magnesium, and other metals sintered at very high temperatures. They are also considered to be resistance thermometers.

Thermistors have a very high temperature coefficient to produce large changes in resistance in response to a change in temperature. The large temperature coefficient of thermistors makes it suitable for small spans (ranges) making large spans (ranges) rather difficult to handle. Typical applications include temperature control circuits and as safety devices when installed between the windings of transformers to detect overheating.

The resistance-temperature characteristic is non-linear and is expressed as shown in Equation 2.5:

$$R = R_0 \times e\left(\beta \frac{T_0 - T}{TT_0}\right) \tag{2.5}$$

where, R is the resistance at given temperature T; R_0 are resistance at referenced temperature T_0 and β is the material constant.

Thermistors resistivity range is typically 10^{-1} to 10^{-9} Ω cm. Physically thermistors are 0.1 mm in diameter and can exhibit negative or positive temperature coefficients (PTC) depending upon the materials used. A pure oxide of nickel, copper will result in negative temperature coefficient (NTC) whereas silicon, manganese combined with lead, barium, etc., result in PTC.

Typically, thermistors can be made to fit in a Wheatstone bridge and for better bridge, balancing can be kept in a differentiated form. Their application can be widely found as anemometers, gas analyzers, and voltage regulators.

2.5 RADIATION PYROMETRY

LO 2

A pyrometer is a device used to measure the temperature of an object or more precisely, the amount of heat being emitted from an object. Radiation pyrometers infer temperature by collection of the thermal radiation from an object and focusing it on a sensor. The sensor or detector is typically a photon detector that produces an output, as the radiant energy striking it releases electrical changes.

The total energy radiated in W/cm^2 of a perfect hot body is defined by Stefan-Boltzmann law as shown in Equation 2.6:

$$E_t = \sigma T_4 \tag{2.6}$$

where, T = Temperature of the hot body, σ = Stephan constant.

The advantage of the radiation pyrometry method is that it produces a stable noncontact output signal. It is useful in applications where the temperatures of higher degree need to be monitored on a continuous basis. An example of such application is continuously moving sheet of material that must be monitored.

Radiation pyrometers are however susceptible to ambient temperature fluctuations and often require special installation or water-cooling to maintain a constant ambient temperature. Pyrometers working on this principle are total radiation pyrometers. For total radiation pyrometer, the entire band needs to be focused on a detector that absorbs entire radiation.

In an optical pyrometer the temperature measurement is done by using the brightness levels radiated by the object whose temperature is to be measured. The device compares the brightness levels with a reference temperature. This reference temperature is set by light emission from a lamp whose brightness intensity is set equal to the brightness intensity of the object whose temperature is to be measured. For an object, whatever might be its wavelength, the light concentration depends on the temperature of the object. After regulating the temperature, the current through it is measured using a multimeter, as its value would be equal to the temperature of the source when calibrated. The functioning of an optical pyrometer is depicted in the figure (Figure 2.4).

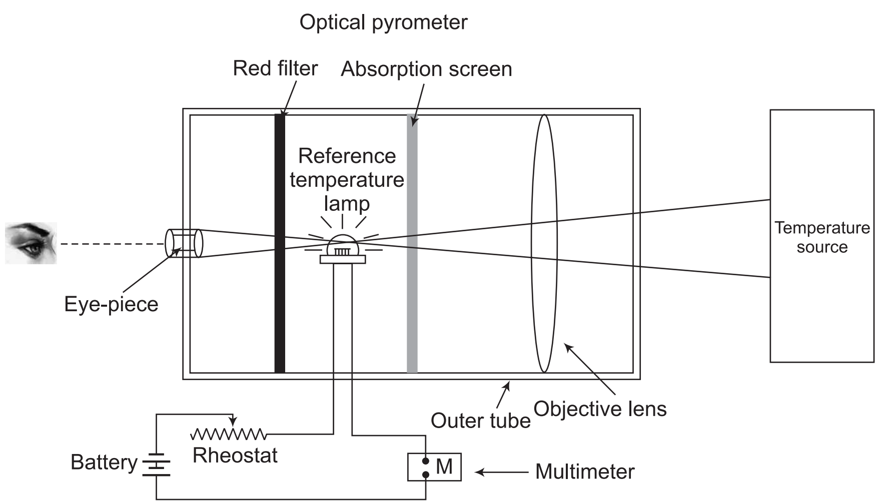

Figure 2.4: Optical pyrometer functionality

2.5.1 Working of Optical Pyrometer

As shown in Figure 2.4, an optical pyrometer contains the following components:

- An eye piece on the left side and an optical lens on the right.
- A reference lamp that is powered by a battery.
- A rheostat to change the intensity of current and brightness.
- To measure the increase in temperature range, an absorption screen is placed between optical lens and reference bulb.
- In order to reduce the wavelength band, a red colored filter is placed between the eye piece and the reference bulb.

The thermal radiation generated from the source is directed to the objective lens which then focuses these on to the reference bulb. The viewer who looks at this process through an eye piece can correct it by changing the rheostat value which changes the current in the reference lamp. This causes the reference filament to have a sharp focus and be superimposed on the temperature source image. The change in current is indicated in one of the following three ways:

- Filament becomes dark indicating it is cooler than the temperature source.
- Filament becomes bright indicating it is hotter than the temperature source.
- Filament disappears indicating equivalent brightness between the filament and temperature source. At this instance, the current flowing through the reference lamp is measured as its value is indicative of the temperature of the radiated light in the temperature source, when calibrated (Figure 2.5).

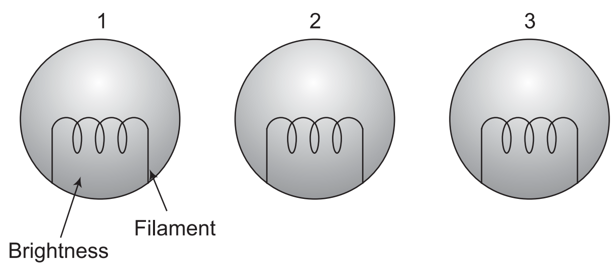

Figure 2.5: Temperature measurement in pyrometer: filament colors

2.5.1.1 Advantages

- Easy fitting of the device allows for comfortable use.
- Very high precision with $\pm$ 5°C.
- No need of body contact between the optical pyrometer and the object. Thereby, it can be used in wide range of applications.
- The device can also be used for remote sensing, as the distance between object and optical pyrometer can be neglected until the size of the object, whose temperature is to be measured, fits with the size of the optical pyrometer.
- This device can also be used to understand the heat produced by an object/source. Hence, optical pyrometers can measure and view wavelengths less than or equal to

0.65 μ whereas, a radiation pyrometer can measure wavelengths between 0.70 μ and 20 μ, making it useful in high-heat applications.

2.5.1.2 Disadvantages

- As the measurement is related to light intensity, the device can be useful in applications, which have a minimum temperature of 700°C.
- The device is not useful for obtaining continuous values of temperatures at small intervals. The device cannot be used to take continuous measurement of temperature at small intervals.

2.5.1.3 Applications

- Temperatures of liquid metals or highly heated materials can be measured.
- Can also measure furnace temperatures.

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Checkpoint

✦✦✦ 1. What is the traditional measurement technique of thermometers?

✦✦✦ 2. What is the basis for radiation pyrometers?

✦✦✦ 3. How temperature sensors can be classified?

✦✦ 4. Why thermal mass of the sensor should be low?

✦ 5. Can display instrument improve the resolution of the sensor?

✦ 6. What is the principle of bimetallic thermometers?

✦ 7. What is the basic principle of filled thermal systems?

✦ 8. What is the basic principle of quartz crystal in temperature measurement?

2.6 THEORY AND APPLICATION OF THERMOCOUPLE AND RTD

LO 3

Illustrate the theory and application of thermocouple and RTD

2.6.1 Thermocouple

A thermocouple is a thermoelectric temperature-measuring device.

It is formed by welding, soldering or merely pressing two dissimilar metals together in series to produce a thermal electromotive force (E) when the junctions are at different temperatures. Thermocouples were the first choice of temperature measurement in modern instrumentation systems for many years before the widespread availability of RTDs. Nevertheless, thermocouples are still widely used.

Before getting into the details of thermocouples, let us understand the basic principle of a thermocouple.

2.6.1.1 Principle of a Thermocouple

One of the most common industrial temperature measurement systems is a thermocouple, discovered by Thomas Seebeck in 1822.

Seebeck Effect In 1821, Seebeck observed the thermoelectric circuits while studying the electromagnetic effects of metals. It was observed that by bonding wires of two dissimilar metals together to form a closed circuit caused an electric current to flow in the loop whenever a difference in temperature was imposed between the end junctions. Figure 2.6 depicts a diagrammatic representation of Seebeck effect.

The direction and magnitude of the Seebeck voltage, Es, depends on the temperature of the junctions and on the materials of the matals used in the thermocouple. For a particular combination of materials X and Y, over a small temperature difference, $dEs = \alpha X, Y\ dT$, where $\alpha X, Y$ are coefficients of proportionality called the Seebeck coefficients.

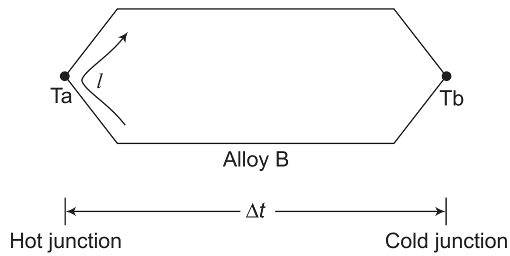


Figure 2.6: Seebeck's circuit

Peltier Effect Jean Peltier in the year 1834, observed that on passing electric current across a junction of two dissimilar metals, heat is either liberated or absorbed at the junction. The Peltier effect may also be defined as the change in heat content when a quantity of charge (1 coulomb) crosses the junction. Heat is absorbed at the hotter junction and liberated at the colder junction when the electric current flows in the same direction as the Seebeck current. Refer to Figure 2.7 for a representation of the Peltier effect. The Peltier effect is the fundamental basis for thermoelectric cooling and heating.

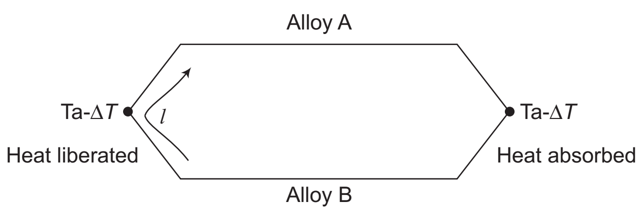


Figure 2.7: Peltier effect

Thomson Effect Thomson effect was discovered in 1851 by Sir William Thomson (Lord Kelvin). It states that a temperature gradient in a metallic conductor generates a minute voltage gradient, the magnitude and direction of which are dependent on the type of metal under consideration. When an electric current flow through this conductor, heat is evolved and absorbed due to the presence of thermoelectric gradient. The net result is that the heat evolved in an interval bounded by different temperatures is slightly less or greater than that accounted for by the resistance of the conductor. It is also observed that no electromotive force (EMF) is added to the circuit in Thomson effect because the EMFs produced are equal and opposite to each other and hence cancel each other's effect. This allows for the use of extension wires with thermocouples.

2.6.1.2 Rules Applying to Thermocouples

Based on extensive practical experience, the following rules have been determined for thermocouples:

- A thermocouple current cannot be sustained in a circuit of a single homogeneous material, either by application of heat alone or by varying the cross section.
- The sum of the thermoelectromotive forces in a circuit composed of any number of dissimilar materials is zero if the whole circuit is at the same temperature. Due to this, a third homogeneous material can be added to a circuit with no effect on the net EMF of the circuit as long as its junctions are at the same temperature. This means if all the junctions of the circuit are at the same temperature, a thermal EMF measuring device can be introduced at any point of the circuit. It also follows that any junction that makes a good electrical contact and has a uniform temperature does not affect the EMF of the circuit regardless of the method used in forming the junction (Figure 2.8).

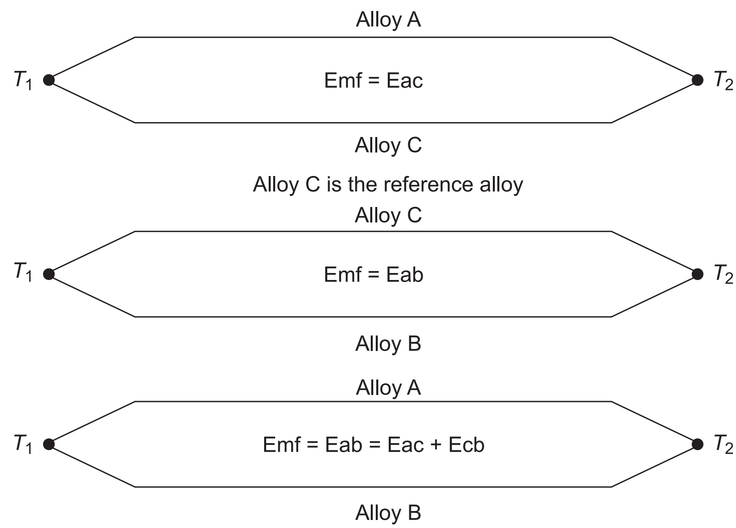


Figure 2.8: Thermocouple EMF algebraic sums

- If two different homogeneous metals are used to produce a thermal EMF of E1 when the junctions are at temperatures T_1 and T_2, and a thermal EMF of E_2 when the junctions are at T_2 and T_3, the EMF generated when the junctions are at T_1 and T_3 is $E_1 + E_2$. This law is applied to allow a thermocouple calibrated for a given reference temperature to be used with another reference temperature through the use of a suitable correction. Another example of this law is that extension wires having the same thermoelectric characteristics as those of the thermocouple wires can be introduced into the thermocouple circuit from region T_2 to region T_3 (Figure 2.7) without affecting the net EMF of the thermocouple (Figure 2.9). The same is the concept of thermocouples wired to the control system using the special thermocouple cables. The thermocouple cables allow the mV signal to be transmitted without affecting the net EMF.

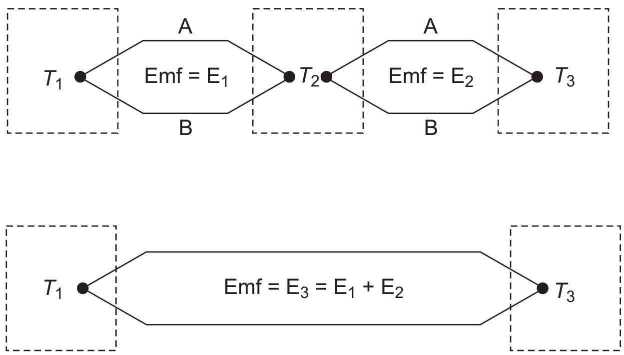


Figure 2.9: EMFs are additive for temperature intervals

2.6.1.3 *Need for a Reference Junction (Cold Junction)*

As seen above, the measurement of the EMF is used as a means of determining the difference in temperature between the measuring junction and reference junction. Thus, if the temperature of one of its junctions (the reference junction) is at some known temperature T_i, such as that of melting ice, the measurement of EMF and hence the ΔT and T_1 is ($T_1 + \Delta T = T_x$). The EMF is dependent only on $T_2 - T_1$ temperatures, can be deduced from the measured EMF once the relationship between EMF and temperature difference has been established for the combination of material A and material B at suitably distributed known temperatures. There are various standard tables available to know the EMF values. Figure 2.10 below represents the concept of cold junction compensation in thermocouple-based temperature measurement.

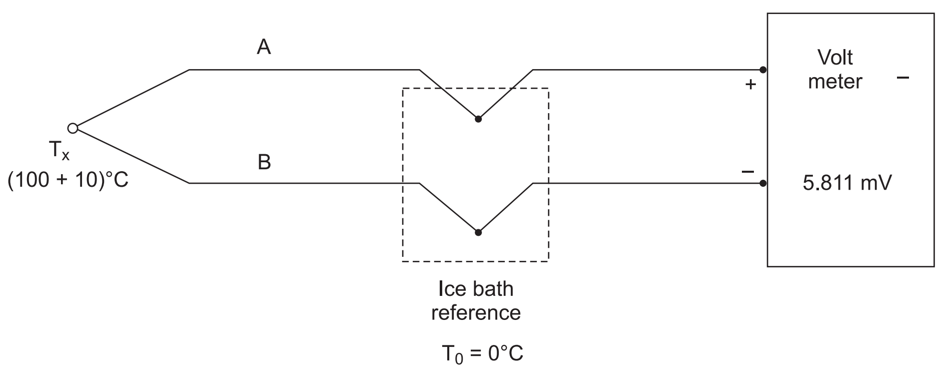


Figure 2.10: Cold junction compensation

2.6.1.4 Cold Junction Compensation

Variations in the reference junction temperature will produce changes in the millivolt output, resulting in temperature measurement errors. Therefore, for accurate measurements, the reference junction must remain constant. Compensation for these calculations can be provided by placing the reference junction in an ice point bath (0°C). Since it is not practical to maintain an ice bath for every thermocouple in use, most instruments are installed with electronic circuitry that takes into account the variation of the reference junction T_0. The phenomenon is called the cold junction compensation. Cold Junction compensation is realized by passing current through a temperature-responsive resistor (usually a thermistor) which measures these variations in the reference temperature and automatically provides the necessary compensations. Compensation is achieved by using resistors whose combined temperature resistance coefficient curves match with that of the voltage temperature curves generated by temperature variations. It is important to place the temperature responsive resistor close to the terminal connections of the reference junctions (Figure 2.11) for more information. This arrangement ensures that the temperature calculation sensed by the temperature responsive resistor corresponds to the actual temperature at the reference junctions. Reference junction and cold junction compensation are incorporated in all industrial thermocouples. Several problems are associated with cold junction compensation. This first consideration in the overall accuracy is dependent on matching the electronics to temperature variations. Instruments, which do not require cold junction compensation, have the advantage in that the error of matching the electronics is eliminated.

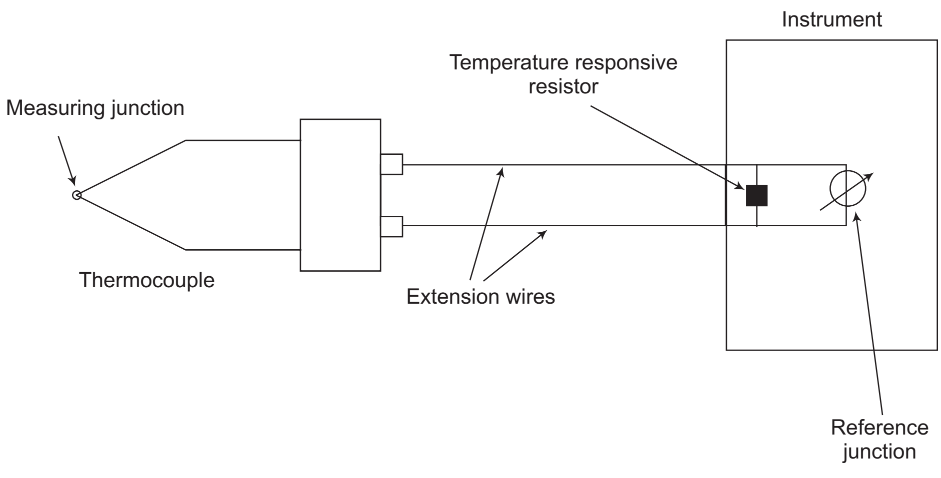


Figure 2.11: Reference junction for cold junction compensation

Another problem in these thermocouples may arise when the temperature of the thermocouples connection is different from that sensed at the cold junction. The electronics may be compensating properly for the temperature sensed at the cold junction, but errors are produced because this temperature is not the one sensed by thermocouple. This problem is apparent in applications with large variations in temperatures and when the cold junction and thermocouple connections are not next to each other (Figures 2.12 and 2.13).

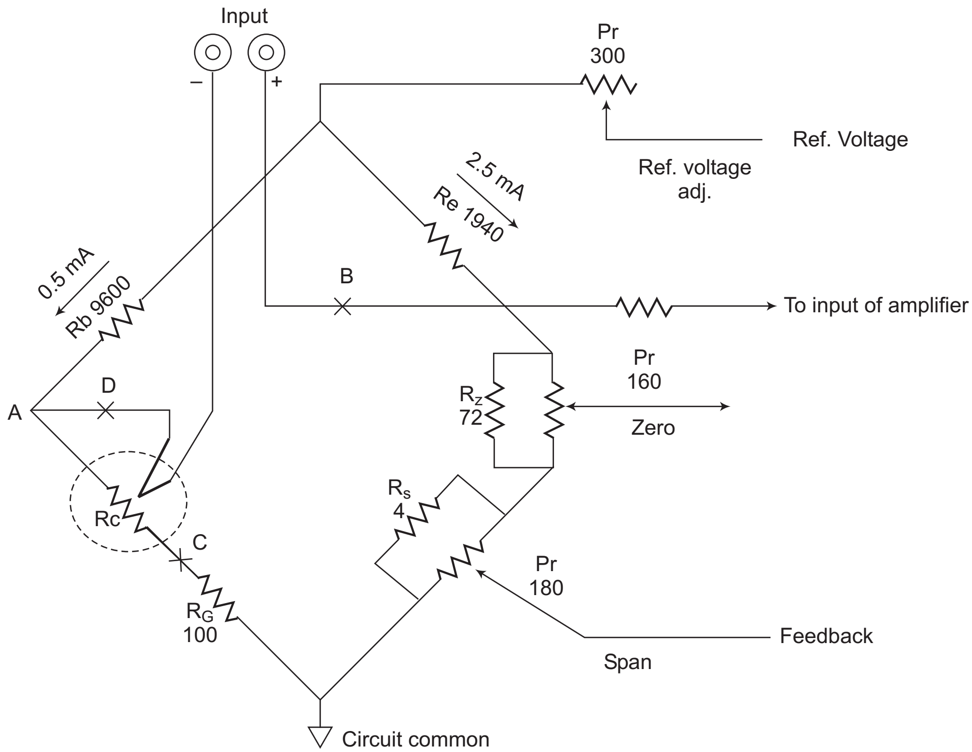


Figure 2.12: Typical cold junction compensation

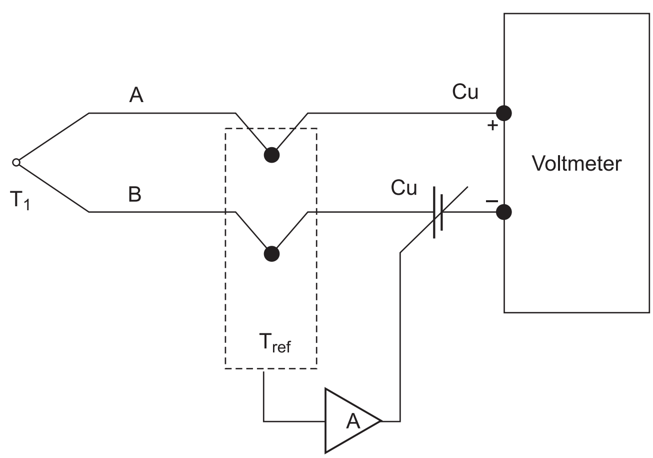


Figure 2.13: Floating reference junction compensation

Another type of electronic reference junction compensation uses the sensor voltage converted to a digital equivalent in the measuring device and the compensation is done in a software technique by the instrument. With this type of compensation the thermocouple type being used can be changed easily by a few programming commands at the front panel of the instrument (Figure 2.13).

2.6.1.5 Types of Thermocouples

With years of intense research, mature technologies have been developed for thermocouple users. With large amount of research gone into finding metal and alloy combinations that provide good millivoltage per degree of temperature and a combination that resists corrosion in oxidizing and reducing atmospheres, many varieties of thermocouples have been created and characterized for industrial usage. Much research has also gone into finding sheaths and protecting walls that can withstand temperature extremities. Despite the widespread research, a universal thermocouple is yet to be established. It takes a lot of experience to make the most optimum thermocouple selection for an application. Various types of thermocouples and their application characteristics are listed in Table 2.2.

Table 2.2: Different types of thermocouples

Type	*Characteristics*
J: Iron-Constantan	• Recommended for reducing atmosphere • High EMF output, low susceptibility to noise • Thermocouple wire is relatively inexpensive • If exposed to temperature above 760°C, magnetic transformations can take place changing the output characteristics over the full range of the thermocouple.
K: Chromel-Alumel	• Recommended for clean, oxidizing atmospheres • Unstable characteristics change over time • Most linear of all standard types
E: Chromel-Constantan	• Can be used in vacuum, inert, mildly oxidizing or reducing atmospheres. • Good for subzero temperatures because of high resistance to corrosion at low temperatures • Highest EMF output for all standard type thermocouples, low susceptibility to noise. • Best choice of low temperature because of high Seebeck coefficient and low thermocouple conductivity.
T: Copper-Constantan	• Can be used at temperatures below 0°C • Has one copper lead allowing special application differential temperature measurements and cheaper installation costs.

(*Contd.*)

B: Platinum, 6% Rhodium- Platinum, 30% Rhodium	• Near zero EMF output between –180°C and 380°C allows use without cold junction compensated measuring device with minimal error • Low EMF output, susceptible to noise • Expensive, platinum lead wire required • Susceptible to metallic vapor diffusion, must be used with a nonmetallic sheath or bare wires • Stable • Double value ambiguities between –180°C and 380°C rendering virtually useless in this range.
R: Platinum, 13% Rhodium-Platinum	• Expensive, platinum lead wire required • Susceptible to metallic vapor diffusion, must be used with a nonmetallic sheath or bare wires • Very stable • Very low EMF output, susceptible to noise
S: Platinum, 10% Rhodium-Platinum	• Most stable, used as a standard between –18°C (0°F) to 538°C (1000°F) and 538°C (1000°F) to 1149°C (2100°F). • Expensive, platinum lead wire required • Low EMF output, susceptible to noise • Use with non-metallic sheath or bare wires
W: Tungsten, 20% Rhodium-Tungsten	• Relatively linear EMF output to 2600°C • Not useful below 400°C • Not useful in oxidizing conditions.

The application suitability of various types of thermocouples is listed in Table 2.3.

Table 2.3: Application suitability of thermocouples

Thermocouple Type	*Oxidizing Atmosphere*	*Reducing Atmosphere*	*Inert Atmosphere*	*Vacuum*	*Sulphurous Atmosphere*	*Subzero Atmosphere*	*Metallic Vapor*
B	✓	×	✓	✓	×	×	×
J	✓	✓	✓	✓	Not < 500	×	✓
K	✓	×	✓	×	×	✓	✓
E	✓	×	✓	×	×	✓	✓
R	✓	✓	✓	✓	×	✓	✓
T	✓	×	✓	×	×	×	×
S	✓	×	✓	×	×	×	×
W	×	✓					

Table 2.4 provides key characteristics of the five mostly used base-metal thermocouples and the three precious or noble-metal thermocouples that essentially are standard for high-temperature and high-accuracy needs of some of the industrial applications. The engineer has

to exercise enough caution to choose the right thermocouple for the type of the application being used in the plant.

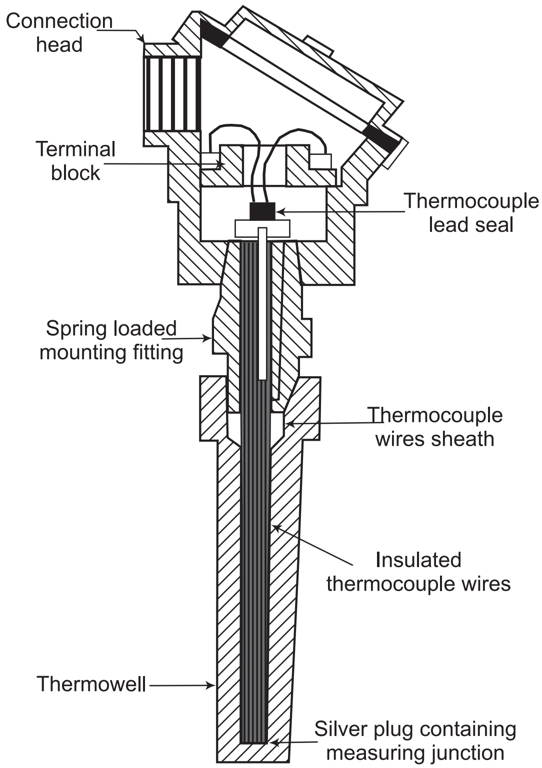
Table 2.4: Principle characteristics of thermocouples

ANSI / ISA Types	*Metal Combinations*	*Chemical Compositions*	*Common Temperature Ranges (°C)*	*Limits of Error*		*Atmosphere Suitability*
				Standard Grade (°C)	*Premium Grade (°C)*	
J	Iron/Constantan	Fe 44Ni:55Cu	–73 to 427 427 to 760	± 2.2	± 1	Oxidizing, Reducing
K	Chromel/Alumel	90Ni:9Cr 94Ni:Al:Mn:Fe	0 to 277 277 to 1149	± 2.2	± 1.1	Oxidizing, Inert
T	Copper/ Constantan	Cu 44Ni:55Cu	–101 to -60 –75 to 93 99 to 371	± 1.7	± 1	Oxidizing, Reducing
E	Chromel/ Constantan	90Ni:9Cr 44Ni:55Cu	0 to 316 316 to 871	± 1.7	± 1.1	Oxidizing, Inert
N	Nicrosil/Nisil	Ni:14.2 Cr:1.4Si Ni:4Si:0.15Mg	0 to 277 277 to 1149	± 2.2	-	Oxidizing, Inert
R	Platinum-Rhodium/Platinum	87Pt:13Rh Pt	Available Upto 1480	± 1.4	-	Oxidizing, Inert
S	Platinum-Rhodium/Platinum	90Pt:10Rh Pt	–18 to 538 538 to 1149	± 1.4	-	Oxidizing, Inert
B	Platinum-Rhodium/ Platinum-Rhodium	70Pt:30Rh 94Pt:6Rh	Available Upto 1700	± 1.4	-	Oxidizing, Inert

Practical thermocouple of assemblies used in plants is depicted in Figure 2.14. Terminal blocks are made of insulating material and is placed on the head of the thermocouples. Terminal blocks are used in supporting and to join termination of metal conductors of thermocouples. Connection head is a housing that has the terminal block in it and is usually provided with threaded cap for attachment to a protection tube and for arrangement for conduit.

Connection head extension is a threaded assembly or a combination of fittings extending between the thermowell and the connection head. Actual configuration is decided on installation and application requirements. The protection tube as shown in the figure is used to protect sensor assembly from environmental effects. For high temperature applications, special protection tubes made of ceramic materials such as mullite, high purity alumina, etc. are used. Special protection tubes are used for lower temperature installations as well for environmental protection.

Figure 2.14 **Representative industrial thermocouple headwell assembly**



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Many of the industrial process applications prefer the spring-loaded thermocouple assemblies. The spring-loaded thermocouple assemblies are effective where a temperature measurement is used for closed loop control applications. Spring-loading thermocouple assemblies improve response time of the measurement and also protect the junction from the effects of high vibration which is common in industrial environment.

For some special spring-loaded thermocouple designs, a retaining ring is brazed to the tube or sheath close to the head end of the thermocouple. A spring is compressed between the ring and a bushing assembly. This spring will be forcing the thermocouple junction into contact with the tip of the thermowell which is in contact with the process. This arrangement results in better response to a temperature change with a time constant of about 12 s including 3.5 s for initial response.

2.6.1.6 Junction Configuration of Thermocouple

Measurement junctions can be configured in different ways to suit plant conditions. Some of the basic considerations are:

- **Single vs dual thermocouples:** Dual thermocouple is more expensive but can provide a backup (in case one element burns out) or dual readings at one location (for example location and control) without using an extra thermo well.
- **Grounded vs ungrounded thermocouples:** Grounded thermocouples provide faster response time to process variations as they are thermally grounded too. However, if the temperature element is subjected to varying ground potentials due to installation conditions at site, conditions then induced EMFs, static charges gets build up. Hence, it is better to float the device so that the millivolt "signal" can be discerned above the "noise".
- **Isolated vs unisolated:** The unisolated arrangement is cheaper and ensures that both elements measure exactly the same temperature. If two different thermocouples are connected to different measurement/control systems at different ground potentials, then electrical isolation is required to inhibit interferences. Unfortunately, electrical insulation also tends to be thermally insulating and gives rise to a lag in the temperature gradient between the two elements.

2.6.2 Resistance Temperature Detector

Cashing in on the characteristic relationship of electrical resistance to temperature the science of measuring temperature has been advanced periodically since the early work of Faraday in 1835. The application of resistance thermometers as primary sensors for industrial temperature measurement gained popularity when certain selected and customized materials started to vary in resistance in a defined and calibrated manner with temperature.

Reproducibility and stability are of critical importance in industrial applications prompting the use of RTDs in industrial applications. RTDs are passive sensors requiring an "excitation" current to be passed through them. The RTD is normally manufactured from a metal with a known resistance, typically 100 ohms at ice point. The resistance at ice point is referred to as the "R_0" (read R subzero).

Platinum resistance thermometers became popular for industrial temperature measurement applications between the triple point of hydrogen at 13.81 K and the freezing point of antimony at 730.75°C. RTDs have become made serious inroads on the thermocouple since the 1970s not just for applications requiring great accuracy but also for practical industrial use. The advantages and limitations of RTDs against thermocouples in today's age are analyzed later in this chapter.

For pure metals, the characteristic relationship that governs resistance thermometry is given by the Equation 2.7. For pure metals, the characteristic relationship that governs resistance:

$$R_t = R_0(1 + at + bt^2 + ct^3 + \cdots) \tag{2.7}$$

where, R_0 = resistance at reference temperature (usually at ice point, 0°C), R_t = resistance at temperature t, a = temperature coefficient of resistance/(°C), b, c = coefficients calculated on the basis of two or more known resistance-temperature (calibration) points.

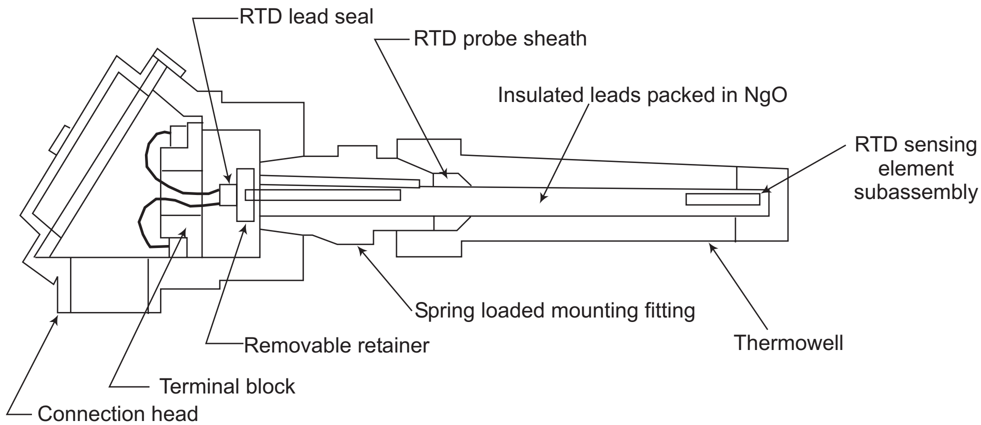
Based on the particular material involved, the relationship follows a unique equation for alloys and semiconductors.

The sensing element is the main component of an RTD. While most elements made up from metal conductors generally exhibits PTC with an increase in temperature indicating increased resistance, there are some semiconductors exhibits a characteristic NTC of resistance. Thus, very few pure metals have a characteristic relationship that makes them suitable for fabricating sensing elements and being used in resistance thermometers. The most basic configuration for an RTD sensing element suitable for practical applications is shown in Table 2.5. The small diameter wire element is wound in a bifilar manner onto a cylindrical mandrel, usually of ceramic. Refer to Figure 2.15 for an RTD with various components.

Lead wires run axially through the tube and are connected to the element wire. The tube assembly is usually covered with a coating or glaze to protect the element wire. The following are some prerequisites for the metals used to fabricate sensing elements:

- The metals used in RTD shall have a stable resistance-temperature relationship. This help neither the resistance at zero degrees and temperature resistance coefficients such as a and b, due to repeated heating and cooling cycles in the specified operating range.
- The material that is used in RTDs, the coefficient of resistance of the metal in ohm/cm^3 must be in a practical limit that permits fabrication.
- The metals and materials used in RTD should be insensitive or less sensitive for non temperature effects such as vibration, strain, etc., which are a common phenomenon in industrial process environment.
- The concept of RTD is based on change in resistance to temperature; it is always best to have a large change in resistance for a small change in temperature, which can make the sensing much more sensitive. This makes the sensor have a better inherent sensitivity than doing so using signal processing in the electronics.
- The metal used in the RTD will be in contact with the process and will be subjected to exposure to high temperature. The metal must not undergo a change in state or phase within the range specified.

Figure 2.15 **Industrial RTD with thermowell assembly**



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- The metal used in the RTD should be commercially available and should have consistent characteristics across the locations, which are key for providing uniformity and reliable response for the same change in temperature.

Industrial resistance thermometers (RTDs) are commonly available with elements or metals made of platinum, nickel, 70% nickel–30% iron or copper. The complete resistance thermometer is a combination of parts which include the sensing part, lead wires, supporting and insulating materials, and protection tube or case. The characteristics of the metal with the temperature and variations of the same with different materials are provided. Figure 2.16 provide information on resistance temperature characteristics of thermoresistive materials at elevated temperatures. Platinum and nickel are thermostatic materials commonly used for industrial applications.

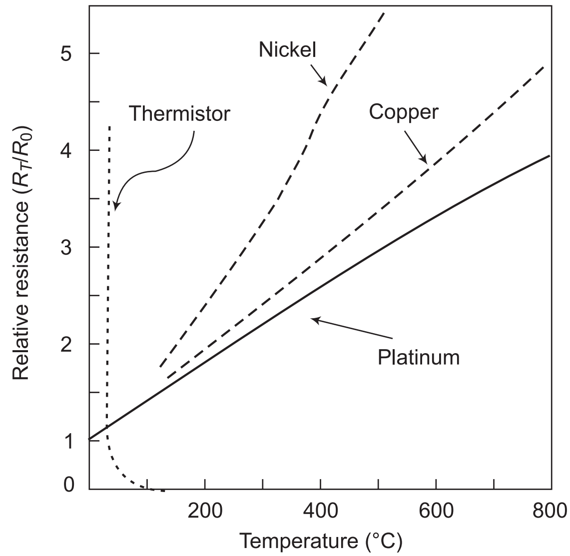

Figure 2.16: Resistance-temperature characteristics of thermoresistive materials at elevated temperatures

Table 2.5: Resistance temperature characteristics of materials

		Relative Resistance R_t/R_0 at 0°C											
Metal	*Resistivity f.ohm.cm*	*200*	*100*	*0*	*100*	*200*	*300*	*400*	*500*	*600*	*700*	*800*	*900*
Alumel	28.1			1.0	1.3	1.5	1.6	1.7	1.8	1.9	1.9	1.9	2.1
Copper	1.56	0.117	0.557	1.000	1.431	0.862	2.299	2.747	3.210	3.695	4.208	4.752	5.334
Iron	8.57			1.000	1.650	2.464	3.485	4.716	6.162	7.839	9.790	12.009	12.790
Nickel	6.38			1.000	1.663	2.501	3.611	4.847	5.398	5.882	6.327	6.751	7.156
Platinum	9.83	0.177	0.599	1.000	1.392	1.773	2.142	2.499	3.178	3.178	3.500	3.810	4.109
Silver	1.50	0.176	0.596	1.000	1.408	1.827	2.256	2.698	3.616	3.616	4.094	5.586	5.091

Most RTDs fall into one of the following two types based on mounting types:

- **Immersion RTDs:** Immersion RTDs are meant to allow a sensing element to be immersed in a media to measure its temperature. Immersion type is the most popular and common method in most of the process plants.
- **Surface-mounted RTDs:** Surface mounting of the sensing device is the most efficient and/or convenient installation method in a number of applications. For surface measurement, conditions such as sensor insulation and lead wire conduction must be investigated to ensure accurate measurement.

2.6.2.1 Platinum RTDs

Out of the many materials used in fabrication of thermoresistive elements, platinum has the best characteristics for usage over a wide range of temperature. Platinum is a noble metal and does not oxidize and is subject to contamination at high temperatures by some gases such as carbon monoxide, other reducing atmospheres and by metallic oxides.

The metal is commercially available in pure form and offers reproducible resistance-temperature curves. Platinum with a temperature coefficient of resistance equal to 0.00385/°C (from 0 to 100°C) is used as a standard for industrial thermometers also called as Pt100 RTDs.

Platinum has a high melting point and does not considerably volatilize at temperatures below 1200°C. It has a tensile strength of 18,000 psi (124 MPa) and a resistivity of 60.0 Ω/Cmil. ft at 0°C (9.83 μΩ cm).

Platinum is the most preferred material for calibration work and is used in making high-precision laboratory standard thermometers. As defined by IPTS, the laboratory-grade platinum resistance thermometer (usually with a basic resistance equal to 25.5 Ohms at 0°C) is considered the defining standard for the temperature range from the liquid oxygen point (−182.96°C) to the antimony point (630.74°C).

The resistance-temperature relationship for platinum resistance elements is determined from the Callendar Equation (Equation 2.8) above 0°C:

$$t = \frac{100(R_t - R_0)}{R_{100} - R_0} + \delta \frac{t}{100} - 1 \frac{t}{100} \tag{2.8}$$

where, t = temperature (°C), R_t = resistance at temperature t, R_0 = resistance at 0 °C, R_{100} = resistance at 100°C, δ = Callendar constant (approximately 1.50).

The fundamental coefficient (temperature coefficient of resistance) δ is defined over the fundamental interval of 0–100°C using Equation 2.9:

$$a = \frac{R_{100} - R_0}{100R_0} \tag{2.9}$$

Thin-film Platinum RTDs Over the last couple of decades, processing techniques have been developed to produce thin-film platinum RTD elements that are essentially indistinguishable from wire-wound elements in reproduction and stability (Figure 2.15) assembly. Automated equipment is generally used to trim thin-film platinum RTD elements to the final desired resistance value. These high-resistance elements have often made obsolete the need to consider base-metal wire-wound sensors of nickel or nickel-iron. Sometimes Thermistors are also replaced with an RTD sensor for a significantly greater stability and temperature range.

The use of sheaths and thermowell for thermocouples (shall be discussed in next section) is also applicable to RTDs.

Wire-wound Platinum RTDs The wire-wound RTDs are still preferred for certain applications. In a practical RTD used in the temperature measurement applications, which is encapsulated with a platinum wire inside usually less than 0.025 mm outer diameter which is wound into a coil. The wire-wound coil is inserted into a multibore high-purity ceramic tube or may be wound directly on the outside of a ceramic tube. The most widely used ceramic material in platinum resistance thermometers is aluminum oxide (99.7% Al_2O_3). The winding is completely embedded and fused within or on the ceramic tube using extremely fine granular powder

(Figure 2.17) below for an illustration of the same. The wirewound platinum element covered and encapsulated inside the protection tube with only two lead wires exposed to the terminal block provides the maximum protection to the sensor element. However, the encapsulation techniques are prone to some additional strain on the element which is addressed using special fusing techniques, such that the inaccuracies associated due to the other factors are minimum and is within the acceptable limit for use in industrial process measurement applications. However, the close contact with the wire-wound platinum element within the ceramic encapsulation provides a better speed of response because of thermal conductivity for the ceramic is adequate to pass through the protection layers. A platinum industrial RTD assembly with a maximum temperature range. Generally, industrial temperature measurement applications with high-temperature combined with high-pressure, high flow and high vibration needs a thermowell protecting tube to be included in the assembly.

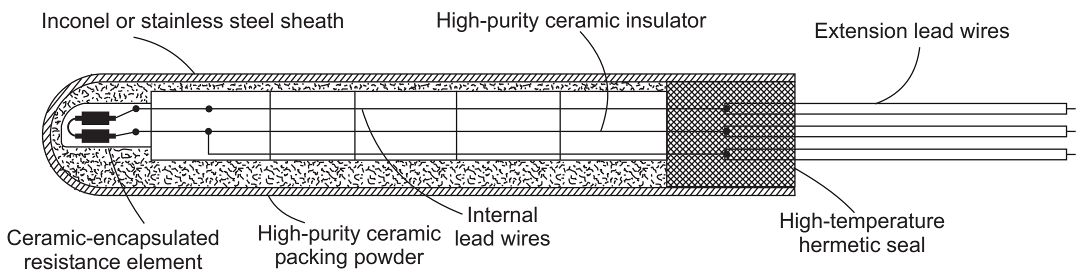

Figure 2.17: Wire-wound industrial RTD

Various types of RTDs are classified based on the mounting technologies, metals used and the fabrication of the metal in the sensor, etc. The instrument engineer is expected to know all of these variants in order to choose the right sensor based on the application.

2.6.2.2 *Nickel RTDs*

Earlier, nickel was also used as an element in the RTD. Recently, the use of platinum RTDs due to their better performance characteristics, at a lower cost, has taken precedence in a wide range of industrial temperature measurement applications. At present nickel RTDs are primarily being used as a component replacement in already existing measurement systems.

2.6.2.3 *Copper RTDs*

Copper RTDs were used earlier before the advancements in the platinum material technologies. Applications such as temperature-difference measurements used copper because it allowed use of two sensors directly owing to its straight-line characteristics. The situations mentioned for the nickel RTDs are applicable in copper as well, wherein it is used in rare applications.

2.6.2.4 *Thermowells Metallic Sheath Protection*

Thermocouples of metal sheath construction offer protection for the wires from the atmospheres and process, and provide mechanical strength. Metallic sheathed RTDs are usually packed with magnesium oxide, aluminum oxide, and beryllium oxide. Generally, the insulating material is in the form of a powder or crushable head that is packed into the metallic tube. The tube is reduced in diameter, crushing, and compressing the insulator into a more dense mass. The material is heat treated to relieve stress from swaging and to drive out any residual moisture.

Some thermocouples are encased in a 304SS or Inconel metallic sheath. Metallic oxide insulation is compacted into the sheath on contact with the wall of the thermocouple wire.

A similar procedure is employed for RTDs and spring loading is used to keep the sheath in contact with the wall of the thermowell. Many different types of thermowell and protection tubes are available depending on the corrosion condition, pressure, costs, response time, replacement, and mounting requirements. Figures 2.18 and 2.19 depict different types of process connections and their configurations.

Thermowell and protection tubes are similar except thermowells provide pressure attachment to the process vessel while protection tubes are only used in installations at atmosphere pressure. Thermocouples or RTDs are connected to the thermowell by an internal thread. Directly welding or using an external thread or flange provides the pressure tight attachment to the vessel.

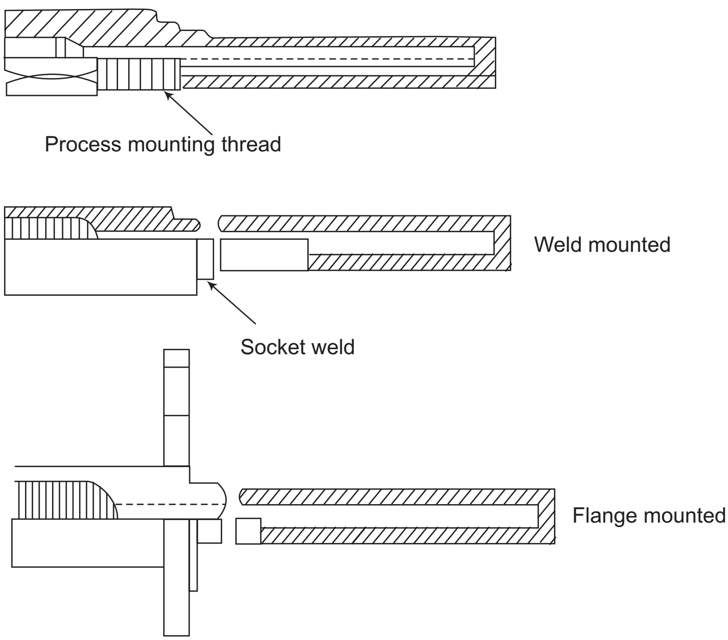

Figure 2.18: Different types of process connections of thermowell

Thermowells comes in various configurations depending on the response time, velocities of process fluid and strength. The straight style in Figure 2.19 provides a fast response but it is limited to low process fluid velocities because of its lack of strength. The tapered thermowell offers additional strength for use in high-fluid velocities. The reinforced neck well or stepped style thermowell is stronger than the straight style and has a faster response than the tapered type.

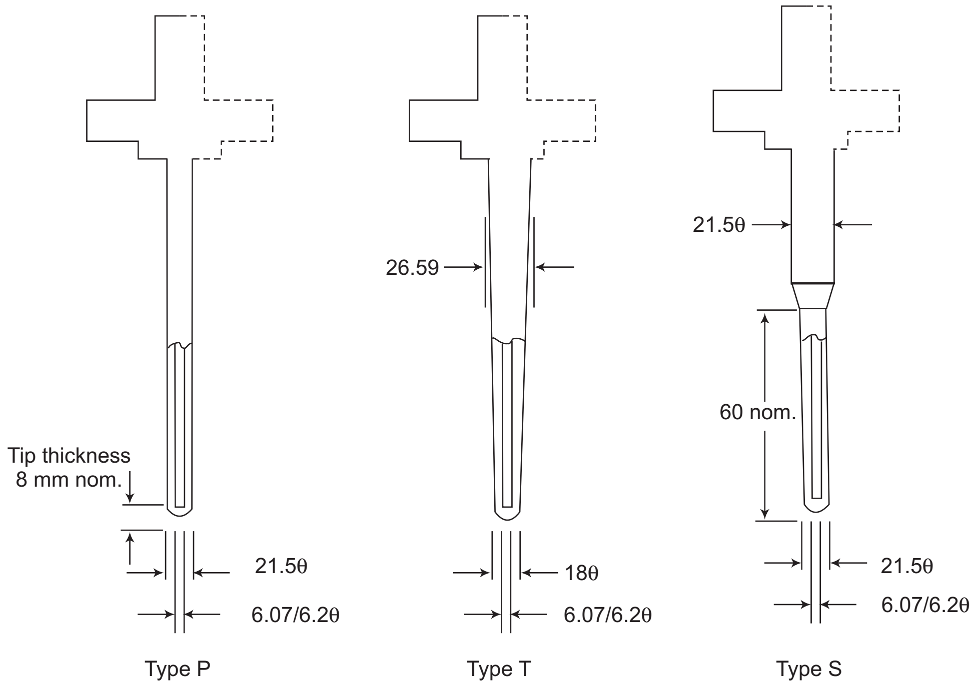

Figure 2.19: Different types of configurations of thermowell

2.6.2.5 Response Time

When thermowells and protection tubes are used, the response time is 3–10 times greater than without protection. Factors influencing the response time are heat transfer from the wall to the sensor and the wall thickness of the thermowell. Following methods can be utilized to counteract the above factors and minimize the response time:

- **Method 1**: Minimize the air separation that slows down the heat transfer rate from the thermowell to the sensor. This can be accomplished by providing a close tolerance between the outer diameters of the sensor and inner diameter of the thermowell. Using a spring-loaded thermocouple or RTD will provide contact between the sensor and inside the thermowell. Further minimizing the effect of air separation on the rate of heat transfer.
- **Method 2**: Another method of minimizing the effect of air separation is to add a small amount of oil or powdered graphite and oil inside to the thermowell. The heat transfer rate is faster than air, reducing the response time. The fill must be chemically compatible with the thermowell and sensor and must not freeze or boil at the temperatures encountered.

The response time is influenced by the thickness of the thermowell or protection tube. The thinner the wall, the faster the response. There is a limit to the thickness of the wall, (usually 1.5 mm) since the wall thickness also provides mechanical strength.

Different thermowell materials are not considered as a significant factor in the response time. Although different thermowell metals have different resistances to heat flow, these differences are insignificant when compared to the rate of heat transfer from the process to the thermowell, thermowell to the sensor and the response of the sensor.

2.6.2.6 *Velocity*

A turbulent wake with a frequency that varies with the velocity of the fluid is formed when fluid flows past a thermowell. The wall thickness of the thermowell must be strong enough to prevent the frequency from equating the natural frequency of the thermowell. If the natural frequency is reached, the thermowell will resonate and fracture.

2.6.2.7 *Ranges and Performance Characteristics of RTDs*

The most common commercially available RTD temperature ranges and additional performance characteristics are summarized in Table 2.6.

2.6.2.8 *RTD Circuitry*

RTDs are electrically connected in various forms to the host system for measurement and control applications. RTD transmitters are available in the market for 2 wire, 3 wire and 4 wire configurations. Diagrams and their equations are presented in Figure 2.20.

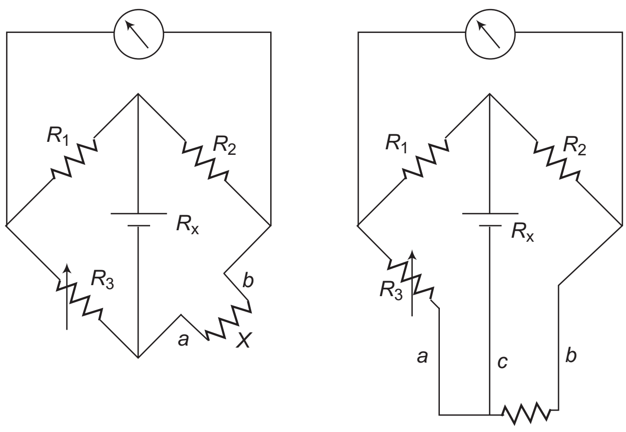

Figure 2.20: RTD circuits in contemporary designs

Two-lead Circuit It is used or selected only when lead wire resistance can be kept to a minimum and only where a moderate degree of accuracy is required (Figure 2.20 and Equation 2.10):

$$\left.\begin{aligned} R_1 + R_3 &= R_2 + a + b + X \\ R_1 &= R_2 \\ \therefore \quad R_3 &= a + b + X \end{aligned}\right\} \tag{2.10}$$

Table 2.6: Representative commercially available RTDs

Parameters	*Platinum*	*Platinum*	*Platinum*	*Platinum*	*Platinum*	*Nickel*
Temperature	–200 to 200	–50 to 200	–100 to 260	–65 to 200	–200 to 650	–130 to 315
Configuration	316 SS Sheath 200°C 17.2 MPa (2500 psig)	316 SS Sheath 200°C 17.2 MPa (2500 psig)	Surface mount	Surface mount	316 SS Sheath 480°C Inconel to 650°C	Stainless steel, other metals
Repeatability	+0.05% max ice-point resistance 0.13°C	+0.025% max ice-point resistance	+0.04% max ice-point resistance 0.1°C	+0.08% max ice-point resistance 0.2°C	+/-0.26°C upto 480°C; +/-0.5% upto 650°C	Limit of error from +0.3°C to +1.7°C at cryogenic temperatures
Stability	+0.08% max ice-point resistance	+0.035% max ice-point resistance	+0.05% max ice-point resistance	+0.15% max ice-point resistance	-	-
Time constant (to reach 63.2% of sensor response	8 s	7 s	1.25 s	2.5 s	-	-
Immersion length	0.6 to 6 m	31, 61, 91, 122 cm	-	-	89 to 914 mm	89 to 914 mm
Lead wire	Teflon insulated nickel coated, 22 gauge standard copper wire	Teflon insulated nickel coated, 22 guage standard copper wire	0.25 mm diameter platinum wires	Teflon insulated 24 awg standard copper wire	-	-

Three-lead Circuit In a three-wire connection, two leads (wires) are connected in close distance to the resistance element at a common mode. Third lead (wire) is connected to the opposite resistance leg of the element. Resistance of lead "a" is added to bridge arm R_3 and resistance of lead "b" remains on bridge arm R_X thereby dividing the lead resistance and retaining a balance in the bridge circuit. Lead resistance ***C*** is common to both left and right loops of the bridge circuit.

Although this method reduces the effect of lead resistance in the circuit, the ultimate accuracy of the circuit depends on leads a and b being of equal resistance. Special matching techniques are used on leads a and b, particularly when distance between sensor and measuring equipment is relatively large.

As shown in the Figure 2.20 the circuit equations for the three-wire system are as follows per the Equation 2.11:

$$\left.\begin{aligned} R_1 + R_3 + a + c &= R_2 + b + X + c \\ R_1 &= R_2 \\ a &= b \\ R_3 &= X \end{aligned}\right\} \tag{2.11}$$

$a = b$ due to the same lead resistance.

Four-lead Circuit A four-lead circuit is used only when the highest degree of accuracy, as in laboratory temperature standards, is required.

Stable constant current source (CCS) power supplies are available in miniature packages at relatively low cost. It provides an alternative to null-balance bridge-type instruments. This is more applicable for industrial process systems that require manual and automatic scanning of up to 100 or more individual RTD points, often located at different distances from a central point. The circuit diagram shown in Figure 2.21 consist of basic four-lead circuit with two leads joined in close proximity at each side of the resistance element. The CCS can be connected across leads T and C with a constant current I_c across the resistance element (X). The value for I_c must be at a minimum of 1 mA or less to avoid errors caused by the self-heating in the circuit. The voltage drop across the resistance element is then measured between T and C. The resultant voltage drops across the thermometer element in the constant-current mode, and then varies with resistance directly as a function of temperature as per Equation 2.12:

$$\left.\begin{aligned} E &= IX \\ I &= \text{Constant} \\ E &= f(X) = f'\,(\text{temperature}) \end{aligned}\right\} \tag{2.12}$$

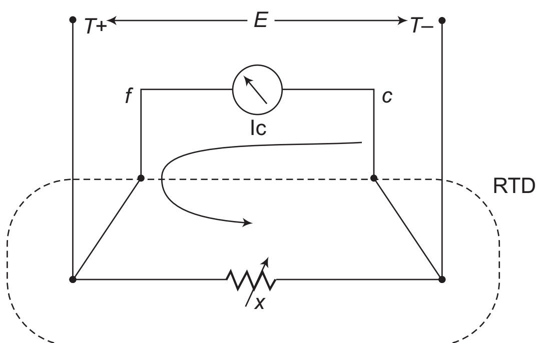

Figure 2.21: Four-lead constant-current measuring circuit

The CCS circuit based connectivity has advantages compared to the bridge based measurement system. The CCS power supply continues to maintain the fixed constant current (within its compliance voltage limitations) across the resistance temperature element by which the expensive matching electronics can be avoided and hence cost can be saved. The ability to interface directly with a variety of voltage measuring instruments is a striking additional feature of the CCS measuring circuit. As a result, digital linearizers can be made to operate on the non-linear platinum resistance thermometer function to display directly in engineering units with linearization conformities of a fraction of a degree (temperature). CCS measuring circuits provide added binary-coded decimal temperature sensor for a given application.

For example, a thermocouple may be opted over an RTD for an application which has an application in vibration, because the thermocouple is less likely to be affected by vibration, even though most other criteria may favor the RTD. Alternatively, short-term reproducibility and high accuracy are key criterion that favors the selection of RTD.

Unless there are some special considerations of the application of the measurement, the principal criteria for the selection of the element is accuracy, response time, size, purchase cost, life cycle cost, sealing the detector from the process environment without significant reducing response time, and the user's experience factors to use the equipment. When all other evaluating criteria are same, the user may prefer one type of sensor over the other because of preferences of the project engineers, operators, and maintenance engineers. These in house engineers have more experience and know-how with a given type of temperature detector either it could be an RTD or a thermocouple or a thermistor.

The relative advantages and limitations of thermocouples versus RTDs as expressed by various professionals are given below. Therefore, a few inconsistencies may be expected.

2.6.3 Comparison of Thermocouples and RTDs

2.6.3.1 Advantages and Disadvantages of Thermocouples

The advantages and disadvantages of thermocouples are listed in Table 2.7.

Table 2.7: Advantages and disadvantages of thermocouples

Advantages	*Disadvantages*
• **Cost**: Although cost of RTDs is trending downward, thermocouples generally continue to be less expensive. • **Ruggedness**: In terms of process environmental conditions high temperatures and vibration, thermocouples are regarded high. • **Higher temperature range**: Extends to about 1150°C (2100°F) or higher. However, the thermocouple's cryogenic range is less than that of RTD. • **Mounting cost**: Generally considered to be same for RTDs.	• The overall thermocouple including system comprise the inaccuracies associated with two separate junctions for temperature measurements—the measuring junction and the cold or reference junction. • **Stability**: Less than for the RTD. Estimated at 0.6°C (1°F) per year. • **Inherently small mV output**: Can be affected by electrical lower than noise. • **Calibration**: Non-linear over normal spans. Signal requires liberalizing. Calibration can be changed by contamination.

2.6.3.2 *Advantages and Disadvantages of RTDs*

The advantages and disadvantages of RTDs are listed in Table 2.8.

Table 2.8: Advantages and disadvantages of RTDs

Advantages	*Disadvantages*
• **Accuracy**: Generally expected after installation, ± 0.5°C for platinum RTD. For example Accuracy is used to IPTS at the oxygen point (–182.97°C) and the point (+630.74°C). No reference junction is required. • **Repeatability**: Within few hundreds of a degrees; can achieve with Platinum RTDs less than 0.1% drift in 5 years • **Substantial output voltage** (1–6 V), this is an advantage that the output can be controlled by adjusting the current and the bridge design in the RTD signal conversion because a higher output voltage to the RTD usually can be achieved and recording, monitoring and controlling of temperature signals is simpler. This permits more accurate measurements without requiring complex • **Short-term reproducibility**: RTDs exhibits better reproducibility than that of thermocouples. The changes in the process temperature and frequency does not impact the reprocability of the element. • **Relatively narrow spans**: some special elements of the RTDs may have spans as small as 5.6°C • **Compensation**: Not required • **Ranges**: Available • **Size**: Generally smaller than thermocouple	• **Cost**: Generally higher than that of thermocouples. However, RTDs do not require compensation; special lead wires define the special signal conditioners for the long runs. With platinum film antimony technology, downwards. • **Less rugged**: For adverse process environments, including high temperatures and vibration, RTDs are not regarded as highly often be as thermocouples. • **Lower temperature range**: Limited to about 870°C. However, RTDs extend to lower cryogenic range than thermocouples do. • **Self heating errors**: This may be a problem unless corrected in modules or transmitter electronics cost is trending

2.6.3.3 *Thermocouple and RTD at a Glance*

The case for RTDs and thermocouples may be summarized as follows (Table 2.9 and Table 2.10):

Table 2.9: Comparison of RTDs and thermocouples

RTD Advantages	*Thermocouple Advantages*
High accuracy, greatest over wide span	Moderate accuracy
Relatively narrow span, (10°F) can be measured	Widest range (0–2000°F)
Reproducibility not affected by temperature change	Rugged

(*Contd.*)

Short time reproducibility is better than that of thermocouples	Remote and versatile mounting
Zero compensation is not required	Moderately stable
Handle suppressed ranges	Medium cost
Small in size compared to others	
RTD Disadvantages	*Thermocouple Disadvantages*
More expensive	Low output signal
Limited above 1500°F	Calibration changed by contamination
Less rugged	Electrical interference can be a problem
Self-heating may become a problem	Calibration is nonlinear over normal spans
Vibration can affect wire wound types	Higher installation costs (extension wires/ thermocouple cables)

Table 2.10: Key characteristics of temperature elements

Parameters	*RTD*	*Thermocouple*
Accuracy	0.005–0.05°C	0.5–5°F
Stability	Less than 0.1% drift in five years	0.5°C drift/year
Sensitivity	0.1–10 ohm/°F	10 to 100 μV/°C
Range	–251–871°C	–184–1500°C
Output		0 to 60 mV
Power (100 Ohm Load)	4×10^{-2} watts	2×10^{-7} watts

Checkpoint

✦✦✦ **1.** What is the thermocouple principle?

✦✦✦ **2.** What is Seebeck effect?

✦✦✦ **3.** What is Peltier effect?

✦✦ **4.** Explain Thomson effect.

✦ **5.** Explain why the reference junction should remain constant.

✦ **6.** What are the benefits of recent advances in metals used in thermocouples?

✦ **7.** What is the J-type thermocouple?

✦ **8.** What is the K-type thermocouple?

✦ **9.** What is the spring-loaded thermocouple?

✦ **10.** What is the advantage of grounded thermocouple?

✦ **11.** What are the critical characteristics of RTD that lead to their adoption?

For answers to checkpoint, scan the QR code

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2.7 ANALOG AND SMART TEMPERATURE TRANSMITTERS

LO 4
Analyze analog and smart temperature transmitters

2.7.1 Thermocouple and RTD Transmitters

Often termed "smart" or "intelligent", temperature (and other process variables) transmitters have many electronically built-in advantages, without compromising the ultimate and self-evident function of maintaining data integrity. This is a critical need in noisy electrical environments as encountered in most industrial process environments. Remaining transmitter capabilities, in essence, are available for use and convenience at low cost from low cost of electronics.

Some of the major advantages of the smart instrumentation are self-diagnostics, elimination of hardware changes, easy recalibration, and hybrid, digital bidirectional communication with a distributed control system. The capability to program the instrument provides a capability to replace one unit with another unit for the same measurement application. These capabilities reduce the inventory of the plant. Temperature is one of the most used parameter and reduced inventory is very much useful for the plant operations and maintenance.

2.7.2 Evolution of Temperature Transmitters

The traditional method of connecting an RTD or a thermocouple to the control system is using of long wire runs to deliver low-level signals to central control rooms. These methods are costly, due to special cable needs. The long run cables are also prone to electrical noise and hence associated increase in cost for installation. The evolution of the temperature transmitters are compared in Table 2.11.

Table 2.11: Comparisons of specifications between main types of temperature transmitters

Traditional Type	*Smart or Intelligent Type*	*Throwaway Type (Potted)*
Analog	Digital	Analog
Thermocouple or RTD must be specified, changes require hardware reconfiguring	One model handles all thermocouple, RTD, mV, and ohm sensors	Limited to one input
Medium cost	High cost, downward trend	Low cost
Variable span; moderate range	Variable span; wide range	Single span; limited range
Sometimes isolated	Isolated	Not isolated
Variety of applications	Almost every application	Only one application
Sometimes intrinsically safe	Nearly always intrinsically safe	Usually not intrinsically safe
Can be reconfigured on site or in shop	Can be reconfigured remotely	Very limited reconfiguration

(*Contd.*)

	Remote diagnostics	
Medium to good performance	Better accuracy	Limited accuracy
RTD models are easily linearized; thermo-couples sometimes linearized	Linearization is selectable from the program	Must linearize at host side
Stability depends on manufacture and application	Quite stable with ambient temperature and time; infrequent needs to recalibrate	Stability depends on manufacture and application

2.7.2.1 Two-wire Analog Temperature Transmitter

Two-wire temperature transmitters provide measurement stability and accuracy and replace signal communication from low-level millivolts or ohm with high-level current signals. This change enables the installation with twisted pair copper cables with high cost shielded cables and costly extension wires for thermocouples.

2.7.3 Microprocessor-based Transmitters

Microprocessor-based transmitters were introduced in the late 1980s to take advantage of the large advances in digital electronics. These transmitters have achieved wide acclaim because of their versatility. Generally the units are preprogrammed by the manufacturer with the information necessary to linearize a given sensor signal, including a given thermocouple, RTD, or other millivolt or ohm device. These transmitters can be reconfigured to accept other sensor inputs without having to make hardware changes and recalibration. In addition, they offer a variety of self-diagnostics for power supply and loop problems as shown in Figure 2.22. The specifications of available transmitters are compared in Table 2.7. Modern day transmitters for temperature are capable of communicating with the control systems using various open communication protocols like hart (highway addressable remote transmitter), foundation fieldbus and Profibus in addition to proprietary communication protocols. Most of the temperature transmitters are built to accept inputs from multiple sensors that translated to low cost of equipment, installation, and maintenance.

Most of the temperature transmitters use applications like FDT/DTM (Field Device Technology/Device Type Manager) and EDDL (Enhanced Device Description Language) to provide a powerful view of the data. The details of these technologies are not explained in this book, but the material is available on internet.

In addition to providing process data, the temperature transmitters/multiplexers provide maintenance data for the instrumentation maintenance. The online diagnostic helps to identify the problems in the device much early and enabling proactive and predictive maintenance for the process plant. The smart transmitters provide remote access to the device enabling maintenance technicians to view the diagnostics of the device, monitor process variables, and calibrate the device in a nonintrusive way without disturbing or disconnecting the device to the process or the control system. Remote access is enabled either through handheld devices or software applications connected to the DCS or even through the wirelessly connected tablet PCs.

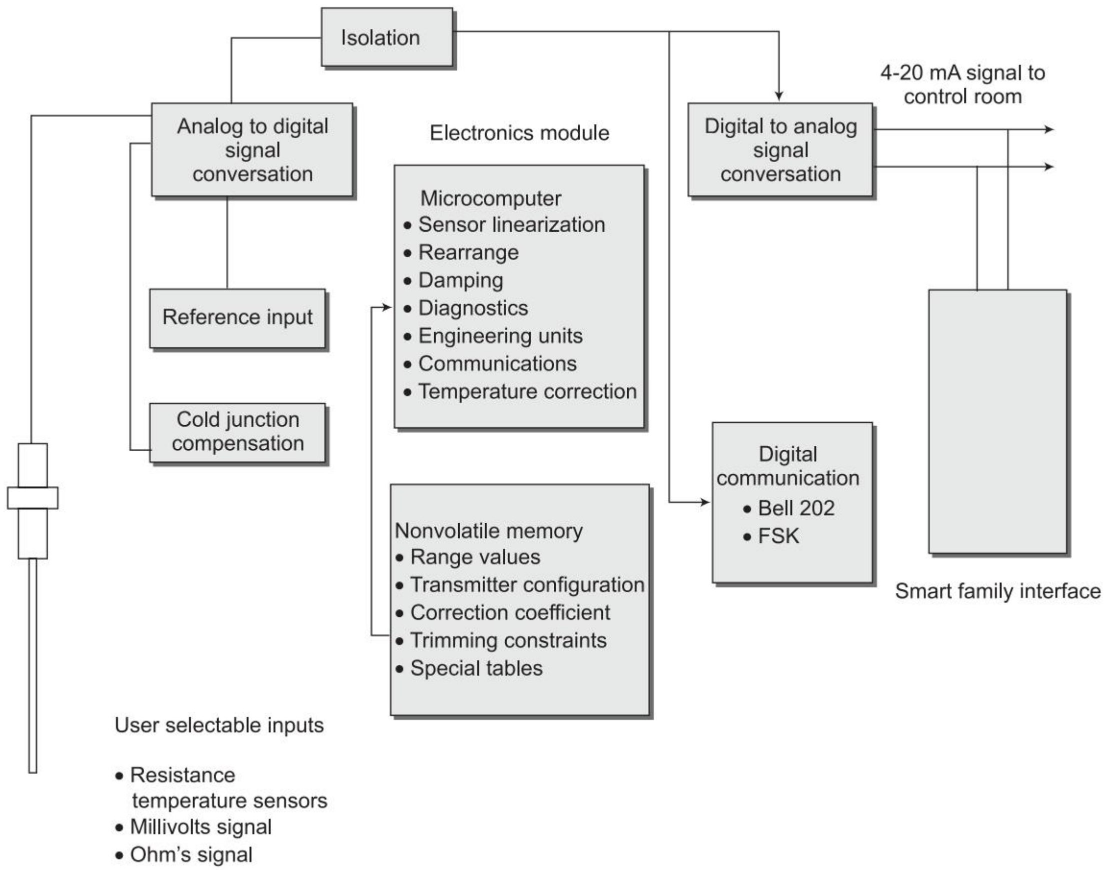
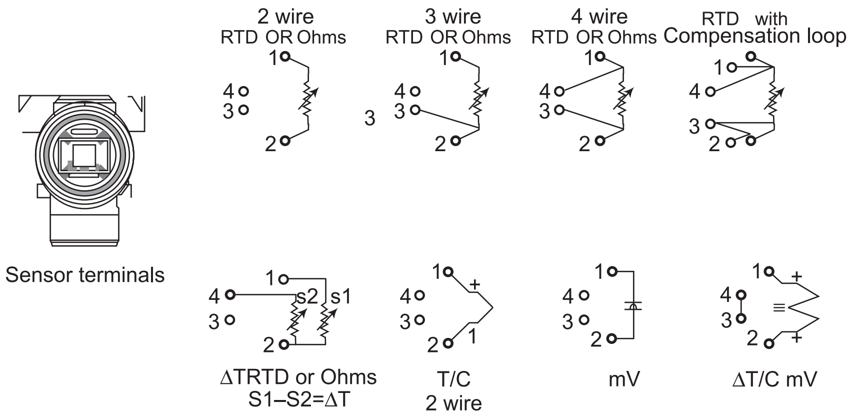


Figure 2.22: Configuration and diagnostics of smart transmitters

As shown in the Figure 2.23, all the temperature transmitters will be provided with multiple connection options. The electrical interface can be connected in series at any termination point in the 4–20 mA signal loop. The transmitter's electronics constitutes of two circuit boards sealed in a body with an integrated sensor board. The electronics boards are generally designed with latest technologies in the circuit boards such as digital ASIC (application-specific integrated circuit), microcomputer, and surface-mount technologies. The electronic modules converts the input signal from the sensor to a digital format and apply correction coefficients selected from nonvolatile memory. The output section of the electronics module converts the digital signal to an analog (4–20 mA) output. The signal is used to handle the communication with other interfaces of the control system.

An optional display unit to the meter may plug into the electronics module to display the selected parameters in user-configured units. User selections and options for the transmitters, called as configuration data is stored in nonvolatile EEPROM (electrically erasable programmable read-only memory) in the electronics module. These data are stored

Figure 2.23 Various connection options to sensors



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in the memory of the transmitter when power is interrupted or transmitter is disconnected for maintenance, etc. The stored configuration data of the transmitter is used to make the transmitter functional immediately upon power-up. Unlike the traditional sensors, the smart transmitters store the process variable (temperature) in digital format after engineering unit conversion. The corrected and converted process data (in digital format) then are converted to a standard analog (4–20 mA) current applied to the output loop. Some of the latest transmitters are provided with digital interface to communicate with control system. These transmitters with digital interfaces can access the sensor reading directly as digital signal, thus bypassing the digital-to-analog conversion process. Most of the commercially available temperature transmitters have the provision to connect with multiple varieties of sensors such as RTDs, thermocouples, thermistors, Ohms, millivolts, and sensors in differential model, etc., as shown in the Figure 2.23. Figure 2.24 represents the transmitter field wiring. The meter interface previously described can be connected at any termination point in the signal loop.

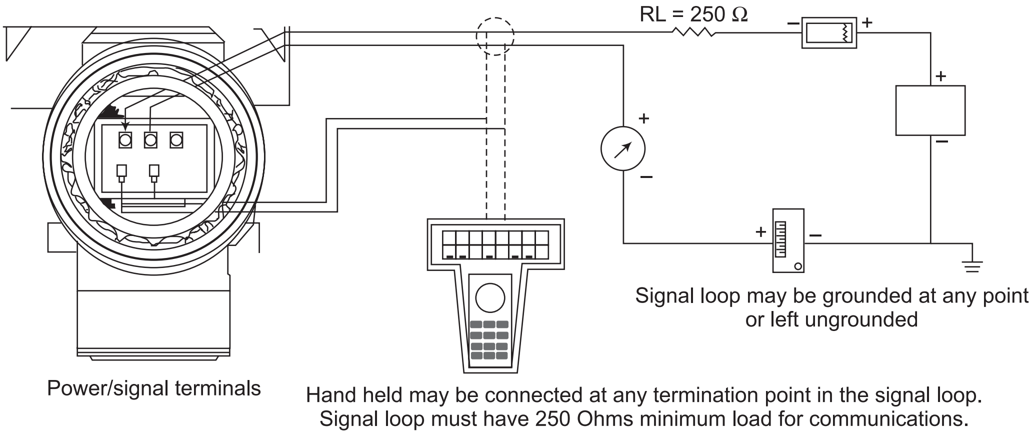

Figure 2.24: Loop connections for smart transmitter

In this connection mechanism, the signal loop must have a minimum load of 250 ohms for communications to occur. In general, if there is no intermediate components in the loop, the input and output module of the control system can add the load to the loop. The transmitter can be configured with operational parameters such as sensor type, number of wires, 4–20 mA points, damping, and unit selection. The transmitter can also be configured with, informational data to allow identification and physical description of the transmitter. The informational data can be the Tag (8 alphanumeric characters), descriptor (16 alphanumeric characters), message (32 alphanumeric characters), date, etc. Additionally, the system software shall be provided with several other parameters which are "read only" in nature, such as transmitter type, sensor limits and software revision levels, etc.

The transmitters can performs routine self-tests periodically. In the event of a detected anomaly, the transmitter activates the user-selectable warning in the form of an analog or digital signal. The meter interface (or other designated control component) can interrogate the transmitter to determine the problem and alert the concerned for corrective actions. The transmitter can send specific information to control system component in the form of digital signals to identify the problem for corrective action and also to record the problem in the system for future archival. The technician can perform a loop test if the need arises to test the loop conditions while troubleshooting the problems in the loop. The modern transmitters are provided with format functions which are used during commissioning and maintenance phases of the projects. The top-level format menu offers two functions: characterize and digital trim. These functions allow the user to select the sensor type and adjust the transmitter's digital electronics as per the need of the plant.

Checkpoint

✦✦✦ 1. What are the advantages of smart transmitters?

✦✦✦ 2. What was enabled by the introduction of temperature transmitters?

✦✦✦ 3. How smart transmitters enable change in the sensor without hardware changes?

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2.8 CALIBRATION METHODS FOR TEMPERATURE TRANSMITTER

LO 5

Illustrate the calibration methods for temperature transmitter

Precision comparison is the science of accurately transferring a temperature scale from an interpolation instrument to the known instrument by an efficient and economic method.

The two types of temperature calibrations commonly used today are fixed-point and comparison calibrations. Fixed-point calibrations are performed at the boiling or freezing points of various pure substances whose temperatures are defined by the IPTS. Properly maintained fixed points are capable of high accuracy but such calibrations are time consuming and not always suitable for calibrating the wide variety of temperature sensitive devices presently used. The techniques of the requirements grow for making accurate temperature measurements and maintaining calibration accuracy in process instruments.

2.8.1 Selecting Calibration System

Before selecting equipment for a calibration system, it is important to have a clear idea of what results are expected. The objective should be to provide the greatest return on investment by selecting the equipment which will satisfy the need. The following points should be considered:

- Size and type of device to be calibrated
- Total number of frequency of calibration
- Temperature range
- Accuracy requirements
- Speed and convenience of changing temperatures
- Speed and convenience of measuring bath temperatures

A typical calibration system is shown in Figure 2.25. The calibration bath and the bath fluid produce a uniform and stable temperature zone. The standard thermometer and appropriate readout device are used to measure the zone calibrated. For maximum accuracy, a 25 ohm standard platinum thermometer is used.

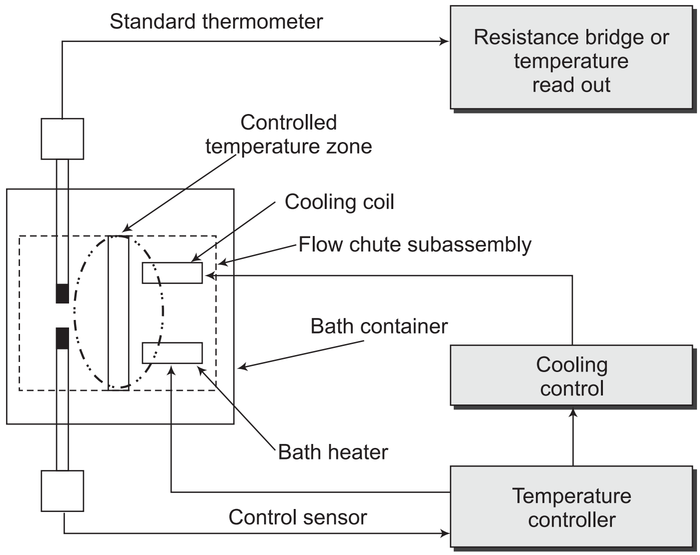

Figure 2.25: Calibration setup

2.8.2 Temperature Transmitter Calibration

2.8.2.1 Resistance Temperature Detectors

RTDs are useful only over a certain temperature range. These are made from platinum due to its stability and linearity throughout the range of use and exhibit a slower response time to temperature changes than thermocouples. RTDs are purchased as 2-wires, 3-wires, or 4-wires RTDs. RTDs must connect correctly during initial installation and upon completion of calibration. Figure 2.26 is the wiring diagram for 2-wires, 3-wires, and 4-wires using calibrator.

2.8.2.2 Thermocouple

Thermocouples are used to cover more temperature ranges than RTDs and 95% of RTDs are used in temperatures below 1000°F. Thermocouples can be used up to 2700°F. While connecting thermocouple make sure that two thermocouple sensor pins are plugged into respective positions. Refer to Figure 2.27 for thermocouple connections. If the calibrator and the thermocouple plug are at different temperatures, wait for a minute or more for the connector temperature to stabilize after plugging the mini-plug into the TC input/output.

2.8.2.3 Procedure to Perform Calibration

Equipment Required

- **Device**: Device under calibration—total temperature effect in worst case including D/A temperature effects is 0.16°C at 30°C ambient temperature.

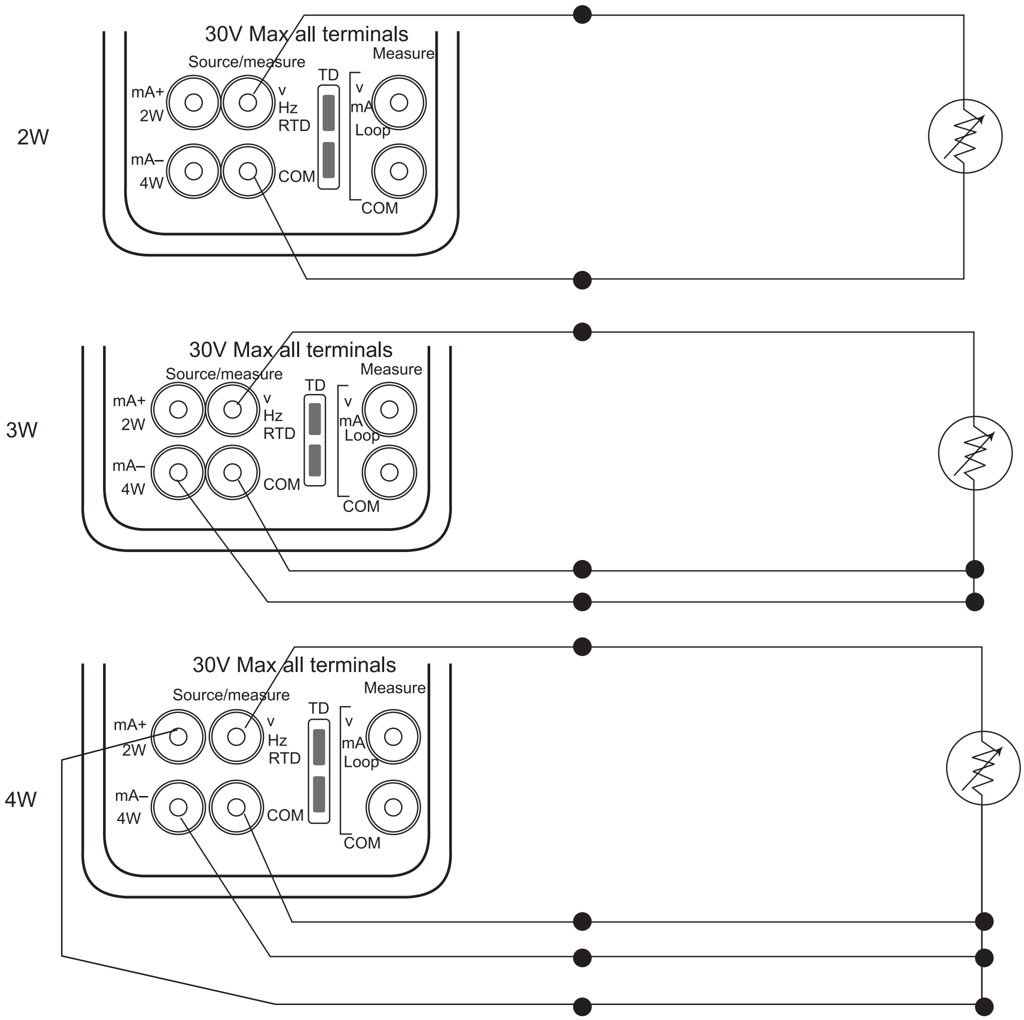

Figure 2.26: Various types of RTD connections

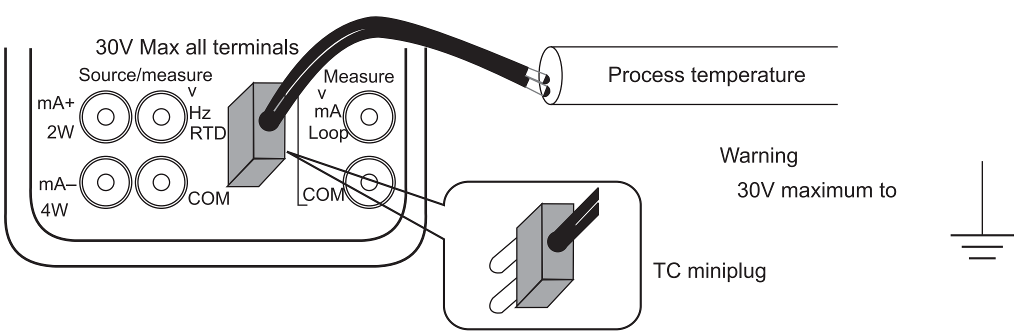

Figure 2.27: Wiring diagram thermocouple temperature source from calibrator

- **Source**:
  - Standard calibrator (depends on the choice of the company)
  - DC current measurement accuracy 0.01% of reading + 0.015% of full scale.
- **Operating voltage**: 24 V
- **Handheld device**: Field communicator

2.8.2.4 *Experimental Setup*

- Connect RTD source probes to the temperature transmitter sensor terminals 1 and 2 and short 2, 3 terminals of the transmitter as shown in Figure 2.29.
- Connect mA measure terminals to the transmitter power terminals. This connection will provide loop power 24V to the transmitter.
- Connect the field communicator terminals to the transmitter power terminals. *Make sure that the probe is inserted in HART communication socket of field communicator.*
- Power on the calibrator and field communicator.

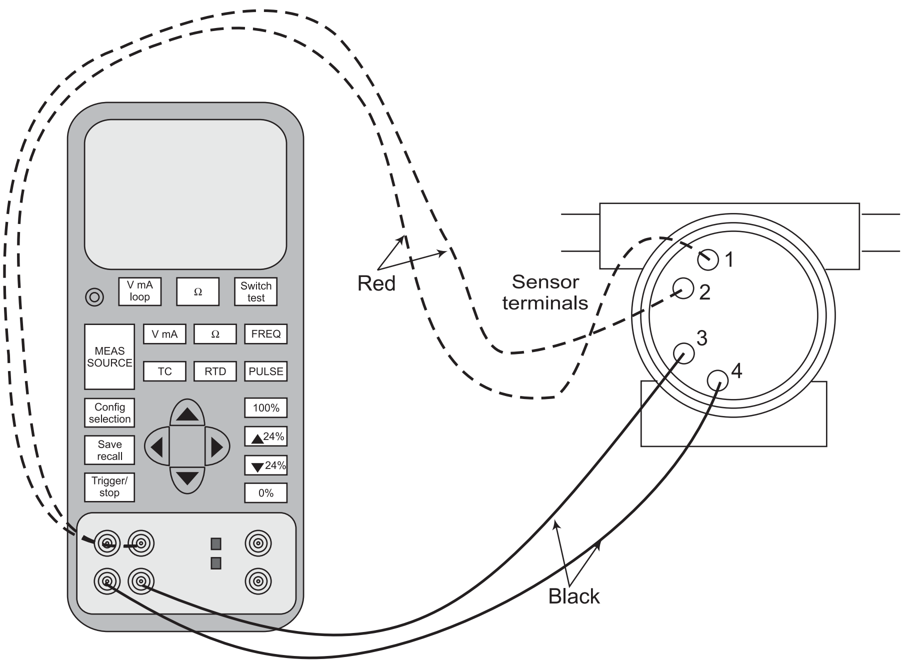

Figure 2.28: Connections for simulating 3-wire and 4-wire RTD

2.8.2.5 *Calibration Procedure*

Before adjusting the output readings in transmitter using field communicator, have to find where the errors occur. If the error is present in the input section, then sensor or input trim is to be done. If the error is present in the output section, then D/A trim is to be done. When the calibrator (say 0°C) applies a standard input then the reading in the handheld device should show the process value as 0°C. In case of this not happening, go for Snsr1 trim. If the current reading in the reference meter is not matched with standard input applied at input block then go for D/A trim (output trim). If the engineer needs to change the output readings, scaled D/A trim helps to get desired readings. In general follow the flow diagram represented in the Figure 2.29.

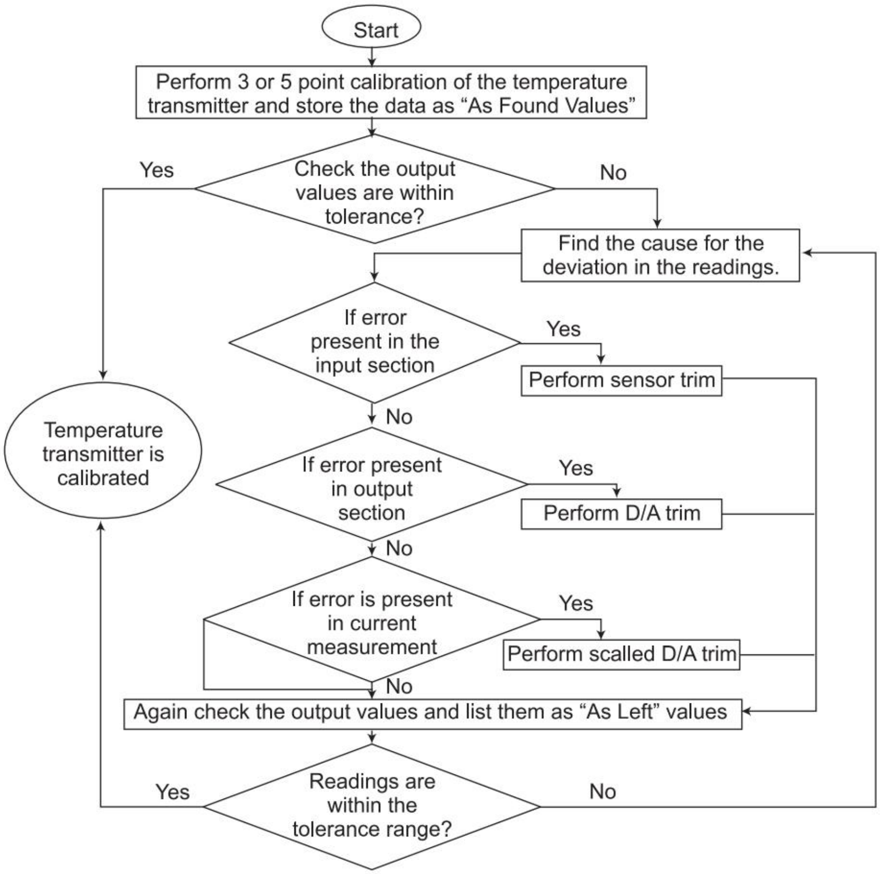

Figure 2.29: Flowchart of calibration of temperature transmitter

The adjustment is done by using field communicator:

- Select the device setup → Diagnostics/service calibration

Following are the types of adjustments:

- Snsr1 trim menu
- D/A trim
- Scaled D/A trim.
    - Select Snsr1 trim Menu → Snsr1 input trim.
- A warning message will appear. After reading message select OK then field communicator will ask if you are using an active calibrator or not (if active calibrator device is connected select YES and Press Enter. If the calibrator device accepts pulse

current then selects NO and if the sensor is connected then select NO and Press Enter).

Field communicator prompts to select sensor trim points.

1. Upper
2. Lower and upper
3. Field communicator displays a message for applying the low reference input to the transmitter, then enters 0°C (lower reference value) in the source window and then selects OK in field communicator.
4. Engineer enters corresponding lower trim reference value (0°C) and press enter. Field communicator will automatically adjust the output to 4 mA to the reference value.
5. Field communicator displays message for applying upper reference input in the range: –200°C to 850°C. Engineer enters OK after applying upper reference value in calibrator.
6. Engineer enters corresponding upper range value displayed on the calibrator screen, field communicator will automatically adjust the output to 20 mA to the upper reference value. (If the correction is very large, it shows excess correction and abort sensor trim process). Engineer can press OK to correct the problem and try again.
7. Engineer Press YES to adjust the upper reference value and enter the upper reference value in the calibrator source window. For D/A trim, a warning message appears indicating that loop should be removed from automatic control to which the engineer clicks on OK. If the reference meter is connected, tap OK then set the field device output to 4 mA and tap OK.
8. Enter meter value and tap Enter. Field communicator will ask whether the reading in reference meter is 4 mA or not. Engineer Press YES if the reading is 4 mA, NO otherwise and then hits Enter to repeat the above process. Once reading is set to 4 mA Field communicator will ask for set the field device output.
9. Same procedure as D/A trim is followed for field device output setting (Scaled D/A trim). If you are an engineer press YES to adjust the field device output value and enter the low reference value in the calibrator source window. If the reference meter is connected tap OK then set the field device output to 4 mA and tap OK if the reading shown on communicator is also 4 mA. Then communicator will ask for upper reference value and display current reading at that value. If the reading shown is 20 mA then field device output is fine. If not click on adjust button then communicator will automatically adjust the output reference current value.

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Checkpoint

✦✦✦ **1.** What are the types of calibration used in temperature transmitter?

✦✦✦ **2.** What is sensor trim?

Summary

LO 1: *Describe the need for temperature measurement and measuring units*

- Temperature can be defined as "The degree of hotness or coldness measured on a defined scale".
- Temperature is the driving force for heat flow the same way as the voltage is the driving force for the flow of electricity.
- Anders Celsius proposed a scale in 1742 that had zero at the melting point of water and 100 at the boiling point of water that eventually resulted in the Celsius scale.
- Pascal reported use of thermometers in which the fundamental interval, ice point to steam point was 100°.
- In International Practical Temperature Scale some of the intermediate reference points on the scale include the triple point of equilibrium of hydrogen, the boiling point of neon, the triple point of oxygen, and the freezing points of zinc, silver, and gold.

LO 2: *Outline different principles in temperature measurement*

- The traditional measurement technique of thermometers is based on the volumetric change in liquids and gases with change in temperature.
- Thermal radiation of the hot bodies served as the basis for radiation pyrometers.
- On a broader picture the sensors can be classified as—mechanical sensors, passive electrical transducers, and electrical transducers.
- The thermal mass of the sensor must be low enough to make it possible to measure a change in temperature. In other words, if a great deal of heat is required to raise the temperature of the sensing element, the sensor would act as a heat sink and a small change would not be detected.
- Any display instrument in no way can improve the resolution of the temperature beyond that of the sensing element.
- In bimetallic thermometers the metals change in volume in response to a change in temperature and secondly that the coefficient of change is different for all metals.
- For filled thermal elements the fluid or gas inside the device expands and contracts with a change in temperature causing a bourdon gauge to move. The response time and accuracy provided by the filled thermal element are sufficient for many industrial-monitoring applications.
- The large temperature coefficient of thermistors makes it suitable for small spans (ranges) making large spans (ranges) rather difficult to handle.
- For thermistors a pure oxide of nickel, copper will result in negative temperature coefficients whereas silicon, manganese combined with lead, barium, etc., result in positive temperature coefficient.

LO 3: *Illustrate the theory and application of thermocouple and RTD*

- A thermocouple is a thermoelectric temperature-measuring device. It is formed by welding, soldering or merely pressing two dissimilar metals together in series to produce a thermal electromotive force (E) when the junctions are at different temperatures.
- Peltier discovered that when an electric current flows across a junction of two dissimilar metals, heat is liberated or absorbed.
- Thomson effect can be explained as that when electric current flows, there is an evolution or absorption of heat due to the presence of the thermoelectric gradient, with the net result that the heat evolved in an interval bounded by different temperatures is slightly greater or less than that accounted for by the resistance of the conductor.

- In a thermocouple based temperature measurement, variations in the reference junction temperature will produce changes in the millivolt output, resulting in temperature measurement errors. Therefore, for accurate measurements, the reference junction must remain constant.
- A lot of research has gone into finding metal and alloy combinations that provide an ample millivoltage per degree of temperature and a combination that resists corrosion in oxidizing and reducing atmospheres.
- Spring-loaded thermocouple assemblies are particularly effective where a temperature measurement is made for control purposes. Spring loading not only improves response but also protects the junction from the effects of severe vibration.
- Reproducibility and stability are of critical importance in industrial applications prompting the use of resistance temperature detectors (RTDs) in industrial temperature measurement.
- Immersion RTDs are meant to allow a sensing element to be immersed in a media to measure its temperature.
- Of all materials used in the fabrication of thermoresistive elements, platinum has the optimum characteristics for service over a wide temperature range.
- Platinum with a temperature coefficient of resistance equal to 0.00385/(°C) (from 0 to 100°C) is used as a standard for industrial thermometers.
- The various types of RTDs are classified based on the mounting technologies, metals used and the fabrication of the metal in the sensor, etc. The instrument engineer is expected to know all of these variants in order to choose the right sensor based on the application.
- The response time of temperature measurement can be improved by minimizing the air separation that slows down the heat transfer rate from the thermowell to the sensor. This can be accomplished by providing a close tolerance between the outer diameters of the sensor and inner diameter of the thermowell. Using a spring-loaded thermocouple or RTD will provide contact between the sensor and inside the thermowell.
- The response time can also be increased by another method of minimizing the effect of air separation is to add a small amount of oil or powdered graphite and oil inside to the thermowell.
- The wall thickness of the thermowell must be strong enough to prevent the frequency from equating the natural frequency of the thermowell. If the natural frequency is reached, the thermowell will resonate and fracture.
- Three-wire RTD method compensates for the effect of lead resistance in which the ultimate accuracy of the circuit depends on leads being of equal resistance. Special matching techniques must be used on leads, particularly when distance between sensor and measuring equipment is relatively large.
- Thermocouple has pros in terms of cost, ruggedness, higher temperature range and mounting cost, and the cons being stability, inherently small millivolt output and calibration.
- RTDs has the pros in terms of accuracy, repeatability, substantial output voltage, short time reproducibility and relative narrow spans, and cons being cost, less rugged, lower temperature range and self heating errors.

LO 4: Analyze analog and smart temperature transmitters

- Smart temperature temperatures bring many advantages such as self-diagnostics, elimination of hardware changes or recalibration, and bidirectional communication with a distributed control system.
- Microprocessor-based smart temperature transmitters can be reconfigured to accept other sensor inputs without having to make hardware changes and recalibration.

- The online diagnostics help in smart temperature transmitters to identify the problems in the device much early and enabling proactive and predictive maintenance for the process plant.
- The smart transmitter stores information in the device itself. These data include Tag (8 alphanumeric characters), descriptor (16 alphanumeric characters), message (32 alphanumeric characters), date, and integral meter. In addition to the configurable parameters, the system's software contains several kinds of information that are not user-changeable like transmitter type, sensor limits, and transmitter software revision levels. The system performs continuous self-tests. In the event of a problem, the transmitter activates the user-selected analog output warning.

LO 5: Illustrate the calibration methods for temperature transmitter

- The two types of temperature calibrations commonly used today are fixed-point and comparison calibrations.

Questions

I. Objective-type questions

✦✦ **1.** Which of the following is true of resistive temperature devices?
- (a) They are more accurate than thermocouples and can be used at high temperatures.
- (b) They respond quickly to changes in resistance since the heat conducts quickly through the protective sheath.
- (c) They rely on resistance change in a metal with the resistance rising linearly with temperature.
- (d) They require the use of a bridge circuit to compensate for low or high temperatures.

✦✦ **2.** Which of the following is true of signals prior to when standard signals were common?
- (a) Measuring flow by differential pressure involved running a thermocouple extension wire to the control room.
- (b) The signal to the final control element for thermocouples was some form of pneumatic or mechanical transmission.
- (c) RTDs developed two-wire applications to overcome the limitations of long leads.
- (d) Measuring flow by differential pressure involved a pneumatic relay in which an electric gate opened and closed a remote airflow.

✦✦✦ **3.** Which of the following statements best describes the calibration of a temperature sensor?
- (a) It is the end user's practice to perform bench calibrations.
- (b) It is normally calibrated in a laboratory environment.

(c) Recalibration can be performed as needed if an out-of-tolerance condition becomes evident.
(d) A field calibration can be performed at the same time as a loop check.

✦ **4.** An instrument that can be programmed and can perform self-diagnostics is:
(a) Repeatable (b) Digital only
(c) Smart (d) Dumb

✦ **5.** Circle the correct SI base unit for temperature:
(a) 0 Centigrade (b) 0 Kelvin
(c) 0 Rankine (d) Celsius
(e) Kelvin

✦✦ **6.** Which of the above is/are absolute temperature units?

✦✦ **7.** A 4–20 mA transmitter is spanned 50–150°C.
(a) What is the span expressed in the units below?
____________ to ____________ °F, ____________ to ____________ K
(b) If the transmitter has an output of 10 mA, what is the temperature?
____________ °C

✦ **8.** Expansion for RTD is:
(a) Resistance thermometer detector
(b) Room temperature detector
(c) Read type DVD
(d) Resistance temperature detector

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II. Short-answer questions

✦✦✦ **1.** What is the temperature measuring range of R-type thermocouple?

✦ **2.** Define Peltier effect.

✦✦✦ **3.** Temperature measurement range for Nickel RTD is -_______ to _______ °C.

✦✦ **4.** Change of temperature coefficient w.r.t temperature is different for all metals. This principle is used in ___________________________ thermometer.

✦✦ **5.** List three advantages of RTD over thermocouple.

✦ **6.** What is the fundamental interval in Fahrenheit scale?

✦✦ **7.** What is the fundamental interval in Réaumur scale?

✦✦✦ **8.** What are the reference points of IPTS?

✦✦ **9.** What is the basic principle of quartz crystal in temperature measurement?

✦✦ **10.** List three advantages of thermocouples.

✦✦ **11.** List three disadvantages of RTDs.

✦✦✦ **12.** Differentiate between two-point calibration and five-point calibration.

III. Unsolved problems

✦✦✦ **1.** A two-wire loop with a loop power supply of 26 V has a 200 ohm load resistor and 50 ohms loop resistance. If the maximum current in the loop should be 20 mA, what is the voltage drop and how much voltage will be across the transmitter at 20 mA?
(a) 4 V drop and 22 V across the transmitter at 20 mA
(b) 4 V drop and 26 V across the transmitter at 20 mA
(c) 5 V drop and 21 V across the transmitter at 20 mA
(d) 6 V drop and 20 V across the transmitter at 20 mA

✦✦✦ **2.** At $\alpha = 0.00385$ pt 100 RTD measures the temperature rise of 30°C. What is the % shift in output signal one can expect?

✦ **3.** A Pt100RTD with $\alpha = 0.004$ is used to measure the temperature inside an oven. When the resistance across a RTD reads 140 ohm, Calculate the temperature of the transmitter.

✦✦ **4.** Calculate at what value, the Degree F and Degree C of the temperature become equal in terms of absolute number.

✦✦✦ **5.** Two HART enabled transmitters (both are calibrated to transmit 4–20 mA for the range of –50°C to 50°C) connected in a multidrop manner and the other end of the cable is connected to a PLC analog input card which is set to measure conventional 0–20 mA signal. Calculate the reading shown on PLC when the actual process temperature is 10°C.

✦✦✦ **6.** In a 3-wire Pt100 RTD, the total resistances measured between the extension leads and between RTD and an extension lead happened to be 40 ohm and 140 ohm respectively. Calculate the temperature of the process.

✦✦ **7.** An ideal gas is filled in a bullet and its pressure and temperature is monitored by a SCADA system. When there is an increase in the temperature of the bullet by 10%, calculate the % change in the pressure.

✦✦ **8.** Calculate the difference ($T_1 - T_2$) in the temperature of a room which is around 25°C when it is measured using RTD (T_1) and thermocouple (T_2).

✦✦ **9.** A resistor has a nominal resistance of 120 Ohms at 0°C. Calculate the resistance at 20°C. Calculate the change in resistance when the temperature drops by 5°.

✦✦✦ **10.** A thermocouple produces an emf in mV according to the temperature difference between the sensor tip q_1 and the gauge head q_2 such that:
(a) $e = a(q_1 - q_2) + b(\mathrm{sqr}(q_1) - \mathrm{sqr}(q_2))$, $a = 3.5 \times 10^{-2}$ and $b = 8.2 \times 10^{-6}$

(b) The gauge head is at 20°C. The mV output is 12 mV. Calculate the temperature at the sensor.

✦✦✦ **11.** A Pt100 with $\alpha = 0.05$ and Pt1000 with $\alpha = 0.004$ are used to measure same temperature inside an oven. At what temperature, both RTDs will read same resistance value? Assume that, the characteristics of RTD are linear over the range of 0–1000°C.

✦✦✦ **12.** According to IEC751, the nonlinearity of the platinum thermometer can be expressed as:

$R_t = R_o[1 + At + Bt^2 + C(t - 100)t^3]$, in which C is only applicable when $t < 0°C$. As an example, approximate sets of coefficients (Callendar Van Dusen coefficients) for a Pt100 resistor are given as $A = 4 \times 10^{-3}$, $B = -6 \times 10^{-7}$, $B = -6 \times 10^{-7}$, $C = -4 \times 10^{-12}$. Calculate the temperature when the RTD resistance reads 134 ohm.

✦✦ **13.** A temperature transmitter has a calibrated range of –80–150°F and its output signal range is 4–20 mA. Complete the following table of values for this transmitter, assuming perfect calibration (no error).

Measured temp. (°F)	*Percent of span (%)*	*Output signal (mA)*
120		
–45		
	42	
	25	
		7.5
		12.9

✦✦ **14.** A thermocouple has a linear sensitivity of 30 µV/°C, calibrated at a cold junction temperature of 0°C. It is used measure an unknown temperature with the cold junction temperature of 30°C. Find the actual hot junction temperature if the emf generated is 3.0 mV.

✦✦✦ **15.** A 2 wire Pt100 RTD with α = 0.004 reads 145 ohm at 100°C. Find out its total lead resistance at 100°C if both leads are having identical characteristics. Also suggest how we can improve the accuracy of RTD.

✦✦ **16.** Consider the sensitivity of a linear thermocouple as 2 µV/°C. When the cold junction is at 40°C, the voltage measured across the thermocouple is 20 mV. What is the actual temperature of the process?

✦✦ **17.** A digital thermometer reads from –120°C to +300°C. The accuracy is guaranteed to plus or minus 2% f.s.d. Determine the possible temperature range when it indicates 80°C.

✦✦✦ **18.** A thermometer has a range from –20°C to 150°C. The accuracy is guaranteed to ±3% f.s.d. Determine the possible temperature range when it indicates a temperature of 80°C.

✦ **19.** What is the output of Pt100 -RTD at 0°C?

✦✦ **20.** When the temperature of the liquid flowing through the process 225°C of the hot line, what would be equivalent value in Fahrenheit?

IV. Critical-thinking questions

✦✦ **1.** The large temperature coefficient of thermistors makes them suitable to which kind of applications?

✦✦✦ **2.** Name the materials used in thermistors which exhibits positive and negative temperature coefficient.

✦ **3.** What is the advantage of radiation pyrometer?

✦✦ **4.** What is the use of immersion RTDs?

✦✦✦ **5.** Which metal is used widely for RTDs?

✦✦ **6.** What is the temperature coefficient of RTD?

✦ **7.** What are the different ways in which RTDs are classified?

✦✦✦ **8.** What are the two methods to improve the response time of RTDs in thermowell?

✦✦✦ **9.** What happens if in a thermowell resonant frequency equals natural frequency?

✦✦✦ **10.** What is the significance of three wires in RTD?

✦✦✦ **11.** What enables proactive and predictive maintenance in process plants?

✦✦ **12.** What are the different types of data that can be stored in smart transmitter?

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Pressure

3

LEARNING OBJECTIVES

After reading this chapter, you will be able to:

1. Describe the basics of pressure measurement
2. Explain different types of pressure sensors, transducers, and transmitters
3. Analyze the performance and installation criteria of a pressure transmitter for specific applications
4. Review selection criteria of pressure measurement devices
5. Explain smart pressure transmitters and their calibration

Pressure is one of the key variable to be measured in most of the industrial operations. The speed of response, accuracy and ruggedness are the key attributes of any pressure measurement sensor. Like any other measurement method, pressure measurement has evolved over a period of time from a mechanical equipments to solid state electronics-based sensors.

Various pressure measuring units, their nomenclature and conversion methods are discussed in the initial sections and different pressure measurement methods are discussed later on. Pressure measurement has also become a means of measuring level and flow; hence, more emphasis has been laid on hydrostatic pressure measurement methods.

A pressure sensor is fully functional as required for the application as long as a proper device is selected and is installed as per the design. Any deviation from the above leads to erroneous calculation and hence the selection and installation guidelines are discussed. The pressure calibration devices and methods are discussed in detail to provide different techniques and equipment needed to perform the calibration.

Finally a set of questions, unsolved problems and critical thinking questions are provided to evaluate the learnings.

Keywords:
Absolute pressure, gauge pressure, vacuum, strain gauge, manometers, bellows, diaphragms, capacitive sensors, piezoresistive and piezoelectric sensors

"What gets measured (and clearly defined) does get done"
Mike Schmoker

3.1 BASICS OF PRESSURE MEASUREMENT

LO 1

Describe the basics of pressure measurement

In process measurement, the values of process variables (for example, pressure, temperature, level, and flow) in a process operation are continually determined to permit the process operation to be monitored or, more specifically, to permit the process variables to be controlled (that is, held at their set point or within their operating ranges).

Accurate measurement of pressure is essential to process measurement that is conducted for monitoring in general and for control. As mentioned above, the values of process variables in the monitoring of a process operation are continually determined. Effective monitoring depends on accurate measurements of pressure for the following reasons:

- Pressure values themselves are essential data for monitoring.
- Often, the values of process variables other than pressure are derived from (inferred from) the values that are measured for pressure.

As an example of inferred values from pressure, the value for the level of a liquid in a storage tank can be derived from the value of the hydrostatic pressure that is exerted by the liquid. As another example, the value for the rate at which a fluid is flowing through a pipeline can be derived from a differential pressure value that is produced by an orifice plate.

In many process operations, accurate measurement of pressure is essential for effective control. In a control loop that functions to control only pressure, accurate measurement of pressure is necessary to allow control instrumentation to detect deviation of pressure from its set point and then to determine the action that is needed to restore pressure to its set point. For example, in Gas Oil Separation Plants (GOSPs), it is necessary to keep the pressure of gas in a high pressure production trap at its assigned set point.

In some process operations, however, accurate pressure measurement is necessarily less for the purpose of pressure control and more for purposes of maintaining other process variables at their set points. In such instances, it is possible for control loops to indirectly control the other process variables by directly controlling pressure.

Note

As an example, the differential pressure (i.e., the difference between pressure values measured at two distinct points) of a fluid that is flowing through a pipeline is often controlled directly in order to control the rate at which the fluid flows through the pipeline.

3.1.1 Examples of Pressure Measurements

In addition to other process variables, a distillation column may require the measurement and control of the tower pressure. The pressure transmitter, located at the top of the tower Figure 3.1 has pressure-sensing technology that converts pressure to a usable signal. The pressure transmitter then provides the pressure variable as a standard output signal to the pressure controller. Because tower temperatures are sensitive to pressure changes, it is important to provide an accurate pressure measurement to the pressure controller.

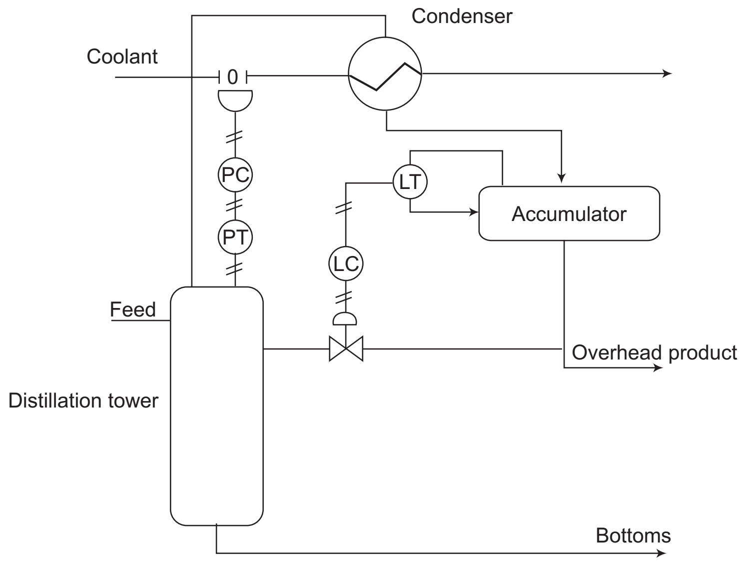

Figure 3.1: Sample distillation process with pressure measurement

A pressure measurement variable can also represent a demand for plant resources. In Figure 3.2 the steam pressure transmitter provides the steam pressure controller an indication of plant steam demand. The steam pressure controller, in turn, maintains steam pressure by providing the necessary control signals to both the fuel control valve and the fuel air controller.

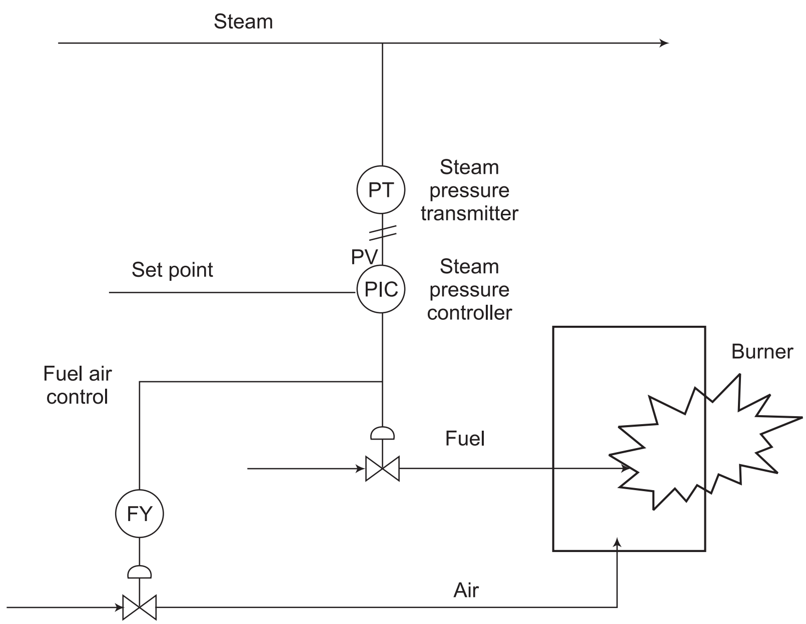

Figure 3.2: Sample boiler process with pressure measurement

3.1.2 Nature and Properties of Matter in Relation to Pressure Measurement

The nature and properties of matter as they relate to pressure measurement are best seen in real gas law equations. Real gas law equations can include a compressibility factor (Z), which accounts for gas behavior deviations from ideal gas laws caused by the attractive and repulsive forces between gas molecules. The following real gas equation shows the influence of temperature, volume, and compressibility upon pressure (Equation 3.1):

$$P = (nR_0TZ)/V \tag{3.1}$$

where, P = absolute pressure, n = number of moles of gas, R_0 = universal gas constant, T = absolute temperature, Z = compressibility factor, V = volume.

The following effects upon measured pressure can be observed from real gas equations:

- Pressure has a direct relationship to temperature. If the temperature increases, the pressure increases.
- Pressure has an indirect relationship to volume. If the volume increases, the pressure decreases. If the volume decreases, the pressure increases.
- Pressure has a direct relationship to compressibility. Compressibility represents that property of a gas that allows it to decrease in volume when subjected to an increase in pressure.

However, note that compressibility is nonlinear and that its effects upon pressure at different temperatures can be derived from engineering handbooks. Pressure measurement is important for a safe and efficient operation of industrial processes such as absorption, desorption, distillation, filtration, steam generation, and vacuum processing, etc. Pressure is a force applied to or distributed over a surface. The pressure (P) of a force (F) distributed over an area (A) is defined as:

$$P = \frac{F}{A} \tag{3.2}$$

By measuring pressure, one can also infer other process variables, such as the tank level (hydrostatic pressure) and flow (differential pressure).

Transmitters are commonly used for measuring the pressure of a liquid or gas in process and utility applications since they are used for measuring actual pressure, level, and flow. Generally, pressure is measured in pounds per square inch, inches of water column, bar, etc. The pressure measurement can be designed to measure the amount of pressure above or below atmospheric pressure (positive and negative pressures, also called as compound range), or it can be the amount that the pressure is above absolute zero pressure (Absolute). At sea level, atmospheric pressure is 14.7 pounds, but it varies about 0.5 psi per 1,000 ft of elevation. There are other units as well N/m^2, bars. Vacuum is generally measured in terms of micron and there is Torr, which are measured as pressure from a column of 1 µm and 1 mm mercury respectively.

The ideal gas law says that PV/T is a constant where P is the pressure, V is the volume, and T is the absolute temperature. Therefore, the pressure is highly dependent on temperature and volume. There are various methods available for pressure measurement, such as manometers, bourdon tubes, and bellows. Most pressure transmitters today, like single pressure, and differential, measure pressure by sensing the deflection of a diaphragm. A strain gauge is normally used as the sensing device for that deflection and is often on a secondary diaphragm for temperature and shock protection. The analog output of the sensor is then amplified for transmission. The output of the sensor is analog irrespective of the signal conditioning and transmission being digital or analog.

Pressure measuring instrumentation ranges from the low-cost bourdon and bellows operated gauges to the advanced pressure sensors transducers (transmitters). Pressure transducers originated as mechanical transducers where visual indication of the readings of pressure is provided by direct change in liquid levels in columns often referred as direct measurement.

As technology originated, pressure is applied on an element and that in turn is read by involving instrumentation in between the sensor and display, which is also referred as indirect measurement.

Modern pressure transmitters are significantly advanced from legacy counterparts mainly in two respects:

1. The links, levels, bellows used in legacy transducers were replaced by electric and electro-optic transducers, piezoelectric, capacitive technologies which enable varying degrees of miniaturization of the force-receiving sensors.
2. Introduction of "smart" or "intelligent" electronics into transmitter design, with the introduction of microprocessors along with other associated electronic circuitry changed the way the pressure is measured in industrial process measurement.

3.1.3 Pressure Units

Pressure can be expressed in different units. Often it is necessary to express a pressure measurement in similar units, requiring a conversion from one unit to another unit. The following discussion describes:

- Pressure measurement units
- Conversions between units

3.1.3.1 Pressure Measurement Units

While pressure measurement can be expressed in different units, two common categories for pressure measurement units are—customary English (also called English Engineering, EE) units and SI (System International d' Unites) metric units.

Customary English Units The customary English system is named because it uses common English units of weight (such as pounds and ounces) and units of area (such as square inches or square feet) in the expression of a pressure measurement. Rather than expressing pressure as "pounds force per square inch (lbF/in^2)", the unit is most often expressed as "pounds per square inch" and is abbreviated as "psi." In addition to psi measurement units, the customary English system also includes the following units:

- Inches of mercury column, abbreviated as "in Hg"
- Inches of water column (WC), abbreviated as "in H_2O"
- Feet of water column (WC), abbreviated as "ft H_2O"

The expression of pressure as a height of liquid column is best illustrated by a simple barometer, which measures atmospheric pressure in terms of the height of a column of mercury. A mercury barometer essentially expresses a gas pressure measurement in units of inches of mercury column (in Hg). In other words, the pressure exerted by the atmosphere (gas) is equal to the pressure exerted by a column of mercury (liquid). Likewise, industrial pressure measurement instruments, some similar in operating principle to the barometer, make pressure measurements calibrated in units of in Hg, in H_2O, or ft H_2O. When expressed in units of in Hg, in H_2O, or ft H_2O, the measured pressure is often referred to as a "head," which means "the equivalent height of a liquid that would create the same pressure".

SI Metric Units For the SI metric system of pressure measurement, the basic SI unit of pressure is the Pascal (Pa). One Pascal represents the pressure exerted by a force of one Newton (N) uniformly acting upon an area of one square meter. One Newton is defined as the force required giving a mass of one kilogram an acceleration of one meter per second.

Example

If a force of 1000 N is applied evenly to an area of 1 m^2, the pressure, *P*, can be easily determined by dividing the force, *F*, by area, *A* as follows:

$$\left.\begin{aligned} P &= F/A \\ P &= 1000\ \text{N}/1\text{m}^2 \\ P &= 1000\ \text{N}/\text{m}^2 \end{aligned}\right\} \tag{3.3}$$

Because 1000 N/m^2 is equal to 1000 Pa, the pressure in this example can be expressed as 1000 Pa.

In industrial process measurements, 1 Pa represents too small of a measurement unit for most pressures that are encountered, so the kilopascal (kPa) unit is frequently used to express a pressure value.

In addition to kPa units, the SI metric system also includes the following units:

- Millimeters of mercury column, abbreviated as "mm Hg"
- Millimeters of water column (WC), abbreviated as "mm H_2O"
- Centimeters of water column (WC), abbreviated as "cm H_2O"
- Kilograms per square centimeter, abbreviated as "kg/cm^2"

The familiar barometer described earlier may have its pressure measurements calibrated in SI metric units of millimeters (mm) Hg instead of inches (in) Hg. Likewise, industrial pressure measurement instruments could be calibrated for pressure measurement in mm Hg, mm H_2O, cm H_2O. When expressed in units of mm Hg, mm H_2O, cm H_2O, the measured pressure can be derived as:

$$P = \gamma h \tag{3.4}$$

where, Pg/gc and is specific weight lbf/ft^3, $h = P/\gamma$(lbf/ft^2/lbf/ft^3 = ft).
and P/γ is known as pressure head be referred to as a "head". The difference between the customary English system of units and SI metric system of units requires a brief review of

some additional pressure concepts. Because pressure is defined as force per unit area, one can take this definition further using Newton's laws and say that force itself is equal to mass times acceleration. In the customary English system of pressure measurement, the distinction between mass and force became confused with terms such as weight and mass. Weight, by definition, is equal to mass times gravitational acceleration.

Because the acceleration caused by gravity is uniform throughout the earth, it became easy to confuse the weight of one pound as if it were the same as the mass of one pound. In fact, weight is not the same as mass. Numerous attempts to resolve the confusion between weight and mass in the customary English measurement system only added to the confusion. Fortunately, the metric unit of the Pascal resolves the problems of distinguishing between weight and mass.

The simple definition of a Pascal removes gravity (and hence, weight) from becoming intertwined in the pressure definition of "force per unit area".

3.1.3.2 Conversion Between Units

Vendors often provide in their instrumentation catalogs an example conversion chart (Table 3.1). These charts vary in format and can be used to perform the following unit conversions:

- Customary English units to customary units
- Customary English units to SI metric units
- SI metric units to SI metric units
- SI metric units to customary units

Table 3.1: Example of a conversion chart

	Equals						
	Inch of Hg	*Inch of H_2O*	*Kgm/m^2*	*PSI (lb/In^2)*	*lb/ft^2*	*mm of Hg*	*Pascal (Pa)*
Inch of Hg	1	7.355×10^{-2}	2.896×10^{-3}	2.036	0.01414	3.937×10^{-2}	2.593×10^{-4}
Inch of H_2O	13.60	1	3.937×10^{-2}	27.68	0.1922	0.5354	4.014×10^{-3}
Kgm/m^2	345.3	25.40	1	7.031×10^{2}	4.882	13.59	1.019×10^{-1}
PSI (lb/In^2)	0.4912	3.613×10^{-3}	1.423×10^{-3}	1	6.95×10^{-3}	1.934×10^{-2}	1.450×10^{-4}
lb/ft^2	70.726	5.202	0.2048	144.0	1	2.7844	2.089×10^{-2}
mm of Hg	25.400	1.866	7.356×10^{-2}	51.715	0.359	1	7.502×10^{-3}
Pascal (Pa)	3.386×10^{3}	2.491×10^{2}	9.8067	6.895×10^{3}	4.788×10^{3}	1.333×10^{2}	1

One approach to converting pressure units involves dimensional analysis. Dimensional analysis is a method of performing calculations where conversions to desired units can be performed by using equivalent units. With a pressure equivalent of one standard atmosphere, the desired pressure unit values can be determined when converting from pressure unit to another. As Table 3.2 shows, 1 standard atmosphere is equivalent to 14.696 psia (English customary units) or 101.325 kPa (SI metric system). Dimensional analysis can be used when converting units from:

- Customary English units to customary units
- Customary English units to SI metric units
- SI metric units to SI metric units
- SI metric units to customary units

Table 3.2: Standard atmosphere as a conversion unit

Standard Atmosphere	*Equivalent Pressure in Units*
1 Standard atmosphere	14.696 psia
	760 mm Hg (0°C)
	76.0 cm Hg (0°C)
	0.76 m Hg (0°C)
	29.9213 in Hg (0oC)
	33.9294 ft water column (60°F)
	33.9569 ft water column (68°F, 20°C)
	407.4828 inches water column (68°F, 20°C)
	10.3501 meters water column (68°F, 20°C)
	0.986920 bars
	101.325 kPa
	760 Torr (mm Hg 0°C)

Dimensional analysis is illustrated by the way of examples.

Example

Converting from Customary Units to Metric Units:

Use dimensional analysis to convert a pressure reading of 8 in H_2O into equivalent kPa units.

First, set equivalent values equal to each other:

1 standard atmosphere = 407.4828 in H_2O = 101.325 kPa

Because the values are equivalent, you can say that dividing one value by another is equal to 1:

$$1 = 101.325 \text{ kPa}/407.4828 \text{ in } H_2O$$

Multiply both sides of the equation by 8 in water:

$$8 \text{ in } H_2O \times 1 = (101.325 \text{ kPa}/407.4828 \text{ in } H_2O)\ 8 \text{ in } H_2O$$

Cancel like units to get the equivalent value:

$$8 \text{ in } H_2O = 1.989 \text{ kPa}$$

or $\quad 8 \text{ in } H_2O \times 101.325 \text{ kPa}/407.4828 \text{ in } H_2O = 1.989 \text{ kPa}$

Example

Converting from Customary Units to Customary Units:

Use dimensional analysis to convert a pressure reading of 5 psia into equivalent in H_2O units.

First, set equivalent values equal to each other:

$$1 \text{ standard atmosphere} = 407.4828 \text{ in } H_2O = 14.696 \text{ psia}$$

Because the values are equivalent, you can say that dividing one value by another is equal to 1:

$$1 = 407.4828 \text{ in } H_2O/14.696 \text{ psia}$$

Multiply both sides of the equation by 5 psia:

$$5 \text{ psia} \times 1 = (407.4828 \text{ in } H_2O/14.696 \text{ psia})\ 5 \text{ psia}$$

Cancel like units to get the equivalent value:

$$5 \text{ psia} = 138.64 \text{ in } H_2O$$

or $5 \text{ psia} \times 407.4828 \text{ in } H_2O/14.696 \text{ psia} = 138.64 \text{ in } H_2O$

3.1.4 Measurable Pressures

Pressure measurements can be either simple pressures (single input port) or differential pressure (two input ports). Differential pressure (DP) transmitters are critical for small differential pressure measurements. For example, it is difficult to electronically measure the differential pressure in the case of 20 in of water in the presence of a high common pressure, say 1,000 pounds. The inaccuracy of the transmitters and subtraction devices would make the resulting difference inaccurate.

3.1.4.1 Definitions of Pressure

- **Absolute pressure**: Absolute pressure is measured above total vacuum or absolute zero pressure. Absolute zero simply means lack of pressure.
- **Atmospheric pressure**: The pressure as felt on the earth is known as atmospheric pressure. This pressure is exerted by the earth's atmosphere. Atmospheric pressure at sea level is 14.696 psia. The value of atmospheric pressure decreases with increasing altitude.
- **Barometric pressure**: Barometric pressure is atmospheric pressure with a different naming convention.
- **Differential pressure**: The difference in magnitude between some pressure valve and some reference pressure. In a sense, absolute pressure could be considered as a differential pressure with total vacuum or zero absolute as the reference. Likewise, gauge pressure could be considered similarly with atmospheric pressure as reference.
- **Gauge pressure**: Gauge pressure represents the positive difference between measured pressure and existing atmospheric pressure. It can be converted to absolute pressure by adding actual atmospheric pressure to it.

- **Hydrostatic pressure**: The pressure below a liquid surface exerted by the liquid above is known as hydrostatic pressure.
- **Line pressure**: Force per unit area exerted on the surface of the pipe by a fluid flowing parallel to a pipe wall is known as line pressure.
- **Static pressure**: Static pressure is the same as line pressure.
- **Vacuum**: Vacuum is the pressure below atmospheric pressure.
- **Working pressure**: Working pressure is also the same as line pressure.
- **Dynamic pressure**: Dynamic pressure is the pressure exerted by a flowing material parallel to the direction of such flow.
- **Compound pressure**: A measurement from a base reference point that is neither the atmosphere nor total vacuum.

The diagrammatic representation of the different nomenclatures of the pressure is shown below in Figure 3.3.

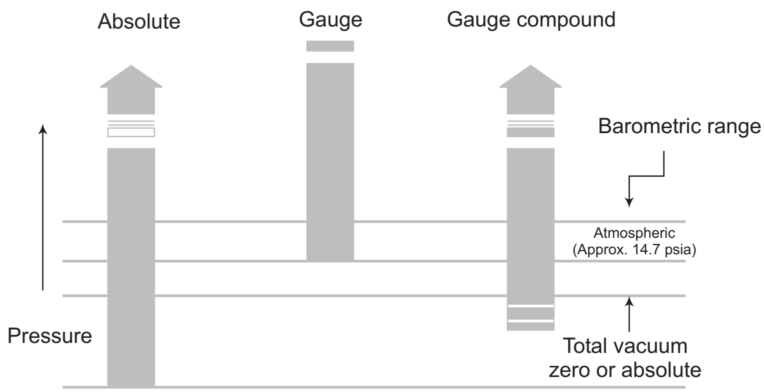

Figure 3.3: Nomenclature of pressure

3.1.5 Factors Influencing Pressure Measurements

In pressure measurement, the factors influencing pressure measurement are the following:

- Depth
- Specific gravity
- Temperature
- Surface pressure
- Homogeneity of the fluid

3.1.5.1 Depth

When a pressure measurement is used to infer liquid level, the pressure measured at any one point below the surface is directly proportional to the depth. Depth, not volume in the vessel, determines the amount of pressure—greater the depth, greater is the pressure.

3.1.5.2 *Specific Gravity*

When a pressure measurement is used to infer liquid level, specific gravity of the liquid has a major influence on the level measurement. Pressure is directly proportional to the specific gravity (density) of the measured liquid. For example, doubling the specific gravity doubles the measured pressure.

3.1.5.3 *Temperature*

Temperature affects the pressure of a fluid because it causes the specific gravity of the fluid to change. As the temperature increases, the fluid's specific gravity decreases.

3.1.5.4 *Surface Pressure*

When a pressure measurement is used to infer liquid level of an open tank, the atmospheric pressure adds to the measured pressure. If the pressure is measured in a closed tank, the surface pressure in the closed tank adds to the measured pressure.

3.1.5.5 *Homogeneity of the Fluid*

If the fluid in the storage tank experiences thermal stratification or density stratification when pressure measurements are used to infer level, the level measurement will be in error. To minimize the pressure measurement error caused by stratification often requires that the vessel use internal mixers.

Checkpoint

✦✦ **1.** List two examples of inferred process variables from the measurement of pressure.

✦✦ **2.** What is compressibility factor in real gas laws?

✦ **3.** What is the relationship between pressure and temperature?

✦ **4.** What is the relationship between pressure and volume?

✦ **5.** What is the relationship between pressure and compressibility?

✦✦ **6.** Define pressure.

✦ **7.** List any three units of pressure.

For answers to checkpoint, scan the QR code

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Note: ✦ Level 1 & Level 2 category
✦✦ Level 3 & Level 4 category
✦✦✦ Level 5 & Level 6 category

3.2 TYPES OF PRESSURE SENSORS, TRANSDUCERS AND TRANSMITTERS

LO 2
Explain different types of pressure sensors, transducers and transmitters

Pressure measuring devices used in industrial applications range from very simple, low-cost devices such as pressure gauges to more complex microprocessor-based instruments. In general, the following two trends are emerging in pressure measurement instrumentation—mechanical links and levers within pressure measuring devices are being replaced with silicon-based sensors; microprocessor-based instruments, particularly the “smart” or “intelligent” transmitters, are emerging as default choices.

The following discussion introduces categories of pressure measuring devices used in general process industries—gravitational gauges, deformation (elastic) sensors and switches, vacuum gauges, and transducers and transmitters.

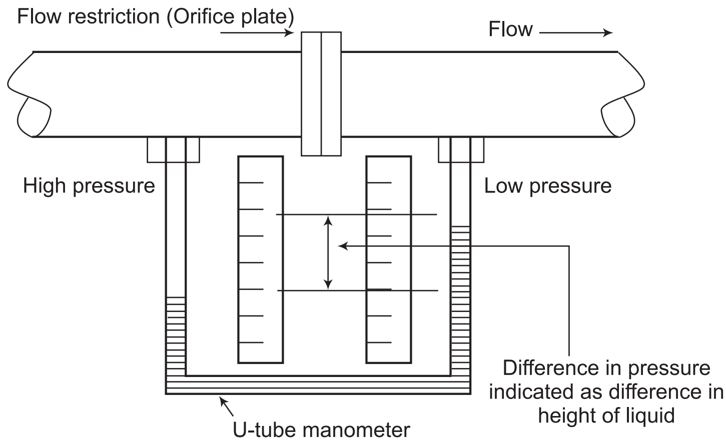
3.2.1 Gravitational Gauges

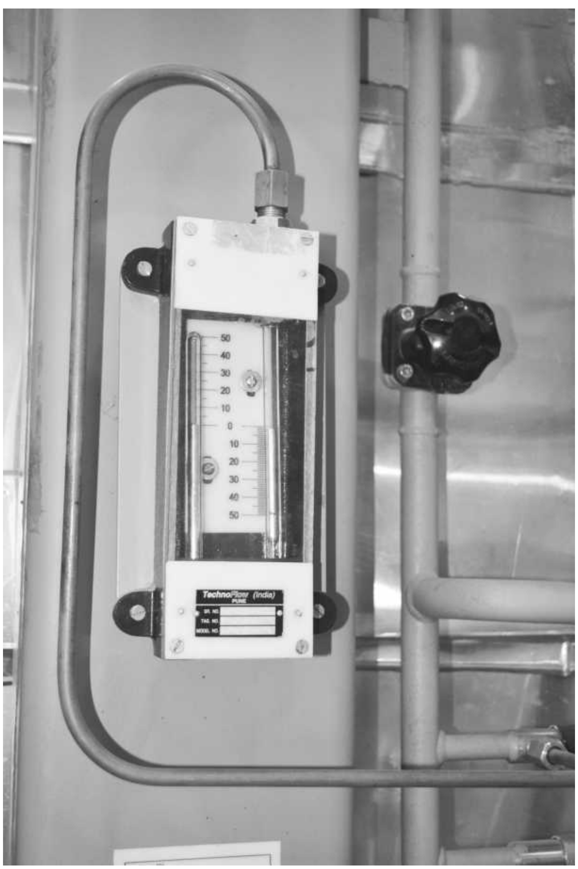
Gravitational gauges (such as U-tube, well tube, and inclined manometers) are highly accurate devices that can directly measure pressure. These devices are the earliest type of measuring devices and are in some ways the most dependable and reliable. These devices typically measure in units of psi, inches of water, and inches of mercury (Hg). The units—psi, inches of water, and inches of mercury—are often referred to as gravity dependent units i.e. the height of the fluid in the manometer is dependent on fluid’s density and force of gravity. A common gravitational gauge is the manometer. The simplest manometer is the U-tube manometer called so because of its U-shaped tube. The U-shaped tube is used to measure differential pressure (one side connected to a high-pressure connection and the other side to a low pressure connection or atmosphere). When a differential pressure is applied, the difference in pressure causes a difference between liquid levels on each side. The applied differential pressure is read as the differential pressure on a graduated scale (Figure 3.4). Manometers are the most basic devices of measuring pressure, commonly manometer is a column with openings on both ends, it may assume a shape of a well/U-shaped column where pressure is applied on one end, and the other end is used to represent the pressure as it is applied. Manometers are calibrated based on the fluids that are used inside the columns.

3.2.2 Deformation (Elastic) Sensors and Switches

Like all pressure sensors that sense pressure, deformation sensors convert the sensed response to a usable signal. The input to a deformation sensor consists of a force. A deformation sensor, in the process of sensing force, deforms in response to the force. The deformation is, in effect, the conversion of an input signal that becomes a pressure indication on a gauge. When used in a pressure switch, a deformation sensor converts the input signal to a switch’s actuation when specified pressures are breached. Thus, deformation sensors are found in more than one type of pressure measuring instruments such as gauges, transmitters, transducers, and switches. This section provides an overview of the following types of deformation sensors—bourdon tube, bellows, and diaphragm.

Figure 3.4 U-tube manometer





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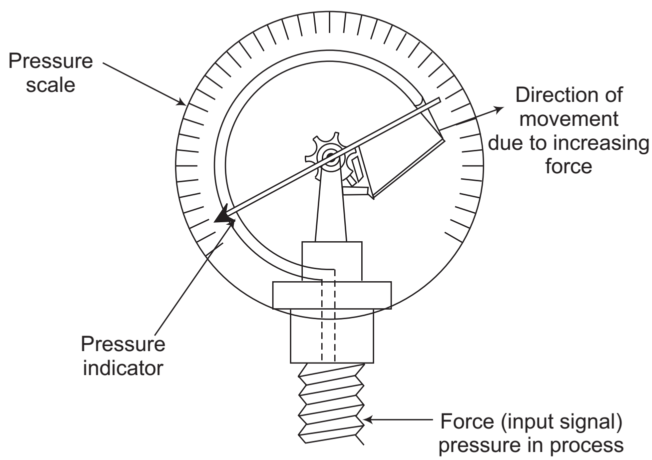
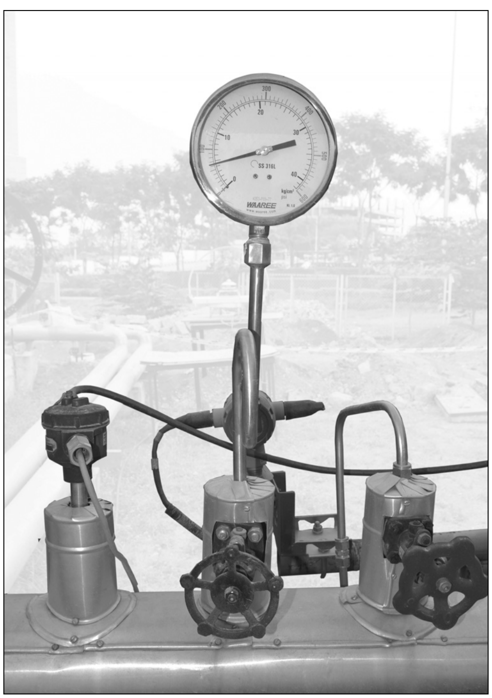
3.2.2.1 Bourdon Tubes

Bourdon tubes were one of the first and popular mechanical sensors. There is a hollow C-shaped tube whose end is fixed and pressure is applied on it, other end is closed and when pressure is applied since it has no other outlet it forces the tube to change its position whose motion is properly calibrated to represent the applied pressure as shown in Figure 3.5.

Figure 3.5 Bourdon tube





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3.2.2.2 *Bellows*

Bellows are popular for direct as well as indirect measurements. Bellows are a device made of thin sheet metal with circular corrugations in it, so that it looks like the olden days air-horn, pneumatic pressure applied inside of the bellows makes it to elongate or expand. The material with which bellows are made should be flexible enough so that it does not restrain the motion of expansion. Hence, the force produced due to expansion will equal the force calculated by the force-pressure-area equation. In case, the bellows' expansion is restrained externally, it will not stretch to the full extent and hence will not act as a restraining spring (Figure 3.6). In this case, the force exerted by the bellows on the restraining object will exactly equal the pneumatic pressure multiplied by the cross-sectional area of the bellows end. When the backpressure builds, the bellows expands in proportion to the backpressure and indicates the pressure on the dial gauge. If the bellow is supposed to control any succeeding/feedback elements, the object is connected directly to the bellows.

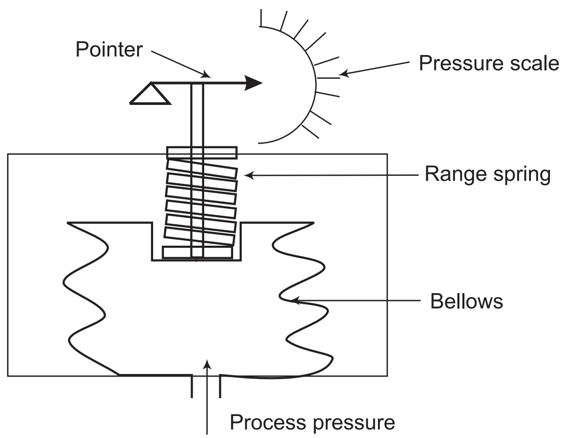

Figure 3.6: Bellows as used in pressure measurement

3.2.2.3 *Diaphragms*

Diaphragms are another type of popular primary transducers. They can be flat or corrugated in structure. They are most popular for measuring differential pressure when corrugated. They can either be used as direct indicators of pressure change by using a sensitive pointer to pick up the changes which is properly calibrated or as primary transducers where the changes in diaphragm are picked up by secondary transducer which in turn processes the signal. Refer to Figure 3.7 for the diaphragm used in pressure measurement.

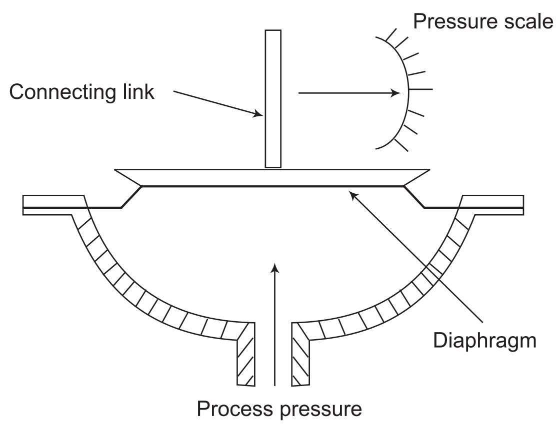

Figure 3.7: Diaphragm as used in pressure measurement

3.2.3 Vacuum Gauges

3.2.3.1 *McLeod Gauge*

A McLeod gauge is a scientific instrument utilized to measure very low pressures, down to 10^{-6} Torr. It has been invented in 1874 by Herbert McLeod (1841–1923). McLeod gauges were usually found combined to equipment that function under a vacuum. However, the present day gauges have been replaced by electronic vacuum gauges.

The design of a McLeod gauge is little similar to a mercury column manometer. A sample volume of gas is captured in a vacuum chamber and this gas is then compressed by tilting it and infilling with mercury. The pressure is then measured for this reduced volume by a mercury manometer. By calculating the compression ratio, the pressure of the real vacuum can be evaluated. Finally, Boyle's law is applied to find the initial and final pressure and volumes. If used wrongly, the mercury can outflow and pollute the vacuum system combined to the gauge; hence, care should be taken.

This method is accurate for noncondensable gases such as oxygen and nitrogen, is easy to use and its calibration is almost same for all noncondensable gases. However, for condensable gases, such as water vapor, ammonia, carbon dioxide, and pump oil vapors this method might be useful in gaseous form in low pressure of the vacuum chamber but is not useful when the gases condense on compression by the McLeod gauge. As a result a wrong reading is obtained showing a pressure reading much lower than the real pressure.

3.2.3.2 Thermal Conductivity Gauge

The Pirani gauge was invented by Marcello Pirani in 1906. It is a strong thermal conductivity gauge, which is utilized for measuring the pressures of vacuum systems. It consists of a metal filament (usually platinum) hanging in a tube which is fixed to the system whose pressure is to be measured. Connection is created either by a ground glass joint or a flanged metal connector and is sealed with an O-ring.

The principle is that a heated metal filament, hanging in a gas, will lose heat to the gas as its molecules collide with the wire. If the gas pressure is low, less number of molecules will collide and the wire shall drop heat very gradually. Measuring this heat is an indirect indication of pressure. It is known that the electrical resistance of a wire differs with its temperature; hence, the resistance signifies the temperature of wire. In many systems, the wire is kept at a fixed resistance, R, and the current, I, is regulated through the wire. The resistance can be set by a bridge circuit. The power sent to the wire is I^2R, and the same power is passed to the gas. Thus, the current at which this balance is attained is a measure of the vacuum.

The gauge is utilized for pressure range between 0.5 Torr and 10^{-4} Torr. The apparatus must be calibrated before usage as the readings of the meter are affected by the heat capacity of the gas and thermal conductivity. In case of low pressure measurements, another type of instrument, Penning gauge, can be used.

3.2.3.3 Ionization Gauge

There are two types of ionization gauges—hot-cathode ionization gauge and cold-cathode ionization gauge.

Hot-cathode Ionization Gauge The hot-filament ionization gauge also called a hot-filament gauge or hot-cathode gauge is the widely preferred low-pressure (vacuum) measuring device for the region from 10^{-3} to 10^{-10} Torr. Regulated electron current (typically 10 mA) is radiated from a heated filament. The electrons are pulled to the helical grid by a dc potential of about

+150 V. Most of the electrons go through the grid, and bombard with gas molecules in the enclosed volume, making a fraction of electrons to be ionized. The gas ions created by the collisions are pulled to the central ion collector wire by the negative voltage on the collector (typically a –30 V). Ion currents are of the order of 1 mA/Pa. This current is further improved and displayed by a high-gain-differential amplifier/electrometer.

This ion current may be different for various gases at a fixed pressure; therefore, a hot filament ionization gauge is dependent on the composition. Over a large range of molecular density, the ion current from a gas of constant composition will be directly equal to the molecular density of the gas in the gauge.

Cold-cathode Ionization Gauge The cold-cathode type ionization gauge can be replaced by hot cathode type, as it produces errors at high temperatures of the cathode. To suppress this problem, the electrodes must be properly cured prior to their use. All these glitches can be abolished by vacuum measurement that use cold-cathode ionization gauge.

A Philips and Penning cold-cathode gauge is shown in Figure 3.8. The device contains two cathodes and a hollow anode in between. An input voltage larger than 2 kV is passed between them. Due to the applied voltage, a strong magnetic field is produced and hence the electrons are expelled which causes the gauge to function at pressures below 10^{-2} Torr. The mean free path of the gas is so great that a collision may never occur and the discharge may discontinue and hence the ionization may not start. This problem can be eradicated by using a collimating magnetic field.

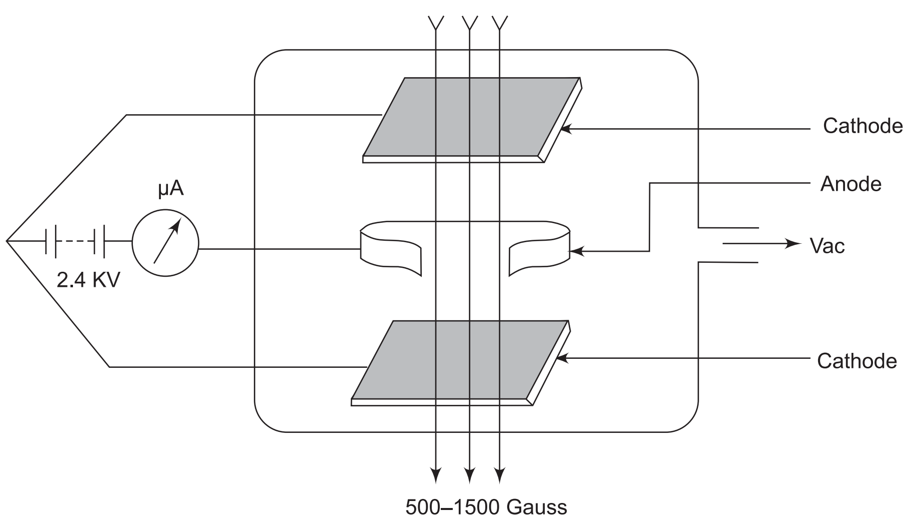

Figure 3.8: Cold-cathode ionization gauge

The use of collimating magnetic field helps in rising the path length for the electrons, thus allowing for discharge to be possible at pressures of 10^{-5} Torr. It is hard to obtain linearity between the meter reading and pressure as there are interactions between the positive ions and electrons at large electric and magnetic fields.

3.2.4 Transducers and Transmitters

The difference between a pressure sensor and a pressure transducer is that the sensor provides the basis of measurement (it converts one physical variable to another physical variable) whereas the transducer converts the measured from one form to another (such as conversion of force into current, displacement into voltage, etc). The measurement of pressure is considered very basic, as this process variable is used for measurement of flow (difference of two pressures), level (head or back pressure), and temperature (fluid pressure in a filled thermal system).

Any pressure measurement device consists of two basic parts—a primary part and a secondary part. The primary part is in direct or indirect contact with this interaction into appropriate values for use in indicating, recording and/or controlling. The secondary elements are connected to the electronics that carry the signal over larger distances and provides features such as display and input for control systems, etc.

A pressure transducer is a device that provides an electrical output signal that is proportional to the applied process pressure. The output signal is specified as millivolt, volt, current, or as frequency output. Pressure transducers tend to have specified operating pressure ranges; the ranges can vary widely. Note that pressure transducers are usually rated in units of psi, rather than units of inches of H_2O or inches of Hg. They are more application-specific than transmitters. For example, a pressure transducer can be specifically designed for a submersible application. They require a regulated power supply because they may not have signal conditioning capabilities.

A pressure transducer always consists of two elements:

- **Force-summing element**: A force-summing element, such as a diaphragm, converts the unknown pressure into a measurable displacement or force.
- **Sensor:** A sensor, such as a strain gauge, converts the displacement or force into a usable, proportional output signal.

A pressure transmitter is defined as a device that provides an industry standard linear output signal (4–20 mA current) that is proportional to an applied process pressure. Although a pressure transmitter can be called a transducer because it performs a conversion of pressure to a proportional electrical signal, the transmitter is considered an instrument in its own right. A pressure transmitter often has built-in signal conditioning and does not require a regulated power supply source.

Several forms of sensors are used in pressure transducers and transmitters, among which are the strain gauge, variable capacitance, variable reluctance, piezoelectric, double-ended tuning fork (DTF), and resonant wire sensors. The next discussion focuses on commonly used sensing technologies in both pressure transducers and transmitters, the most common being the strain gauge.

3.2.4.1 Pressure Transducer and its Working Principle

Although a pressure sensor (such as a deformation sensor) may provide a pressure measurement, it is consider that a deformation pressure sensor by itself does not provide an electrical signal suitable for interfacing to other pressure measurement instruments by itself. To provide an electrical signal, a pressure sensor must undergo additional calibration, compensation, and manufacturing steps.

The result of these steps forms what is called a “pressure transducer” or “electrical pressure transducer.” Recall that the purpose of any transducer is to convert a sensed force or displacement to a usable signal. In a pressure transducer, a pressure having sensed force is converted to an electrical signal. A pressure transducer physically consists of a deformation sensor, such as a diaphragm that senses force, and passive electrical components that can show output as an electrical signal. The transducer’s passive electrical components, often in the form of a strain-gauge sensor, provide the proportional electrical signal that represents pressure. After undergoing the calibration, compensation, and manufacturing steps, the combination of deformation and passive electrical component, the sensor becomes a pressure transducer. In other words, the pressure transducer consists of two sensors. In a pressure transducer, the deformation sensor represents the force-summing element while the strain-gauge sensor represents the force sensing element that converts the force to a proportional electrical signal. Figure 3.9 summarizes the relationship of the pressure deformation sensor and strain-gauge sensor to the assembled pressure transducer.

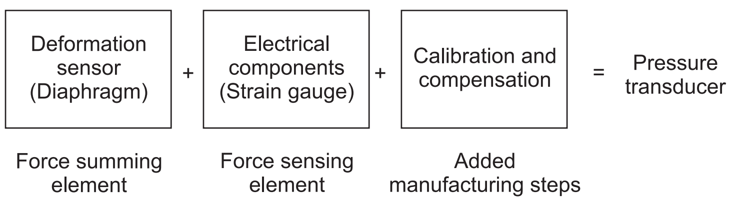

Figure 3.9: Transducer block diagram

A pressure transducer is a pressure measurement instrument in its own right. As noted earlier in this chapter, a pressure transducer, when compared to a pressure transmitter, has a specified pressure application range and a specified output signal (millivolt, volt, frequency, current). The terms “transducer” and “pressure transducer” are frequently used in industry to represent various entities or functions. For example, the previously described pressure transducer can be a subassembly of another pressure measurement instrument, such as a switch, conventional pressure transmitter, or microprocessor-based pressure transmitter. As mentioned earlier in this chapter, a pressure transmitter itself is often described in some documentation as a “transducer.” This would lead one to believe that a transmitter is a “transducer that consists of a transducer. Furthermore, the term “pressure transducer” is frequently used in industry to refer to a device (not described in this chapter) that adjusts a control valve’s position.

Admittedly, the term “transducer” can be very confusing and must be interpreted in the context of the discussion that it is presented in. To help clarify terminology, note that the term “transducer” is often used to generically describe an instrument in terms of an instrument’s function—an instrument that converts one form of energy to another energy form is called a transducer. The term “pressure transducer,” as it is used in the following discussion, refers to a specific measurement instrument that is used to convert a sensed pressure process variable to a proportional electrical output signal.

Pressure transducers are found in industrial gas and liquid pressure measurements and are used to measure gauge, absolute, or differential pressures. In pressure measurement and control systems, the means by which the instrument interfaces with the process is a prime consideration to achieve reliable operation. The measuring device must come in physical contact with the process, but in some instances, special precautions must be exercised to prevent damage to the pressure element.

Transducers used in pressure measurement applications include the following—strain-gauge transducer, potentiometric element transducer, piezoresistive pressure transducer, piezoelectric gauge transducer, capacitive transducer, and resonant-wire pressure transducer.

Strain-gauge Transducers A strain-gauge sensor changes its electrical resistance when it stretches or compresses (Figure 3.10). A strain gauge is often attached (bonded) to a diaphragm force element. In this approach, the strain gauge converts the diaphragm movement to an electrical signal. Bonded strain gauges are placed on a surface bonded to an element and it is more popular for measuring the local strain. Normally they assume the form of a wire/foil or film. The element that forms this is different from the element that connects this sensor to the instrumentation circuitry. Normally copper wire connects the instrumentation to the sensor. Proper adhesives are to be used for avoiding the noise that may be induced due to bonding of the sensor to a structure. Popular cement for adhering these to the surface is nitrocellulose cement.

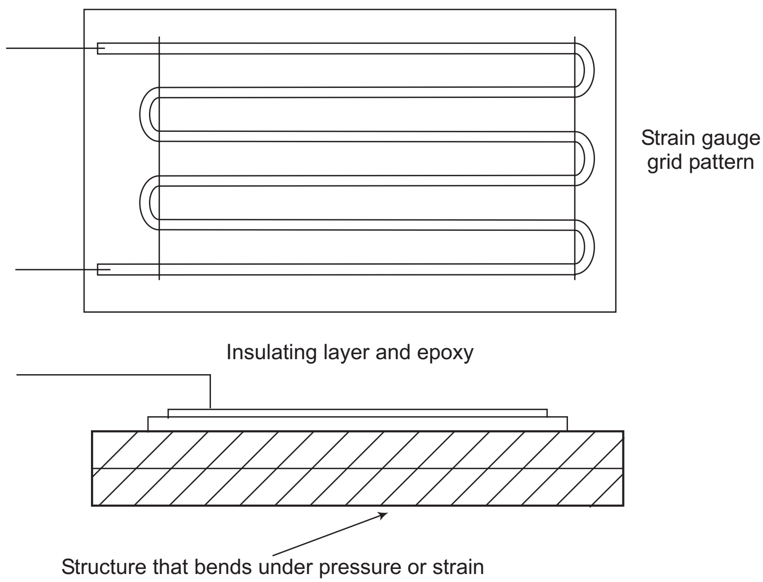

Figure 3.10: Bonded strain gauge

Strain-gauge transducers are the most used sensing element in pressure and weighing load-cell applications in most industrial pressure measurement applications. Strain gauges are usually directly mounted on the edge of the pressure sensor capsule or force-summing element of the transducer. The strain gauge is supported by sensing diaphragms or bonded to cantilever springs, which become a restoring force. The operating principle of a resistance-type strain gauge is illustrated in Figure 3.11.

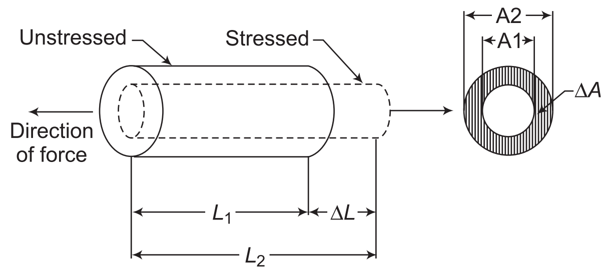

Figure 3.11: Operating principle of resistance-type strain gauge

The sensitivity in a strain gauge also called as gauge factor will be specific to strain-gauge material. The sensitivity in this case is Poisson's ratio and for most wires is approximately 0.3. When considering only the dimensional change aspect, the strain sensitivity or gauge factor is approximately 1.6. This implies that a 0.1% increase in length within the elastic range will produce a 0.16% increase in resistance. During actual tests, a metal or alloy exhibits different values of strain sensitivity to wide range of temperatures as specified.

During the application of the stress, the wire changes in length from L_1 to L_2 and hence an area from A1 to A2. The resistance is:

$$R = \rho \frac{L}{A} \tag{3.5}$$

where, L = conductor length, A = cross section area, ρ = resistivity constant.

By applying log on both ends the equation turns out to be:

$$\ln R = \ln l - \ln a + \ln \rho$$

Differentiation gives Equations 3.6 and 3.7:

$$\frac{dR}{R} = \frac{dl}{l} - \left(\left(\frac{da}{a} \right) + \left(\frac{d\rho}{\rho} \right) \right) \tag{3.6}$$

$$\frac{da}{a} = -2\mu \left(\frac{dl}{l} \right) \tag{3.7}$$

But the relation between longitudinal stress due to tensile strain along its axis, and decrease in cross sectional area due to compressive strain results in Equation 3.8:

$$\frac{dR}{R} = \left(\frac{dl}{l} \right)(1 + 2\mu) + \frac{d\rho}{\rho} \tag{3.8}$$

Hence, gauge factor is:

$$\frac{dR/R}{dl/l} = G = \left[1 + 2\mu + \left(\frac{d\rho/\rho}{dl/l} \right) \right] \tag{3.9}$$

where, μ = poisons ration often considered as 0.3 and $(d\rho/\rho/dl/l)$ is normally considered to be almost "0".

Advantages

- Connecting a transducer to multiple measurement devices
- General handling and installation guidelines

Transducer Output Signals and Wiring Configurations A pressure transducer can provide an output signal that is either in millivolt, amplified voltage or as standard (4–20 mA) current output. The wiring configuration is dependent on the output signal type as follows:

- A transducer that provides a millivolt output signal is limited to distances less than 60 m (200 ft) because of its small signal levels. The millivolt signal level is also prone to interference from other electrical signal sources. A typical wiring configuration is shown in Figure 3.12(a).
- A transducer that provides an amplified voltage output, such as 1 V dc to 5 V dc, has built-in signal conditioning and can provide signals over moderate distances, up to 300 m (1000 ft), to receiving instruments. Amplified voltage transducers provide better noise immunity than millivolt output transducers. A typical wiring configuration is shown in Figure 3.12(b).
- A transducer that provides a standard current output, 4 mA to 20 mA, has built-in signal conditioning. The current output can provide signals over distances greater than 300 m (1000 ft), to receiving instruments with virtually no signal degradation. A typical wiring configuration is shown in Figure 3.12(c).

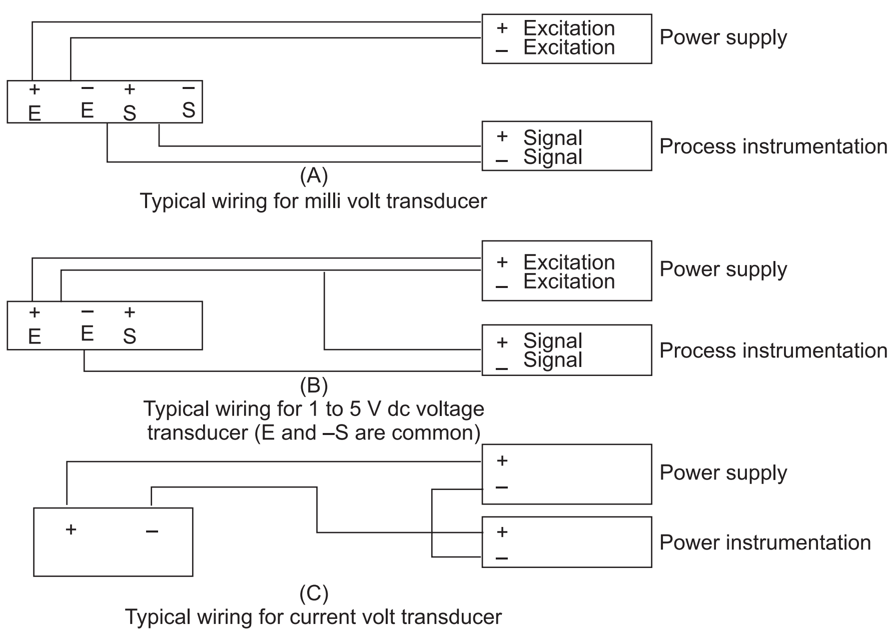

Figure 3.12: Installation of typical transmitters

Connecting a Transducer to Multiple Measurement Devices A pressure transducer that provides a current output tends to be frequently used in industrial environments because a current signal offers better signal noise immunity than millivolt or voltage signals. One advantage of a transducer with a current output signal is that it can be applied in a system with multiple measurement devices. For example, the signal may be required by chart recorders, panel meters, and control systems. Figure 3.13 shows a typical wiring arrangement.

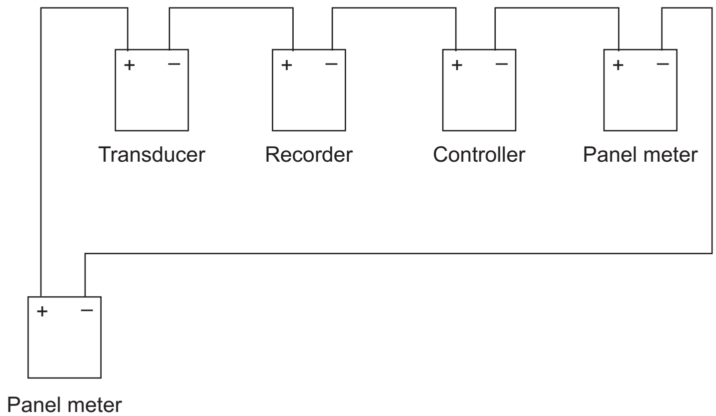

Figure 3.13: Installation of typical analog loops

In this system, a loop wiring load resistance must be calculated. The loop resistance determines the minimum voltage required to drive the loop and is based on Ohm's Law ($V = I \times R$).

The minimum voltage requirement is based upon the following formula:

$$\text{Minimum operating voltage} = (20\text{ mA})\,(R_{\text{line}} + R_{\text{load}}) + V_s \tag{3.10}$$

where, R_{line} = lead wire resistance, R_{load} = resistance total for other measurement devices, V_s = minimum operating supply voltage of the transducer.

Example

Assume a system configured with a pressure transducer with current output 14–30 V dc supply voltage, lead wire resistance of 8 ohm, recorder with 30 ohm input impedance, controller with 250 ohm input impedance, panel meter with 15 ohm input impedance. Calculate the voltage required.

The voltage required is calculated as follows:

Minimum operating voltage = (20 mA) (R_{line} + R_{load}) + V_s

Minimum operating voltage = (20 mA) (8 + 30 + 250 + 15) + 14

Minimum operating voltage = 20 V

Because a 24 V power supply is provided in most applications, the example arrangement will have adequate power driving the loop.

General application examples for pressure transducers include the following:

- Compressor and pump control
- Flow measurement and control
- Water level measurement and control
- Sewage level measurement and control
- Engine monitoring and control
- Monitoring oil tanker loading
- Monitoring oil pressure in turbines
- Monitoring lube oil pressure in a compressor
- Hydraulic system control
- Interfacing to other pressure instrumentation (recorders)

Potentiometric Element Transducer Potentiometric element is a variable resistance element in which the varying resistance can be used to determine the amount of variable pressure. The simplest potentiometer can be a wire wrapped around a cylinder as shown in Figure 3.14. As a pointer moves across the cylinder, the proportional resistance change represents the change in pressure.

Variable resistance pressure transducers, shown in Figure 3.15, typically use a bellows, diaphragm, or Bourdon tube as the force-summing system to convert the process pressure into a mechanical motion. This mechanical motion is then linked to a wiper arm of a potentiometer. The potentiometer, which is a variable resistor, is one of the simplest elements used to convert the mechanical motion to an electrical output.

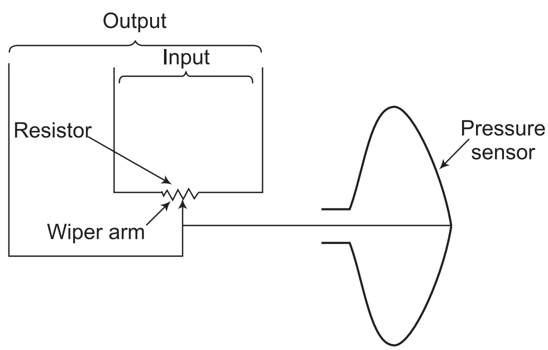

Figure 3.14: Variable resistance transducer: principles and design

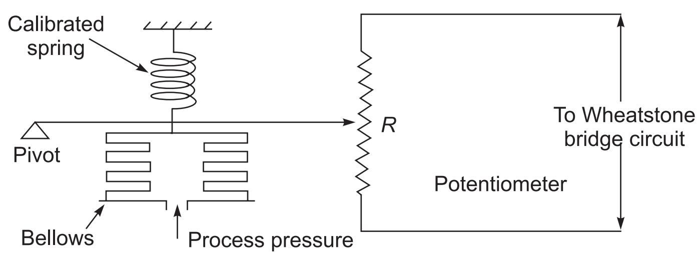

Figure 3.15: Pressure measurement using variable resistance

Advantages

- Variable resistance pressure transducers have high output signals.
- Variable resistance pressure transducers have good accuracy. Typical accuracies are about 0.5–1.0 % of full scale.

- Typical variable resistance pressure transducers support a wide pressure range, from 35 kPa to 70 MPa (5–10,000 psig).

Disadvantages

- Mechanical wear on potentiometer's wiper arm can cause short life and noisy signals. *Use of semiconductors in newer versions of the variable resistance transducer has minimized these disadvantages.*
- The use of a regulated power supply may be required.

Piezoresistive Pressure Transducers The first piezoresistive pressure transducers were developed as pressure inputs for a commercial airliner in the 1960s, arising from research on the piezoresistive properties of silicon-diffused layers and the development of a piezoresistive device for a solid-state accelerometer. Although piezoresistive transducers have been available for other applications over an input pressure range of 1 to 680 atm, the principal application of usage in the earlier days was limited to the automotive field.

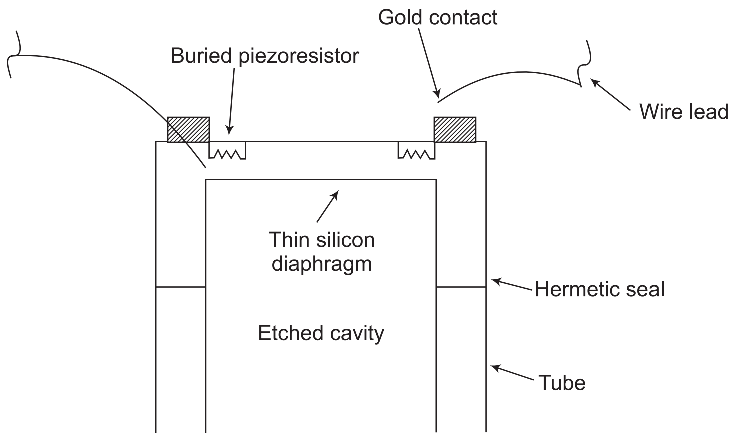

Figure 3.16: Cross-section of piezoresistive sensing element

Later, piezoresistive pressure transducers have been used in process control and industrial applications more frequently. The sensing element constitutes four identical piezoresistors embedded on the surface of the diaphragm. The diaphragm is generally thin and circular and made of silicon. Silicon diaphragm surface is attached with gold pads which connects to the piezoresistors and serve as pads for probe-type resistance measurements or for bonding of wire leads. The thin diaphragm of the piezoresistive element is made by chemically etching a circular cavity onto the surface opposite the piezoresistors. The unetched part of the silicon material provides a tough boundary constraint for the diaphragm and a surface for mounting. A cross-sectional view of the sensing element with wire leads bonded to the metal contacts is shown in Figure 3.16.

Pressure causes the diaphragm, which is thin, to bend, inducing a stress or strain in the diaphragm and the embedded resistor. Due to the stress applied, the resistance value of the element changes based on the amount of pressure applied to the diaphragm and the strain received. Hence, the sensing element converts energy from one form to another as a mechanical input (change in pressure) is converted to an electrical output (resistance). The resistor can be connected either to a half-bridge or a full Wheatstone bridge arrangement. For pressure applied to the diaphragm using a full bridge, the resistors can theoretically be approximated as shown Figure 3.17 (nonamplified units). The signal generated from the sensor arrangement (in a full-bridge arrangement) is proportional to the supply voltage and amount of change in resistance, which is proportional to the pressure applied.

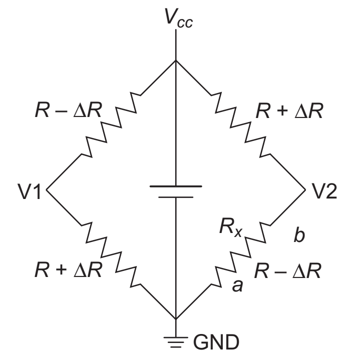

Figure 3.17: Full-bridge arrangement of piezoresistive transducer

$R + \Delta R$ and $R - \Delta R$ in the bridge arms as shown in Figure 3.17, represent actual resistor values at the amount of applied pressure. R represents resistor value for diaphragm ($P = 0$) when there is no pressure. In this case, all four resistors are almost equal in value and change by approximately the same value. ΔR represents a change in resistance due to the applied pressure. Note that of the four, two resistors increase while two decrease based on their position with respect to the crystalline direction of the silicon material.

A half-bridge configuration used in a signal-conditioned version of the piezoresistive pressure transducer is shown in Figure 3.18. The most frequently used pressure ranges of the transducers are 0 to 1, 0 to 13, 3 to 16, 0 to 30, 0 to 100, and 0 to 250 psi. In a piezoresistive transducer, the effect of repeatability and hysteresis are typically less than 0.1% of full-scale. Similarly the combined linearity and hysteresis effects do not exceed ±1% of full-scale output. The operating temperature range for standard units is from −40 to 125°C (−40 to 252°F).

Voltage across piezoresistors: $V_R = I_1 R_R = I_1(R_{RO} + kP)$ for radial resistor; and $V_T = I_2 R_T = I_2\ (R_{TO} = kP)$ across tangential resistor. I_1 and I_2 are adjusted at zero pressure to obtain $V_R = V_T$ or $I_1 R_{RO} = I_2 R_{TO}$. At other temperatures, when R_{RO} and R_{TO} vary, the equality holds provided that the temperature coefficients of R_{RO} and R_{TO} are equal. I_1 and I_2 increase with temperature to compensate for the chip's negative temperature coefficient of span while the sum of temperature-dependent voltage $V_N(T)$ and piezoresistor voltage compensates for the temperature coefficient of null which may be

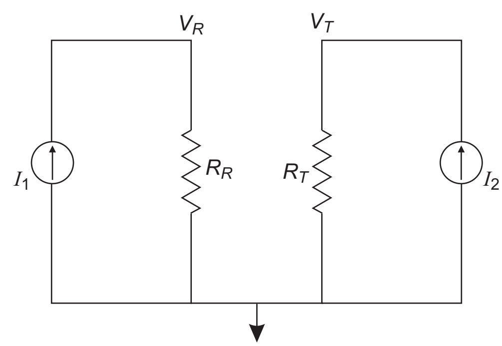

Figure 3.18: Half-bridge configuration for signal-conditioning of piezoresistive pressure transducer

of either polarity; thus, giving the output $V_O = V_R - V_T \pm V_N(T)$, with the polarity of $V_N(T)$ selected to provide compensation.

Piezoelectric Pressure Transducers Piezoelectric gauges use materials that create an electrical voltage when a force is applied. Piezoelectric sensors as shown in Figure 3.19 measure rapidly changing pressures, and respond to rapid pressure changes that occur over a short period.

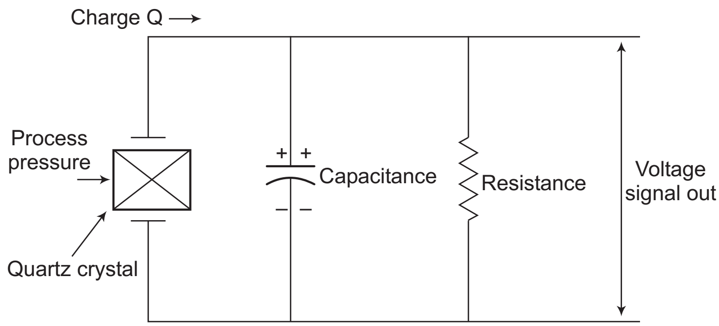

Figure 3.19: Piezoelectric gauge

The piezoelectric effect is created if certain asymmetrical crystals are deformed in specific axes. The deformation generates an electric potential within the crystal which causes a flow of electric charge in external circuits.

Transducers use this principle of operation to measure dynamic pressure, force, and shock or vibratory motion. In a piezoelectric pressure transducer, as shown in Figure 3.20, the crystal elements form an elastic structure that transfers displacement caused by force into an electric signal proportional to the pressure applied. Pressure acting on a flush diaphragm generates the force.

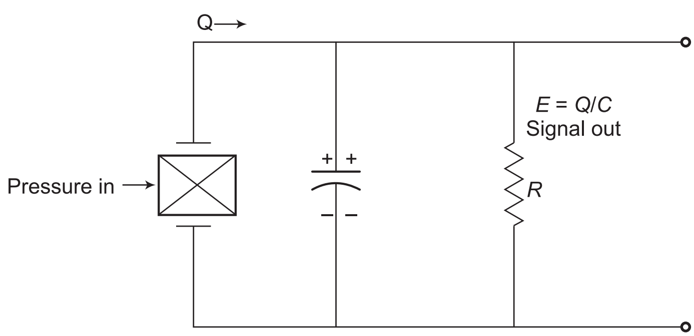

Figure 3.20: Piezoelectric crystal circuit

Earlier, piezoelectric pressure transducers used two types of crystals: natural single crystals, such as quartz and tourmaline, and synthetic polycrystalline ceramic materials, such as barium titanate and lead zirconate.

Cultured quartz has the advantage of being low-priced and easily available. These crystals have near-perfect elasticity and stability, and insensitivity to temperature. These attributes make the quartz as ideal transduction element for the pressure measurement applications. The preference of quartz in pressure transducers is also because of its ultra-high insulation resistance and low leakage allowing the same to have a static calibration capability.

Natural tourmaline offers sub microsecond response in pressure-bar-type blast transducers, owing to its rigid, anisotropic nature. Artificial ceramic piezoelectric crystals and electret (permanently polarized dielectric material, the analog of a magnet) materials readily form compliant transducer structures for generating and measuring sound pressures. According to the law of electrostatics, the charge signal from a piezoelectric pressure transducer is converted into a voltage-type signal using a capacitor:

$$E = \frac{Q}{C}$$

where, E = voltage signal, Q = charge, and C = capacitance.

This circuit diagram is shown in Figure 3.20. For a given step input, the response will be the charge signals stored in capacitor which discharges exponentially. The exponential response will be through the finite insulation resistance of the circuit components, precluding static measurements. The initial leakage rate is set by the time constant $R \times C$, where R is the leakage resistance value, which can be as high as 108 MHz in quartz crystals.

Piezoelectric sensors measure relative pressure, denoted as psir because of the automatic re-zeroing action of the discharge circuit. The crystal measures the pressure relative to the initial level for transient conditions and relative to the average level for pressure changes. Sometimes slow action of these circuits is misunderstood as zero drift.

A special isolation amplifier is required between the crystal and the recorder to prevent rapid leakage of the charge signal through the recorder or oscilloscope input resistance. The amplifier is called a voltage amplifier if the capacitor for charge conversion is located at the input of this isolation amplifier. It is called a charge amplifier if the capacitor is in the feedback path. Amplifiers are classified into two types—dc-coupled (electrostatic) or ac-coupled (vibration) amplifiers of which the ac-coupling circuitry behaves similarly to the sensor discharge circuit.

The high-frequency responses of piezoelectric sensor systems depend either on the resonant behavior of the mechanical structure of the sensor, or on electronic low-pass filters in the amplifier, sensor, or recorder. The design of piezoelectric sensors has changed greatly ever since the introduction of microelectronics and charge-operated field-effect transistors (JFET and MOSFET). Most of the current day sensors come with a package with amplifiers and signal conditioning. These sensors with built in electronics are commercially available as ASICs and are used in both traditional and smart sensors.

A lot of sophistication has been built into the mechanical structures of some piezoelectric pressure sensors to eliminate spurious signals caused by environmental effects, such as temperature and motion. A typical acceleration-compensated pressure sensor containing an integrated accelerometer to offset motion signals is shown in Figure 3.21. A durable coating on the sensor case and diaphragm ensures electrical and thermal insulation. Hermetic seals are electron-beam welded.

Piezoelectric pressure sensors are generally small, lightweight, and very rugged, offering many advantages for measuring dynamic pressures. The rangeability of transducer is very high and some of the sophisticated transducers may cover a measuring range of greater than 10,000:1 and a frequency range from less than 1 Hz to hundreds of kilohertz with little or no phase shift (time delay).

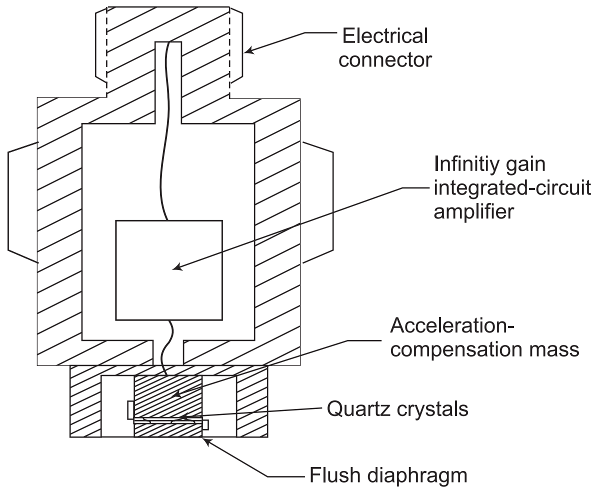

Figure 3.21: Acceleration-compensated quartz pressure sensor with built-in microelectronic unity-gain isolation amplifier

Piezoelectric pressure sensors are widely used in difficult applications, such as hydraulics, internal combustion, blasts, high-intensity sound, explosions, fuel injection, flow instabilities, and, which are known for being highly rugged. They are also used in pneumatic pulsations to overcome problems encountered in connection with guns, shock tubes, closed bombs, rocket motors, internal-combustion engines, pumps, compressors, pipelines, mufflers, and oil exploration implodes.

Capacitive Pressure Transducers In any capacitive transducer, a measuring diaphragm (elastic element) displaces relative to one or two fixed plates. An oscillator or bridge circuit is used to detect changes in capacitance. Generally, capacitive transducers are of low mass and high resolution, and they have good frequency response. Some of the limitations of a capacitive transducer include the need for sophisticated signal conditioning, some sensitivity to temperature, and the effects of stray noise on sensor leads. Over the years, the capacitive pressure transducers are improved in performance with excellent stability. These improvements can be attributed for testing and substituting new materials and advances in microelectronics with their miniaturization of circuitry, by increased use of microprocessors. The improvement in transducer design is based on the following error sources:

- **Deficiencies such as in long-term stability:** These are the error sources that cannot be corrected by built-in electronics. Testing by utilizing new materials like micromachined silicon, ceramics, quartz, and sapphire, which by nature exhibit minimal hysteresis, have led to improved answers to these error sources.
- **Deficiencies that are corrected by electronic circuits:** These include signal conditioning, calibration, and self-diagnosis and prognostics.

In a capacitive pressure transducer, based on the pressure applied, the distance between two parallel plates changes. This change in distance alters the electric capacitance, and can be amplified and used to operate in phase, amplitude, or frequency-modulated carrier systems.

A frequency-modulated system using a tuned resonant circuit is shown in simple form in Figure 3.22. In this electric circuit, the capacitance C3 is a part of the tuned resonant circuit L2C2C3. L1C1 forms part of a stable high-frequency oscillator circuit. The tuned circuit L2C2C3 is loosely coupled to the circuit L1C1. The high-frequency potential induced in circuit L2C2C3 is rectified, and the DC output current of the rectifier is indicated on an ammeter. The response of the tuned circuit L2C2C3 to a constant frequency is shown in Figure 3.22 as a function of the capacitance C2 + C3 of this circuit. Peak output occurs at point A when the circuit is tuned to resonate at the oscillator frequency. This circuit is tuned to its operating point B by increasing capacitor C2 until the rectifier meter reads approximately 70% of maximum. Any small change in pressure transducer capacitance C3, due to pressure on the diaphragm, affects the response of the circuit according to Figures 3.22 and 3.23.

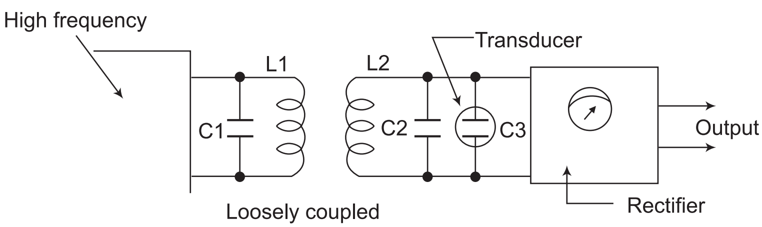

Figure 3.22: Schematic of tuned resonant circuit used in some capacitive pressure transducers

To eliminate the effect of cable capacity between the transducer C3 and the tuned circuit L2C2, a circuit as shown in Figure 3.24 can be used. In this circuit, a coil L3 is built as an integral part of the capacitive-transducer assembly. The coil L3 is connected in parallel with the transducer capacitor C3 to form a tuned circuit with a resonant frequency (for example, 600 kHz). The tuned circuit L3C3 is close-coupled to the tuned circuit L through the link coils L4 and L5, which are connected by a low-impedance (70 ohm) untuned cable. Any change in cable capacity, such as that produced by vibration is negligible when reflected into the high-impedance tuned circuit. Therefore, long cables can be used between the transducer and the electronic unit. The tuning characteristics of a link-coupled circuit are shown in Figure 3.25. The operating range is the linear section noted midway between the maximum and minimum readings obtained with changing capacity.

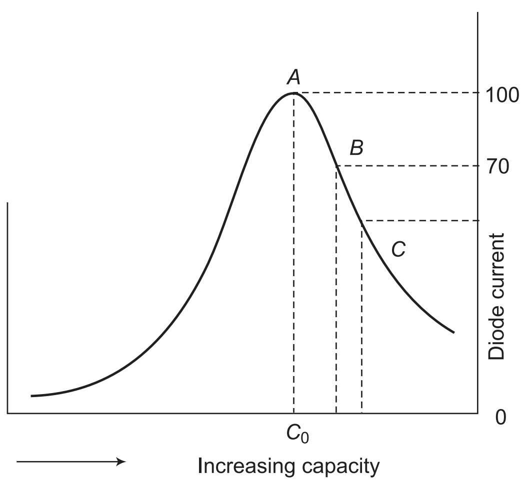

Figure 3.23: Response of resonant circuit to constant frequency

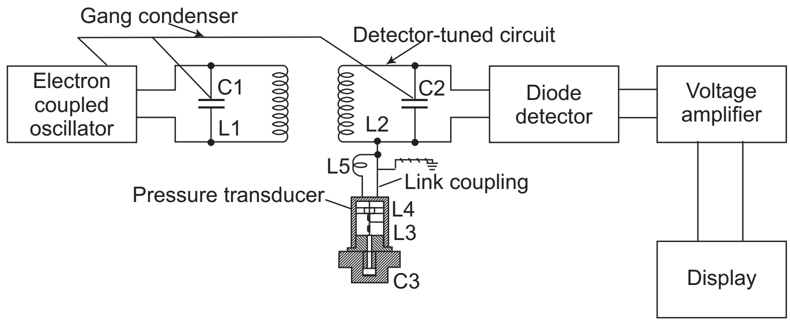

Figure 3.24: Circuit used to eliminate effect of cable capacity

A phase-modulated carrier system can be used in combination with transducers. The transducer must have a radio-frequency matching transformer that is tuned with the fixed condenser plate and stray capacitances in the pickup of around the oscillator frequency and must be properly matched to the transducer connecting coaxial cable. On applying pressure to the diaphragm, the increase in capacity lowers the resonant frequency of the circuit. The resulting change in reactance is coupled back to the indicator by a transmission line, producing a phase change in the discriminator as shown in Figure 3.24. This, in turn, produces an output voltage that is a function of the pressure on the diaphragm. The voltage can be indicated or recorded by the usual methods.

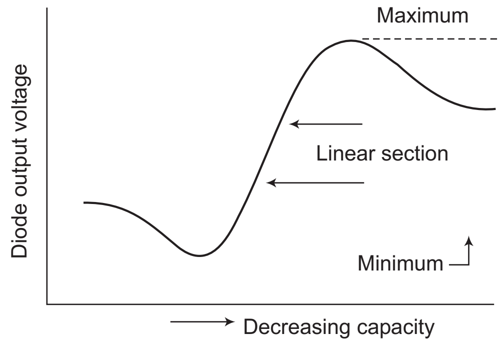

Figure 3.25: Tuning characteristic of a link-coupled circuit

The schematic measuring circuit of a capacitive differential-pressure transducer transmitter is shown in Figure 3.26. In this mechanism two process diaphragms (high pressure and low pressure) are mechanically attached to a joining rod. The movable electrode is attached to the middle of the connecting rod and held in position by a spring diaphragm. The restoring force of the spring diaphragm balances the differential pressure. In this scheme, the spring diaphragm represents the measuring element. When a differential pressure is applied on the system, the movable electrode shifts and the distances d_1 and d_2 to the fixed electrodes change simultaneously. As a result of the change in distance between the fixed and

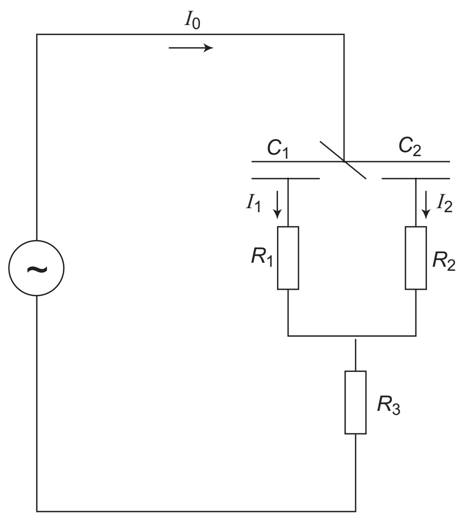

Figure 3.26: Schematic of a type of measuring circuit used in capacitive DP transducer

movable electrodes, the capacitances of the differential capacitor also change. This change is amplified and processed electronically to generate a 4–20 mA dc output signal. The generated current signal is directly proportional to the differential pressure.

If the gap between the movable electrode and two fixed electrodes are both equal to d_0, when differential pressure $P_1 - P_2$ is applied, the connecting rod moves a distance of d.

Then as per Equation 3.11:

$$\left.\begin{aligned} d_1 &= d_0 + \Delta d \\ d_2 &= d_0 - \Delta d \\ \Delta d &= K_1(P_1 - P_2) \end{aligned}\right\} \tag{3.11}$$

where, d_1 and d_2 represent the inter-electrode gaps on the high and low pressure sides, respectively; K_1 is a proportional constant. The capacitances C_1 and C_2 with respective gaps d_1 and d_2 are, respectively as per Equations 3.12 and 3.13, we have:

$$C_1 = \frac{K_2}{d_1} = \frac{K_2}{d_0 + \Delta d} \tag{3.12}$$

$$C_2 = \frac{K_2}{d_2} = \frac{K_2}{d_0 - \Delta d} \tag{3.13}$$

where, K_2 is a proportional constant and depends on the electrode area and the dielectric constant of the material filling the gap in the electrodes. The material used for the diaphragm of a conventional capacitive pressure sensor is selected in such way that the device produces a 25% change in capacitance for a full-scale pressure change. This large change means high sensitivity enables the measurement of low pressure as well. The schematic also permits the designer to include backstops on either side of the diaphragm for overpressure protection.

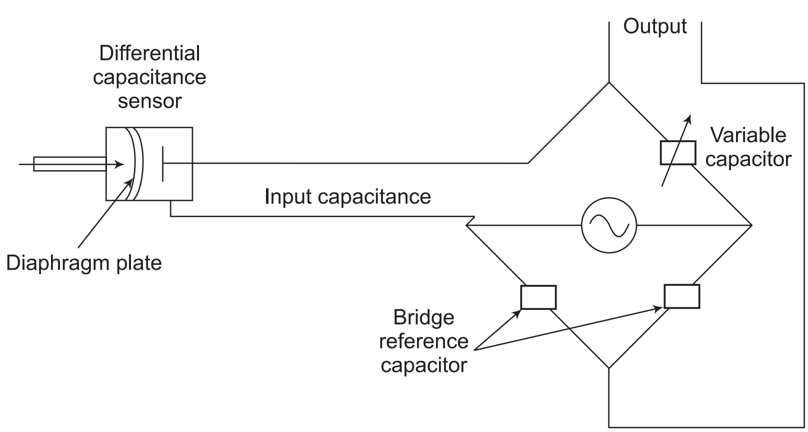

Figure 3.27: Capacitive sensor

One example of the capacitance-type sensor is the all-silicon differential capacitance sensor. The capacitance cell has a silicon diaphragm between two fixed silicon plates. Please refer to Figure 3.27 for the representation. Pressure is permitted through a hole in each of the plates, which can move the diaphragm, for example, a maximum of 0.0004 in. Capacitance, *C*, is directly proportional to the plate area and the dielectric constant of the material and inversely proportional to the plate gap. The measured pressure, *p*, is based on the following relationship:

$$p \propto (C+ - C-)/ (C+ + C-)$$

Advantages

- Capacitance-type pressure transducers have good range ability and speed of response.
- Capacitance-type pressure transducers have very good accuracy. Typical accuracies are about 0.1% of reading or 0.01% of full scale.
- Typical capacitance-type pressure transducers support a very wide pressure range, from 0.25 Pa to 70 MPa. High vacuum and low differential pressure ranges are supported.

Disadvantages

- Capacitance-type pressure transducers may be sensitive to temperature effects. An operating range of 32°C to 74°C is typical.
- Earlier capacitance-type pressure transducer designs were sensitive to stray capacitance, vibration, and corrosion.
- The use of a regulated power supply may be required.

Resonant-wire Pressure Transducers In an oscillative element transducer, an element such as a resonating wire's tension represents a process pressure. The following discussion describes an oscillative element transducer's function in terms of principles and design of an oscillative element, transducer performance, transducer installation, and transducer application.

Oscillative Element Transducer—Principles and Design Oscillative elements include both the resonating wire sensor and the double-ended tuning fork pressure sensor. The sensors are called an oscillative element because as they oscillate under tension from a force-summing element.

In the DTF design, when a change in pressure occurs, a change in the DTF's frequency results. In the DTF, the force displacement causes a frequency shift. The frequency shift represents a pressure measurement. The DTF did not become popular.

In the resonating wire design, a diaphragm causes a tension change in a fine resonating wire or ribbon. The wire, which already is in a natural resonance caused by the magnetic field it is placed in, changes its frequency as the pressure force is transmitted to the wire from the diaphragm. The resonating frequency is inversely proportional to the wire's length and mass. The frequency is directly proportional to the square root of the applied tensile force. Because the wire's length and mass are constant, the pressure and resonating frequency are proportional to the square root of the tension:

$$P \;\alpha\, \text{Hz}\;\alpha\,(\text{tension})^{1/2}$$

A wire under tension is used to oscillate at its resonant (or natural) frequency and the changes in pressure applied reflect as changes in frequency. This method of detecting force is based on fundamental principles of Rayleigh's equations for a bar vibrating in vacuum. Holst et al. (1979) modified Rayleigh's equations to fit an oscillating wire. Their approximation of the resonant frequency f_n of a wire in a vacuum is given as:

$$f_n = \frac{\dfrac{\dfrac{1}{2l\sqrt{\left(\dfrac{T}{\rho A}+(12+\pi^2)\right)EK^2}}}{\rho l^2}+\dfrac{1}{l}\sqrt{EK^2}}{\rho} \tag{3.14}$$

where, ρ = density of wire material, A = cross-sectional area of wire, T = tension in wire, E = modulus of elasticity of wire material, K = radius of gyration and l = length of wire.

Practical use of a resonant-wire pressure sensor requires that the wire be in a nonvacuum environment. To account for this, Holst and some others modified and refined the prior equation (1979).

Assume that length, density, and area are constant in the range of tension applied to the wire, the equation can be approximated as:

$$f_n \propto T^2 \tag{3.15}$$

A representative resonant-wire sensor for differential pressure measurement is shown in Figure 3.28; a resonant-wire sensor for measuring gauge pressure is shown schematically in Figure 3.29. This principle is used in liquid-level measurement where the head or gravity of the liquid is measured to infer the level. A block diagram representation of the electronic circuitry of a resonant-wire pressure transducer is shown in Figure 3.30.

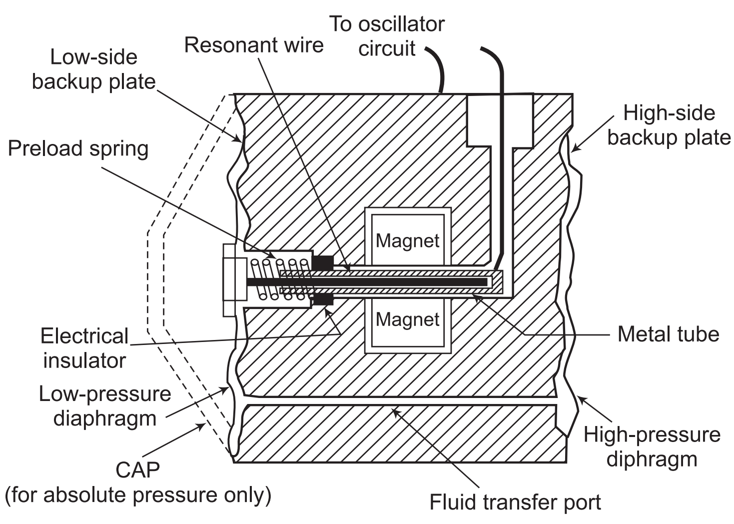

Figure 3.28: Schematic diagram DP transmitter utilizing resonant-wire principle

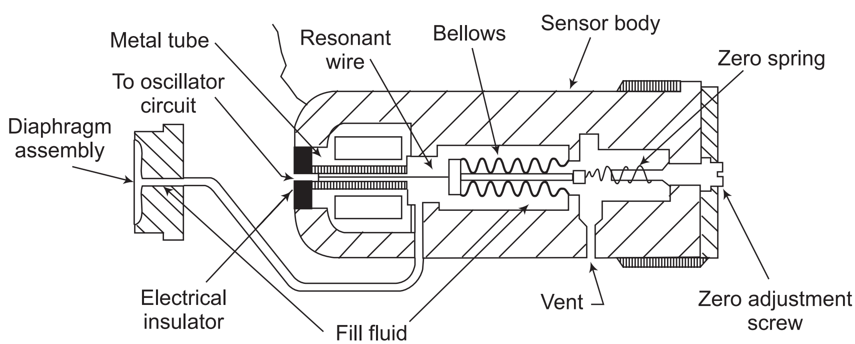

Figure 3.29: Schematic diagram of resonant-wire for measuring gauge pressure

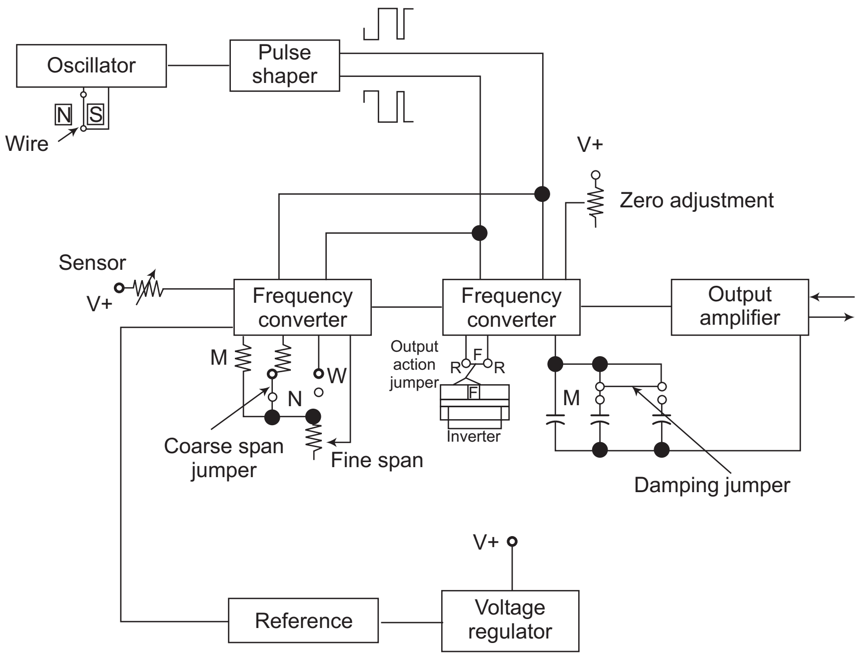

Figure 3.30: Block diagram of electronic circuitry of resonant-wire pressure transducer

A permanent magnet is placed near to the wire under tension. The wire will be inside the field of magnetic force and becomes a part of an oscillator circuit which makes it to oscillate at its natural and resonant frequency. Wire is connected to the closed end of a metal tube at one end, which is attached to the sensor body by an electrical insulator. The other side of this wire is connected to the low-pressure diaphragm which is loaded in tension by a preloaded spring. An applied pressure on the high-pressure side of the diaphragm tends to move the diaphragm toward its backup plate. The spaces between the diaphragms and the backup plates, the fluid transfer port, and the metal tube are filled with fluid. The fluid which is displaced due to the pressure moves through the fluid transfer port and tends to push the low-pressure diaphragm away from its backup plate. This movement increases the tension on the wire and hence raises its resonant frequency. The increased frequency increases the output signal of the transducer. In order to protect the equipment from over pressure, an over-range protection for the wire is provided by an over-range spring. The range of the spring is selected to limit the maximum tension on the wire to about two-thirds of its maximum strength. The protection to the diaphragms from over range is provided by the backup plates.

Advantages

- Oscillative element pressure transducers have good repeatability and high resolution.
- Oscillative element pressure transducers provide a strong output signal. Additionally, the signal lends itself directly to interfacing digitally with microprocessors.
- Oscillative element pressure transducers have very good accuracy. Typical accuracies are about 0.1% of calibrated span.
- Typical oscillative element pressure transducers support a wide pressure range, up to 42 MPa. Absolute, differential, and gauge pressure ranges are supported.

Disadvantages

- Oscillative element pressure transducers may be sensitive to shock and vibration.
- Oscillative element pressure transducers may be sensitive to temperature effects. *Temperature compensation overcomes this effect.*
- Oscillative element pressure transducers have nonlinear output signals.
- The use of a regulated power supply may be required.

For answers to checkpoint, scan the QR code

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Checkpoint

✦✦ **1.** List the gravitational gauges used in pressure measurement.

✦✦ **2.** What is measured using U-tube manometer?

✦✦ **3.** Deformation sensor converts which quantity a usable signal?

✦ **4.** How does a Bourdon tube functions to measure the pressure?

✦ **5.** How does bellows functions to measure the pressure?

✦✦✦ **6.** What is the difference between a pressure sensor and pressure transducer?

✦✦ **7.** What is the purpose of primary and secondary element in a pressure measurement system?

✦ **8.** Define pressure transducer.

✦✦ **9.** What is the purpose of force summing unit in pressure transducer?

✦✦✦ **10.** Define a pressure transmitter.

✦✦✦ **11.** How a strain gauge sensor functions to measure the pressure?

✦✦✦ **12.** A pressure transducer consists of how many sensors?

✦✦ **13.** What is called as strain sensitivity in strain gauge transducers?

✦✦✦ **14.** Where the bonded strain gauges are placed and what is their form in the sensor?

3.3 PERFORMANCE AND INSTALLATION CRITERIA OF PRESSURE TRANSMITTER

LO 3
Analyze the performance and installation criteria of a pressure transmitter

Because some sensors and transducers are often limited to local indication, a measurement device must be available to transmit signals for long distances to a remote receiving device or system. In those situations, a pressure transmitter is used to transmit the pressure value in a scaled signal level of either analog (4–20 mA), pneumatic (3–15 psig), or proprietary digital (HART or Honeywell DE) or digital such as FF. One of the first steps in determining whether pressure transmitters meet performance criteria and installation requirements is to interpret the pressure transmitter specifications and balance their relative importance. Reference accuracy, is as important as repeatability. Depending upon the pressure measurement applications, the benefits of a highly accurate device may not be required. For example, a series of pressure readings on a shut-in well may only require confirmation of hydrocarbon inventories that are already known; however, in some applications, such as hydrostatic tank gauging and custody transfer operations, highly accurate measurements are important. Custody transfer operations, where ownership of the hydrocarbon products transfer from company to company, are often referred to as the "cash register of the business," so the need for accuracy becomes significant.

3.3.1 Principle of Pressure Transmitters

In general, pressure transmitters fall into several application categories—differential, gauge, and absolute pressure. Regardless of the category, the functional elements of transmitter types (pneumatic, analog, or microprocessor) are the same.

3.3.1.1 Functional Elements

A block diagram of a pressure transmitter is depicted in Figure 3.31. The diagram applies to any pneumatic, analog, or microprocessor pressure transmitter. The block diagram shows that a transmitter consists of an element that senses a pressure input, a transducer that performs the signal conversion, and an amplifier to output a signal to a receiving device.

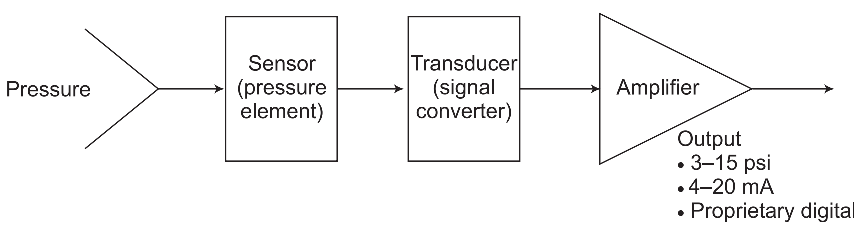

Figure 3.31: Block diagram of pressure transmitter

Pneumatic-type Transmitter Pneumatic-type transmitters may vary in design, but most employ the same type of force balance principle shown in Figure 3.32. The process pressure moves bar B that pivots on X; an increase in process pressure causes bellows AA to expand which in turn causes bar B to move. Bar B also acts as a baffle to an orifice opening Y, which causes the pressure within the orifice housing to increase. The pressure is also transmitted to a remote indicator. The higher-pressure causes bellows BB to expand and move the bar B away from the orifice opening until a force balance is reached. The range spring helps the balancing bellows BB resist the movement of bellows AA. Thus, a force balance is achieved with very little movement at bar B. Pneumatic transmitters using force balance methods can balance with very little movement of the bar, occasionally with movements in increments from thousandths to millionths of an inch.

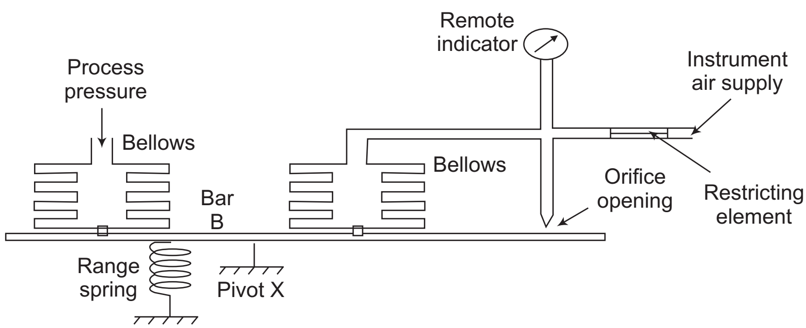

Figure 3.32: Pneumatic pressure transmitter principles

Analog-type Transmitter In analog-type transmitters, the sensors—strain gauge, diaphragm, piezoelectric and oscillating—are similar to those described earlier in the pressure transducer section. An analog type transmitter using a strain gauge is described here (Figure 3.33). The direct conversion of pressure into an electrical signal is accomplished when the strain-gauge sensors are activated. The change in the resistance of the Wheatstone bridge causes a change in the transmitter's amplifier output. The amplifier output of 4–20 mA output signal is sent to a receiving device, such as a controller. The same output is sent to a feedback resistor, which balances the bridge and provides stability.

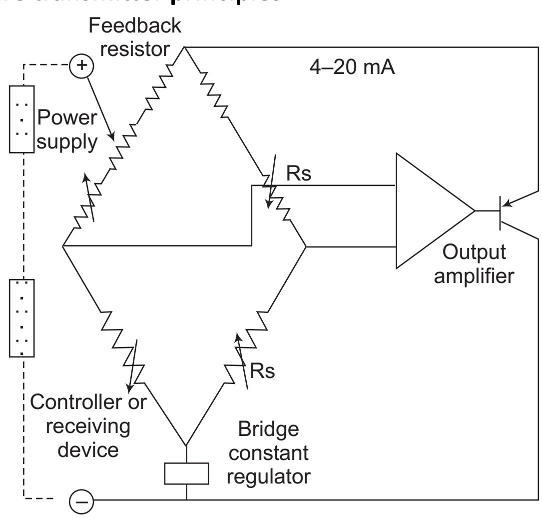

Figure 3.33: Analog pressure transmitter principles

Microprocessor-based Transmitter Microprocessor-based transmitters use sensors similar to those described in the pressure transducer section. Thus, a microprocessor-based transmitter's principle of operation is similar to a pressure transducer as far as the sensor is concerned. After the sensor has provided a representation of pressure, the microprocessor-based transmitter provides additional operations (Figure 3.34). The microprocessor-based transmitter's operation is described in the following terms.

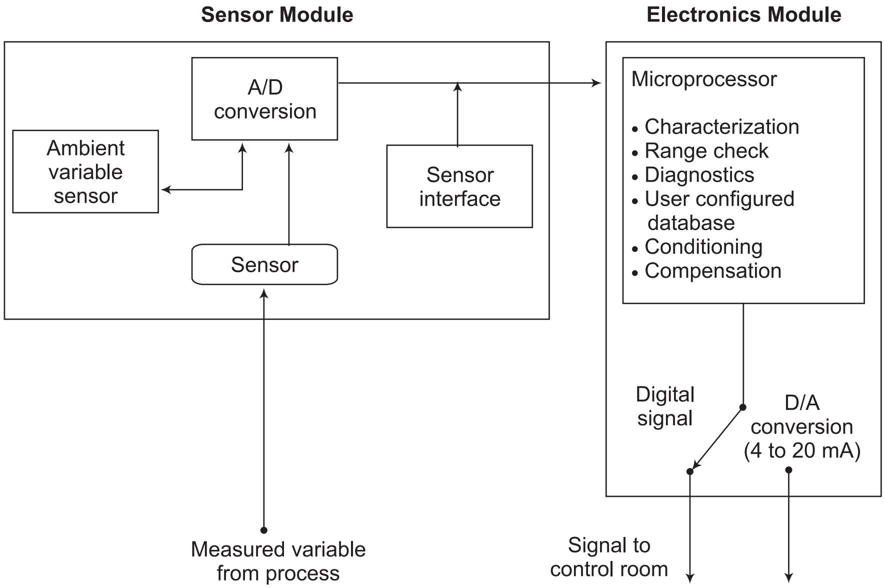

Figure 3.34: Microprocessor instrument architecture

Accuracy Microprocessor-based transmitters can measure pressure with accuracies better than 0.1% of span. With pressure and temperature compensation techniques, the accuracy is maintained over a wide range of operating pressures and temperatures.

Turndown (rangeability) Microprocessor-based pressure transmitters offer extremely high turndown and rangeability, up to 400:1 for some models.

Calibration Temperature variations, both from the process and ambient temperature changes, affect the accuracy of uncompensated pressure transmitters. The sensor's accuracy is affected when the seal fill fluid changes volume, while the electronics accuracy is affected through changes in resistance. In the case of conventional pressure transmitters, the accuracy can degrade to several percent of span. Microprocessor-based pressure transmitter manufacturers calibrate (compensate) for these changes either in a programmable chip (EPROM) or through laser trimmed compensation resistors. The sensor technology and measurement techniques used by a transmitter manufacturer are normally the same for the gauge, absolute, and differential pressure transmitters from the same manufacturer. With microprocessor-based pressure transmitters, any nonlinear sensor effects are overcome through characterization of the transmitter meter body during manufacturing. The meter body is subjected to various pressures in its operating range. Manufacturers measure the transmitter's response to the various pressures and compute the correction terms. The computed correction terms are stored in the transmitter's memory. The microprocessor is now able to compensate a pressure signal for nonlinearities, which means that the transmitter can be used over a much wider span. For microprocessor-based instruments, the linearity is maintained. Span shifts caused by ambient temperature and static pressure are minimized or nullified.

Interference Microprocessor-based pressure transmitters have an additional advantage over conventional transmitters, which is the capability to have high signal resolutions at low pressures. Techniques include the use of analog to digital (A/D) converters of high resolution, multi-gain A/D converters, or logarithmic converters that optimize the signal-to-noise ratio over the entire signal range.

Scan Rate Typical scan rates for the process pressure variable are 3 to 5 times per second. The scan rates are a function of the digital circuit's clock speed. Recall that a microprocessor-based transmitter is doing more than just providing a pressure variable. Microprocessor-based pressure transmitters provide two-way communication that provides data in addition to the scanned pressure variable.

3.3.1.2 Comparison of Different Types of Pressure Transmitters

The types of pressure transmitters are pneumatic, electronic (conventional 4 mA to 20 mA), or microprocessor-based. In an era of microprocessor-based instruments, it may seem unusual to discuss pneumatic instruments; however, as Table 3.3 shows, pneumatic as well as conventional electronic transmitters, continue to have applications where their use is appropriate. As the cost of microprocessor-based transmitters continues to decrease, the more likely it is that they will become preferred devices.

Table 3.3: Comparison of various communication types

	Pneumatic (3–15 psig)	*Electronic (4–20 mA)*	*Microprocessors (digital)*
Performance (accuracy, drift, ambient effects)	Moderate to good	Moderate to good	High accuracy
Span	Variable span, limited range	Variable span, moderate range	Variable span, wide range
Flexibility	Specific to application	Variety of applications	Almost any application
Intrinsic safety	Intrinsically safe	Intrinsic safety usually can be supported	Intrinsic safety can be supported
Signal type	Pneumatic analog	Electronic analog	Digital or analog
Diagnostics	Local	Local	Remote
Reliability	Less than electronic type	Good	Better than electronic type
EMI	Not susceptible	susceptible	Susceptible
Distance (typical maximums)	Less than 300–400 ft	Up to 2 km	Up to 2 km
Applications	Used in explosion proofing	Most applications	All applications, especially where high accuracy needed

3.3.2 Comparison of Transmitters

3.3.2.1 Design of Pressure Transmitters

The design of pressure transmitters that determines whether a pressure transmitter meets performance and installation requirements includes evaluating criteria as per the following parameters—sensor technology, electronics, meter body design, housing, feed-through assembly, process connections and accessories. Figure 3.35 provides an overview of the terminology used in the following discussion regarding pressure transmitter design.

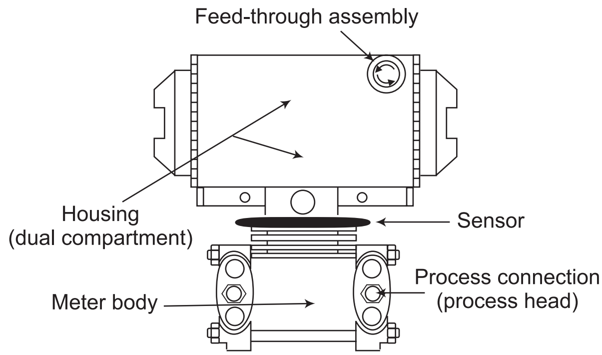

Figure 3.35: Pressure transmitter design

Sensor Technology Generally, pressure transmitters use the same sensor technology as conventional pressure transducers. Sensor technology used in pressure transmitters is listed in order of their frequency of use. This includes the components as mentioned next.

Capacitive This technology uses capacitive plates that are manufactured from stainless steel or silicon. The capacitive plates also incorporate ceramic, quartz, or sapphire to provide stability. A sensing diaphragm is located between the capacitive plates. As the sensing diaphragm moves, the capacitance of each plate changes. The changed capacitance, which is proportional to pressure, is used as the basis for the pressure measurement.

Strain gauge This technology can be manufactured using metal or semiconductor material. The strain gauge itself could be bonded, vapor deposited, or etched in place upon a deformation sensor. The strain gauge senses movement or strain of a diaphragm or other type of stressed sensor. The diaphragm or stressed sensor could be manufactured from metal, ceramic, semiconductor, or piezoresistive material.

Resonant This sensor technology uses the movement of a sensing diaphragm to create tension that is translated into a pressure measurement. This technology is similar to the action of a guitar or piano string, where greater the stretching movement, higher is the resulting frequency. The movement causes a tension on a resonant wire or solid state sensor to resonate at a frequency determined by the tension. The resulting digital pressure signal is read without any additional amplification or signal conditioning by low power CMOS digital electronics.

Resonant sensors can also be based upon a DTF design. An advantage of the DTF-type sensor over the resonating wire sensor is that it can generate a signal with either tension or compression.

Electronics In microprocessor-based and conventional transmitters, an A/D conversion is needed to make the analog sensor voltage usable as digital data for the microprocessor.

The benefits from electronics in analog and microprocessor-based transmitters are that there are no mechanical linkages, levers, or pivots required as in the case of pneumatic transmitters.

All adjustments are performed by internal electronics instead of mechanical elements that could age, wear, or break. Electronics provide microprocessor-based transmitters added reliability that benefits measurement applications. Figure 3.36 shows a block diagram for the electronics of a microprocessor-based pressure transmitter.

Microprocessor-based pressure transmitters have better reliability because their electronics do the following:

- Monitor meter body temperature and static pressure to compensate for ambient conditions
- Detect meter body faults
- Detect sensor over temperature conditions
- Detect electronic fault such as characterization from failure and loss of input
- Filter noise

Other benefits that electronics provides to plant measurement applications include the transmitter's ability to permit the following:

- Upscale/downscale failsafe configuration
- Remote range reconfiguration
- Remote calibration and diagnostics

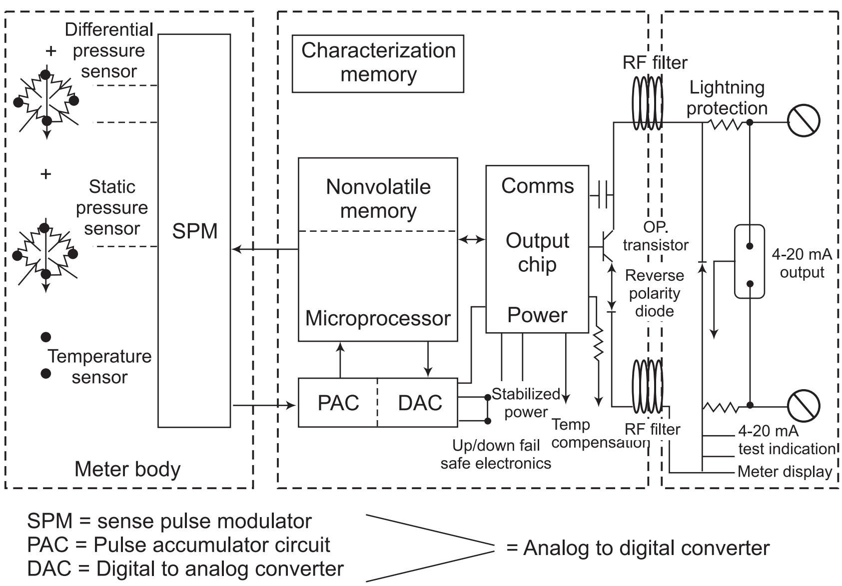

Figure 3.36: Microprocessor-based pressure transmitter diagram

Meter Body Design When determining whether a pressure transmitter meets performance and installation requirements, the meter body design as shown in Figure 3.37 is evaluated in the following terms:

Type of Pressure Measurement Required Meter bodies vary for the type of pressure measurement required. Meter bodies are available for gauge, differential and absolute pressure measurements. Meter bodies are also available for pressure measurements that infer a level and flow variable.

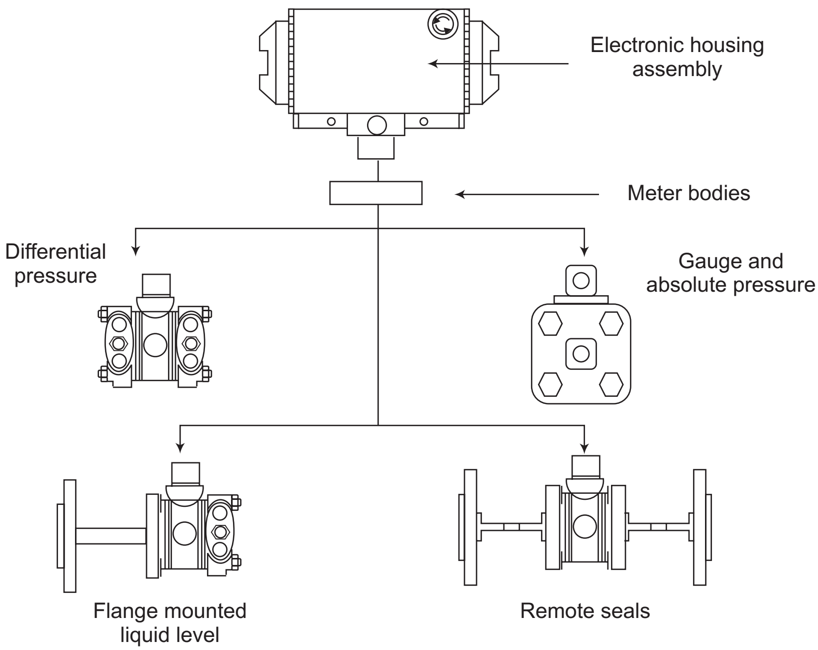

Figure 3.37: Meter body design

Note

A pressure transmitter can be specified with special flanges required for a liquid-level measurement application.

Materials of Construction In addition to the type of pressure measurement, the engineer evaluates the materials of construction used in a meter body for its compatibility with the process media. Materials such as carbon steel, stainless steel, Hastelloy C, or Monel are used to construct the meter body's process heads whereas Corrosion-resistant materials are used to construct vent/drain plugs. Materials such as stainless steel, Hastelloy C, Tantalum or Monel are used to construct the meter body's barrier diaphragms.

Barrier diaphragms are used to protect internal sensing diaphragm from process media. As pressure measurement applications involve contact with conductive and corrosive fluids, silicon sensors are isolated from the process fluid through thin stainless steel barrier (isolation) diaphragms.

Pressure is transferred to the internal sensing diaphragm on the silicon chip through the use of fill fluid oils. In order to minimize the thermal effects upon the fill fluid, the volume of the fill fluid surrounding the diaphragm is kept to a minimum. A wide range of oils can be specified depending on the operating temperatures or special application needs. The fill fluid surrounding the internal sensing diaphragm is mostly silicon oil.

Transmitters with silicon oil fill fluids are standard for most process measurement needs. Special fill fluids such as fluorolube or chlortrifluorethylene (CTFE) are available upon request for special application needs. As silicone can react violently with oxygen or wet chlorine, if a transmitter diaphragm leak occurs, fill fluids such as Fluorolube represent a safer choice. Fluorolube is stable if leakage occurs in an oxygen or wet chlorine service.

Housing The transmitter's electronics housing is evaluated for its resistance to shock, vibration, corrosion and moisture. The housing typically has separate compartments (dual compartments) for the electronics module and junction box for field wiring connections.

Feed-through Assembly As pressure transmitters do not have their own power supply, it becomes necessary to have a means of providing power as well as receiving a transmitter's process signal without compromising the transmitter's electronics. Transmitters used in an industrial environment have ports or openings in the housing for power and signal connections.

The ports can be referred to as a "feed through assembly" as it is through these electrical connection ports that the power supply and signal wiring are "fed" into the transmitter.

The electrical connection ports are often simply specified as a number of inches of pipe thread. The abbreviations NPT (national pipe threads), FNPT or NPTF (national pipe thread, female connection) specify the pipe threads per inch. The conduit for the plant's electrical wiring fits into these threaded ports. Plant wiring standards using nonmating conduit, adaptors and bushings can be ordered to bring the transmitter into compliance. Once wiring is complete, the port connection openings must be properly sealed to prevent the entry of contaminants and corrosive vapors into the housing.

Process Connections The process connections from the transmitter to the process are made by using impulse tubing or piping connected to the transmitter's pressure port(s). The pressure port is specified in number of inches of pipe threads (NPT, FNPT, or NPTF). The NPT specification can be reviewed to determine if any adaptors are necessary to bring the piping into compliance with plant piping practices.

The pressure port threading is made into a metal flange of the transmitter that is often referred to as a process head. Process head configurations vary depending upon the type of pressure transmitter. The variations include the following:

- Single-ended process heads appear on absolute and gauge pressure transmitters.
- Double-ended process heads appear on differential pressure transmitters.

For liquid level measurements, a flange-mounted diaphragm appears on end of the meter body and a standard differential process head appears on the other end.

Accessories The perception of pressure measurement accessories varies among users:

- **Siphons:** Siphons should be installed in steam service and fluids above 250°F.
- **Snubbers:** Snubbers are used for pulsation dampening and filtering.

In addition to the above, some vendors consider the following items as accessories:

- **Adaptor fittings:** Special adaptor fittings can be purchased for a transmitter's electrical and/or process connections to bring the transmitter into compliance with plant practices or to accommodate an existing piping configuration.
- **Remote meters:** Transmitters can be ordered with integral output meters that display an analog or digital representation of the pressure value.
- **Calibration software:** Vendors provide software that records and assists in the calibration activities.
- **Microprocessor handheld communicators:** Field communicators are useful for performing remote maintenance and configuration on microprocessor-based transmitters. However, field communicators are not universal because of the proprietary and nonstandard nature of a transmitter's digital output signal.

3.3.2.2 *Performance*

Performance of pressure transmitter can be evaluated in several ways as explained.

Field Loop Accuracy Improvements The performance of conventional transmitters versus microprocessor-based transmitters can be evaluated from the perspective of overall control loop accuracy improvements as shown in Table 3.4. This table illustrates the difference in control loop accuracy when digital signal outputs are used.

Table 3.4: Field control loop accuracy comparison

Transmitter Type/Signal O/p	*Transmitter Accuracy (% of Span)*	*Control Loop Accuracy*
Conventional 4–20 mA	0.150	0.225
Microprocessor-based 4–20 mA	0.075	0.150
Microprocessor-based/digital	0.075	0.075

Performance Comparison Following are three different types of transmitters—pneumatic, conventional and microprocessor-based—whose performances are compared in Table 3.5 using typical data.

Table 3.5: Performance comparison

Characteristics	*Pneumatic*	*Conventional*	*Microprocessor-based*
Sensor-type	Force balance	Resonant wire	Piezoresistive
Accuracy	$\pm$0.5% to $\pm$1.5% of span	$\pm$0.3% of span	$\pm$0.1% to $\pm$0.5% of span
Operating temperature limits (°F)	–20–180	-40–100	–40–200

(*Contd.*)

Resistance to shock and vibration	Fair to good	Good	Excellent
Retention of calibration	Fair	Fair	Very good
Temperature effects	±1% span/100°F at maximum span; ±3% span/100°F at minimum span	+/– 1% span/100°F at maximum span; +/– 7% span/100°F at minimum span	±0.5% span/100°F at maximum span; ±2.2% span/100°F at minimum span

Evaluation of an Application Example A flow measurement application that has widely varying flows illustrates the performance advantage of microprocessor-based pressure transmitters over conventional transmitters. A conventional transmitter inferring flow from the differential pressure across a restriction is limited in its rangeability. Conventional differential pressure (DP) transmitters have performance limitations when used in flow applications. Flow elements that create a pressure drop are based on the square root law relationship between the differential pressure and flow rate. In other words, if a 10:1 reduction in flow rate occurs, a 100:1 reduction occurs in the developed signal because of the square root relationship. Conventional 4–20 mA DP transmitters are an exception to this as their turndown is often 6:1. When using conventional transmitters, a common way to increase transmitter rangeability is to cascade two differential pressure transmitters with different operating ranges in the same flow line. As a microprocessor-based transmitter has higher rangeability, only one transmitter is installed in the flow-line to measure flow.

Comparison of Microprocessor-based Transmitters Performance Tiers While microprocessor-based transmitters are superior in performance to conventional and pneumatic transmitters, it should be noted that some users believe that microprocessor-based pressure transmitters fall into three distinct performance tiers. The following discussion describes the microprocessor-based transmitter performance tiers.

High-performance Transmitters High-performance transmitters spend more time in the manufacturer's characterization chambers as compared to mid-range pressure transmitters. As a result, the transmitters have more data for temperature and static pressure compensation over a wider operating range. High performance transmitters are used in critical applications such as custody transfer that require a very high degree of measurement accuracy. Measurement accuracies ranges from ±0.075% to ±0.1% of span. High performance transmitters tend to cost more than mid-range transmitters.

Mid-range Performance Transmitters Mid-range performance transmitters are more commonly used for applications that require a high degree of accuracy. Applications include flows that do not represent custody transfer, or vessel gauge and absolute pressure measurements. Accuracies are in the ±0.1% of span range. Mid-range performance transmitters cost less than high performance transmitters, and more than low-end performance transmitters.

Low-end Performance Transmitters Low-end performance transmitters are more commonly used for applications where the transmitter is installed in remote or hazardous locations and good accuracy is required. The decision in these applications is to use either a low-end microprocessor-based transmitter or a conventional 4–20 mA transmitter. The microprocessor-based transmitter's remote communication ability often becomes the deciding factor. The cost difference between a low-end performance transmitter and conventional 4–20 mA transmitter is very minimal.

3.3.2.3 Installation

Transmitters have meter bodies that are appropriate for gauge, absolute and differential pressure measurements. An installation criterion includes the following:

- Type of service
- Mounting procedures and options

Type of Service A transmitter's process connections depend on the process media and / or service intended for the transmitter. Gas, liquid or steam pressure measurements require the transmitter to be located properly. Refer to Table 3.6 for process connection information on each of the transmitter types.

Table 3.6: Transmitter process locations

Transmitter	*Usage*	*Comments*
Differential	Liquid flow with solids	Transmitter located above process tap to avoid sediment from entering impulse piping
Differential	Liquid flow, no solids	Transmitter located below process tap, impulse piping minimizes gas pockets
Differential	Gas	Transmitter located above process tap to permit condensate draining
Differential	Liquid level, open tank	High pressure side of transmitter connected neat the bottom of the tank, low pressure side open to atmospheric pressure
Differential	Liquid level, closed tank	High pressure side of transmitter connected near the bottom of the tank, low pressure side connected near the top of the tank. Dry legs mist be kept dry, and wet legs must be kept level
Gauge	Gas	Transmitter located at side process tap to prevent air and sediment entering impulse piping
Gauge	Liquid	Transmitter located below process tap to permit steam from entering sealed impulse piping
Gauge	Steam	Transmitter located below process tap to permit steam from entering sealed impulse piping
Gauge	Liquid level	Transmitter can be located at ground level and zero suppressed for elevated tank measurements
Absolute	various	Transmitter located above the process tap to permit condensate draining

Mounting Procedures and Options A differential pressure transmitter has two process inlet port connections. One inlet port connection is for the high-pressure input and the other connection for the low-pressure input.

Although differential pressure transmitters are used in a variety of pressure measurement applications, differential pressure transmitter is most frequently used as a flow meter.

Differential pressure is created in a flow through the creation of a pressure drop across a flow element such as an orifice plate. DP measurements for flow applications often use a series of block-off valves and manifolds (Figures 3.38 and 3.39).

The mounting position's philosophy is to maintain the sensing line full of the fluid of interest and allow condensation in the case of gas or steam to avoid a change in the measurement. For liquid service, the preferred method is to have the transmitter below the orifice. The lines should be insulated if the fluid changes temperature from the flowing state to static in the measurement area.

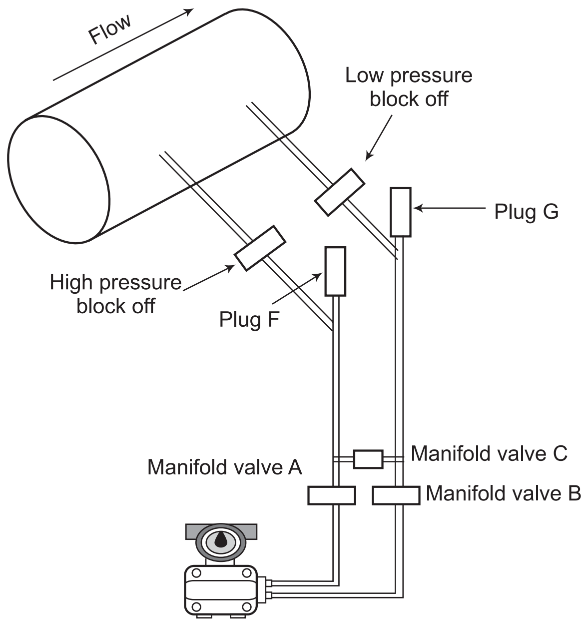

Figure 3.38: Flow measurement with impulse lines with valves and manifolds

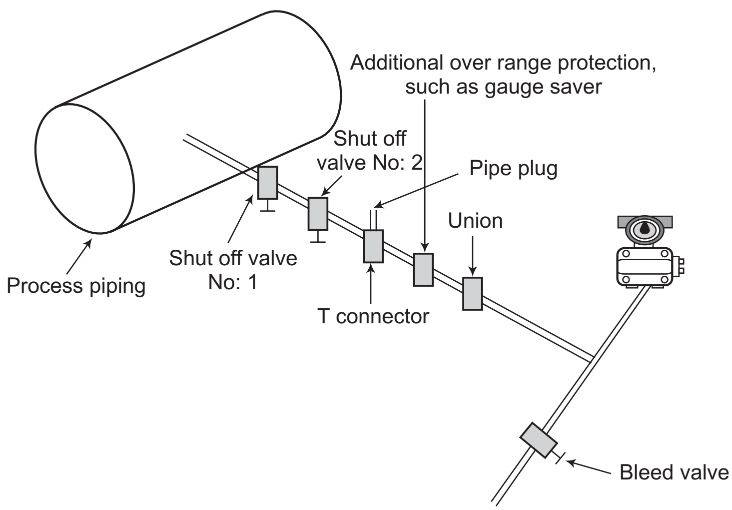

Figure 3.39: Pressure measurement with manifold, valves and gauge pressure connections for pipes

An absolute pressure transmitter has only one process connection to measure pressure. Absolute pressure transmitters can be used to measure the pressure in a vessel or pipe. The transmitter is usually located above the process tap to permit condensate draining.

Following are some of the features of absolute pressure transmitters:

- The calibration procedure for an absolute pressure transmitter can be complex.
- Absolute pressure transmitters mixed with gauge pressure transmitters in a control configuration can be confusing to support personnel and possibly result in calibration or configuration errors.

A gauge pressure transmitter has only one process connection to measure pressure. A gauge pressure transmitter can be used for open tank-level measurements. Figures 3.39 and 3.40 display a typical industry piping arrangement for a gauge pressure transmitter measurement. In this type of level measurement, the high-pressure side of the transmitter is connected to the tank, while the low side of the pressure transmitter is open to atmospheric pressure.

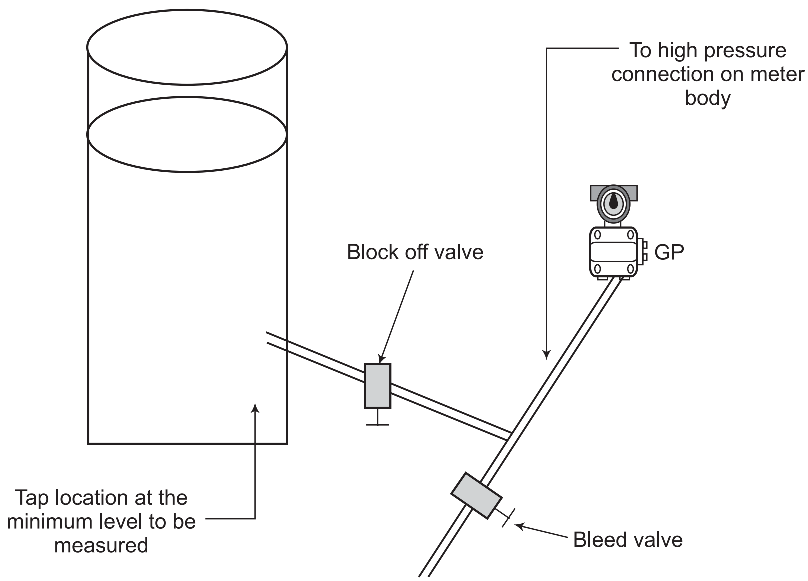

Figure 3.40: Gauge pressure connections for pipes

The vendor's mounting procedures must be followed when installing a pressure transmitter failing which the quality of measurement is likely to be compromised. Proper transmitter mounting includes reviewing the following aspects:

- **Impulse piping:** Impulse piping (gauge lines) transfers the process pressure to the transmitter. For proper measurement, it is ideal to shorten the pipe's length and minimize the bends and turns to the best possible extent. Preventing gas in liquid piping, liquid in gas piping, temperature-induced density variations, leaks, high points in liquid piping and low points in gas piping are preventive measures. Proper sloping of lines (usually 80 mm/m, for a 1:10 ratio) to the tap connections is often required in many installations.

- **Mounting supports:** Pipe mounting or wall mounting brackets are options.
- **Manifolds and block valves:** Manifolds and block valves installed in the impulse piping permit servicing during calibration, commissioning and troubleshooting.
- **Signal wiring:** Manufacturer's documentation provide the guidelines for wiring practices.
- **Process proximity to meter body:** Transmitter meter bodies should not be exposed to corrosive and hot material.

3.3.3 Applications

An overview of pressure transmitter applications includes a discussion about—pressure measurement applications, local indication, remote indication, and control.

3.3.3.1 Pressure Measurement Applications

The most commonly used pressure transmitter is the differential pressure transmitter. DP transmitters are used to measure levels, density interfaces, and flows. Although differential pressure measurements predominate, examples of typical pressure measurements using either a gauge, absolute, differential, or vacuum pressure transmitters include the following:

- Gauge pressure is measured in oil and gas separations, pumping systems, pressure vessels, and compressor control systems.
- Absolute pressure is measured in a refinery's vacuum distillation tower. A vacuum tower distills most of the gas oil out of crude, leaving an asphalt residual material. Operating pressures of typical vacuum towers are 1–5 psia.
- DP measurements are made
- Across trays in a distillation column
- In heating ducts to indicate damper position
- In a scrubber to monitor pressure drops
- In heating ducts to indicate damper position
- In a duct to measure air velocity
- Across filters to monitor filter condition
- Vacuum pressure is measured in fired heaters for an indication of heater draft.

An application could require several forms of pressure measurement. Figure 3.41 shows a crude oil stabilizer column where differential pressure measurements (PdT 4 and PdT 5) are made across column trays. Differential pressure measurement is also used to infer level at LIT 6.

The same crude oil stabilizer column requires gauge pressure measurements for the crude feed to the column (PIT 2 and PIT 3) and the gas exiting the column (PIT 1) (Figure 3.42).

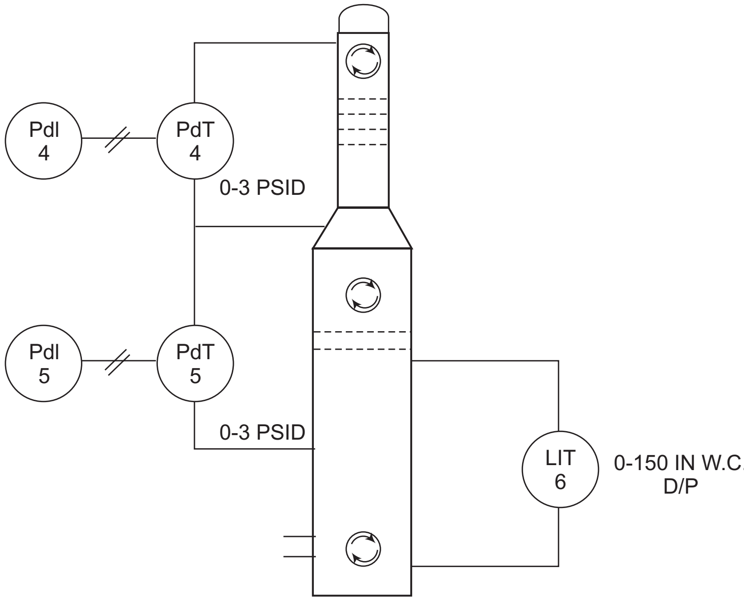

Figure 3.41: Differential pressure measurement in column

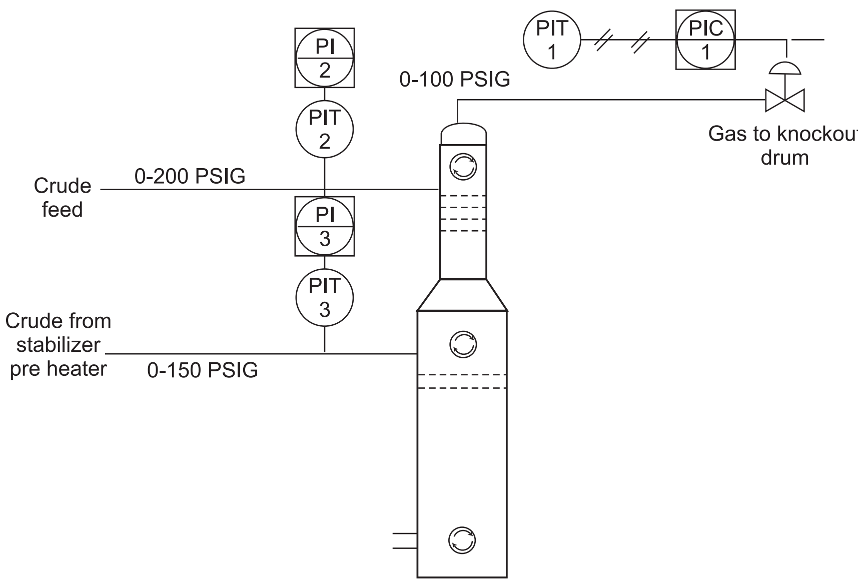

Figure 3.42: Gauge pressure in a column

Absolute pressure transmitters can be used to measure the pressure in a vessel or pipe. For example, a vacuum tower operates at pressures of 1–5 psia. The pressure below atmospheric pressure is necessary in a vacuum tower to distill most of the gas oil out of crude without the need for excess temperatures that could cause decomposition (Figure 3.43).

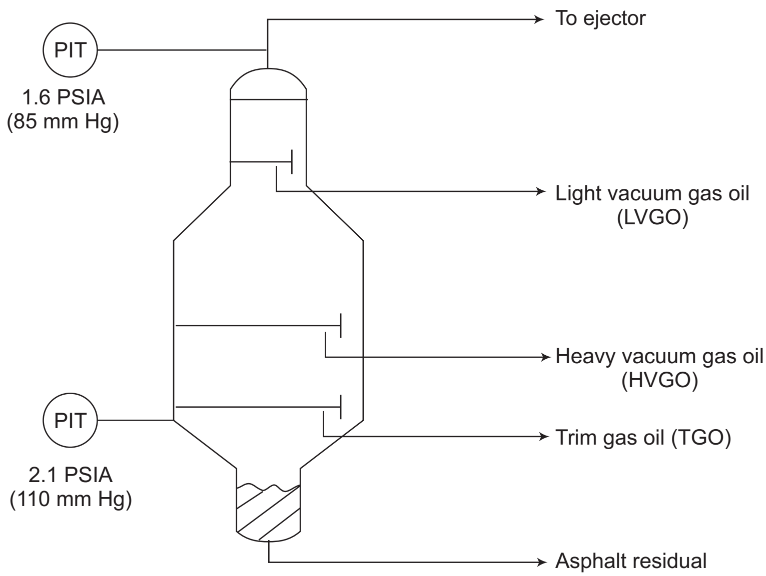

Figure 3.43: Example of absolute pressure measurement

3.3.3.2 *Local Indications*

Local indication meters are available as an option for pressure transmitters as shown in Figure 3.44. Microprocessor-based instruments have the option of using either an analog display meter or a digital display meter.

The digital display meter provides data such as the process variable in engineering units, digital readout of the process variable and transmitter diagnostic status.

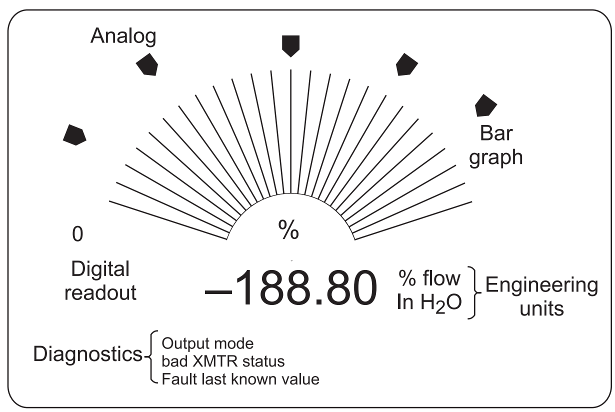

Figure 3.44: Local indication

3.3.3.3 *Remote Indications*

Remote indication is possible for pressure transmitters. The example shown in Figure 3.44 represents a transmitter's display that appears at a distributed control system (DCS) operator station.

3.3.3.4 *Control*

Major DCS vendors have digital option cards that can be installed in their controllers. The digital option cards allow communication between their respective microprocessor-based instruments and DCSs to occur as shown below Figure 3.45.

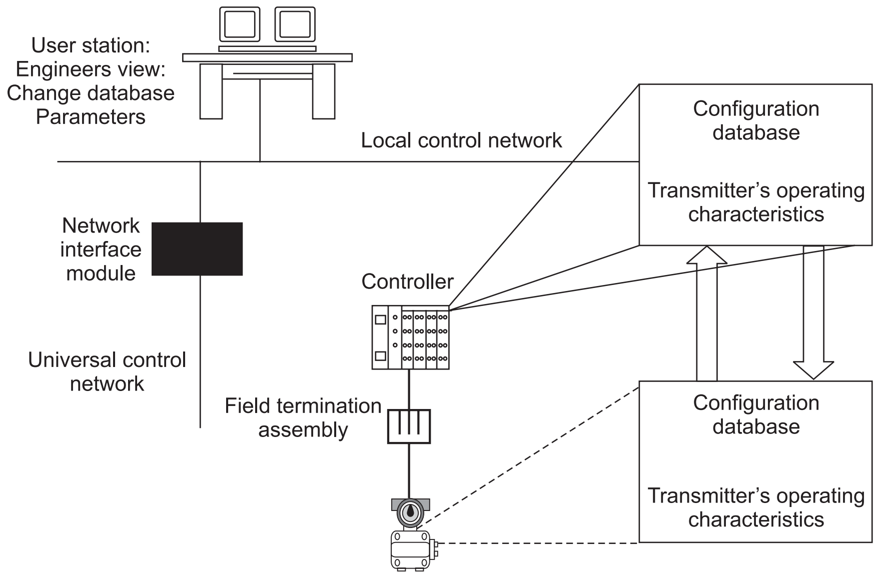

Figure 3.45: Control systems with smart transmitters

3.3.4 Evaluating Sealing Techniques and Their Applications

Pressure transmitters connect to the process directly through impulse piping lines. Process fluid (gas or liquid) leaves the process pipe and enters the impulse piping lines. The same process fluid also enters the body of the pressure transmitter. In certain applications, however, some process fluids could be harmful to the pressure transmitter's body. For that reason, sealing techniques are used in certain applications (particularly sour applications). If chemical and remote seal technologies were not available, many process measurements would be impossible.

The goal of sealing techniques and applications is to protect the pressure measurement device and related equipment and also the personnel who maintain and operate such equipment. Seals are applied where:

- A process fluid (gas or liquid) is hot, corrosive, and/or toxic and can potentially damage the pressure sensor.
- A process liquid is viscous and can plug the pressure sensor.

The sealing techniques generally fall into two categories:

- **Chemical seals:** Chemical seals essentially are local diaphragm protectors, directly connected (close coupled) to process piping.
- **Remote seals:** Remote seals essentially are "remotely located" diaphragm protectors installed at the process piping and connected to the transmitter's capillary tubing. Note that vendors place responsibility upon the user for the seal selection. An improper selection will not work properly and could injure personnel.

3.3.4.1 Chemical Seals

A very common type of chemical seal is the diaphragm seal. Diaphragm seals can be used with most pressure sensor technologies. The chemical seal consists of a diaphragm (constructed of either an elastomer, metal, or Teflon) sandwiched between an upper housing and a lower housing. The upper housing is attached to the pressure measurement instrument. The upper housing contains a fill fluid (such as silicone or instrument oil) which acts as the hydraulic medium to transfer the pressure signal. The lower housing is designed to adapt to the process connection and contain the process fluid. When process pressure is applied to the process connection side of the diaphragm, an equal pressure is exerted on the instrument side of the housing to the instrument's pressure sensor (Figure 3.46).

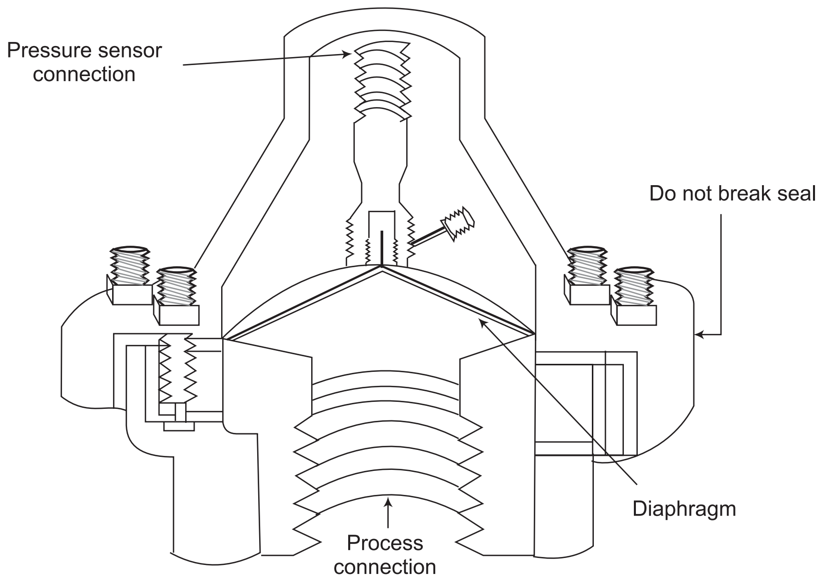

Figure 3.46: Process connection to pressure transmitter

Most chemical seals permit the removal and replacement of pressure measurement instruments. Some seals allow removal of the upper housing and seal diaphragm, while the lower housing remains attached to the process connection. Hazardous applications typically use this type of seals called as continuous duty seals.

3.3.4.2 Other Seal Types

Another type of chemical seal is the volumetric seal. This type of seal consists of a flexible member, housing and fill fluid. The flexible member can be bellows, Bourdon tube or diaphragm. An example of a volumetric seal is the extended diaphragm seal that protrudes into a process vessel minimizing the area in which process fluid could build up against the diaphragm and cause a measurement error.

Remote Seal Pressure Transmitters Key to understand the remote seal pressure transmitter is that it must be thought of as a measurement system. That is, the measurement system is influenced by the interaction of several factors such as diaphragm size, types of fill fluids, capillary lengths and diameters, and temperature variations. Influencing factors in any system are complex and interdependent.

Remote seal pressure transmitters have a similar body as the standard pressure transmitter, but are often considered as a separate type of pressure transmitter. The remote seal differential pressure transmitter is made up of a transmitter body that has a differential pressure sensor and two diaphragm seal elements. Capillary tubes connect to the seal element of the transmitter body. These capillary tubes are armored to protect the tube from environmental conditions and also to inhibit corrosion. The seal elements, capillaries and transmitter body are filled with a fluid such as silicone, water and glycol, fluorolube or other specially required liquids.

While the transmitter body is similar to that of a pressure transmitter, the manufacturer may have modified the transmitter body to minimize the volume of fill fluid. The volume is minimized to offset the errors of fluid expansion and contraction caused by temperature changes. Remote seals are becoming more popular in many plants as a simple solution rather than legs with fill fluids that can be variable.

The sealing element consists of a thin metallic diaphragm with convolutions. The capillary connects the cavity under the diaphragm to one of the inlet port pressure connections of the remote seal pressure transmitter. Note that there are three areas of fill fluid in the remote seal differential pressure transmitter—the capillaries, the chamber of the transmitter itself and the cavity formed between the diaphragm and the flange. Manufacturers try to keep total volume of fill fluids as small as possible to minimize effects on transmitter speed of response (Figure 3.47).

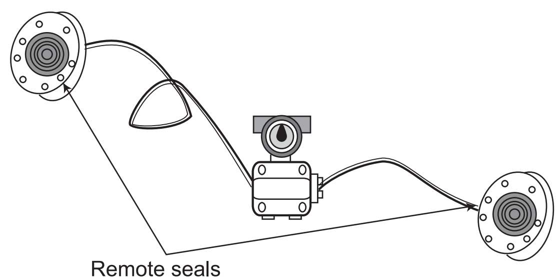

Figure 3.47: Remote seal transmitter

A wide range of remote seals are available. The pressure range to be measured and the process connections required for installation help determine the type of seal to be used. Following are few of the remote seals types available—pancake, extended diaphragm, saddle, flush flanged, chemical tee.

3.3.4.3 *Diaphragm Size Considerations*

Generally, the diaphragm size selected should make it flexible enough to measure the desired span while having minimal response to temperature-induced fill fluid volume changes. For example, small diameter diaphragms are not used with very small pressure spans. A diaphragm's flexibility is specified by its spring rate. In other words, flexible diaphragms have lower spring rate values.

The response of the filled fluid system changes because of temperature-induced volume changes.

If the temperature decreases, the internal pressure decreases by a corresponding amount. The amount of pressure change in the filled system is given as:

$$\Delta P = Ve\Delta T/C \tag{3.16}$$

where, P = pressure change, inches water column (in wc) gauge, V = volume of liquid subject to the temperature change (in^3), e = coefficient of volumetric thermal expansion of the liquid, in^3/in^3°F, T = temperature change applied to the liquid, °F, C = compliance of the seal diaphragm, in^3/ in wc.

Response of the filled fluid system is dependent on the compliance of the seal diaphragm. Temperature changes both such as ambient and process related can cause the fluid volume in the filled system to change.

The only element that can move in the system is the seal diaphragm. The relationship between change in volume applied to a diaphragm and the corresponding change in pressure is called compliance. Compliance is often shown as a graphic curve, which plots pressure differential across the diaphragm against volume confined by the diaphragm. Manufacturers of remote seal assemblies offer Silicone DC 200, CTFE and Silicone DC 704 (Figures 3.47 and 3.48) for such a sample.

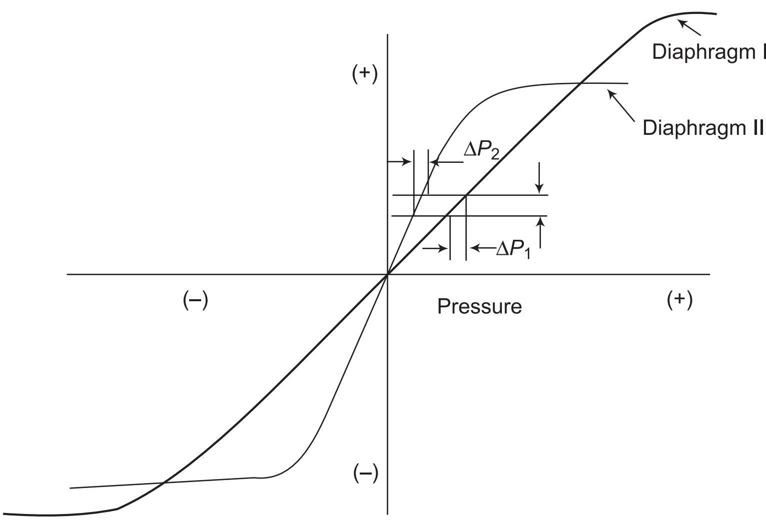

Figure 3.48: Diaphragm changes with pressure

The DC704 can be used in process temperatures from 30°F to 450°F, DC 200 from –40°F to 350°F and CTFE from –5°F to 300°F. DC 200 has the quickest time constant of 0.2 s for a 10 ft capillary at 85°C.

3.3.4.4 Fill Fluids

Different types of fill fluids can be used in a remote seal system. The fill fluid choices include instrument oil, different grades of silicon, fluorolube and halocarbon. The major consideration when evaluating a fill fluid is that the fluid does not react chemically with the process and other materials. In addition to the above, the fill fluid is evaluated for the following:

- **Compressibility**: The fill fluid should be incompressible so that the deflection of the remote seal diaphragm must move the seal fluid. For example, if a seal fluid were air, then air would compress and exert less pressure against the transmitter diaphragm resulting in less than desirable performance.
- **Viscosity:** The seal fluid should have low viscosity because the speed of response is affected by the fill fluid's viscosity. The higher the viscosity, the slower the response.
- **Temperature range:** The fill fluid should remain a liquid over the temperature range.
- **Chemical inertness:** The fill fluid should be nonreactive with the transmitter components and capillary tubing.
- **Coefficient of thermal expansion:** Ideally, the fill fluid's volume should remain constant as the temperature changes, i.e., low thermal expansion.
- **Density:** Response time is longer for denser liquids.
- **Vapor pressure:** Vacuum pressure measurement should use fill fluids with low vapor pressure to prevent bulging diaphragms.
- **Capillary considerations:** Capillary considerations include reviewing the capillary length and capillary bore size (diameter).
- **Length:** Capillary length is usually predetermined by the installation requirements.
- **Bore size:** Capillary bore size sometimes involves making engineering tradeoffs. A small-bore size minimizes temperature effects. A large bore size minimizes effects on response time. Vendors may offer only one capillary size.

3.3.4.5 Remote Seal Characteristics

Remote seal characteristics that are evaluated consist of the following components.

3.3.4.6 Temperature Effect

When the temperature changes, the fill fluid will expand or contract based on its physical properties. As the temperature increases, the fill fluid's volume increases. The change in fill fluid properties means that the internal pressure changes potentially resulting in a zero shift or measurement error.

3.3.4.7 Response Time

The response time of a remote seal pressure measurement system depends upon four factors:

- The fill fluid volume change that a pressure transmitter responds to.
- The total capillary length. Response time is directly proportional to the capillary lengths.
- The capillary diameter. Response time is inversely proportional to the fourth power of the capillary's diameter.
- The filling fluid viscosity. The average temperature that is present along the capillary lengths affects speed of response.

3.3.4.8 Zero and Span Adjustment

After the transmitter is installed, the transmitter zero adjustment is made to eliminate any zero shift.

3.3.4.9 *Accuracy*

The error of the seal system can be estimated using the following relationships:

$$\left.\begin{aligned} V_T &= (V_{CAV}) + (V_{\text{CAP}}) + (V_{\text{SEAL}}) \\ \text{Error} &= \frac{[(V_T)(S_R)(100)]}{P_S} \end{aligned}\right\} \tag{3.17}$$

where, V_T = total fill fluid volume change, V_{CAV} = fill fluid volume change in cavity, V_{CAP} = fill fluid volume change in capillaries, V_{SEAL} = fill fluid volume change in seal diaphragm(s), S_R = diaphragm spring rate, P_S = calibrated pressure span in psi or inches H_2O.

Note

The calculation expresses only the error for the seal system. It can be added to the transmitter's error to derive the total probable error (TPE).

For answers to checkpoint, scan the QR code

Or

Visit http://qrcode.flipick.com/index.php/400

Checkpoint

✦✦ 1. Which is called cash registers in flow measurement?

✦✦ 2. Which principle is used in pneumatic type transmitters?

✦ 3. A change in resistance causes changes in transmitter's output using which principle?

✦✦ 4. What is turndown ratio?

✦✦✦ 5. Explain how the temperature affects the accuracy of the conventional transmitters.

✦✦ 6. What is the typical scan rate of pressure transmitters?

✦✦ 7. List three parameters for evaluation of pressure transmitter for any application.

✦✦✦ 8. What is the benefit of electronics in transmitters compared to legacy pneumatic instruments?

✦✦✦ 9. What are the additional functionalities available with microprocessor-based transmitters compared to analog counterparts?

✦✦✦ 10. What is the need for the barrier diaphragms?

✦✦ 11. What is the most commonly used fill fluid in pressure transmitters?

✦✦ 12. What is feed through assembly in pressure transmitters?

✦✦ 13. What is the process head?

3.4 SELECTION CRITERIA OF PRESSURE MEASUREMENT DEVICE

LO 4

Review selection criteria of pressure measurement device

Pressure measurement devices perform the following general functions:

- Allow the values of pressure in a process to be monitored.
- Contribute to the indication and/or control of pressure at its assigned set-point.
- Contribute to the operation of alarm systems and emergency shutdown systems (ESD).

Given these general functions, an engineer would benefit from an approach that narrows the selection criteria to several pressure measurement technologies. An approach that assists the engineer to begin selecting the device best suited for the process is outlined in various literatures available on the subject. The instrument engineer is encouraged to review the selection criteria listed in this chapter when encountering pressure measurement device selection and installation criteria. After reviewing the initial selection approach, the selection criteria for pressure measurement devices also includes reviewing the following:

- Application fundamentals
- Specifications (Properties of measurement)
- Safety considerations
- Metallurgy
- Installation considerations
- Maintenance and calibration
- Compatibility with existing process instrumentation
- Economic considerations
- Technical direction

3.4.1 Application Fundamentals

Selection of a proper pressure measurement device requires a complete understanding of the application intended for the device. The two most common types of applications are pressure-measurement applications and pressure-switch applications. The following section will overview the basic requirements for instruments that are used for these applications.

3.4.1.1 Pressure-measurement Applications

For pressure measurement applications, the major considerations are—range, over-range protection, temperature and process fluid compatibility.

Range A pressure-measurement device is calibrated to indicate pressure values within a specific range. The lowest value in the range is a device's lower range value (LRV). The highest value in the range is a device's upper range value (URV). As an example, a pressure-measurement device could be calibrated to indicate pressure in the range of 0 psi (LRV) to 1000 psi (URV).

General practice is that the normal value of pressure in a process, i.e. the value that a pressure measurement device would normally indicate) must be between 30% and 70% of the URV of the pressure-measurement device. As an example, a pressure measurement device with a range of 0 psi (LRV) to 1000 psi (URV) would be suitable for use in processes in which the normal value of pressure is between 300 psi (30% of 1000 psi) and 700 psi (70% of 1000 psi).

Over-range Protection A pressure-measurement device must be constructed so that it is able to withstand over-range pressures (i.e. pressures that exceed the device's URV). The general industry guideline is that a pressure measurement device must be able to withstand a pressure that is 125% of (or 25% greater than) the device's URV. For some companies, the requirement for over-range protection is more stringent such that a pressure-measurement device must be able to withstand a pressure that is 130% of (or 30% greater than) the device's URV.

Note

As an example, a pressure measurement device that is calibrated for a URV of 1000 psi must be constructed so that it can withstand pressures as high a 1300 psi (130% of 1000 psi).

Temperature Pressure-measurement devices are designed to measure pressure accurately and to otherwise operate without failure within a specific range of temperatures. For example, a Bourdon tube-type gauge would be expected to operate accurately and reliably within a temperature range of –60° F to 375° F.

Process Fluid Compatibility The pressure measurement device's wetted materials (i.e. materials that come in contact with process fluids) must be compatible with the process fluid to minimize or avoid corrosion.

3.4.1.2 Pressure-switch Applications

A pressure switch often initiates corrective action in the event that pressure values in a process drop below or rise above the values to which the switch is calibrated.

For example, a switch may restore lost pressure (caused by failure of a pump) by actuating a backup pump. Pressure switch devices are also used to trip alarms or control devices when pressure limits are exceeded. Traditionally, pressure switches have been installed in pneumatic systems to detect when alarm values for pneumatically transmitted variables have been reached.

The current applications include the following:

- To actuate corrective action or alarms when flow rates through pipelines exceed limits.
- To actuate corrective action or alarms for pressure loss across items such as filters.
- To actuate corrective action or alarms for oil pressure loss in compressors that can be used to turn on backup lube pumps.

- To actuate corrective action or alarms when liquid levels exceed limits in pressurized vessels. In this case, the switch typically requires a differential pressure set-point to trip the device.

As pressure switches use similar sensors as pressure measurement devices, the considerations for pressure switch applications are the same as those for pressure measurement applications. Additional considerations for pressure switches are summarized as follows:

- **Mounting:** Switches are to be mounted in locations where they will not accumulate corrosive fluids.
- **Type of switch applications:** A switch that is used in ESD service should have its own direct connection to the process vessel. A specific application may also require a differential pressure type switch.
- **Type of switch actuations:** The snap acting mechanism and contact-rating requirements should be sufficient to operate solenoids, relays, or other process devices without needing additional interposing relays.
- **Type of switch enclosures:** The enclosure may require NEMA 4 weatherproof or explosion proof housing.

Switch Operating Characteristics To determine a pressure switch's function relative to the process requirements, engineers generally has to review the following operating characteristics of a switch:

- Indication type (whether or not the switch has local pressure indication)
- Switch dead-band (or differential action)
- Over-range pressure
- Normal operating pressure of the switch

Pressure switches come in two types—those that have a local pressure-indicating gauge and those without a local indicator that are called nonindicating or blind switches. A switch with a local indicator has a scale graduated in units such as kPa or psi. The scale allows the pressure trip point or set point to be set to a specified value. Factors to be considered while selecting a switch of this type include accuracy (which can vary widely), resolution (so that the set point is properly set), and ease of accessibility of set-point adjustment. Blind switches constitute a better choice when it is desirable to keep unauthorized personnel from adjusting the set-point. The switch set points often have fixtures such as locknuts that prevent set-point changes. According to general industry practice, switches with nonindicating (blind) set points are acceptable for most applications. In an ESD application, the selection and installation requirements for a switch are much more stringent.

A critical characteristic to be aware of in a pressure switch application is the switch dead-band, also called a switch's differential action or differential limits.

The switch dead-band represents a gap of operation where a switch actuates in the pressure-increasing direction and de-actuates in the opposite direction as the pressure decreases. In other words, dead-band or differential action could be described as a range where no switch deactivation occurs. Engineers often want differential action to prevent switches from actuating and resetting (chattering) if the measured pressure fluctuates around the alarm set point. Engineers also evaluate the switch's differential action to determine whether the switch can reset itself after the process returns to normal. The differential action is either adjustable or fixed. Refer to Figure 3.49 for the illustration of the concept.

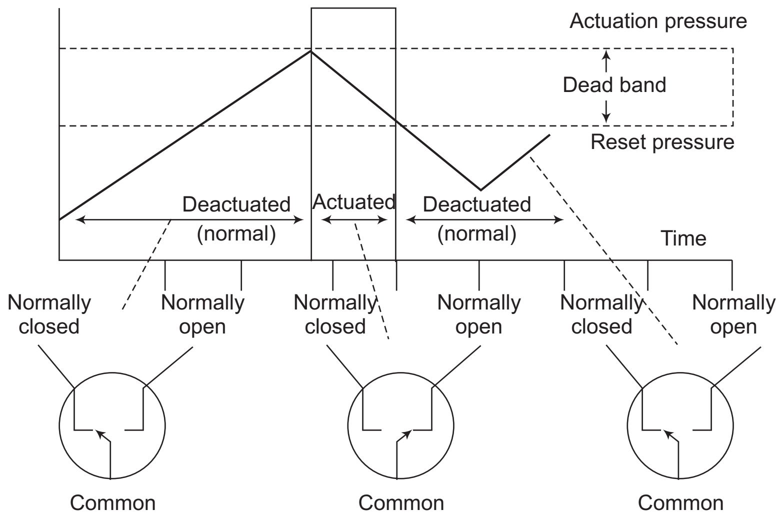

Figure 3.49: Switch dead band

Functionality varies across switches and this is inherent in a snap switch. The differential action cannot be eliminated, as it is a result of the force required to actuate the switch. Engineer must be aware of the fixed differential action, which could be as high as 25% of the span. Inappropriate application of switches is often caused by not being aware of the differential action inherent in a switch. Users review the overpressure characteristics of a switch to make sure that the switch has been constructed within the required overpressure protection. Finally, users determine whether a pressure switch is appropriate for the process requirement or not.

For example, in pump discharge systems, pressure switches often function to actuate or alarm in case of a pump failure. However, if the normal operating pressure in the pump circulating system is low, the pressure difference experienced between normal and abnormal conditions is minimal. A flow switch would be more suitable in this case as abnormal flow is the condition that must actuate an alarm.

3.4.2 Specifications (Properties of Measurement)

When evaluating a pressure instrument for a given application, the same basic method of evaluating an instrument should be used. For example, linearity specifications are often listed in three different ways—independent, zero-based and terminal-based. The same basis for instrument performance evaluation should be used to evaluate and compare instruments on an equal basis.

3.4.2.1 Linearity Specifications

Specifications used to quantify the nonlinearity of an instrument are of three types—independent linearity, zero-based linearity and terminal-based linearity.

Independent Linearity Independent linearity (also called best straight line) allows the zero and full-scale values of the reference line to be such that they minimize the nonlinearity specification of the instrument. In this case, zero and full scale of the reference line may often not be the same as the zero and full-scale value of the actual or desired full-scale value of the instrument. When installing the instrument by changing the zero and span, the optimized factory settings also are changed.

Zero-based Linearity When nonlinearity is expressed in terms of zero-based linearity, the zero is fixed at the lower end of the span. The full-scale point can be at the point that minimizes the effect of nonlinearity. The actual value depends on the nature of the nonlinearity, as is the case with independent linearity.

Terminal-based Linearity Terminal-based linearity is the most stringent linearity specification in which the zero and full-scale values are fixed. In other words, no opportunity exists to improve the specification by moving the reference line. This specification indeed should provide accuracy that a user is most likely to experience in actual practice. Figure 3.50 illustrates the comparison of the linearity.

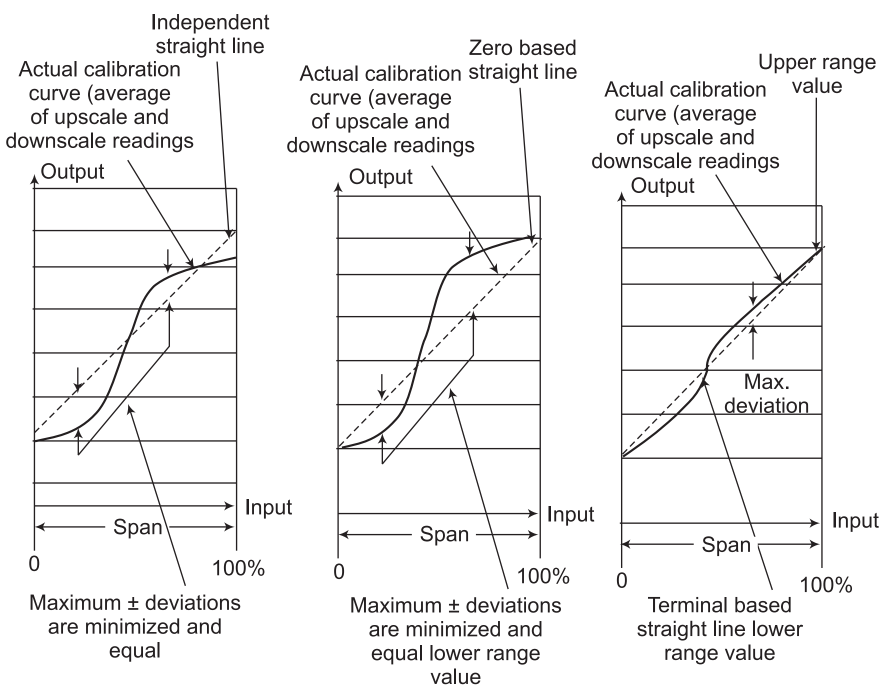

Figure 3.50: Linearity comparison

3.4.2.2 Statistical Specifications

A pressure measurement's instrument performance can be specified in terms of statistical specifications. To evaluate an instrument's performance means interpreting whether the instrument is specified in terms of one of the following methods—confidence limits, root sum of the squares (RSS) or root mean square (RMS).

Confidence Limits Confidence limits may be expressed as an indication of the devices expected accuracy. For example, an accuracy specification may say that the "achievable accuracy with a 95% confidence level is 0.1%". This means that 95 out of 100 instruments will meet the accuracy specification of 0.1%. Alternatively, 1 out of 20 instruments will not meet the specification, which can be difficult to verify if the instrument is used as a calibration standard. In most of the cases, the confidence limits are based on a statistical sample.

RSS or RMS Another statistical method that is used is RSS or RMS. In this method (RSS and RMS), the devices undergo test and calibration and their nonlinearity (n), hysteresis (h) and nonrepeatability (r) measurements are done.

The nonlinearity (n), hysteresis (h) and nonrepeatability (r) measurements are squared. If n, h, and are each 0.1%, the square of each is 0.01%. The sum of the squares is 0.03%, while the RSS is 0.17%. Although there are different ways of representing the accuracy specification, its actual accuracy remains the same.

In other words, one instrument may have an algebraic sum technique showing 0.3% accuracy, while another shows an accuracy of 0.17% using the RSS method as:

$$\text{RSS} = (n^2 + h^2 + r^2) \tag{3.18}$$

If $n = h = r = 0.1$, then $(n^2 + h^2 + r^2) = 0.03$ and RSS = 0.17

In this example, both instruments have the same accuracy. Refer to Table 3.7 for the comparison of some characteristics using two different methods.

Table 3.7: Statistical method comparison

	Algebraic Sum (%)	*Square of Values (%)*
Nonlinearity	0.1	0.01
Hysteresis	0.1	0.01
Nonrepeatability	0.1	0.01
Accuracy using algebraic sum	0.3	NA
Accuracy using sum of squares	NA	0.03
Accuracy using square root total	NA	0.17

Note

Some industrial users as acceptable pressure instrument specifications for noncritical applications consider the RSS and confidence limit methods. As the specification is not a worst case specification, devices specified by using RSS and confidence limits generally are not acceptable for test and calibration needs.

3.4.3 Safety Considerations

When evaluating pressure instruments, the safety considerations include the following:

- Hazardous location requirements
- Overpressure ratings
- Fill fluid selection
- Special application requirements
- Device safety feature requirements
- Failsafe configurations

3.4.3.1 Hazardous Location Requirements

Irrespective of the usage of the device in a hazardous location, it is essential that it meet certain electrical criteria. The location of the instrument needs to be carefully evaluated considering the zone of the installation.

3.4.3.2 Overpressure Ratings

Devices such as transmitters have pressures set to a maximum. Overpressure limits define the maximum pressure an instrument can withstand without damaging the sensor. For example, a common misunderstanding is to mistake the overpressure rating of a transmitter's meter body for that of the sensor or flange rating. This mistake occurs because the pressure rating is stamped on the meter body itself and is confused with a flange rating. Manufacturers often design pressure devices to withstand pressures above the rated pressures and may even test them to 1.5 times the rated pressure. However, that extra margin of safety is not a reliable factor. Pressure instruments should not be stressed beyond their rated operating pressures.

3.4.3.3 Fill Fluid Selection

Some pressure instruments may require fill fluids as part of their instrument's design to properly sense pressure. In addition, to review if the selected fill fluid is compatible with the process application, the engineer must also review if the fill fluid could potentially represent a safety hazard in times of an accident. Liquid fill fluids such as the standard silicone can react violently with oxygen or wet chlorine should a leak occur. Safer fill fluids such as Fluorolube can be ordered at additional cost.

3.4.3.4 Special Application Requirements

Applications in demand may require pressure instruments designed specifically for them. For example, oxygen service applications require pressure transmitters specifically identified for that service because the applications are extremely combustible. The transmitter is cleaned by the vendor to remove contaminants. The cleanliness of the transmitter must be maintained by the end user and not contaminated by inexperienced personnel.

3.4.3.5 Device Safety Feature Requirements

Some plants have standards to determine whether the instrument requires safety features. For example, pressure gauges have options such as blowout backs and rupture discs to prevent gauge glass from exploding towards operations personnel.

3.4.3.6 Failsafe Configurations

Pressure devices, such as microprocessor-based transmitters, permit the engineer to configure what type of signal to send to the controller in the event a sensed signal is considered bad or unreliable.

3.4.4 Metallurgy

Metallurgy considerations that influence device selection are as follows:

- Metal compatibility with process media
- Compliance to NACE MR-01-75

3.4.4.1 Metal Compatibility with Process Media

Pressure measurement devices generally use stainless steel for what are called "wetted" parts (i.e. parts that are in contact with the process fluid). Though stainless steel tends to be acceptable in most cases, not all devices isolate the sensor from the process fluid. The engineer should consult ANSI B40.1 for additional guidance on metal compatibility, as the engineer is eventually responsible for selecting the compatible metal.

3.4.4.2 Compliance to NACE MR-01-75

One of the applicable industry standards for pressure measurement instruments is NACE MR-01-75.

Purpose of NACE and NACE MR-01-75 The National Association of Corrosion Engineers (NACE) lists the metallic requirements for resistance to sulfide stress cracking (SSC). The NACE publishes the standard. NACE is a worldwide organization that studies corrosion and is primarily concerned with the protection of materials used in petroleum production, refining, pipelines (its original focus), and other process industries. It is important to note that the standard MR-01-75 covers only metal requirements for resistance to SSC and does not deal with other forms of corrosion. Although its original intent was for hydrocarbon production and field processing equipment, many industries require MR-01-75 materials for components in sour applications. As a rule, most instrument vendors comply with NACE MR-01-75 when introducing a new product.

Sulfide Stress Cracking Sulfide stress cracking refers to the fracturing of metal in response to pressure (or more accurately, tensile stress) and a corrosive fluid. All metals, including gold are susceptible to stress corrosion cracking in certain environments. For example, stainless steel will crack in a chloride medium but not in an ammonia medium. Brass will crack in an ammonia medium but not in a chloride medium. If sulfides (such as H_2S) are present in a fluid, carbon and low alloy steels are susceptible to SSC. SSC occurs without any visible warning indications and occasionally with no visible signs of corrosion. As corrosion occurs in a sour environment, free hydrogen is formed that diffuses into the metal causing the crystalline structure of the metal to become brittle. If the concentration occurs along an area of stress, cracking can occur.

Sulfide stress cracking is most severe when temperatures are between 20°F and 120°F. Below 20°F, the critical concentration of hydrogen is unlikely because the diffusion rate of hydrogen is low. Above 120°F, hydrogen passes through the material quickly because the diffusion rate of hydrogen is high. Above 120°F other forms of stress corrosion cracking can occur, such as chloride stress cracking in a sour well.

Limits of NACE NACE does not review a vendor's manufacturing procedures, nor does it issue certifications of compliance. As NACE is not a design standard, it does not explain the instrument engineer about situations where its requirements are applicable. However, the standards do give guidance to the instrument engineer as to the relationship between pressure and hydrogen sulfide for both sour gas and multiphased sour oil. An overview of the sour gas region is shown Figure 3.51 (refer to NACE for a more detailed description).

3.4.5 Installation Considerations

Temperature changes, shock, vibration, and everyday use cause electrical and physical properties to change. The change in the electrical and physical properties ultimately affects a pressure instrument's error and drift. Additionally, pressure instrument technologies (such as strain gauge, capacitance, and resonance) may have limits to their ability to withstand pressure and temperature extremes, vibration, and electrical noise. Fortunately, technological advancements in materials and manufacturing methods have led to better capabilities. In pressure measurement and control systems, the means by which the instrument interfaces with the process is a prime consideration to achieve reliable operation.

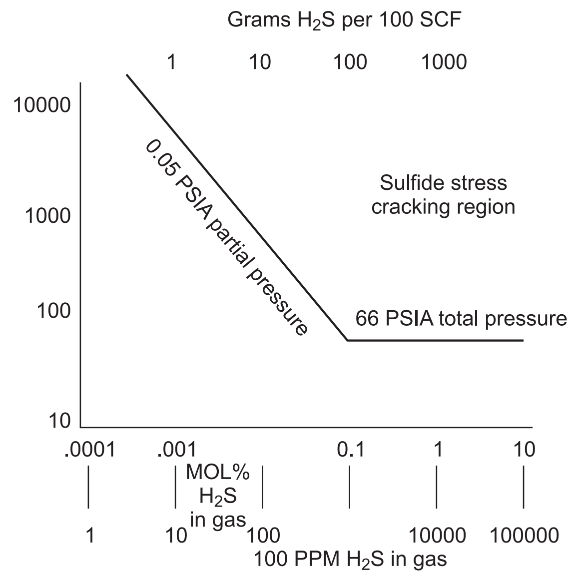

Figure 3.51: Sour gas region

3.4.6 Maintenance and Calibration

For more information, refer Section 3.5.2.

3.4.7 Compatibility with Existing Process Instrumentation

A process measurement device must be compatible with existing process instrumentation. Other existing process measurement instrumentation includes controllers, recorders, data loggers, test and calibration equipment, digital panel meters, and computer interfaces. When evaluating if a pressure measurement device is compatible, users review the devices as per the following terms and conditions—output signal type, power supply and wiring considerations and intended use of the output signal.

3.4.7.1 Output Signal Type

The pressure measurement device's output should be compatible with the input range of the signal-receiving instrument. Pressure measurement devices have several types of outputs—millivolts (mV), volts (V), milliamps (mA), proprietary digital protocols (HART, Honeywell DE), and mechanical types (PSI).

3.4.7.2 Power Supply and Wiring Considerations

The power supply and wiring considerations include how many process measurement devices are powered, how many receiving devices are sensing the output signal, and if multiple pressure measurement devices are sending signals to one instrument.

3.4.7.3 Intended Use of the Output Signal

Reviewing the intended use of the output signal includes determining whether the receiving device can display the signal. For instance, does the receiving device have sufficient gain and sensitivity for the signal? Should the signal be alarmed? Reviewing the intended use of the output signal includes determining whether the process value represented by the output signal should be stored for historical purposes.

3.4.8 Economic Considerations

Economic considerations that influence pressure measurement instrument selection include—cost category of the instrument, cost of ownership, and general cost considerations.

3.4.8.1 Cost Category of Instrument

Occasionally, users divide the available pressure measurement instruments into three or more categories. For the purpose of discussion, the three categories are—low-cost instruments, conventional instruments, and microprocessor-based instruments.

Low-cost Instruments Pressure measurement instruments in this category provide reliable pressure measurement at low cost and have minimum accuracy and functionality. As their low cost may mean that potential repairs are not cost effective, the devices are considered "throwaway" devices.

Conventional Instruments Pressure measurement instruments in this category provide standard 4–20 mA outputs and have adequate accuracy and functionality.

Microprocessor-based Instruments Pressure measurement instruments in this category provide increased accuracy and compensation.

3.4.8.2 Cost of Ownership

In addition to the initial purchase price of the pressure measurement instrument, engineers may consider the cost of ownership of the device. Cost of ownership reflects the life cycle cost of a product. Cost of ownership includes reliability, repair philosophy, and operating costs.

Reliability Reliability is defined by failure occurrence and drift activity along with experiential data or mean time between failure (MTBF) specifications. It is not unusual to see MTBF specifications in excess of a hundred years. In that case, experiential data (if available) is reviewed.

Repair Philosophy The repair philosophy includes whether the device is repaired to the sensor or circuit board level versus replacing the failed device.

Operating Costs Calculating total cost of operations can include the maintenance of the device itself, along with its impact on process loop performance.

3.4.8.3 General Cost Considerations

A general checklist of cost considerations is useful to review when evaluating a pressure measurement device.

- Is accuracy and stability important?
- Is the device easily accessible?
- Is direct mounting possible? If yes, a conventional device may be suitable.
- Can the device (such as a pressure transmitter) meet more than one application need?
- What is the plant's repair philosophy?
- Does the manufacturer have a reputation for quality?
- Is technical expertise available to implement the device?
- Do compatibility problems represent additional costs?

3.4.9 Technical Direction

Technical directions that influence pressure measurement selection are described in the following terms—improvements in sensor manufacturing, trend to smaller devices, and fieldbus technology.

3.4.9.1 Improvements in Sensor Manufacturing

Pressure sensor design has as its goals very low noncorrectable errors and long-term stability. The errors, which today are corrected by microprocessors, are minimized by advanced manufacturing techniques and the use of new sensor materials. Elastic materials used in pressure sensors include silicon, ceramic, quartz, and sapphire. Elastic materials make it possible for pressure measurement devices that have little or no hysteresis or repeatability errors.

As silicon has great elasticity and fatigue resistance, its use in pressure sensors is quite common. Sensor technology is frequently manufactured by using a technology called micromachining. In this technology, manufacturers make some of the smallest devices, some seen under a microscope. Micromachining provides increased electronics integration at a decreased size and cost.

Note

Another technique used in manufacturing silicon pressure sensors is called silicon fusion bonding. This technique provides pressure sensors that sense lower pressure ranges with built-in overpressure protection.

3.4.9.2 *Trend to Smaller Devices*

Smaller sensors and electronics lead to development of smaller pressure measurement devices, such as smaller pressure transmitters. Smaller pressure transmitters, for example, simplify installation tasks in that pipe stands and mounting brackets may not be necessary.

3.4.9.3 *Fieldbus Technology*

The fieldbus standard can allow users to have pressure measurement instruments in a common system and interfaced to compatible control equipment. Microprocessor-based instruments become more versatile. For example, a differential pressure transmitter used in a tank gauging application could conceivably include or access tank correction factors.

For answers to checkpoint, scan the QR code

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Checkpoint

✦ **1.** What is LRV and URV?

✦✦ **2.** What is the general practice of normal pressure value in the range of LRV to URV?

✦✦✦ **3.** What are the general guidelines for the over-range protection value on top of the URV?

✦✦✦ **4.** A pressure measurement device that is calibrated for a URV of 1000 psi must be constructed so that it can withstand pressures as high a ______ psi.

✦✦ **5.** What is the purpose of a pressure switch?

✦✦✦ **6.** List two operating characteristics of a pressure switch.

✦✦✦ **7.** What is a blind pressure switch?

✦✦✦ **8.** Which is a critical characteristic of a pressure switch?

✦✦ **9.** What is avoided by the dead band if the process value fluctuates around the set-point?

3.5 SMART PRESSURE TRANSMITTERS AND THEIR CALIBRATION

LO 5
Explain smart pressure transmitters and their calibration

3.5.1 Smart Pressure Transmitters

A smart field device is generally any device that includes a microprocessor. Typically, this means a pressure transmitter is that device which is capable of providing better accuracy, linearity correction such as linear, square root, etc. and temperature compensation, damping factors, etc. The smart transmitters also can provide more than one process variable from the same process tapping. The transmitter can coexist in the same control loop in which other transmitters such as pressure and temperature are connected.

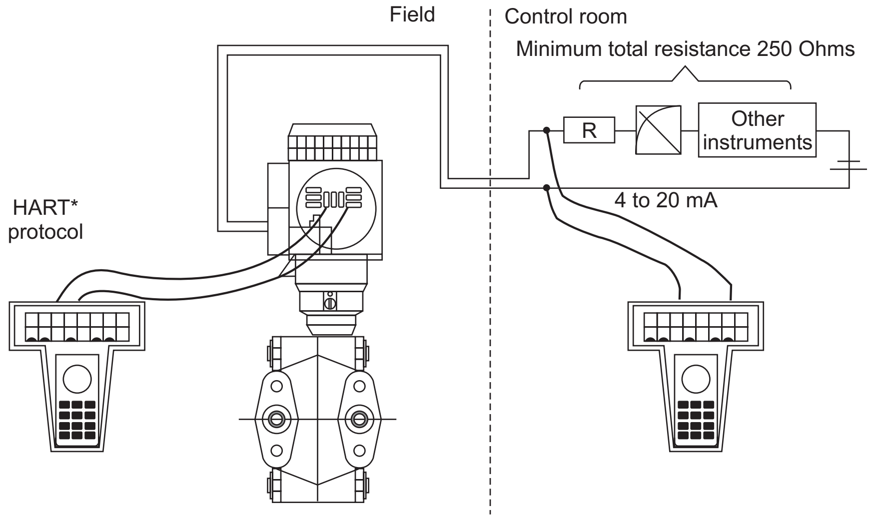
The transmitters can provide advanced functions and features that enable self diagnostics, semi-automatic calibration and prognostics. Smart pressure transmitters utilize a digital ASIC microcomputer which has the signal processing, amplification, etc., built in to a miniature chip. The electronics inside the module digitize the input signal from the sensor and apply corrections and configurations from its nonvolatile memory. All the pressure transmitters have settings to be done at the commissioning time based on the application. This settings is saved and called as configuration data. The configuration data is stored in a nonvolatile electrically erasable programmable read-only memory (EEPROM) in the electronics module. This configuration data and settings are stored and used whenever there is an intentional or unintentional power interruptions. This data helps ensure the device coming up fully functional once it recovers from power.

Note

The output section of the electronics converts the data into a 4–20 mA signal with a superimposed digital protocol or into digital form for pure digital data transmission.

A field-mounted smart device is usually remotely configured through a user interface from a handheld terminal or a personal computer. HART is the most common communication protocol (superimposed on the 4–20 mA signal), which offers an open solution to use the same handheld terminal for different measuring devices (Figure 3.52). Lately, pure digital protocols such as foundation fieldbus and Profibus-PA have become popular. Digital signal transmission provides the advantage of improving performance by eliminating the digital/analog conversion step. Another advantage is that multiple measured process variables can be transmitted, together with diagnostic data at high speed (31.25 Kbytes/s) in the same bus shared with other similar devices. Refer to Figure 3.53 for concept of the system and Figure 3.54 for various configuration options.

Figure 3.52 HART protocol (superimposed on the 4–20 mA signal)



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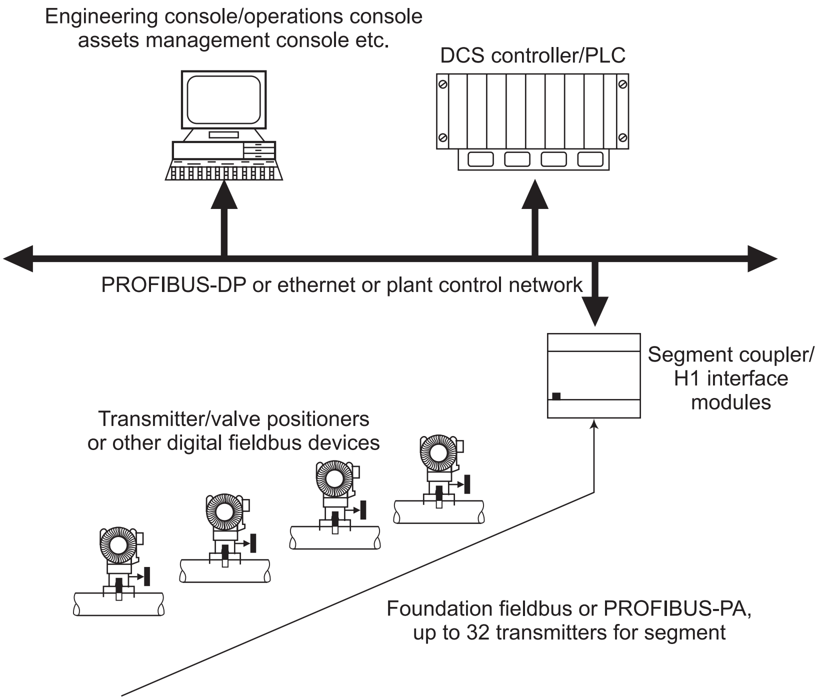

Figure 3.53: Fieldbus with Profibus-PA or FF (up to 32 transmitters per segment)

3.5.2 Pressure Transmitter Calibration

Maintenance and calibration considerations that bear on pressure measurement instrument selection are described as general maintenance approaches, typical calibration approaches, measuring pressure using calibrator and calibrating pressure transmitter.

3.5.2.1 General Maintenance Approaches

Preventive maintenance on pressure instruments includes maintenance tasks such as a check for zero and span drift. Pressure measurement systems can be checked for leaks, corrosion, aging, and damage. Additionally, microprocessor-based instruments provide self-diagnostics, to ease the maintenance effort.

Pressure instrument user manuals describe repair procedures. Common repairs on pressure measurement devices include replacing leaking O-ring seals, replacing failed sensor modules (caused by failure or overpressure operation), or replacing the failed electronics module.

3.5.2.2 Typical Calibration Approaches

Calibration approaches are described as typical calibration procedures and types of calibration equipment.

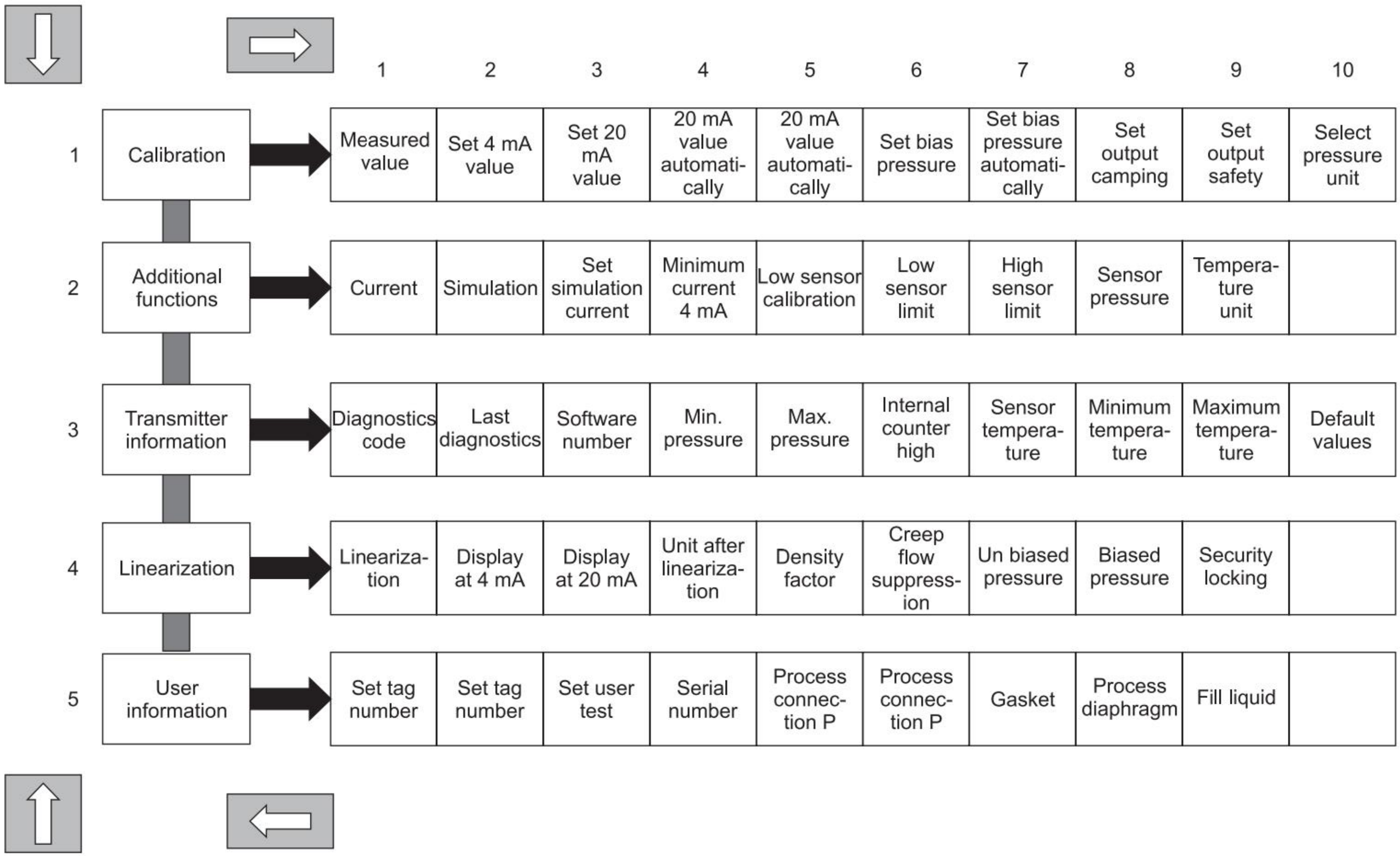

Figure 3.54: Configuration of smart pressure transmitter

Typical Calibration Procedures Proper calibration is best accomplished by following vendor recommended procedures. As an overview, the procedures usually include the following:

- Test and eliminate all leaks before calibrating a pressure measurement device.
- Purge all liquids from the pressure measurement system before calibration.
- To avoid temperature effects on the transmitter, do not blow down through the transmitter drain and vent valves. Rather, blow down through the impulse piping at a point near the process tap connections.
- It is always recommended to use acceptable calibration equipment. In other words, the accuracy of the calibrating equipment must be greater than that of the pressure measurement system.
- Make zero, span, and linearity adjustments following the vendor's calibration procedure. Note that linearity is adjusted at one point only and checked at others.
- Damping adjustments may be necessary.
- Additional factors that contribute to successful calibration include calibrating at temperature, at static line pressure, and if necessary, re-zeroing the transmitter.

Types of Calibration Equipment Generally, calibration is accomplished through two types of calibration equipment:

- Electronic digital gauges are used to compare pressure to electronic pressure standard. In this case, traceability can be requested.

Deadweight testers that are used to compare pressure to accurately know pressure standard (Figure 3.55) for a better understanding of the concept of dead weight tester. In this case, traceability can be requested. Industry approaches for pressure instrument calibration always

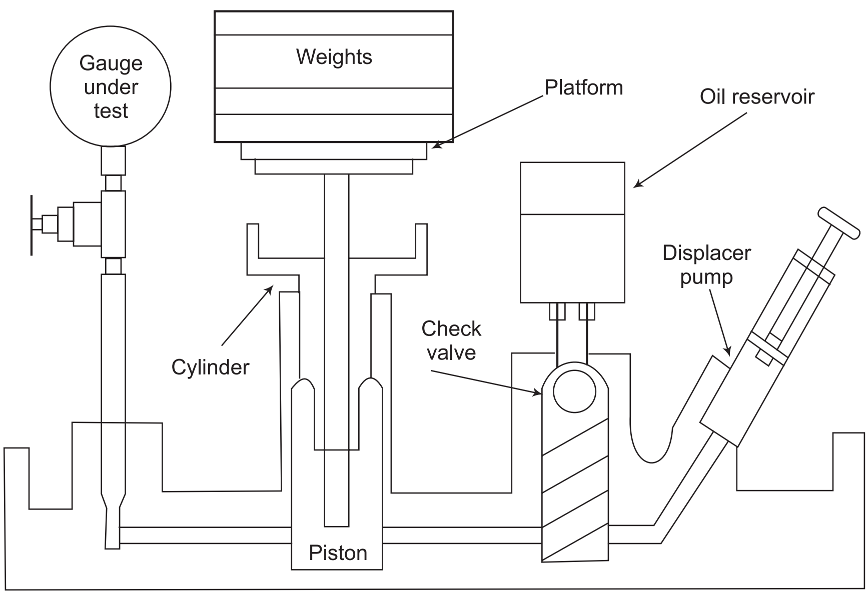

Figure 3.55: Deadweight tester

require the calibrating equipment to be more than 2–10 times greater in pressure measurement accuracy than the device under calibration. Deadweight testers are used in as found conditions and in calibrated conditions for the following reasons:

- Deadweight testers are highly accurate up to 0.025% of reading.
- Deadweight testers are easy to use.
- The ambient temperature error of a deadweight tester is small, as low as 0.01% for a 10°F change.
- Pressure is controlled during calibration and is not sealed in, which means that small leaks do not cause large errors.
- Range of 0.01 to greater than 10,000 psig.

3.5.2.3 Measuring Pressure Using Calibrator

Many ranges and types of pressure modules are available in the market. It is recommended to read the instruction sheet prior to using a pressure module. Different types of modules are available for varying use, for different media and accuracy levels expected, etc. Figure below Figure 3.56 shows the gauge and differential modules which are most widely used in calibration. Differential modules can also work in gauge mode by leaving the low side pressure fitting open to atmosphere. To measure pressure, or to calibrate the pressure, an appropriate pressure module is attached and tested. The actual steps for such operations are as follows:

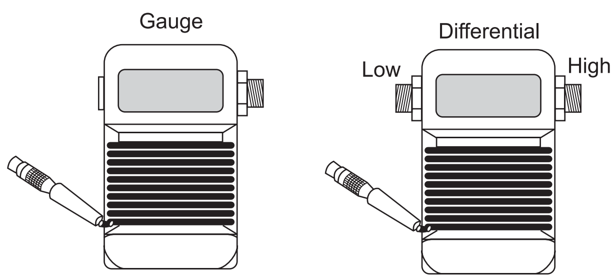

Figure 3.56: Gauge and differential pressure modules

- Connect an appropriate pressure module to the calibrator as shown in Figure 3.57. The threads on the pressure modules accept standard ¼ NPT pipe fittings. Generally the fittings shall be supplied along with the modules.
- Engineer performing the operation press an appropriate button in calibrator to sense. The calibrator automatically senses the pressure module attached and set its range accordingly.
- Engineer performs the zero operation on the pressure module as described in the module's instruction sheet. Modules vary in zeroing procedures depending on module type, but all require pressing calibration button for 3 seconds. Users get options to select the pressure units or change the pressure display to psi, mmHg, in Hg, cm H_2O @ 4°C, cm H_2O @ 20°C, in H_2O @ 4°C, in H_2O @ 20°C, in H_2O @ 60°F, m bar, bar, kg/cm^2, or kPa).

Zeroing with Absolute Pressure Modules Adjust the calibrator to read a known pressure to make its reading zero. This can be barometric pressure, if it is accurately known. Therefore, the reference pressure must be applied with a vacuum pump. An accurate pressure standard can also apply a pressure within range for any absolute pressure module. To adjust the calibrator reading, proceed as follows:

- Engineer press appropriate button in calibrator to adjust value to the right of the pressure reading.
- Engineer will press adjustment buttons for increasing and deceasing to change the calibrator reading to equal the reference pressure.
- Engineer performing the operation presses the appropriate button again to exit the zeroing procedure. The calibrator stores the information and automatically reuses the zero offset correction for one absolute-pressure module so that the module is not re-zeroed every time you use it.

Connections to the pressure modules with the instrument under calibration is shown in the Figure 3.57.

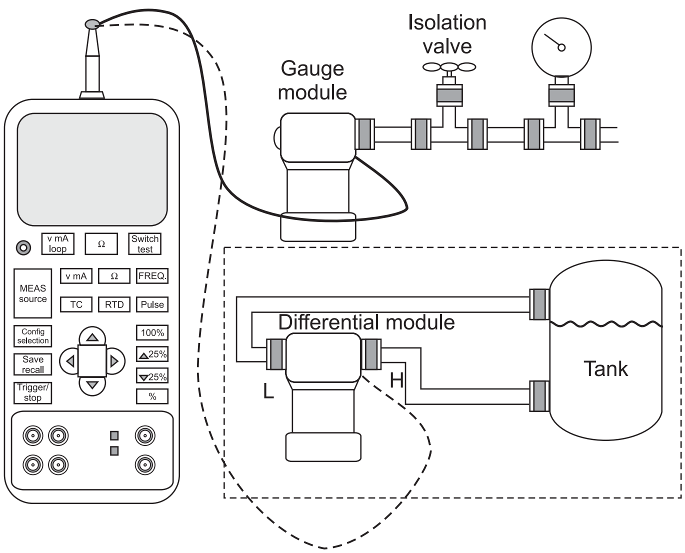

Figure 3.57: Connections for measuring pressure

3.5.2.4 Calibrating Pressure Transmitter

The elastic element to expands and contracts owing to the pressure changes applied to the gauge. The movement of the element is translated into movement of the pointer through links and gears. The measurement values of the gauges are read directly on the gauge scale from the position of the pointer. The Figure 3.58 represents the connections for the experimental setup for the calibration and Figure 3.59 representing the calibration procedure in the form of a flow chart.

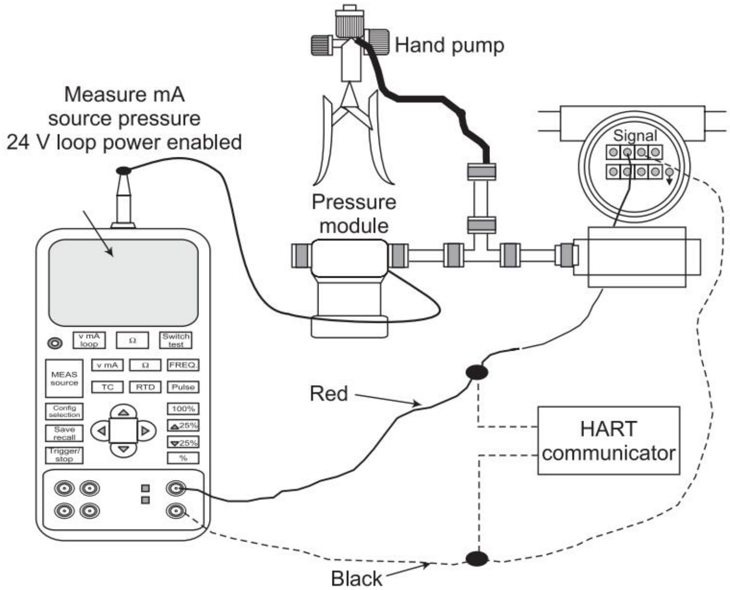

Figure 3.58: Experimental setup

Calibration Procedure Determine the five test points used for the upscale and downscale checks of the gauge under test with mechanical instrument. It is important to accurately determine whether hysteresis is present in the instrument so that one would begin the upscale check from 0% and approach the first test point 10% from below. It is recommended to approach each increasing test point 100% from below (do not overshoot as it reduces pressure to previous test point) and then approach 90% from above.

- Setup the system as shown in Figure 3.58 and apply source pressure using hand pump.
- See the readings on calibrator and tabulate "as found" values against the current measured at applied pressure zero and span values.
- The test results are then checked against the allowable tolerance. If the results are outside the allowable tolerance, zero and span interact in the mechanical device, so

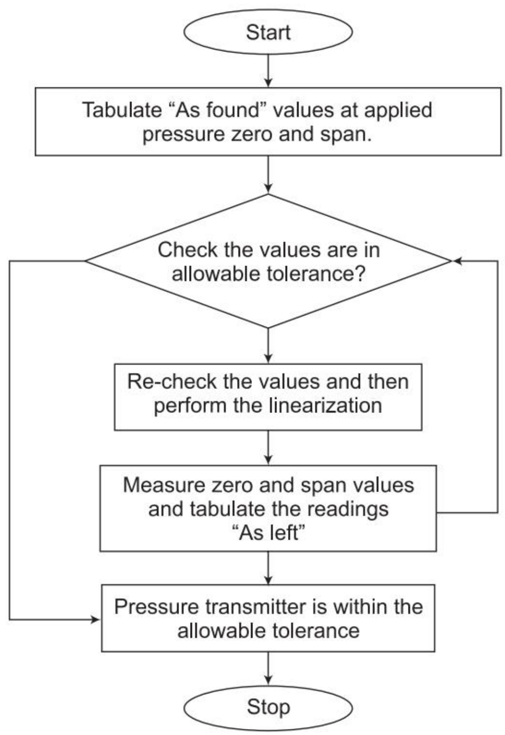

Figure 3.59: Flowchart for pressure transmitter calibration

rechecking them is necessary. When zero and span requires no further adjustments, recheck the linearity to make sure it is still properly adjusted. There are no adjustments for hysteresis.

- Adjust the reading (linearization) in-order to minimize the error % as specified in the instructions given by calibration manual.
- After adjusting linearity, zero and span, perform another full scale check and record as-left calibration data.

Checkpoint

✦✦ 1. What are the different output options of a smart pressure transmitter?

✦ 2. Which is the popular protocol used for remote configuration of the transmitter?

✦✦✦ 3. Which are the pure digital communication protocols used by the pressure transmitters?

✦✦ 4. What is the industry standard accuracy of the calibration equipment compared to the device under calibration?

✦✦✦ 5. List at least three reasons on why deadweight testers are preferred method of calibration of a pressure transmitter.

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Summary

LO 1: Describe the basics of pressure measurement

- Pressure values themselves are essential data for monitoring. Often, the values of process variables other than pressure are derived from (inferred from) the values that are measured for pressure. As an example of inferred values from pressure, the value for the level of a liquid in a storage tank can be derived from the value of the hydrostatic pressure that is exerted by the liquid. As another example, the value for the rate at which a fluid is flowing through a pipeline can be derived from a differential pressure value that is produced by an orifice plate.
- Pressure has a direct relationship to temperature. If the temperature increases, the pressure increases. Pressure has an indirect relationship to volume. If the volume increases, the pressure decreases. If the volume decreases, the pressure increases. Pressure has a direct relationship to compressibility.
- Generally, pressure is measured in pounds per square inch, inches of water column, bar N/m^2, etc.
- Vacuum is generally measured in terms of micron and there is Torr which is measured as pressure from a column of 1 μm and 1 mm mercury respectively.
- When expressed in units of in Hg, in H_2O, or ft H_2O, the measured pressure is often referred to as a "head," which means "the equivalent height of a liquid that would create the same pressure."

LO 2: Explain different types of pressure sensors, transducers and transmitters

- Gravitational gauges (such as U-tube, well tube, and inclined manometers) are highly accurate devices that can directly measure pressure.

- The U-shaped tube is used to measure differential pressure—one side connected to a high-pressure connection and the other side to a low-pressure connection or atmosphere.
- The input to a deformation sensor consists of a force. A deformation sensor, in the process of sensing force, deforms in response to the force. The deformation is, in effect, the conversion of an input signal that becomes a pressure indication on a gauge.
- The difference between a pressure sensor and a pressure transducer is that the sensor provides the basis of measurement, while the transducer converts the measurand from one form to another.
- All pressure measurement systems consist of two basic parts—a primary part and a secondary part. The primary part is in direct or indirect contact with this interaction into appropriate values for use in indicating, recording and/or controlling.
- A pressure transducer is a device that provides an electrical output signal that is proportional to the applied process pressure.
- A pressure transmitter is defined as a device that provides an industry standard linear output signal (4–20 mA current) that is proportional to an applied process pressure.
- The pressure transducer consists of two sensors. In a pressure transducer, the deformation sensor represents the force summing element, while the strain-gauge sensor represents the force sensing element that converts the force to a proportional electrical signal.
- A strain-gauge sensor changes its electrical resistance when it stretches or compresses.
- Pressure causes the thin diaphragm to bend, inducing a strain in the diaphragm and the embedded resistor. The resistor values change depending on the amount of strain, which in turn depends on the amount of pressure applied to the diaphragm.
- On application of force, the material of piezoelectric gauge creates an electrical voltage.
- An electric potential is produced within the crystal when asymmetrical crystals are deformed elastically along specific axes, and this causes a flow of electric charge in external circuit.
- In a traditional capacitive transducer, a measuring diaphragm (elastic element) moves relative to one or two fixed plates. An oscillator or bridge circuit is used to detect changes in capacitance.
- In a typical capacitive pressure transducer, the distance between two parallel plates varies with changes in the pressure applied—thereby altering the electric capacitance. This capacitive change can be amplified and used to operate into phase-modulated, amplitude-modulated, or frequency-modulated carrier systems.
- In the double-ended tuning fork design, the force displacement causes a frequency shift. The frequency shift represents a pressure measurement.
- In the resonating wire design, a diaphragm causes a tension change in a fine resonating wire or ribbon.

LO 3: Analyze the performance and installation criteria of a pressure transmitter for specific applications

- Temperature variations, both from the process and ambient temperature changes, affect the accuracy of uncompensated pressure transmitters. The sensor's accuracy is affected when the seal fill fluid changes volume, while the electronics accuracy is affected through changes in resistance. In the case of conventional pressure transmitters, the accuracy can degrade to several percent of span.
- The benefits from electronics in analog and microprocessor-based transmitters are that there are no mechanical linkages, levers, or pivots required as in the case of pneumatic transmitters.
- Barrier diaphragms are used to protect internal sensing diaphragm from process media. As pressure measurement applications involve contact with conductive and corrosive fluids, silicon sensors are isolated from the process fluid through thin stainless steel barrier (isolation) diaphragms.

- The fill fluid surrounding the internal sensing diaphragm is mostly silicon oil.
- The pressure port threading is made into a metal flange of the transmitter that is often referred to as a process head.
- An absolute pressure transmitter has only one process connection to measure pressure. Absolute pressure transmitters can be used to measure the pressure in a vessel or pipe. The transmitter is usually located above the process tap to permit condensate draining.
- For level measurement applications, the high pressure side of the transmitter is connected to the tank, while the low side of the pressure transmitter is open to atmospheric pressure.
- Impulse piping (gauge lines) transfers the process pressure to the transmitter.
- Absolute pressure is measured in a refinery's vacuum distillation tower. A vacuum tower distills most of the gas oil out of crude, leaving an asphalt residual material. Operating pressures of typical vacuum towers are 1–5 psia.
- Another type of chemical seal is the volumetric seal. This type of seal consists of a flexible member, housing and fill fluid. The flexible member can be bellows, Bourdon tube or diaphragm.
- The remote seal differential pressure transmitter is made up of a transmitter body that has a differential pressure sensor and two diaphragm seal elements. Capillaries connect each of the seal elements to the transmitter body.
- The sealing element consists of a thin metallic diaphragm with convolutions. The capillary connects the cavity under the diaphragm to one of the inlet port pressure connections of the remote seal pressure transmitter.

LO 4: Review selection criteria of pressure measurement devices

- The lowest value in the range is a device's lower range value (LRV). The highest value in the range is a device's upper range value (URV).
- General practice is that the normal value of pressure in a process (i.e. the value that a pressure measurement device would normally indicate) must be between 30% and 70% of the URV of a pressure measurement device.
- Pressure switches come in two types—those that have a local pressure-indicating gauge and those without a local indicator that are called nonindicating or blind switches.
- A critical characteristic to be aware of in a pressure switch application is the switch dead band, also called a switch's differential action or differential limits.
- Devices such as transmitters have pressures set to a maximum. Overpressure limits define the maximum pressure an instrument can withstand without damaging the sensor.
- Pressure measurement devices generally use stainless steel for what are called "wetted" parts (that is, parts that are in contact with the process fluid).
- Sulfide stress cracking refers to the fracturing of metal in response to pressure (or more accurately, tensile stress) and a corrosive fluid.

LO 5: Explain smart pressure transmitters and their calibration

- HART is the most common communication protocol (superimposed on the 4–20 mA signal), which offers an open solution to use the same hand-held terminal for different measuring devices. Lately, pure digital protocols such as foundation fieldbus and Profibus-PA have become popular.
- Industry approaches for pressure instrument calibration always require the calibrating equipment to be more than 2–10 times greater in pressure measurement accuracy than the device under calibration.

Questions

I. Objective-type questions

✦ **1.** Which of the following lists the standard range of pressure determined to represent the lower and upper range values for the input signal?

(a) 0–10 psi (b) 0–15 psi
(c) 3–10 psi (d) 3–15 psi

✦✦ **2.** When using a two-wire electric signal loop to carry both the current and the signal, which of the following is true?

(a) A solid-state device such as a bipolar triode transistor is required to keep variance in voltage from affecting current (within reason).
(b) Ohm's Law states that as voltage is raised across a device, the current is proportionally increased and the change in current is used as the signal.
(c) A solid-state device such as a bipolar triode transistor will determine the collector current and not the emitter-base current (within reason).
(d) Ohm's Law states that as voltage is raised across a device, the current remains constant and current can therefore be used to carry the signal.

✦✦ **3.** A constant current transmitter with a 24 V power supply drops 1.2 V at minimum current at a resistance of 300 ohms. Which of the following correctly identifies how the output current is determined?

(a) The output current is decided by voltage on the transmitter per Ohm's Law.
(b) The transmitter will have 24 V resulting in a 4 mA current.
(c) The output current is decided by process variable and calibration.
(d) The transmitter will have 22.8 V resulting in 7.6 mA current.

✦ **4.** Which of the following pressure measurements refers to the amount of pressure that is above or below atmospheric pressure?

(a) Absolute (b) Compound range
(c) Column (d) Vacuum

✦✦ **5.** Which of the following is true of analog versus digital communications?

(a) Analog signals model a physical quantity using a number of discrete states between an upper and lower range limit.
(b) Analog signals are obsolete and are being entirely replaced by digital signals.
(c) The telephone and telegraph are early examples of analog communications.
(d) The lowest level of communications in the control hierarchy is still predominantly analog.

✦✦✦ **6.** Which of the following is true of most pressure measurement methods?

(a) They are sensitive to volume but not temperature.
(b) They are not able to measure a small differential pressure.
(c) They measure pressure by sensing the deflection of the diaphragm.
(d) The sensor matches the digital or analog signal conditioning and transmission.

✦✦ **7.** What is the advantage of connecting the pressure transmitter to the process by a length of tubing?
(a) It provides easy access for service.
(b) It minimizes cost.
(c) It minimizes leakage.
(d) It eliminates the need for service.

✦ **8.** Which one of the below given statements is true?
(a) Absolute pr = Gauge pr – atm pr
(b) Absolute pr = Gauge pr + atm pr
(c) Absolute pr = Gauge pr * atm pr
(d) Absolute pr = Gauge pr / atm pr

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II. Short-answer questions

✦✦ **1.** Absolute pressure defines pressure with respect to?

✦ **2.** Define ideal gas law.

✦ **3.** What is atmospheric pressure at sea level is?

✦ **4.** Define the term "head" in pressure measurement

✦ **5.** What is vacuum?

✦✦ **6.** Define differential pressure.

✦✦ **7.** Define hydrostatic pressure.

✦✦ **8.** Define atmospheric pressure.

✦✦✦ **9.** List two performance advantages of strain gauge transducers.

✦✦✦ **10.** How the piezoresistive sensor measures the pressure from a diaphragm?

✦✦ **11.** Define a piezoelectric effect.

✦✦ **12.** What are the types of the crystals used in piezoelectric pressure transducers?

✦✦ **13.** List the advantages of piezoelectric pressure sensors.

✦✦✦ **14.** What is the functionality of a capacitive transducer?

✦✦ **15.** List two disadvantages of capacitive transducers.

✦✦ **16.** In a resonating wire design, what causes a tension change in a fine resonating wire or ribbon?

✦✦✦ **17.** What is snubber?

✦✦ **18.** What is the reason for connecting one side to the process leaving the other side open to the atmosphere in a gauge pressure transmitter?

✦ **19.** What is independent linearity?

✦ **20.** What is zero based linearity?

✦ **21.** What is confidence limit and how it is expressed?

✦ **22.** What is overpressure rating of a transmitter?

✦✦ **23.** What are called wetted parts?

III. Unsolved problems

✦✦ **1.** A gauge pressure transmitter measures a value of 5 kg/cm^2 valve. Calculate the pressure in terms of absolute pressure.

✦✦ **2.** An analog meter face is calibrated so that the lower range value is 0% at 1 V and the upper range value is 100% at 5 V, with markings on the meter for every 10%. What is the scale of the meter, and what is its resolution?
(a) 1–5 V scale; resolution of 10%
(b) 1–5 V scale; resolution of 100%
(c) Full scale; resolution of 10%
(d) Full scale; resolution of 100%

✦✦ **3.** In an application, the flow rate of the gas is measured using a 4–20 mA differential pressure transmitter. The differential pressure is calibrated to provide (0–100) mm H_2O pressure corresponding to (0–10,000) m^3/h gas flow and the flow is calculated in the PLC using the differential pressure. When the transmitter sends 8 mA signal to a PLC, calculate the flow rate of the gas.

✦✦ **4.** An ideal gas is filled in an expandable balloon and its pressure and temperature is monitored by a SCADA system. When there is a 25% increase in the temperature of the balloon, the volume of the balloon increases by 10%. Calculate the percentage change in the pressure.

✦✦ **5.** A gauge pressure (TX), absolute pressure (TY) and differential pressure (TZ) 4–20 transmitter (high pressure end is vented to atmosphere) are connected to measure the pressure inside a vessel over the range of -760 mm Hg to 760 mm Hg. If an absolute vacuum is created in the vessel, calculate what would be the mA sent by the transmitters.

✦✦✦ **6.** An instrument system consists of pressure transducer with a range of 0–5 bar and a corresponding output of 0–10 mV. The output is connected to an electronic processor which converts the output into a current in the range 4–20 mA, and an analogue meter which indicates the measured pressure.
(a) Deduce and write down the equation linking the input and output of the processor.
(b) The output of the signal processor is 15 mA. Deduce the indicated pressure.

✦✦✦ **7.** A pressure transmitter has a range 0 to 3000 mm Hg with a guaranteed accuracy of plus or minus 1% and its output is between 4–20 mA. Determine the possible correct pressure when the transmitter output is 12 mA.

✦✦ **8.** Water pressure available at a fire hydrant is 80 psi. If a fire hose is connected to the hydrant and the hydrant valve opened, how high can the end of the hose be raised and still have water flow out the end?

✦✦✦ **9.** An important part of performing instrument calibration is determining the extent of an instrument's error. Error is usually measured in percent of span. Calculate the percent of span error for each of the following examples, and be sure to note the sign of the error (positive or negative): Pressure gauge • LRV = 0 psi • URV = 100 psi • Test pressure = 65 psi • Instrument indication = 67 psi • Error = % of span.

IV. Critical-thinking questions

✦✦ **1.** What are the significance of digital protocols such as foundation fieldbus and profibus?

✦✦ **2.** What is the significance of the HART protocol in transmitters

✦✦ **3.** What is the difference between HART and FF protocols?

✦✦✦ **4.** What are impulse lines for pressure transmitter process connection?

✦ **5.** What is dimensional analysis in unit conversion?

✦✦ **6.** List the factors that influence the pressure measurement?

✦ **7.** How temperature of the fluid influence the pressure measurement?

✦✦ **8.** What is the popular cement used for adhering the strain?

✦✦✦ **9.** What is the advantage of transducer with current output signal?

✦✦✦ **10.** How minimum operating voltage is calculated in transducer connected to multiple systems?

✦✦✦ **11.** Explain the reasons for quartz being the ideal piezo electric transducer.

✦✦✦ **12.** In an oscillative wire, which is represented as process pressure?

✦✦ **13.** In a double ended tuning fork design, what causes a frequency shift?

✦✦ **14.** What is Rayleigh's equation for a bar vibrating in vacuum and how is applicable in measurement of pressure?

✦✦✦ **15.** Why multiple DP transmitters of conventional type are required to get desired rangeability?

✦✦ **16.** What is the mounting philosophy of pressure transmitter in steam service?

✦✦✦ **17.** What are the mounting options for the absolute pressure transmitters?

✦✦ **18.** What is the purpose of impulse lines?

✦✦✦ **19.** What is the typical application of absolute pressure measurement in a refinery?

✦✦ **20.** What is the purpose of local indication in pressure transmitter?

✦✦✦ **21.** What does a chemical seal consists of?

✦✦✦ **22.** What is volumetric seal?

✦✦✦ **23.** What connects seals to the transmitter body in a remote seal DP transmitter?

✦✦ **24.** What does sealing element consists of in a remote seal transmitter?

✦✦✦ **25.** Which is the switch suitable for the pump discharge conditions?

✦✦✦ **26.** What is sulphide stress cracking?

✦✦✦ **27.** Define cost of ownership of the transmitters.

✦✦ **28.** What is the sensor manufacturing technique that senses lower pressure ranges with overpressure protection?

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Level

4

Level measurement, is one of the common instrumentation application in the process industry. The range of applications for level measurement varies from a simple open channel water measurement to most advanced level measurements used for custody transfer applications or as in distillation columns in refineries. The level measurement instruments have evolved from reading glass tubes to radar-based sensors. The shapes of the tanks, the process conditions, application of the instrument are critical for the selection of the right instrument and technology. The design and installation of the instrument is critical to derive the intended needs of the instrument. The hydrostatic level measurement using the differential pressure transmitters is discussed in detail along with some simple calculations of the hydrostatic head.

Additionally, the interface level measurement applications which are considered as one of the challenging applications are discussed in detail through various methods, advantages and their disadvantages. The smart level instrumentation provides more information than the traditionally measured process value. The additional information is used for diagnosing the instrument from the remote places and also to drive the decisions on the scheduling of the maintenance activities. Like any other instrument, the level transmitters need the calibration and a detailed procedures and different types of the calibrations are discussed.

Keywords:
Direct methods, indirect methods, capacitance, ultrasonic, differential pressure, calibration, wet leg, dry leg, zero elevation, zero suppression, bubble, float, nucleonic, vacuumed

LEARNING OBJECTIVES

After reading this chapter, you will be able to:

1. Describe level instrumentation in process industry
2. Explain direct methods of level measurement
3. Explain inferential methods of level measurement
4. Analyze interface level measurement
5. Analyze automatic tank gauging system
6. Review general considerations in selecting level measurement technology
7. Illustrate calibration of level transmitters

"If you can't measure it, you can't improve it"
Lord Kelvin

4.1 LEVEL INSTRUMENTATION IN PROCESS INDUSTRIES

LO 1

Describe level instrumentation in process industry

4.1.1 Purpose of Level Measurement

In many industrial processes, it is important to know the level of a liquid in a tank or a vessel. The need to measure level probably arose with the invention of the steam engine. It is essential to know the level of water in the boiler, when it is in use and under pressure, which is impossible to view through naked eyes. Therefore, the purpose of the level measurement is to provide a measured variable representing the height or material presence within a vessel. The measured variable is then used in one or more of the following ways, where the measured variable becomes:

- A local level indication
- A detection of material presence
- An input signal to a level control loop
- A measured quantity in hydrocarbon inventory management

The purpose and importance of level measurement is best illustrated in the following plant operations, where the level measurement variable is used:

- Control a vessel's process material level in order to provide satisfactory process performance
- Accurately measure a crude oil storage tank's level in order to calculate hydrocarbon inventories.

Level measurement is essential for the effective control of a vessel's process material level. The level control scheme for a vessel requires a level measurement value which provides level control scheme either a quantity, such as a representation of height; or a logical value, such as the on/off condition of a limit switch that represents the detection of process material presence. As an example (the general importance of controlling a vessel's level for satisfactory process performance), consider the effects of inadequate level control in a vessel.

If the level is too low, damage to a vessel's discharge centrifugal pump from cavitation's and excessive wear occurs. If the level is too high, then additional storage capacity will not be available in the vessel to store unplanned increases in process inlet quantities. As a more specific example of the role of level measurement in level control, consider a typical spherical three-phase oil/gas/water separator as shown in Figure 4.1. For separation to occur, a liquid fasten should occur in the lower part of the vessel. The liquid fasten restricts the loss of gas within the oil. The liquid seal is accomplished through level control, which in turn, is dependent upon a level measurement value.

Accurate level measurement is also necessary while measuring the storage tank levels as shown in Figure 4.2.

Consider the role of level measurement when calculating the hydrocarbon inventory for a 45.7 m (150 ft) diameter storage tank. The inventory calculation requires accurate level measurement values. A level measurement error of 3.2 mm (1/8 in) represents 5680 L (1500 gallons) of a hydrocarbon product. Assuming that the product is crude oil, this represents 35.7 barrels of crude.

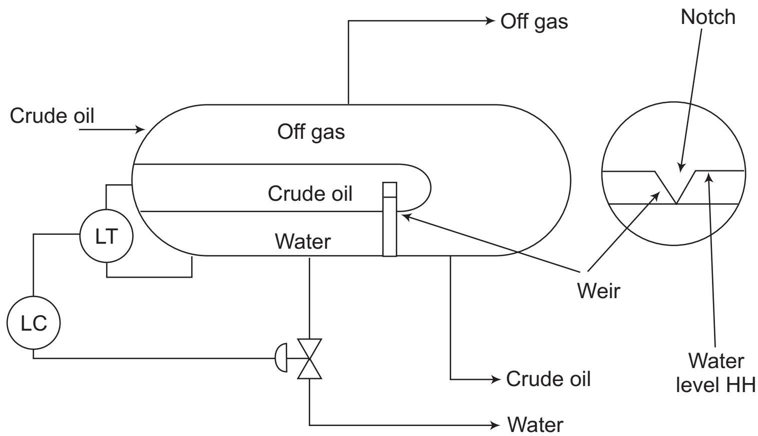


Figure 4.1: Example of oil separation

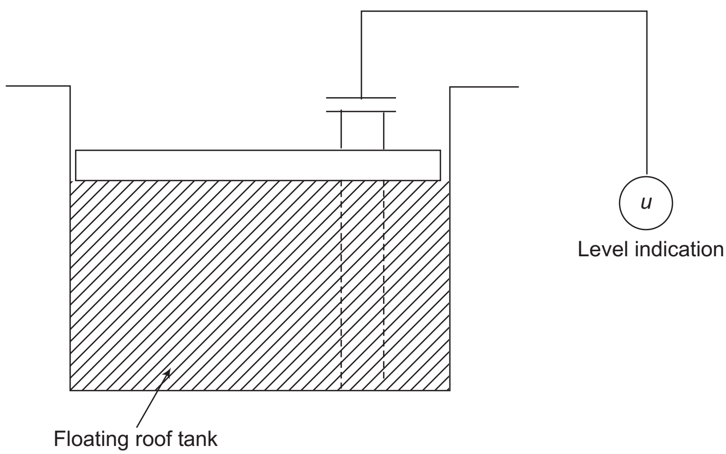


Figure 4.2: Example of oil storage

The broad variety of level measurement devices available to accomplish level measurement make the measurement device selection process challenging. Additionally, more than one device will be required in a level measurement application, forming a level measurement system.

The intended use for the level measured variable, such as process control and/or inventory accounting, has a major influence upon the selection of a level measurement device. Because the selection of a level measurement device or system is dependent upon the intended use of the level measurement variable, the selection process becomes application dependent. The application itself may require one or more types of level measurements.

The level measurement-selection process begins with identifying the type of level measurement that is required in the application. The types of level measurement encountered in applications can be broadly categorized as the following—point level process measurement, continuous level process measurement, and level measurement in automatic tank gauging (ATG) application.

4.1.1.1 Point Level Process Measurement

Point level process measurement is a type of level measurement, where the level measurement device or system provides a logical (true or false, on-off) representation of material presence at some predetermined point(s) within the vessel. Point level process measurement is also referred to as "point level detection" or "level set point" measurement. Point level process measurement is often accomplished with level switches (LS). Each LS is installed at a predetermined height or "point level" within the vessel. Uses for point level measurements include one or both of the following—point level process indication and point level process control.

Point Level Process Indication Point level process indication provides an indication of process material level at a point within a vessel. A single point level alarm, such as a vessel level high alarm limit, is an example of point level process indication.

Point Level Process Control Point level process control provides the control of a material level between two points in a vessel. To accomplish point level process control, more than one LS senses a liquid presence at two (or more) measured "point levels" in a tank. For example, in a vessel the conditions controlling level can be dependent upon the level measurement device, such as a switch, sensing the material presence. When the high LS is on, a discharge pump is turned on, which lowers the level and when the level drops and activates the lower level limit switch, the pump is turned off.

An application could require both point level indication and control, hence the phrase "point level process indication and control."

4.1.1.2 Continuous Level Process Measurement

In continuous level process measurements, a level measurement system can provide numeric representation of the current position (height) of the process material's surface. The numeric value, sometimes expressed in meters or feet, is based upon a proportion of material currently sensed by the level measurement system. The level is measured continuously between a lower reference level and an upper reference level. Uses for continuous level measurements include one or both of the following—continuous level process indication and continuous level process control.

Continuous Level Process Indication Continuous level process indication provides a continuous numeric indication of level within a vessel. A numeric indication of level height, such as the liquid level in a non-critical water storage vessel, is an example of continuous level process indication. In this example, only an indication of the level is provided because automatic control is not necessary. If it is necessary to adjust the level, an operator could manually open or close the fill or drain valves.

Continuous Level Process Control Continuous level process control provides the control of process material level between two points in a vessel. For example, in a distillation tower, level control is accomplished by adjusting the flow through a bottoms valve. A level sensor measures the level between the two reference points. The sensor's signal is sent to a level transmitter that generates an output signal which is connected as an input signal to a level controller. The level controller's output is connected to a bottoms flow valve, which controls the bottoms flow based on the difference between a known set point and the current process level signal.

An application could require both continuous level indication and control, hence the phrase "continuous level process indication and control."

4.1.1.3 Level Measurement in ATG Applications

While one could argue that level measurement within an ATG application is indeed continuous or point level measurement, an exception to that categorization is made here. An ATG application does not necessarily have as its primary objective, the use of a level measurement quantity as part of a process control scheme. While an objective of level measurement in ATG application is to measure, the material level within the tank, as accurately as possible, the level measurement quantity is used to calculate inventory quantities.

Automatic tank gauging system may also provide temperature and density measurement, which are necessary for calculating inventory at standard conditions. Therefore, ATG is regarded as not just another form of process level measurement, but as a separate discipline involving several process measurements. The level measurement aspect of an ATG application, however, does have a major influence on which level measurement device an engineer selects.

4.1.2 Typical Level Control Loops

As implied in the previous discussion, typical level control loops can use a measured variable from either a point level measurement or continuous level measurement. Thus, the examples that follow describe typical point level control loop and typical continuous level control loop.

4.1.2.1 Typical Point Level Control Loop

Point level control is possible using on-off LSs for controlling the interface level control in an oil and water separator. The oil and water mixture is separated with the oil removed from the top of the vessel and water drained from the vessel's bottom. In this example, the control of level does not require continuous level measurement and level control. A lower LS and upper LS can be used to provide point level measurements as shown in Figure 4.3. The two LSs provide input, in the form of on/off values, to the level control logic in a programmable controller. The level control

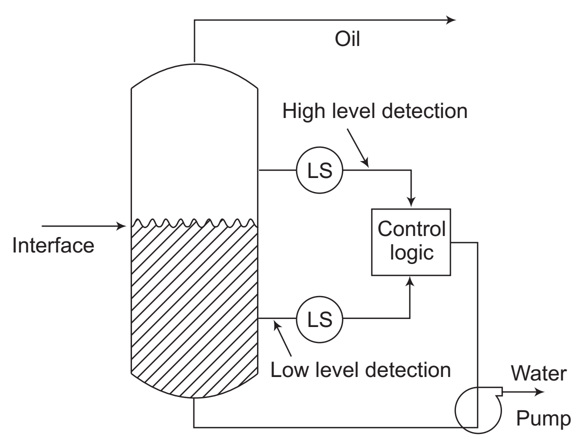


Figure 4.3: Point level process control loop

logic could represent the conditions—if the lower LS is on, then the level measurement indicates oil, so close the valve; if the upper LS is on, then the level measurement indicates water, so open the valve.

The level control logic starts with the interface level between the LSs. When water reaches the upper LS, the valve opens and remains open until the lower LS indicates oil. The interface level can then fluctuate between the two LSs. Because the water is often pumped to a holding tank and recovery system, the level control logic could also be connected to a pump to turn it on and off when needed.

4.1.2.2 *Typical Continuous Level Control Loop*

A crude oil desalter in Figure 4.4 illustrates how a continuous level measurement is used in continuous level control. Before raw crude is refined, it is washed in a desalter to reduce the crude oil's salt content. The desalter is a long horizontal vessel containing crude oil and water. The position where water and crude oil meet is called the "Interface". The level measurement device used here consists of a level sensing device and a level transmitter. The position of the interface is measured with a level sensing device that provides its level transmitter a physical variable, such as a voltage or displacement, to represent the interface position. The level transmitter sends its signal representing the position of the interface to the level controller. In order for the vessel to have a constant throughput of crude oil, the level controller must closely control the interface position, as water and oil densities change; the position of the interface changes. The need to control the interface's changing position requires a level measurement device that can accurately locate the interface.

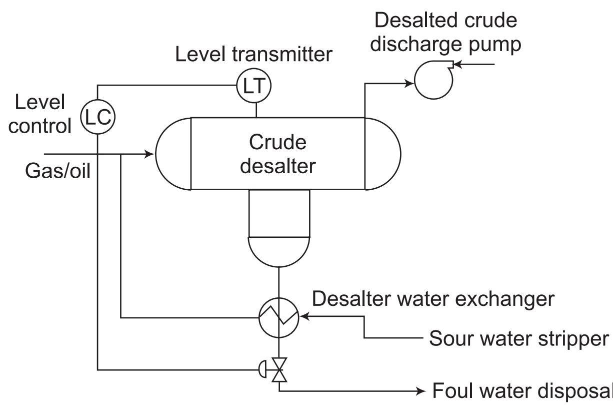


Figure 4.4: Continuous level process control loop

4.1.3 Units of Level Measurement

Depending upon the level measurement application, the units of measure are in distance, weight, or volume. In continuous level indication and control, the level distance is typically measured in units of meters (feet), while for smaller tanks the level distance can be measured in centimeters (inches). The term "head" is also used to represent the measurement of the height of a process material. When level is inferred from a pressure measurement, the units of measure are often in either millimeters or inches of water column.

When volume is measured, the units may be in cubic feet, gallons, million gallons, cubic meters, liters, million liters, and petroleum barrels. In tank gauging and custody transfer operations, where the concern is accurate measurement of inventory, the units can include weight, such as kilograms (pounds).

Level measurements, while representing as a height of a liquid surface from a reference (datum) line, are also used for the following—volume determination and weight determination.

4.1.3.1 Volume Determination

Volume determination can be calculated from a measurement of level height (distance). For example, a volume for a cylindrical tank can be determined from a direct measurement of height, based on the calculation per equation 4.1:

$$V = A \times L \tag{4.1}$$

where, V is volume; A is vessel area; L is the height of process material.

4.1.3.2 Weight Determination

Weight determination can be calculated using a direct measurement of level height (distance). For example, a weight measurement, using a process material's density, may be determined from a direct level measurement of height, based on the calculation as per equation 4.2:

$$W = A \times L \times D \tag{4.2}$$

where, W is weight; A is vessel area; L is the height of process materials; D is density.

4.1.4 Symbols of Level Measurement

The most common terms and abbreviations for level measurement devices are "LT" for level transmitter, and "LS" for level switch. An example of how level symbols could appear in a Process Instrument and Drawing (P&ID) is shown in Figure 4.5.

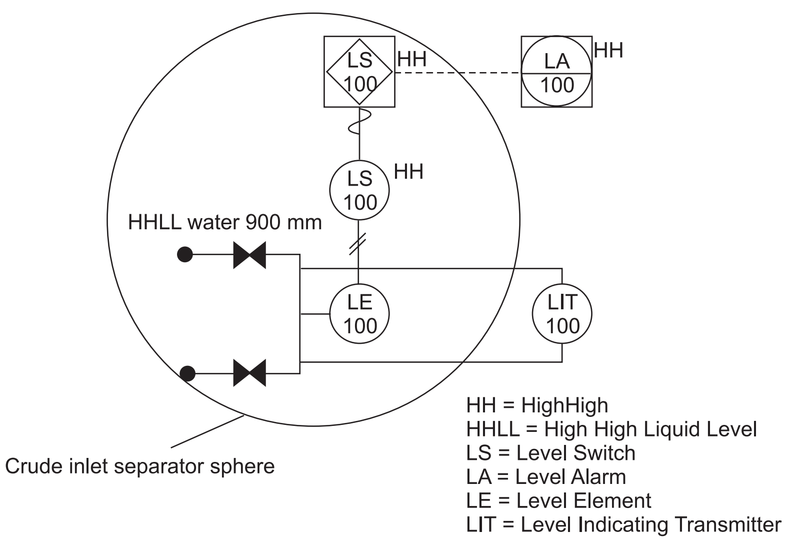
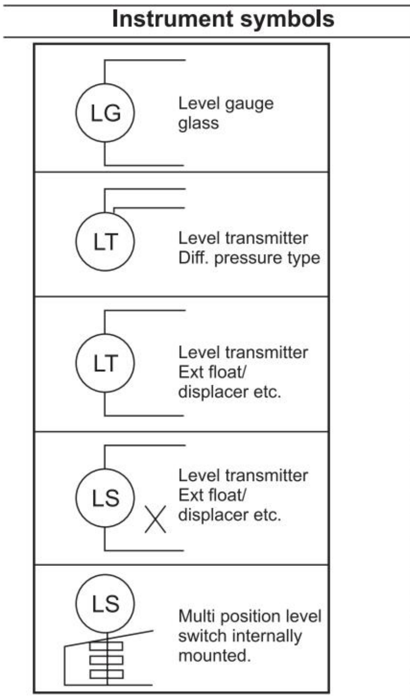
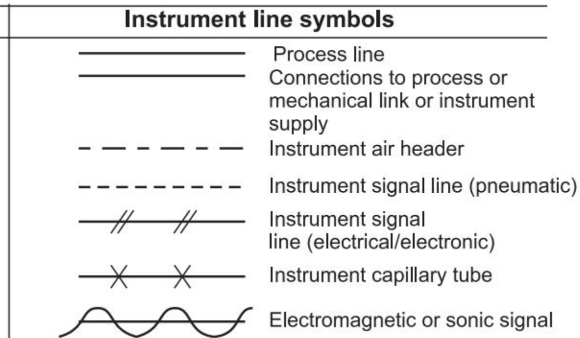


Figure 4.5: Example of level symbols and terms

4.1.4.1 *Drawing Symbols*

Drawing symbols representing level instruments are shown in Figure 4.6. Having seen that level measurements may be expressed in terms of distance, weight, or volume will lead us to believe that level measurement device selection is easy. However, we must also consider the physical characteristics of a vessel when selecting a level measurement device.





Instrument legend

LA	Level alarm
LC	Level control
LE	Level element
LG	Level gauge glass
LIC	Level indicating controller
LI	Level indicator
LIT	Level indicating transmitter
LR	Level recorder
LS	Level switch
LT	Level transmitter
LTd	Level transducer
LH	Level high
LHH	Level HighHigh
LLL	Level LowLow

Figure 4.6: Drawing symbols and legends

4.1.5 Vessel Characteristics in Level Measurement

The vessel's characteristics do affect level measurements. Not all vessels are perfect geometric shapes with easy to calculate volumes. The physical characteristics that can be relevant in level measurement device selection are—vessel deformations and vessel geometries.

4.1.5.1 *Vessel Deformations*

Vessel deformations can occur during level measurement. Deformation may occur when the vessel is filled. For example, walls stretch in a crude oil storage tank because of the increasing hydrostatic pressure on the walls as the vessel fills. Vessel deformation must be taken into account when performing a level measurement. Some level measurement systems provide means for compensating deformation effects through the use of tank correction tables.

4.1.5.2 Vessel Geometries

Vessel geometrics can include horizontal flat, horizontal elliptical, horizontal spherical, vertical flat, vertical conical, spherical, and other irregularly shaped vessels. Vessel shape becomes important when a level measurement is used to infer a volume or mass of process material. This consideration can be seen in Figure 4.7 where three vessel shapes (each with the same level reading) contain different volumes of liquid.

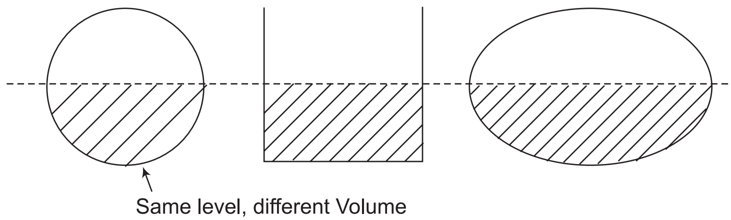


Figure 4.7: Same level but different volume

4.1.5.3 Calculating Vessel Characteristics

As an example of how a vessel's shape relates to level measurement and the subsequently derived volume, consider the calculation for the volume of a storage vessel. Various departments often require volume data as well as level data. If the storage vessel (Figure 4.8) is a cylindrically shaped vessel, such as skimmed oil drum, then the volume calculation can be complex.

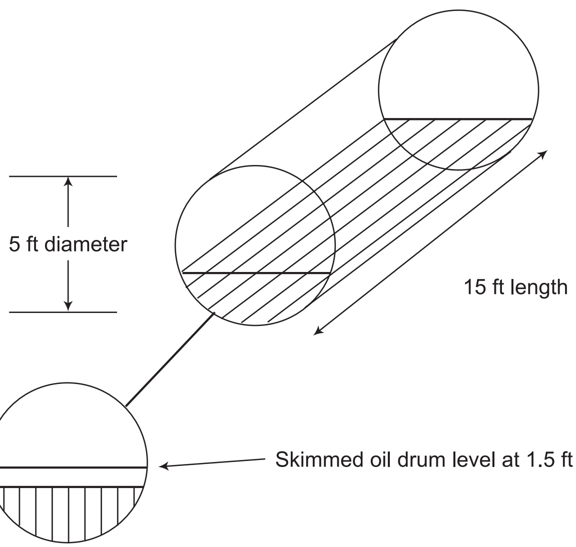


Figure 4.8: Calculating vessel characteristics

Example

A flat end cylindrical tank has tank diameter, 5 ft; tank length, 15 ft; tank level, 1.5 ft. Calculate the volume of skimmed oil currently in the vessel.

To begin the volume calculation, you must first know the area of *BCDE*:

$$\text{Area } BCD = \text{Area } ABCD - \text{Area } ABD.$$

Area ABCD's calculation is based upon:

$$\text{Area } ABCD = (2\ \angle DAE°/360°) \times \text{Area of circle}$$

The calculation for the volume follows as per Figure 4.9 and Equations 4.3 and 4.4.

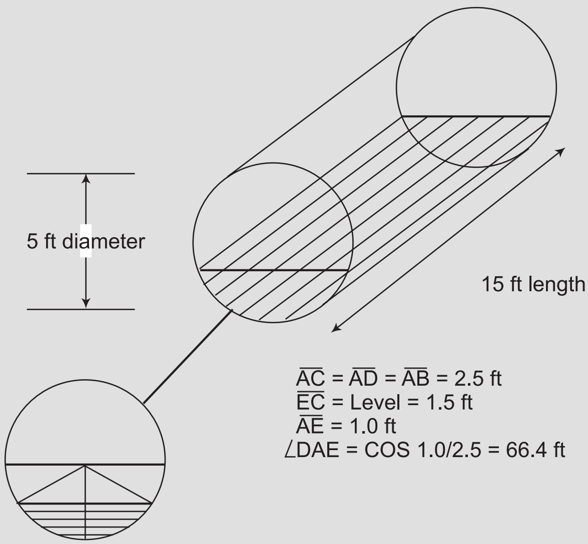


Figure 4.9: Calculating volume

Determine the area *ABD*:

$$\text{Area } ABD = 1.0 \times 1.5 \times \sin \angle DAE° \tag{4.3}$$

where, sin $\angle DAE°$ requires knowing $\angle DAE°$.

Since $DAE° = \cos (1.0/2.5)$, then $\angle DAE° = 66.42°$ (4.4)

Calculate area *ABD*: As per Equation 4.5

$$\text{Area } ABD = 1.0 \times 2.5 \times \sin 66.42°$$

$$\text{Area } ABD = 1.0 \times 2.5 \times .916$$

$$\text{Area } ABD = 2.3 \text{ ft}^2 \tag{4.5}$$

Calculate area *ABCD*: Using Equation 4.6, we get

$$\text{Area } ABCD = (2\ \angle DAE°/360°) \times \text{area of circle}$$

$$\text{Area } ABCD = (2 \times 66.42°/360°) \times \pi \times (2.5)^2$$

$$\text{Area } ABCD = 7.3 \text{ ft}^2 \qquad (4.6)$$

Volume calculation: As per Equation 4.7

$$\text{Area } BCD = \text{Area } ABCD - \text{Area } ABD.$$

$$\text{Area } BCD = 7.3 \text{ ft}^2 - 2.3 \text{ ft}^2$$

$$\text{Area } BCD = 5.0 \text{ ft}^2$$

$$\text{Volume} = \text{Area } BCD \times 1 \text{ gal}/.1337 \text{ ft}^3 \text{ (conversion)} \times \text{vessel length}$$

$$\text{Volume} = 5.0 \text{ ft}^2 \times 1 \text{ gal}/.1337 \text{ ft}^3 \times 15 \text{ feet}$$

$$\text{Volume} = 560.9 \text{ gallons} \qquad (4.7)$$

The volume calculation can become more complex if the vessel is a bullet shape with spherical ends. Note that if the vessel's length gets doubled, one can easily see that the volume doubles. An important conclusion, then, is that, depending upon the vessel's shape and length, a small level change can represent a large change in volume. From this example, one can observe that a vessel's shape can influence level measurement device selection.

4.1.6 Categories of Level Measurement

Level measuring instruments, can be classified into two ways on a broader level. Direct measuring devices that provide the level as a direct visual indication using mechanical instruments without much instrumentation involved, indirect-measuring devices provide a level indication by measuring a primary parameter such as pressure and so on and converting it to indicate level reading into a usable format. Few examples are given as follows:

- The level of a liquid may be measured directly by means of a hook-type level indicator, a sight glass, or float-actuated mechanism.
- Another way of measuring the level of a liquid makes use of the fact that the pressure due to a column of liquid does not depend upon the cross-sectional area of the column, but only upon the depth and density.

4.1.6.1 Types of Level Measurement

A broad diversity of level measurement systems is available to address the broad spectrum of applications, precision, necessities of installation, and procedures. There is a wide range of measurement needs and different measurement technologies have been developed to address these needs or sometimes to address just one specific application. Level measurement systems have been developed to address the broad spectrum of applications, accuracy needs, installation requirements, and practices.

The family of level measurement systems is divided into various groups:

- Solids or liquids level measurement
- Continuous or point level measurement
- Electrical/electromagnetic or electromechanical level measurement
- Contacting or non-contacting/non-intrusive level measurement

4.1.6.2 Methods of Level Measurement

Industrial methods of determining level are divided into two groups:

- Direct methods
  - Hook-type
  - Sight glass
  - Float gauging
  - Bubblers
- Indirect methods
  - Servo-level gauging
  - Capacitive probes
  - Pressure-operated gauging
  - Nucleonic gauging
  - Ultrasonic/radar gauging

For answers to checkpoint, scan the QR code

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Checkpoint

✦✦ **1.** List the type of level measurement encountered in process applications.

✦ **2.** How point level process measurement is accomplished?

✦✦ **3.** Give an example of point level process indication.

✦✦ **4.** How many switches are required to achieve point level process control?

✦✦ **5.** In a continuous level process measurement, a level measurement is provided with height of the process material surface in which representation?

✦ **6.** Give an example of continuous level process indication.

✦✦ **7.** What is the objective of automatic tank gauging system?

✦✦ **8.** What is an interface level?

✦✦ **9.** If the level is inferred from a pressure measurement, what are the units of measurement for water column?

Note: ✦ Level 1 & Level 2 category
✦✦ Level 3 & Level 4 category
✦✦✦ Level 5 & Level 6 category

4.2 DIRECT METHODS OF LEVEL MEASUREMENT

LO 2
Explain direct methods of level measurement

4.2.1 Hook-Type

It is difficult to measure the height of a liquid in an unclosed tank, on a scale which might be in a liquid or alongside it. In such cases, a hook type of level indicator is used. It consists of a wire of a corrosion-resisting alloy, about 6mm in diameter, made into a U with one arm more than the other. The short arm is indicated with a taper, whereas the larger one is fixed to a slider, having a Vernier scale that slides above the main scale and indicates level.

4.2.2 Sight Glass

Sight glass is a simple device used to determine the level within a boiler in steam boilers and similar applications. It consists of a tube of toughened glass connected at both ends through asbestos packed unions and valves into the boiler, in which the water level is to be determined.

4.2.3 Float Actuated Mechanisms

Float-operated gauge-level indicator indicates liquid level in cone or flat roof un-pressurized tanks. Float actuated mechanisms are recommended for use in tanks storing water, fuel oil, chemicals or other liquid products where operations do not require extreme accuracy.

4.2.4 Bubblers

Bubblers work on hydrostatic pressure matching. A simple bubbler system consists of a dip tube filled with an inert gas/air and inserted into the tank where the level is measured. Once inserted, the air pressure is increased until a bubble is generated. Bubble generation means that the air/inert gas pressure is equivalent to the hydrostatic pressure that bears a proportionate relation that is calibrated as an external reading. If the tank is closed, a reference tube is used to provide the pressure of the empty (vapor) space in the tank. The advantage of such arrangement is equipment encountering the liquid, eradicating product corrosiveness issues. Benefits of the bubble pipe system are its easy assembly and aptness for corrosive substances. Drawbacks contain the necessity for airlines and air consumption and the danger of increase of medium on the bubble pipe that render the process as inappropriate for utilization in pressure vessels. Lately, top-mounted rod- or cable-suspended pressure sensors are replacing bubbler systems.

4.3 INFERENTIAL METHODS IN LEVEL MEASUREMENT

LO 3
Explain inferential methods of level measurement

4.3.1 Level Measurement with Servo-level Gauge

Servo gauges are used when there is a need for a high-level accuracy. The measuring surface must only be mildly turbulent. The liquid level-sensing element is a small solid displacer, suspended by a flexible wire or cable. This measuring cable is stored on a precision-machined type 316 stainless steel grooved measuring drum, mounted on precision stainless steel ball bearings.

Through a magnetic coupling, the drum shaft is coupled to a weighing balance consisting of a slot initiator and detection plate. In equilibrium condition, the weight of the displacer, partly immersed in the product, balances the force of a balance spring. A rising or falling level causes a change in buoyancy and the detection plate moves in the slot initiator. The gauge operates via an integration circuit and a servo motor, which turns the measuring drum, raising or lowering the displacer until the balance position is restored.

A positive tooth-belt drives a mechanical digital counter that provides local level indication. The counter mechanism is mechanically linked to either a brush type or optical type digital encoder, or an analog encoder for remote level data transmission. Five limit/level/alarm switches are provided as standard, two of which are required for displacer high/low limit settings. The sensitivity of such devices is better than 0.5mm change in level.

4.3.2 Level Measurement Using Pressure Transmitters

The principle of level measurement using pressure transmitters depends on the measurement of the hydrostatic pressure produced by a column of liquid at a specified height.

The pressure is measured by formula given in equation 4.8:

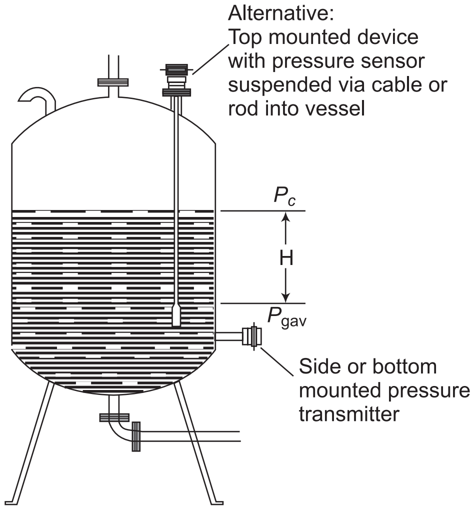
$$P = h \times \rho \times g \tag{4.8}$$

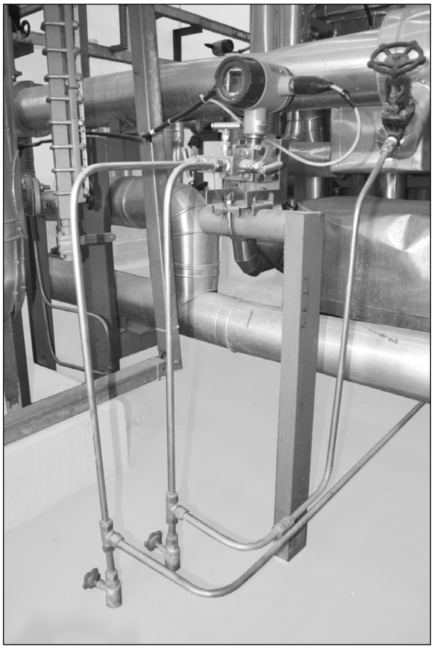
where, P = pressure, h = height of the liquid column, g = acceleration due to gravity, ρ = relative density.

From this formula, it may be observed that the only variable in the formula is height "h" (if the specific gravity of the medium does not vary). It follows that the pressure measured is directly proportional to height h, the point of the liquid in the tank.

The drawing in Figure 4.10 also shows that the pressure calculated is same as the pressure of the liquid column and the surface pressure. In an open tank, the surface of the liquid is exposed to the atmosphere and hence the liquid experiences pressure due to the atmosphere. Hence, the low pressure side of the transmitter is open to the atmosphere to get it compensated and to measure the pressure due to the head of the liquid. In case of closed tanks where the pressure on the surface of the liquid is either more or less than the atmospheric pressure, the low pressure side of the differential pressure (DP) compensates the pressure exterted on top and can measure only the head due to the liquid alone.

Figure 4.10 Pressure transmitters for measuring level





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The SI unit of pressure is the Pascal (Pa), whereas pressure can also be indicated in psi or head of a liquid column.

Note

1 Pascal = 1 N/m^2; 14,504 psi = 100 kPa and 1 bar = 10 m head of water

4.3.2.1 *Open Vessels*

Bottom Mounted Transmitter As discussed earlier, in open tank, the pressure transmitter installed at the bottom of the tank, measures the liquid head which is directly proportional to the height of liquid above the transmitter. The impulse line connects the transmitter with high pressure side of the tank (somewhere in the bottom as shown in Figure 4.11). If the transmitter is installed below the tank and measuring range of the level in the liquid due to operational convenience, then transmitter's zero point is higher than required. In such case, the zero suppression of the transmitter has to be performed over the measuring range at 4 mA. The adjustment (which can be zero suppression or zero elevation) is limited to 500% of the span on the DP transmitters and 500% of span on the gauge pressure transmitters.

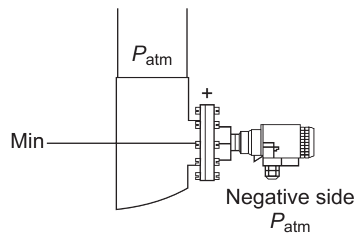


Figure 4.11: Flange-mounted devices for open tank

Top Mounted Transmitter A "bubbler" structure, which uses a top mounted pressure transmitter, might be utilized in unclosed vessels. Such a system contains an air supply, a pressure regulator, a constant flow meter, a pressure transmitter, and tube extending downward to the vessel. Air is bubbled all the way through the tube at a fixed flow rate. The pressure necessary to uphold flow is determined by the vertical height of the liquid above the tube opening times the specific gravity.

Mounting A pressure sensor has to be in contact with the gas or liquid which is measured. In case of tanks, generally the pressure transmitter is installed at the bottom or side of the tank at an appropriate height. The transmitter is exposed to the tank or pipe, through a nozzle, impulse lines or sometimes a remote flange with liquid in it. Some of the applications are installed inside the deep reservoirs or wells are provided with long cables for the communication purposes. In either the case of installation, the process (either the liquid or gas) should be proper and should not create a crystallization or obstruction to the transmitter. If this happens, the pressure is not sent to the membrane and so could not be measured. To avoid this, either select an unusual mounting system or arrange for heating the nozzle or pipe.

Figure 4.12 shows example of suggested pressure and DP transmitter mountings for level measurement. In case of the application of the transmitter is to measure a liquid which is corrosive in nature, then the standard diaphragms of the pressure transmitters are not suitable. The instrument engineers select different types of diaphragms based on the application and some of them are Monel, Hastelloy and tantalum, etc. The material of the construction such as, transmitter's body and flanges are also selected with corrosion resistant material to avoid failures or degradation in the functionality.

When a pressure transmitter (level or gauge) is installed in an open tank application, the transmitter's high side connection is made to a tank nozzle for the process connection. The pressure transmitter's low side connection is vented to atmospheric pressure. The effect of atmospheric pressure is cancelled because it acts upon both the high and low side of the pressure transmitter. Thus, the hydrostatic pressure from the liquid acts upon the high side of the pressure transmitter, and becomes an inferred measurement of level height.

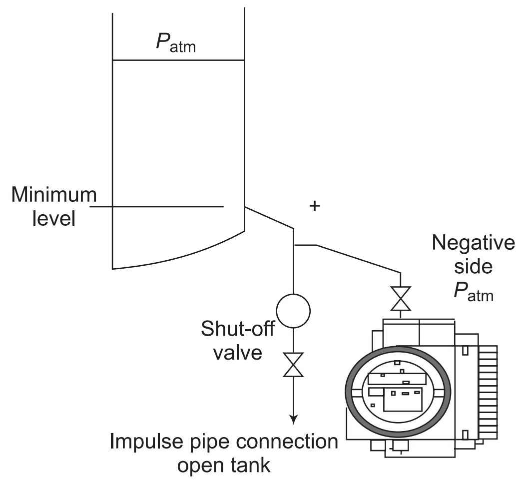


Figure 4.12: Impulse pipe connections, open tank

Installation A common level measurement installation for a pressure transmitter is an open or vented tank application. No other type of pressure, such as nitrogen blankets or vaporization pressure should be applied to the liquid surface because that pressure causes an erroneous level measurement. The error occurs because the pressure transmitter is often referenced to atmospheric pressure, not the added pressure of the nitrogen blanket or vaporization pressure. If a nitrogen blanket or vaporization pressure is present, a DP transmitter is more suitable.

When a level transmitter is installed, the diaphragm is insensitive to level changes over the lower half. The transmitter therefore has a reference line, called a datum line, which must be aligned with the centerline of the tank nozzle. The tank nozzle, and consequently the diaphragm of the pressure transmitter, must be positioned so that the minimum liquid level is always at or above the datum line. Refer to Figure 4.13 for the datum line representation.

4.3.2.2 Open Tank Range Calculation

In an open tank, the transmitter is often installed below the lower process tap connection. Because the transmitter is below the lower process tap, fill fluid is present from the lower process tap to the transmitter high side connection. Although the level may be measured at the lower process tap connection, a hydrostatic pressure (due to the fill fluid) is present at the high side of the DP transmitter. For the transmitter to output a signal representing just the level from its maximum height to the lower process tap, the effect of the fluid in high side connection must

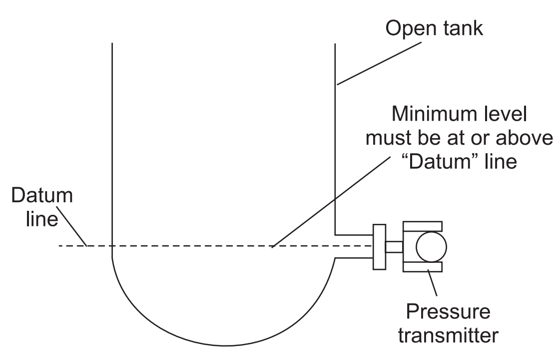


Figure 4.13: Datum line

be "suppressed". In this situation, it is desirable that a 4 mA signal, representing 0 DP (thus the minimum level), is output when the liquid level is at lower process tap connection. A suppressed-zero range must be configured for the transmitter.

The calculations given next explain about the transmitter range for an open tank with low-pressure side vented and differential pressure transmitter below the lower process tap. The maximum height of the liquid is 10 ft (120 in) above the minimum level, the process fluid has a specific gravity of 1.1, and the fill fluid in the process connection from the lower tap to the transmitter's high side connection has a specific gravity of 1.1 and is a length of 1 foot (12 in).

When using a DP transmitter, the fill fluid is the process fluid from the lower tap to the transmitter's high side connection. When using a remote seal transmitter, the fill fluid from the lower tap to the transmitter's high side connection will be a fill fluid with a specific gravity that is different from the process fluids. The reason for the specific gravity difference is that the capillary is filled with a fill fluid that is not permitted to combine with the process fluid. Refer to Figure 4.14 for the illustration.

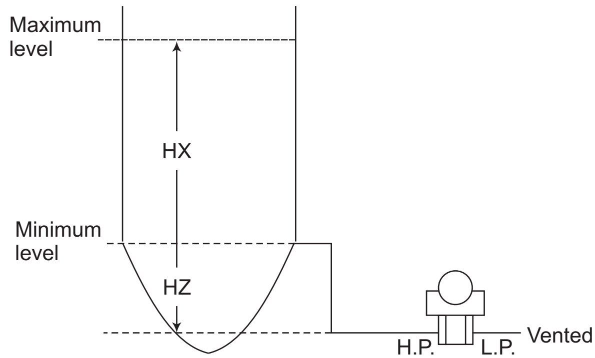


Figure 4.14: Open tank range calculations

Considering 4 mA as the minimum level, any offset can be solved using the expression given in Equation 4.9:

$$P_{\text{high side of transmitter @4 mA}} - P_{\text{low side of transmitter @4 mA}} + \text{Offset} = 0$$
$$(h \times SG_{\text{process liquid}} + h \times SG_{\text{fill fluid}}) - 0 + \text{Offset} = 0$$
$$(0 \times 1.1 + 12 \times 1.1) - 0 + \text{Offset} = 0$$
$$(0 + 13.2) - 0 + \text{Offset} = 0$$
$$\text{Offset} = -13.2 \tag{4.9}$$

Considering 20 mA as the maximum level, any offset calculated previously, can be used to solve the expected span:

Calibrate the transmitter to a range of - offset to (–offset + span) range = –offset to (–offset + Span)

$$\text{Range} = -(-13.2) \text{ to } (-(-z13.2) + 132)$$

$$\text{Range} = 13.2 \text{ to } 145.2 \text{ in } H_2O$$

From the example, it is observed that the zero of the transmitter's range represents a suppressed-zero range, i.e. 0 does not appear as a measurement unit on the range of 13.2 to 145.2 in H_2O as per Equation 4.10:

According to accepted practice, suppressed-zero range is the preferred terminology. Note that terms such as "elevation," "elevated range," and "elevated span" are also used to express this condition. Some companies also use the term "range elevation".

$$P_{\text{high side of transmitter @20 mA}} - P_{\text{low side of transmitter @20 mA}} + \text{Offset} = \text{Span}$$
$$(h \times SG_{\text{process liquid}} + h \times SG_{\text{fill fluid}}) - 0 + \text{Offset} = \text{Span}$$
$$(120 \times 1.1 + 12 \times 1.1) - 0 + \text{Offset} = \text{Span}$$
$$(132 + 13.2) - 0 + (-13.2) = \text{Span}$$
$$(145.2) - 0 + (-13.2) = \text{Span}$$
$$\text{Span} = 132 \quad (4.10)$$

Open Tank with Wet-leg Transmitter Range Calculation This section illustrates calculating the transmitter range for an open tank with a wet leg, again with the DP transmitter installed below the lower process tap. Consider, the maximum height of the liquid to be 10 ft; process fluid having specific gravity 1.1; fill fluid in the process connection from the lower tap to the transmitter's high side connection having a specific gravity of 1.5 and a length of 12 in; fill fluid in the wet leg having a specific gravity of 1.5 and is 144 in height. Thus, the span can be readily seen to be 132 in H_2O (120 in height × 1.1). Ideally, a zero DP would generate a 4 mA signal, while a 132 in H_2O would generate a 20 mA signal (Figure 4.15).

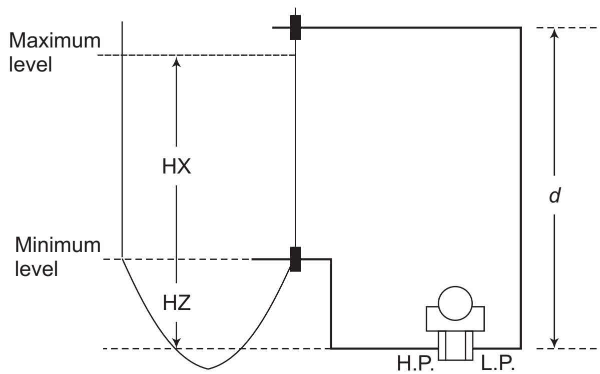


Figure 4.15: Open tank wet leg range calculation

Note that the pressure due to the fill fluid in the wet leg forces you to place an elevated zero range on the transmitter. The elevated zero range is necessary because the pressure effects of the fill fluid from the wet leg must be cancelled to make the level measurement. The elevated zero range is necessary for the differential transmitter to read a minimum or maximum level at pressures other than 0 and 132 in H_2O.

In a level measurement with differential pressure transmitter, the process fluid itself becomes the fill fluid while connecting the bottom side of the vessel to high pressure connection in the transmitter through impulse lines. When using a remote seal transmitter, the fill fluid from the lower tap to the transmitter's high side connection will be a fill fluid with a specific gravity that is different from the process fluids. The reason for the specific gravity difference is that the capillary is filled with a fill fluid that is not permitted to combine with the process fluid.)

As an example using Equation 4.11:

$$P_{\text{high side of transmitter @20 mA}} - P_{\text{low side of transmitter @20 mA}} = P$$
$$(h \times SG_{\text{process liquid}} + h \times SG_{\text{fill fluid}}) - (h \times SG_{\text{fill fluid}}) = P$$
$$(120 \times 1.1 + 12 \times 1.1)\,(144 \times 1.5) = P$$
$$(132 + 13.2) - 216 = P$$
$$145.2 - 216 = P_{@20\text{ mA}}$$
$$-70.8 = P_{@20\text{ mA}} \quad (4.11)$$

In transmitter terms, as seen from the following calculations, for the transmitter to generate a 4 mA signal, the DP will be –202.8 in H_2O when the liquid level is at a minimum height.

Refer Equation 4.12:

$$P_{\text{high side of transmitter @20 mA}} - P_{\text{low side of transmitter @20 mA}} = P$$
$$(h \times SG_{\text{process liquid}} + h \times SG_{\text{fill fluid}}) - (h \times SG_{\text{fill fluid}}) = P$$
$$(120 \times 1.1 + 12 \times 1.1) - (144 \times 1.5) = P$$
$$(132 + 13.2) - 216 = P$$
$$(132 + 13.2) - 216 = P_{@20\text{ mA}}$$
$$-70.8 = P_{@20\text{ mA}} \tag{4.12}$$

In transmitter terms, as seen from the following calculations, for the transmitter to generate a 20 mA signal, the DP will be –66 in H_2O when the liquid level is at a maximum height.

The calculation for the transmitter range follows. The range calculation using the procedure follows and verifies the expected DP calculated previously.

Example

Use the 4 mA minimum level and solve for any offset in the expression Equation 4.13:

$$P_{\text{high side of transmitter @4 mA}} - P_{\text{lowside of transmitter @4 mA}} + \text{Offset} = 0$$
$$(h \times SG_{\text{process liquid}} + h \times SG_{\text{fill fluid}}\ (\text{h} \times SG_{\text{fill fluid}}) + \text{Offset} = 0$$
$$(0 \times 1.1 + 12 \times 1.1\ ) - (144 \times 1.5) + \text{Offset} = 0$$
$$(0 + 13.2) - 216 + \text{Offset} = 0$$
$$(13.2) - 216 + \text{Offset} = 0$$
$$\text{Offset} = 202.8 \tag{4.13}$$

Use the 20 mA maximum level, any offset calculated previously, and solve for the expected span using Equation 4.14:

$$P_{\text{high side of transmitter @20 mA}} - P_{\text{low side of transmitter @20 mA}} + \text{Offset} = \text{Span}$$
$$(h \times SG_{\text{process liquid}} + h \times SG_{\text{fills fluid}})\ (h \times SG_{\text{fill fluid}}) + \text{Offset} = \text{Span}$$
$$(120 \times 1.1 + 12 \times 1.1) - (144 \times 1.5) + \text{Offset} = \text{Span}$$
$$(132 + 13.2) - 216 + (202.8) = \text{Span}$$
$$(145.2) - 216 + (202.8) = \text{Span} \tag{4.14}$$

Span = 132 (note: by definition, span cannot be zero or negative)

Calibrate the transmitter to a range of – offset to (–offset + span)

Range = –offset to (–offset + span)
Range = –(202.8) to (–(202.8) + 132)
Range = –202.8 to –70.8 in H_2O

In the previous example, the zero of the transmitter's range represents an elevated-zero range, i.e. 0 is greater than the lower range value. In this example, the zero is also greater than the upper range value. According to accepted practice, "elevated-zero range" is the preferred terminology. Note that terms such as "suppression," "suppressed range," and "suppressed span" are used to express this condition. Some companies also use the term "range suppression".

4.3.2.3 Performance

Pressure transmitters are not practical for liquid level measurements whose specific gravity or density is changing (unless the accuracy requirements are not stringent). A reason for the impracticality is that a percentage change in the specific gravity causes an equal percentage change in the pressure transmitter's output. If, for example, a hydrostatic head device measuring 24 in H_2O experiences a specific gravity change from 1.0 to 1.5, and then the pressure instrument will be in error by 50%. The error can be seen from the following calculations using Equation 4.15:

When example conditions of specific gravity of 1.0 occur, pressure is:

Despite the limitation of a liquid's changing specific gravity, the pressure transmitter has several advantages in liquid level measurement:

$$P = h \times \text{SG} = 24 \text{ inches } H_2O \times 1.0 = 24 \text{ inches } H_2O$$

However, the resulting pressure when specific gravity changes to 1.5 is:

$$p = h \times \text{SG} = 24 \text{ inches } H_2O \times 1.5 = 36 \text{ inches } H_2O$$

$$\text{Error} = (36 - 24)/24 = 50\% \tag{4.15}$$

4.3.2.4 Advantages

Wide ranges are supported with a pressure transmitter. For example as shown in Figure 4.16, other level measuring devices, such as a displacer, may be distance limited to measuring heights less than 2 m (8 ft). Pressure transmitters can measure heights represented by pressures as low as 0–12 cm H_2O (0–5 in H_2O) and over 134 m H_2O (433 ft H_2O).

Pressure transmitters are suitable for a variety of liquids that would clog or settle in another device's external measurement chamber or pipe. Pressure transmitters are externally accessible for maintenance.

4.3.2.5 Applications

Pressure transmitters are suitable for a wide variety of fluids, pressures, and temperature ranges. The example in Figure 4.16 shows a pressure transmitter used to measure level in a vented storage vessel.

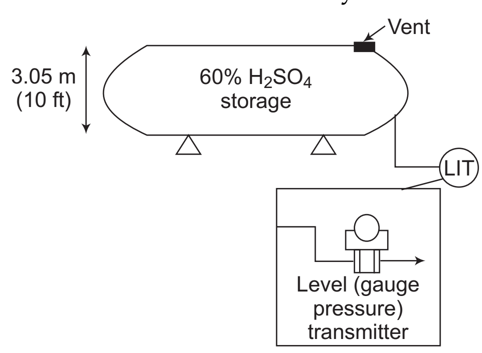


Figure 4.16: Level measurement in storage vessel

4.3.3 Differential Head Devices

In closed or pressurized tank applications, a differential head device is used for the hydrostatic pressure measurement, which is used to infer the level. The differential head device, when measuring hydrostatic pressure in a closed tank, cancels the pressure effects of the internal tank because the internal tank pressure is sensed at both high and low side of pressure device. The differential head device described in the following discussion is a conventional electronic DP transmitter used for level measurement in a closed tank. The principles of a conventional electronic differential pressure transmitter would apply to pneumatic and microprocessor based instruments as well. When using hydrostatic pressure for level measurement in closed or pressurized tank applications, the effects of any fill fluids used in a differential pressure transmitter's high and/or low side pressure connections must be taken into account when calculating the range for the transmitter. Otherwise, a level measurement would include the hydrostatic pressure effects of the fill fluid.

4.3.3.1 Closed Vessels

In a closed tank, the pressure on the surface of the liquid gets added to the head of the liquid when measured at the bottom of the tank. In this case, the head of the liquid at the bottom is height of the liquid multiplied by density of the liquid and specific gravity added with the pressure in the tank as seen on the top of the liquid.

To measure the actual level, the pressure on the top of the liquid/the pressure in the tank should be subtracted. In order to subtract the pressure in the tank, an impulse line from the top of the tank is connected to the lower side of the pressure transmitters and another impulse line from the bottom of the tank is connected to the high side of the transmitter. With this the pressure in the tank is applied to lower and high side of the transmitter and being a differential transmitter, only difference pressure is used to calculate the measurement. The resultant differential pressure is equal to liquid height multiplied by specific gravity as shown in Figure 4.17.

Dry Leg If the gas above the liquid does not compress, the piping for the low side of the transmitter remains empty. Calculations used to determine the range are similar to that shown in nonclosed vessel bottom fixed transmitter.

Wet Leg In a closed tank, the lower side of the transmitter which is connected with the impulse lines are filled with a liquid with known density (reference fluids). The primary reason for doing so is to avoid the error in measurement due to condensate of the liquid from the top of the tank being collected on the transmitter using the impulse lines gradually. By filling the impulse lines with reference fluids a head pressure is created on the lower side of the transmitter. In such a case, the differential calculations have to be made and if required a zero elevation of the range is performed. Typically, these modifications are limited to 600% of the span on the differential pressure transmitters.

4.3.3.2 Principles and Design

The key to understanding how level measurement is accomplished using a typical differential pressure transmitter is to first recall how the transmitter generates an output signal, such as a 4–20 mA signal. Recall that a differential pressure transmitter has two pressure connections for measuring differential pressure—a high-pressure connection and a low-pressure connection.

For an increasing output signal to occur in a typical differential pressure transmitter, the high side connection of the pressure transmitter must always be increasing in pressure relative to the low side pressure connection. To achieve a maximum output signal (20 mA), the net pressure on both the high side and the low side must be such that the pressure on the high side represents the hydrostatic pressure for maximum liquid level. Alternatively, described in terms of transmitter operation, for a maximum level measurement to occur, the net pressure on both the sides must be such that the pressure on the high side is greater than the low side by an amount equal to the configured span of the transmitter. Thus, when using differential pressure transmitters for a level measurement, the high side pressure connection is made to the lower process tap connection of a vessel.

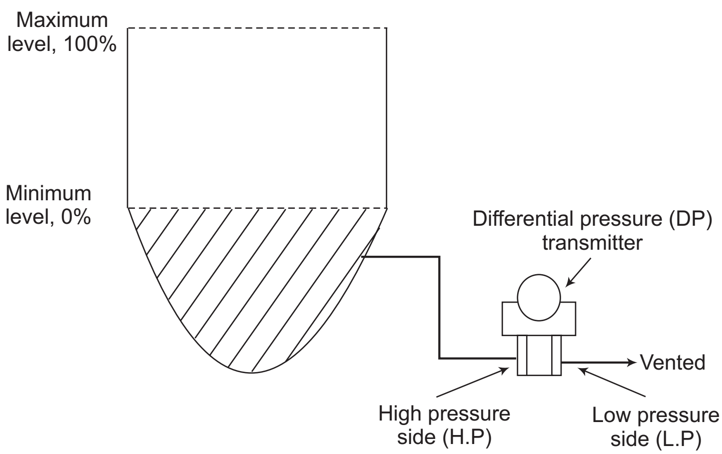


Figure 4.17: High side to tank bottom

When a differential pressure device is used in a closed tank application, the internal tank pressure must be compensated for. In a closed tank application, as the level falls, the pressure inside the tank may decrease. The change in pressure has an effect on the measured level indication. A common way to account for the change in internal tank pressure due to changing levels is to connect the low side of the differential pressure transmitter to the top side of the tank (Figure 4.18). The connections to the tank require two process taps.

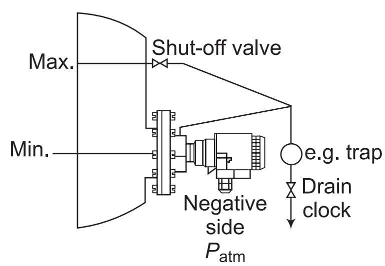


Figure 4.18: Flange-mounted device, closed tank

Connection for Closed Tank As long as the level is between the two taps of the differential pressure transmitter, the difference in pressure is based upon the following formula Equation 4.16:

$$P = h \times \text{SG} \tag{4.16}$$

where, P = difference in pressure, h = liquid height or head, SG = specific gravity

The level's relationship to hydrostatic pressure is seen by changing the calculation to Equation 4.17:

$$h = P/SG \tag{4.17}$$

where, P = difference in pressure, h = liquid height or head, SG = specific gravity

Assume that a differential pressure transmitter's high side connection is installed at a lower process tap connection. The upper process tap connection (also referred to as a "leg") goes to the low side of the pressure transmitter. On the high side of the pressure transmitter, which is connected to the lower process tap, the transmitter senses the pressure in the tank, plus the pressure due to the height of the liquid. That relationship can be shown in the expression in Equation 4.18:

$$P_{\text{high side of transmitter}} = P_{\text{tank}} + (h \times SG) \tag{4.18}$$

where, p tank = pressure in tank, h = liquid height or head, SG = specific gravity of process material.

Assuming that the other low pressure connection to the upper process tap is a dry leg, which means that the leg is "dry" if it is kept full of gas, then the pressure at the low side of the transmitter is the pressure within the upper space of the tank per Equation 4.19:

$$P_{\text{low side of transmitter}} = P_{\text{tank}} \tag{4.19}$$

The differential head (pressure), P, measurement is thus based on Equation 4.20:

$$\begin{aligned} P &= \mathrm{P}_{\text{high side of transmitter}} - P_{\text{low side of transmitter}} = P_{\text{tank}} + (h \times SG) - P_{\text{tank}} \\ &= h \times SG \end{aligned} \tag{4.20}$$

The calculations show that the effect of pressure within the closed or pressurized vessel is cancelled when a differential head device is used to perform a level measurement. To keep a leg dry, one must keep the leg sufficiently heated to keep the condensation liquids out of it, which is not always practical. In practice, it is difficult to keep process material out of the dry leg.

Another approach to keeping process material out of the leg to the upper process tap is to use fill fluids in the transmitter's low-pressure connection to the upper process tap. For the transmitter's connection to the upper part of the tank, the pressure effect of the seal fill fluid must now be accounted for, as shown in the following calculation in Equation 4.21:

$$P_{\text{low side of transmitter}} = P_{\text{tank}} + h_{\text{leg}} \times SG_{\text{fill fluid}} \tag{4.21}$$

where, $\mathrm{SG}_{\text{fill fluid}}$ = specific gravity for the fill fluid, P_{tank} = pressure in tank h_{leg} = height of wet leg, measured from lower tap to upper tap

$$P = P_{\text{high side of transmitter}} - P_{\text{low side of transmitter}}$$

$$P = (P_{\text{tank}} + (h \times \mathrm{SG}))\ (P_{\text{tank}} + (h \times SG_{\text{fill fluid}}))$$

$$P = (h \times \mathrm{SG}) - (h \times \mathrm{SG}_{\text{fill fluid}}) \tag{4.22}$$

4.3.3.3 Installation

The following discussion describes installation considerations "Differential pressure level detectors lend themselves best to transmitter installations. They should be used for fluids that contain little or no suspended solids and do not have a tendency to develop solids under static conditions or process temperature changes. The solids will precipitate out in the diaphragm cavity and limit the travel of the diaphragm. The deposition of solids in the cavity containing the diaphragm is usually indicated by output signal/zero shift and nonlinear errors in the output signal. Direct flange mounting transmitters are preferred for installations which have a 2 in pipe nozzle or larger and which require a differential pressure transmitter regardless of solid content. However, it should be remembered that the solids could form in the nozzle next to the diaphragm in the same manner that they develop in a standard diaphragm cavity.

A common error in the installation of a differential pressure level transmitter is the intent to track small level changes in a very high level that is totally read by the transmitter.

Example

A 15 m high tank level is totally measured and you would like to read the level to an accuracy of + 15 mm. (Oil tank in and out gauges that are tape read require this degree of accuracy). The true indication of the performance of a differential pressure-transmitting meter is repeatability. Repeatability is typically 0.15 percent of calibrated range.

Therefore, the signal could vary 22.5 mm for the same tank level that is not satisfactory for this application. This performance characteristic is the reason why this type of meter is rated fair to poor as an accounting type meter.

The approach recommended in selecting the range of level to be measured is to place the high-pressure sensing nozzle no lower than 25 percent below the lowest level of interest in the vessel.

Example

If there is a 15 m tank in which the level will be between 8 m and 12 m for 90% of the operating life of the tank, the level operating range is only 4 m and this is the range for which the transmitter would be calibrated. The sensing nozzle would be installed at 1 m below the 8 m level at 7 m. The transmitter would be zero elevated to compensate for the 1 m. The scale on the receiving instrument should read 8 at zero input signal and 12 at maximum input signal. However, care should be exercised in selecting ranges in relation to standard scales. When possible, the instrument manufacturer's standard scale, which will bracket your desired range as closely as possible, should be used. Special scale ranges will increase cost in scales and charts that can exceed the cost of the instrument over a 1000 times.

Various types of installations of the differential pressure transmitters in the applications of level are represented in Figures 4.19–4.22. Differential pressure transmitters used for measuring level in open tanks have the low pressure port is kept open to atmosphere. This port should be equipped with a 90° fitting which is turned down and which contains a large mesh screen.

The 90° fitting will keep dust and liquid out of the low-pressure cavity. The screen will keep out insects and other small objects which could interfere with the diaphragm's operation. As discussed earlier the top process connection (top tap) must be positioned so that the maximum liquid level is always below the top tap. If the process liquid meets the top tap, the low side pressure measurement will be incorrect.

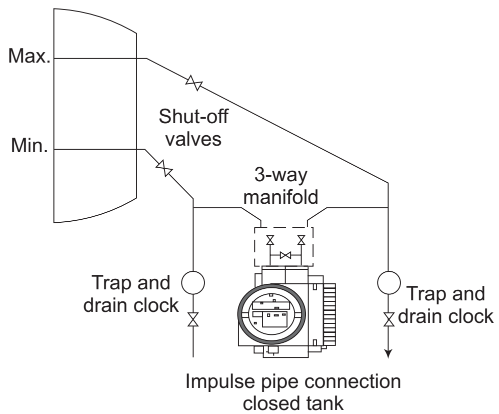


Figure 4.19: Impulse pipe connections, closed tank

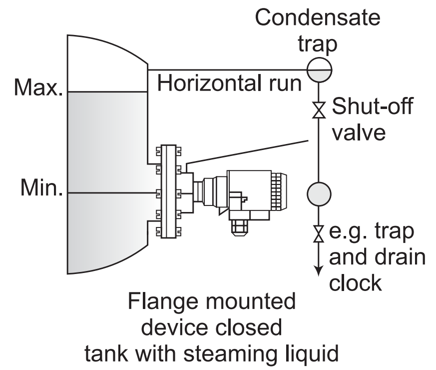


Figure 4.21: Impulse pipe connections, covered tank with steaming liquid

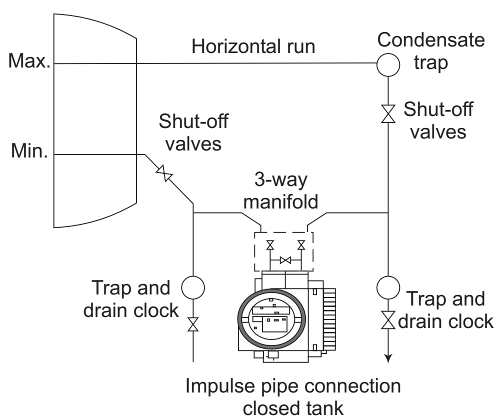


Figure 4.20: Flange-mounted device, closed tank with steaming liquid

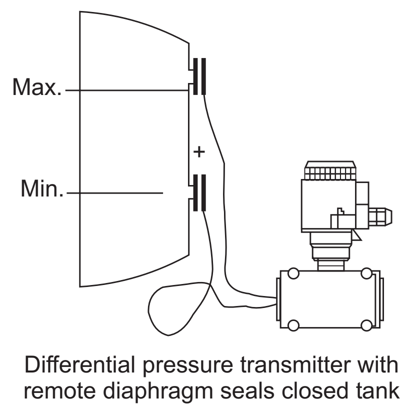


Figure 4.22: DP transmitter with distant diaphragm seals, covered tank

4.3.3.4 Applications

Differential pressure type instruments shall be used for measurement ranges exceeding 1850 mm (72 in). They may also be used for lower ranges where process conditions prohibit the use of displacement type instruments. Transmitters with diaphragm seals may be used for extremely viscous materials, for materials containing solids or in hot service.

Additionally, differential pressure type instruments are not restricted to use on levels of 1850 mm (72 in) and greater as this paragraph implies. However, for simplification of design, "use only on levels higher than 1850 mm" could be used as a rule of thumb. All process parameters should be considered to select the proper level instrument to be used on any level.

Levels in vessels which are subjected to high vibration are best measured by differential pressure transmitters. The transmitter can be mounted away from the vessel and mounted on a non-vibrating surface. Electronic transmitters can be mounted directly on a vibrating vessel without any ill effects.

Differential pressure transmitters should not be installed in a service where the measured liquid specific gravity will vary widely and often. For example, a vessel is used for oil at a SG of 0.8 and salt water at a SG of 1.0; when in oil service, a transmitter calibrated for water would actually contain 3.6 m of oil when indicating 3 m of level. In addition, differential pressure transmitters work best on clean fluids that are constant in specific gravity, temperature, and pressure. Differential pressure transmitters must be installed as level transmitters for controllers when the level will vary over ranges that exceed 1800 mm (72 in). A displacer type controller can control only when the level is on the displacer. The longest standard displacer available is 1800 mm (72 in).

A typical industry approach is to apply differential pressure transmitters in clean applications that have a temperature of less than 149°C (300°F). While differential pressure transmitters tend to have relatively low temperature limits, techniques exist for extending the temperature with filled capillaries and/or remote seals. *The filled capillaries contain oil that does not readily transfer heat so that the transmitter can be located away from the process.*

Differential transmitters are also suitable for process that contains suspended solids. However, the application involving suspended solids should be carefully reviewed. Suspended solids can accumulate over time and plug the sensor. While extended diaphragms overcome this problem, over a period suspended solids can accumulate in the bottom of the vessel to a point above the pressure sensor. An application in Figure 4.23 shows a differential pressure transmitter used to measure the level in a butane product sphere.

Application Examples Figure 4.23 references standards and practices that influence hydrostatic head device selection. Review these references (as well as the vendor's supporting documentation) for additional detail when determining a device's suitability for an application.

The earlier discussion of using gauge and/or differential pressure transmitters for level measurement assumed that the transmitter is installed at the same level as the lower process tap; however, that is not always the case. A transmitter for an open tank level measurement is often installed below the lower process tap.

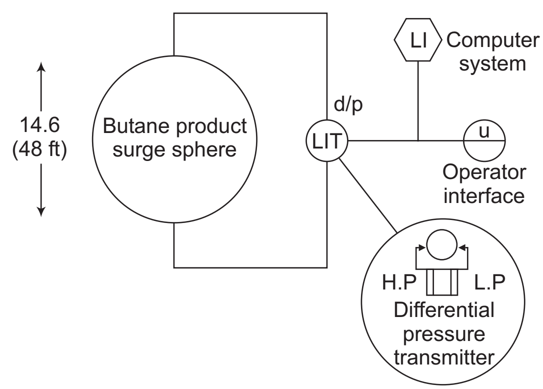


Figure 4.23: Differential pressure transmitter for the measurement of level

When that happens, the pressure effect of the fluid in the lower process tap connection to the high side of the pressure transmitter must also be taken into account. The use of fill fluids in a differential pressure transmitter's legs leads to one of the most misunderstood concepts in making a level measurement with differential pressure transmitters.

The concepts of zero elevation and zero suppression are confusing to most novice engineers. These concepts can be easily explained by performing some transmitter range calculations.

When transmitters ranges are mathematically calculated, then the effect of a leg's fill fluid on zero suppression or zero elevation of the range are no mystery at all.

Transmitter Range Calculations The following transmitter range calculations account for the pressure measurement effects of a fill fluid in a transmitter's leg, and make the concepts of zero suppression and zero elevation much easier to understand when the relationship of suppression and elevation to range are shown mathematically. To be sure, a brief review of the terms "suppression" and "elevation" is necessary. The terms "suppression" and "elevation" can be confusing; the interpretation depends on the context they are presented in. The terms "elevation," "elevated range," and "elevated span" represent the condition where 0 (Zero) does not appear on the measurement scale or range of the pressure transmitter. The zero, in effect, is less than the lower range value. Some companies use the term "range elevation" to represent this condition.

For example, when the range is 20 to 100 measurement units, range elevation occurs because zero measurement units are not part of this range. At 20 measurement units, a 4 mA output is generated by a transmitter, while at 100 measurement units, a 20 mA signal is generated.

However, you should note that the industry preferred description for this condition is that it represents a "suppressed-zero range."

The terms "suppression," "suppressed range," and "suppressed span" represent the condition where zero does appear within (or even above) the measurement scale or range of the pressure transmitter. The zero, in effect, is greater than the lower range value. Some companies use the term "range suppression" to represent this condition.

For example, when the range is –25 to 100 measurement units, range suppression occurs because zero is within this range. At –25 measurement units, a transmitter, while at 100 measurement units generates a 4 mA output; a 20 mA signal is generated.

However, you should note that the industry preferred description for this condition is that it represents an "elevated-zero range." In summary, the terms zero "elevation" and "suppression" refers to the relationship between zero and the lower range value. For any application, whether or not the range configuration requires suppression or elevation, the following relationships can be used to calculate the transmitter range. Begin first by noting that for a differential pressure transmitter to have a 4 mA output, the sum total effects on the differential pressure transmitter should be zero.

A 4 mA output, representing a minimum level, is generated when:

$$P_{\text{high side of transmitter}} - P_{\text{low side of transmitter}} + \text{Offset} = 0, \tag{4.23}$$

where, $P_{\text{high side of transmitter}}$ = pressure applied to the high side of the pressure transmitter in inches of H_2O, $P_{\text{low side of transmitter}}$ = pressure applied to the low side of the pressure transmitter in inches of H_2O.

Offset = an offset factor that is either positive or negative, in inches or millimeters of H_2O. The offset factor automatically accounts for any effects of fill fluid upon range suppression or elevation.

A 20 mA output, representing the maximum level, would occur when:

$$P_{\text{high side of transmitter}} - P_{\text{low side of transmitter}} + \text{Offset} = \text{Span},$$

where, Span represents the configured span of the transmitter.

The two expressions for calculating a transmitters range are then:

$$P_{\text{high side of transmitter @4 mA}} - P_{\text{low side of transmitter @4 mA}} + \text{Offset} = 0$$

$$P_{\text{high side of transmitter @20 mA}} - P_{\text{low side of transmitter @20 mA}} + \text{Offset} = \text{Span} \tag{4.24}$$

The range calculation procedure is summarized as follows:

- Identify the expected pressures on both the high and low sides of the pressure transmitter at the points where you want a 4 mA output to represent minimum level and where you want 20 mA to represent maximum level.
- Use the 4 mA minimum level and solve for any offset with the expression:
  $$P_{\text{high side of transmitter @4 mA}} - P_{\text{low side of transmitter @4 mA}} + \text{Offset} = 0$$
- Use the 20 mA maximum level, any Offset calculated previously, and solve for the expected span.
  $$P_{\text{high side of transmitter @20 mA}} - P_{\text{low side of transmitter @20 mA}} + \text{Offset} = \text{Span}.$$
- Calibrate the transmitter to a range of – Offset to (–Offset + Span). In other words, the lower range value (LRV) is –Offset, while the upper range value (URV) is (–Offset + Span).

Closed Tank with Dry Leg Transmitter Range Calculation The following example illustrates calculating the transmitter range for a closed tank with a dry leg, with the differential pressure transmitter below the lower process tap. In the closed tank example, the low-pressure connection is connected to a process tap at the top of the tank above the process liquid's maximum level. The pressure within the tank is then sensed at both the low side and the high side of the differential pressure transmitter, effectively cancelling out the internal tank pressures for the level measurement. In a closed tank, the transmitter is often installed below the lower process tap connection. When the level is at the lower process tap connection, a hydrostatic pressure, due to the fill fluid, is present at the high side of the differential pressure transmitter. For the transmitter to output a signal representing just the level from its maximum height to the lower process tap, the effect of the fluid in the high side connection must be "suppressed". In this situation, it is desirable that a 4 mA signal, representing 0 (zero) differential

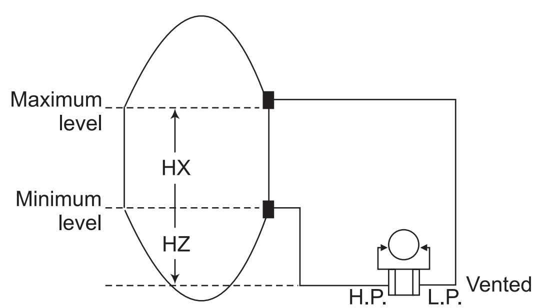


Figure 4.24: Closed tank dry leg range calculations

pressure and thus the minimum level, is output when the liquid level is at the lower process tap connection.

Closed Tank Dry Leg Calculation Note that when using a differential pressure transmitter, the fill fluid is the process fluid from the lower tap to the transmitter's high side connection. When using a remote seal transmitter, the fill fluid from the lower tap to the transmitter's high side connection will be a fill fluid with a specific gravity that is different than the process fluids. The reason for the specific gravity difference is that the capillary is filled with a fill fluid that is not permitted to combine with the process fluid (Figure 4.24).

$$P_{\text{high side of transmitter @20 mA}} - P_{\text{low side of transmitter @20 mA}} + \text{Offset} = \text{Span}$$
$$(h \times SG_{\text{process liquid}} + h \times SG_{\text{fill fluid}}) - 0 + \text{Offset} = \text{Span}$$
$$(120 \times 1.1 + 12 \times 1.1) - 0 + \text{Offset} = \text{Span}$$
$$(132 + 13.2) - 0 + (-13.2) = \text{Span}$$
$$(145.2) - 0 + (-13.2) = \text{Span}$$
$$\text{Span} = 132 \tag{4.25}$$

The following example illustrates calculating the transmitter range for a closed tank with a dry leg, with the differential pressure transmitter below the lower process tap. The maximum height of the liquid is 10 ft above the minimum level, the process fluid has a specific gravity of 1.1, and the fill fluid in the process connection from the lower tap to the transmitter's high side connection has a specific gravity of 1.1 and is a length of 1 ft. The range calculation using the procedure follows.

Use the 4 mA minimum level and solve for any offset in the expression:

Use the 20 mA maximum level, any offset calculated previously, and solve for the expected span.

$$P_{\text{high side of transmitter @4 mA}} - P_{\text{low side of transmitter @4 mA}} + \text{Offset} = 0$$
$$(h \times SG_{\text{process liquid}} + h \times SG_{\text{fills fluid}}) - 0 + \text{Offset} = 0$$
$$(0 \times 1.1 + 12 \times 1.1) - 0 + \text{Offset} = 0$$
$$(0 + 13.2) - 0 + \text{Offset} = 0$$
$$(13.2) - 0 + \text{Offset} = 0$$
$$\text{Offset} = -13.2$$

Calibrate the transmitter to a range of – Offset to (–Offset + Span)

$$\text{Range} = -\text{Offset to } (-\text{Offset} + \text{Span})$$
$$\text{Range} = -(-13.2) \text{ to } (-13.2) + 145.2)$$
$$\text{Range} = 13.2 \text{ to } 145.2 \text{ inches } H_2O \tag{4.26}$$

When using a differential pressure transmitter, the fill fluid is the process fluid from the lower tap to the transmitter's high side connection. When using a remote seal transmitter, the fill fluid from the lower tap to the transmitter's high side connection will be a fill fluid with a specific gravity that is different from the process fluids.

In the previous example, the zero of the transmitter's range represents a "suppressed zero range" i.e. zero does not appear as a measurement unit on the range of 13.2 to 145.2 in H_2O.

According to accepted practice, suppressed zero range is the preferred terminology. Note that terms such as "elevation," "elevated range," and "elevated span" are used to express this condition. Some companies use the term "range elevation".

Closed Tank with Wet Leg Transmitter Range Calculation The following example in Figure 4.25 illustrates calculating the transmitter range for a closed tank with a wet leg, with the differential pressure transmitter below the lower process tap. Ideally, the span or range of the instrument should be dependent on what is measured in the tank. In the following example, the span is again 132 in H_2O. Ideally, a 0 differential pressure would generate a 4 mA signal, while a 132 in H_2O would generate a 20 mA signal.

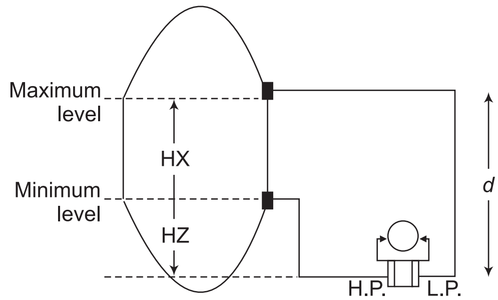


Figure 4.25: Closed tank wet leg range calculations

The reason for the specific gravity difference is that the capillary is filled with a fill fluid that is not permitted to combine with the process fluid. Like the calculation for the open tank with wet leg range calculation, the pressure, due to the fill fluid in the wet leg, forces you to place an elevated-zero range on the transmitter. The elevated zero range is necessary in order for the differential transmitter to read a minimum or maximum level at pressures other than 0 and 132 in H_2O.

In transmitter terms, as seen in the following calculations, for the transmitter to generate a 4 mA signal, the differential pressure must be – 202.8 in H_2O.

For the transmitter to generate a 20 mA signal, the differential pressure must be –70.8 in H_2O.

Note the following calculation:

$$P_{\text{high side of transmitter @4 mA}} - P_{\text{low side of transmitter @4 mA}} = P$$

$$(h \times SG_{\text{process liquid}} + h \times SG_{\text{fill fluid}}) - (h \times SG_{\text{fill fluid}}) = P$$

$$(0 \times 1.1 + 12 \times 1.1) - (144 \text{ x } 1.5) = \text{P}$$

$$13.2 - 216 = \text{P @4 mA}$$

$$-202.8 = \text{P @4 mA}$$

$$P_{\text{high side of transmitter @20 mA}} - \text{P}_{\text{low side of transmitter @20 mA}} + \text{Offset} = \text{Span}$$

$$(h \times SG_{\text{process liquid}} + h \times SG_{\text{fills fluid}})\ (h \times SG_{\text{fill fluid}}) + \text{Offset} = \text{Span}$$

$$(120 \times 1.1 + 12 \times 1.1) - (144 \times 1.5) + \text{Offset} = \text{Span}$$

$$(132 + 13.2) - 216 + (202.8) = \text{Span}$$

$$(145.2) - 216 + (202.8) = \text{Span}$$

$$\text{Span} = 132 \tag{4.27}$$

The calculation for the transmitter range is as follows:

The maximum height of the liquid is 10 ft above the minimum level, the process fluid has a specific gravity of 1.1, the fill fluid in the process connection from the lower tap to the transmitter's high side connection has a specific gravity of 1.1 and is a length of 12 in. The fill fluid in the wet leg is 144 in high and has a specific gravity of 1.5. The range calculation procedure follows.

Use the 4 mA minimum level and solve for any offset with the expression

- Use the 20 mA maximum level, any offset calculated previously, and solve for the expected span.

Note

By definition, span cannot be zero or negative.

$$P_{\text{high side of transmitter @4 mA}} - P_{\text{low side of transmitter @4 mA}} + \text{Offset} = 0$$

$$(h \times \text{SG}_{\text{process liquid}} + h \times \text{SG}_{\text{fill fluid}}) - (h \times \text{SG}_{\text{fill fluid}}) + \text{Offset} = 0$$

$$(0 \times 1.1 + 12 \times 1.1) - (144 \times 1.5) + \text{Offset} = 0$$

$$(0 + 13.2) - 216 + \text{Offset} = 0$$

$$(13.2) - 216 + \text{Offset} = 0$$

$$\text{Offset} = 202.8$$

$$P_{\text{high side of transmitter @20 mA}} - P_{\text{low side of transmitter @20 mA}} = P$$

$$(h \times \text{SG}_{\text{process liquid}} + h \times \text{SG}_{\text{fills fluid}}) - (h \times \text{SG}_{\text{fill fluid}}) = P$$

$$(120 \times 1.1 + 12 \times 1.1) - (144 \times 1.5) = P$$

$$(132 + 13.2) - 216 = P$$

$$145.2 - 216 = P_{@20\text{ mA}}$$

$$-70.8 = P_{@20\text{ mA}} \tag{4.28}$$

In the previous example, the zero of the transmitter's range represents an "elevated-zero range", i.e. zero is greater than the lower range value. In this example, the zero is also greater than the upper range value. According to accepted practice, "elevated-zero range" is the preferred terminology. Note that terms such as "suppression," "suppressed range," and "suppressed span" are used to express this condition. Some companies use the term "range suppression".

For any transmitter range calculation, when the range calculation procedure is followed, the engineer will not have to be concerned with whether the zero is suppressed or elevated. The range calculation procedure automatically accounts for suppression or elevation. The engineer may now wish to compare the transmitter range calculation procedure described earlier with the approach in vendor manual. The examples previously described assume the minimum level is at the datum line. In practice, that is not always the case. Sometimes, you need to include calculating the range when the minimum level is above the datum line.

Calibrate the transmitter to a range of – Offset to (–Offset + Span)

$$\text{Range} = -\text{Offset to } (-\text{Offset} + \text{Span})$$

$$\text{Range} = -(202.8) \text{ to } (202.8) + 132)$$

$$\text{Range} = -202.8 \text{ to } -70.8 \text{ inches } H_2O \quad (4.29)$$

4.3.4 Simple Displacement Device

Displacement devices are based upon Archimedes' principle which states that a body immersed in a liquid is buoyed up by a force equal to the weight of the liquid that is displaced. Weight of the displacer float-like element is known. As the liquid level changes, the apparent weight of the displacer changes (Figure 4.26). The apparent weight change is sensed by a mechanism that converts the weight change to a level measurement.

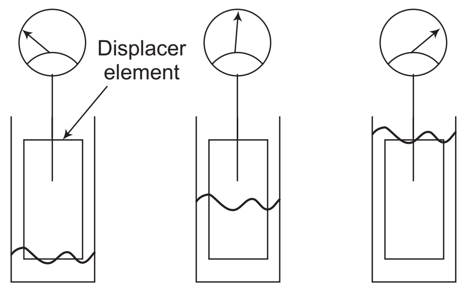


Figure 4.26: Displacement principle based level measurement

4.3.4.1 Displacement Principle

As the liquid level rises, the actual weight of the displacer float-like element now becomes the displacer element weight minus the displaced weight of liquid. The distance, h, which is the level above the bottom of the displacer element, and the cross sectional area, a, of the displacer element are also known. The weight of displaced liquid is equal to $a \times h \times$ density. The basic principle is that the weight of the displacer element decreases as the level increases. Because the displacer is kept in a relatively fixed position, the displacer experiences upward buoyancy forces. All displacers transmit a signal related to its changes in upward buoyant forces as level rises and falls.

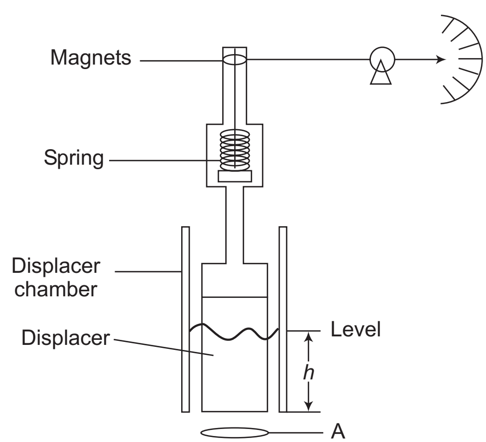


Figure 4.27: Displacement design

The float-like element of the displacer (Figure 4.27) does have some movement. The motion is restricted or dampened by a range spring. The range spring, which is contained within an enclosed tube, is connected to a magnetic attractor ball. The magnetic attractor ball is magnetically coupled to an external magnet that encircles the tube. The external magnet's motion is transferred to a rotating cam that indicates position and operates either pneumatic or electronic control equipment.

4.3.4.2 Displacement Design

Although the displacer assembly can be installed inside a vessel, the displacer is usually installed in an external chamber outside of the vessel. A reason for using an external chamber is to keep displacer element vertical at all times. The displacer element that is not kept vertical would cause measurement errors.

4.3.4.3 Performance

Displacers tend to be limited in their potential span. Approximately 8 ft is the maximum span length. One reason for the 8 ft limitation is that it is hard to keep a displacer element that is more than 8 ft in length upright, even when using an external chamber. A potential for material buildups or coatings on the displacer element is possible. The buildups change the weight of the displacer and change the displaced volume of liquid. Because buildups on the displacer element are undesirable, displacers are often used in reasonably clean liquids.

Because performance specifications vary for displacers, the main consideration becomes the susceptibility of the displacer to changes in specific gravity (density) of the liquid. While the effects of buildups on the displacer have been noted, *the main contributor to a displacer's measurement error is a change in a liquid's specific gravity.* (Displacers also have performance considerations when used in an interface application. Interface considerations are described later in a separate learning objective. If the displacer is thought of as a sink rather than float-like, some of the misconceptions will disappear. One problem with displacers is material building up below the displacer element and causing a different amount of apparent weight to be registered.

4.3.4.4 Installation

Installation of a displacement device is somewhat dependent on the application requirements. The available installation arrangements are:

- Flanged top mounting from the top of the tank
- External cage mounting so that the displacer is isolated from the process for maintenance.
- Side mounting for level applications that have a narrow range.

External cage mountings have advantages. For maintenance purposes, it is often desirable for maintenance to be able to access the device for cleaning. When the displacer is externally mounted, the process does not have to be shut down for repair and cleaning. However, external cage mountings also have their own special considerations. The special considerations are described in the section on using displacers for interface applications. Briefly, the considerations may involve purging the chamber to keep the displacer element clean, heating the chamber if the fluid is viscous, and avoiding boiling liquids in the chambers.

4.3.4.5 Applications

Simple displacement devices are typically used in industrial applications such as boiler feed water heaters, boilers, scrubbers, and condensate drip pots. Displacement devices are usually limited to clean processing applications. Prior to the introduction of the electronic pressure measuring devices, displacers were the preferred devices for narrow operating ranges, often used on level ranges that are less than 6 or 8 ft. As more microprocessor-based pressure-measuring technologies become available, displacers become used less frequently for level measurement applications.

Displacement type instruments may be used for:

- Ranges up to and including 1850 mm (72 in)
- Nonviscous materials
- Process liquids that do not contain high concentrations of solids.

Displacement devices are recommended for liquid-liquid interface level measurement.

4.3.5 Torque Tube Displacers

A torque tube displacer (Figure 4.28) is so called because it uses a tube assembly that converts displacement into a torque movement. A torque tube displacer relies on buoyancy forces to move the displacer element. The resulting movement is transferred through a torque assembly. The torque movement is then converted to a level measurement.

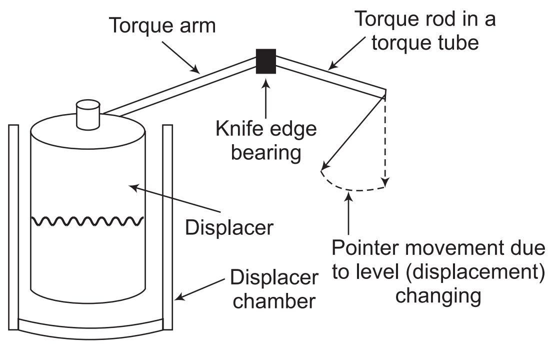


Figure 4.28: Principle of torque displacers

The displacer is attached to a torque tube assembly, which consists of assemblies such as a torque arm, torque tube, torque rod, torque arm block, and knife-edge bearing. As the displacer responds to buoyancy forces, the resulting torque arm movement twists the torque rod within the torque tube. The displacer is designed so that the angular displacement of up to 5° or 6° is proportionally linear to displacer weight. The angular displacement is then converted to a level measurement.

4.3.5.1 Torque Tube Performance

Torque tube displacers, like simple displacement devices, have considerations regarding material buildup and changing fluid density occurrence.

4.3.5.2 Installation

The displacer permits external vessel mounting so that process operations can continue without interference. Torque tube displacers can also be mounted on an internal stilling well if internal vessel mounting is needed.

4.3.5.3 Applications

The applications are the same as those for simple displacement devices. Clean processing applications for torque tube displacers are preferable.

4.3.6 Level Measurement Using Ultrasonic Gauging

Sound waves travel in a medium with a speed which is dependent on temperature and density of the medium. The ultrasonic level transmitters were designed with the sound travel technique called "pulse time of flight (PTOF)". In this technique, a short ultrasonic pulse produced by the transducer which propagates in air or gas, etc., and reflects back when hit with a measurand such as surface of the liquid or solid, etc. The difference in time taken from pulse generation to pulse receiving, divided by 2 gives the distance of the transducer to top of the level surface. However, due to the dependency of the temperature and denstity of the medium of the sound waves, necessary compensation is performed depending on programmed calibration values.

The noncontact nature of the transmitter with process makes the ultrasonic level measurement in advantage for some of the applications such as corrosive process conditions, varying process conditions, difficult to maintain, etc. Ultrasonic level measurement is also used in measuring open channel flow, differential level across flumes, and reservoir level, etc. They are also used to measure the level of solids in applications such as hopper level and bulk storage supply, etc.

The ultrasonic level measurement instrument constitutes a transducer or sensor and local/remote electronics meant for processing the signals and communication with the other instrumentation systems. Sometimes both the above come in a single enclosure which makes it compact and easy to install in many different and difficult to mount applications. The modern, compact instruments provide advantages such as low cost, calibration options and flexible displays, etc. The ultrasonic level measurement instrument typically constitutes a piezoelectric sensor installed on the top of the tank. The signal processing electronic units are available in a remote place or on top of the sensor itself. The compact units with sensor and electronics built together helps in measurement with applications where it is difficult to install, but critical to measure such as conveyors. Condensed systems provide many advantages such as ease of installation, onsite calibration, and low prices. Such systems are very effective in applications namely conveyor-belt monitoring, pump control, two-point control, and distance measurement.

Predicting all the circumstances that affect an ultrasonic level measurement system can be a hard task. Applications that appear to be easy might turn out to be extremely challenging due to filling noise, nuisance reflections, or variable material profiles. More demanding are applications for which these and other interfering conditions are altering continuously.

4.3.6.1 Echo Suppression or Tank Mapping

When ultrasonics is used for level measurement, several false echoes are generated by reflections of the inlets, reinforcement beams, welding beams, etc. To avoid such false echoes, the transmitter can be set up to neglect these reflections by calculating a threshold curve that overlays the real reflected signal. The procedure has to be done when the tank is empty or at least partly empty down to the utmost preferred mapping range. Each genuine level reflection all the time adds to the concealed signal, thus generating a resultant signal above the threshold. After that, the transmitter ignores signals below the threshold curve and evaluates only those signals that appear above it (Figure 4.29).

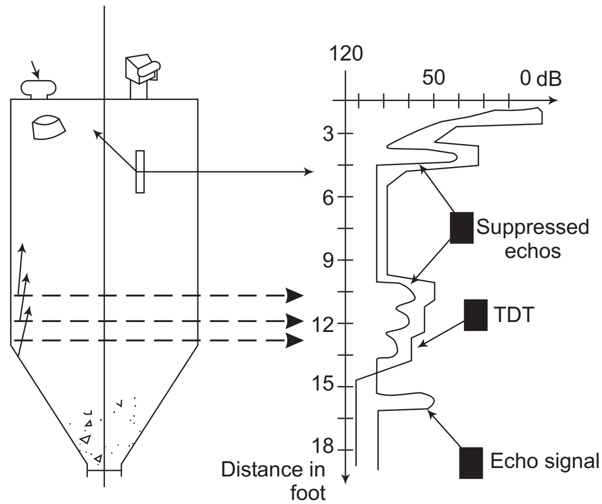


Figure 4.29: Tank mapping function

4.3.6.2 Selection Criteria

It is important to take several factors into consideration, for using ultrasonic measurement principle for a specific level measurement application.

- The technique being used is PTOF, hence the distance from the sensor to the actual measurement range is very important. The higher the distance, the larger the power of pulse to be transmitted and hence associated power related constraints and accuracy limitations. In general, the ultrasonic level measurement is applied in places where the distances are small and high level of accuracy is expected. The second consideration is the type of material of the surface of the measurement. As discussed, the ultrasonic level transmitter functions based on time of flight from a reflected surface for the sound waves, the material shall be such that at least a small amount of sound is reflected back. As a result, turbulent surfaces or very soft medium surfaces either reflected away from the transducer or were completely absorbed. In such cases, higher power of the sensor is needed within the power constraints of measurement system.
- The presence or absence of foam can play a role in the application of ultrasonic level measurement for a given process. In general, a layer of solid thick foam, based on the density can make the waves to reflect off from the transducer. Similarly, a layer of soft thick foam, again based on the density can absorb the entire wave. Sometimes a light and thin foam layer might not influence the waves in any noticeable way.
- In the solid level measurement applications, the size of the granules made up for the solid becomes an attribute for selection. The finer the granules, more sound waves are reflected off from the transducer, which necessitates more power for the pulses generated from the transducer. In other words, it needs more power to measure the same distance in solids with bulk granules.

- In any tank or open channels, during the application of the ultrasonic PTOF technique of measuring the distance, both the waves from/to transducer, i.e. waves generated and waves sensed after reflection have to propagate through the medium which is atmosphere. The atmospheric factors such as dust, pressure, temperature and composition of the gases affect the measurement and hence become an attribute for consideration while selecting the instrument.
- In general, the ultrasonic level measurement (PTOF) is not sensitive to pressure from the time of flight basis. However, the ultrasonic level instruments are mechanically (force exerted on the sensor) capable to sustain high pressure at low price. There are ultrasonic measurement applications used in high pressure gas flow measurement applications, but they come costly. In case of the low pressure, the medium of propagation such as air or gas becomes limited to the transmission of the quality signal in partial vacuum.
- As discussed earlier, variations in temperature of the medium has an impact on the measurement of the level using ultrasonic level instruments. The influence of temperature on the measurement is due to difference in velocity of sound at different temperatures. In order to compensate the effect of temperature on the measurement accuracy, a temperature sensor is attached to each of the ultrasonic level instruments. The temperature measured from this sensor is used to compensate the level using the electronic processing and calculations. If the distance is high and if there are layers of temperature in the path of the propagation of the wave, multiple sensors can be attached to positively compensate the accuracy of the measurement.
- In case of situations where the medium of propagation is different from air, then the speed of the sound waves differ and hence becomes an attribute in the selection of the instrument.

The system must be calibrated to compensate for different propagation speeds but precise readings can result due to the hypothesis that these gas properties are fixed for the given application and may modify with time.

4.3.6.3 Mounting

The ultrasonic level transmitters are generally installed on the top of the tank or above the channel where there is no obstruction between the transmitter and the surface of the liquid for the propagation of the sound waves. In general, many items that usually appear in the tanks such as ladders, agitators, pump inlets, or liquid falling from top introduce interference echoes or the waves propagated back to the transducer. These obstructions are either removed or instrument is used in a different orientation or different place to avoid the above said elements. The transmitter should be installed in a place where the receiver gets the maximum echo signal with minimum hurdles in the path of sound wave propagation. In the ultrasonic level measurement the sensor is fixed in one convenient position and is in line of sight to the reflected echo.

Given the factors that affect the measurement accuracy, such as vessel obstructions, geometry of the vessel and the related reflections of the echoes. If the tank is conical or dished at the bottom, the transducer is mounted away from the center of the tank to avoid the reflection from these curvatures and the associated incorrect measurement.

Maximum echo sensor can be received if the sensor is not mounted in the places where there is large amount of fill streams or where huge parts of the output beam is absorbed into the vessel walls.

The ultrasonic sensor also needs to be mounted in a place above some distance also called as blind space, dead space, etc. The blocking distance is the minimum distance below which the sensor cannot measure the level. In other words, blocking distance is the area directly underneath the transducer in which level could not be measured. Generally, transducer sends a series of pulses to the medium with certain energy and stops after some pulses. After the completion sending pulses, the transducer shall wait for receiving pulses for a period of time. The delta of time for the processed echo curve is used as the basis for measuring the distance and hence the level. The transducer ringing (sending pulse and waiting for echo) is based on the type of the transducer. The transducer design, power of the signal and angle of the beam defines the blocking distance for each of the instrument.

Advantages/Disadvantages The noncontacting principle is the main advantages of an ultrasonic system; it is not influenced by modifications of the material properties, its sensor is not made to wear and tear, and it has a large range of applications. Disadvantage of an ultrasonic system is its response to inconsistent gas concentrations in the free space between sensor and product. Foam should be taken into account, rendering in foam unsuitable for huge temperatures and pressures.

4.3.7 Level Measurement Using Capacitive Probes

A capacitive probe works in most liquids (and solids), as it relies on the dielectric constant of the liquid to operate. As the liquid rises in the space between two electrodes, which are in effect the two plates of a capacitor, the variation in capacitance can be monitored and set to alarm.

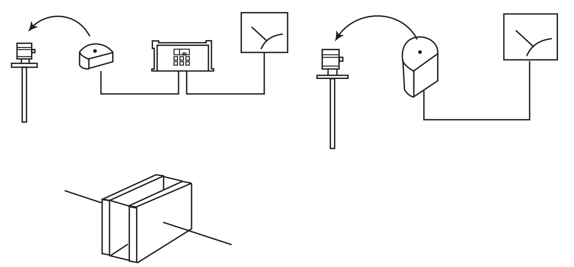


Figure 4.30: Capacitance level measuring principle

Level measurement based on the capacitance probe works on the technique where the whole capacitance between wall of the tank and an externally inserted probe or rod or cable is measured on continuous basis as shown in Figure 4.30. This measured capacitance is directly proportional to the level of the liquid in the tank. In an electrical engineering terminology, a capacitor is an electrical module that preserves a specific electrical charge. It contains two metal plates divided by an insulator called as dielectric.

The electrical size (capacitance) of a capacitor is based on surface area of the plates/rod or cable, distance between the plates, and dielectric constant of the material inside the plates.

For a given measurement point to another, the material inside is constant and hence dielectric constant is fixed for a medium and the distance between the plates is also constant. The only variable is the surface area which changes with the level of the liquid. The process material or liquid to be measured changes the free space or air (dielectric 1) in the tank, the capacitance increases with increase in level.

The dielectric constant of most of the liquids and solids is more than 1. The electronics in the transmitter measures the changes in the capacitance of the measurement system and does a signal processing to generate a stable output (analog or digital) on the measurand. Based on the discussion above, in order to get an error free measurement, the dielectric constant should be fixed. If there is any change in dielectric constant, then a recalibration needs to be performed. Some of the smart transmitters are supplied with the table of dielectric constant stored in the instrument and gets calibrated to those values based on the settings. The advances in level measurement using capacitance probes has solutions for automatic self compensating system for dielectric constant changes, etc.

The capacitance probes are used either as LSs (point level) or as level transmitters (continuous level) applications for liquids as well as solids. However, the continuous level measurement for solid applications has constraints due to the influence of moisture on the dielectric constant of the solids. The changes in dielectric constant due to moisture leads to drift and erroneous measurements.

4.3.7.1 Fully and Partially Insulated Probes

Irrespective of the type of construction of the probe such as rod, cable or custom shapes, there are two variants of the probes widely used in the capacitance based level measurement applications. The two variants are fully and partially insulated probes.

Fully insulated probes (Figure 4.31) are completely coated by an insulated material based sensing element while partially insulated probes are coated with a blank metal with a sensing element isolated from ground. Fully insulated probes are galvanically isolated to the process material while the partially insulated probes are in direct galvanic contact.

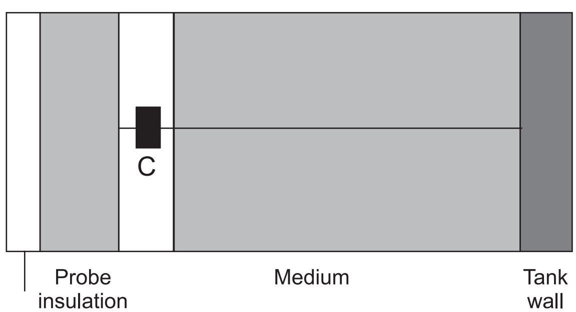


Figure 4.31: Example of a fully insulated probe

The necessary probe type for a known application can be chosen from the following Table 4.1.

Table 4.1: Required probe type for a given application

Application	*Fully Insulated*	*Partially Insulated*
Point level, tip sensitive, process material nonconductive	Suitable	Suitable
Point level, adjustable switch point, process material nonconductive	Suitable	Suitable
Point level, tip sensitive, process material	Suitable	Suitable
Point level, adjustable switch point, process material conductive	Suitable	Not suitable
Continuous level, process material nonconductive	Suitable	Suitable
Continuous level, process material conductive	Suitable	Not suitable
Process material with extremely low dielectric constant	Limited suitability	Suitable
Process material chemically aggressive	Suitable	Only with special probe materials

4.3.7.2 *Capacitance Probes and Ground References*

A capacitance probe-based level measurement requires a reference potential such that the wall and probe becomes a capacitor. In general, the reference potential is previously built into the probe or tank wall and an additional mounted probe becomes a reference electrode. Since the tank is connected to ground potential, this reference is more referred as ground reference. Point level probes do not need an additional ground reference because they are already built into the probe.

It is more expensive to manufacture point level probes than plain rod or cable types because of higher mechanical requirements arising from the need to build in a ground reference or making an additional ground reference electrode. The following are some guidelines to help in deciding between a standard probe and a probe with an integral or separate ground reference.

- A built in or external ground reference is required for the tanks with nonconductive materials. Lack of such a reference leads to incorrect and unpredictable readings.
- A ground reference is also preferred to measure level in the tanks which are horizontally cylindrical or cone bottom tanks or tanks with un even shapes and tank with built in items (cooling and heating coils). Even though such tanks are made of metals, the space between the tank wall and the probe is not uniform and hence capacitance change per unit length varies. Sometimes the measurement is nonlinear in such cases.
- In case of level measurement in tanks with very low dielectric constant of the liquid both continuous level measurements and point level applications require an inbuilt or external ground reference fixed at equivalent places to the probe. These reference

points are closer to the probe due to which the capacitance change per length unit (i.e. pF/in) is greater in comparison to a system which does not have an additional reference. This makes the measurement more reliable and accurate over the specified range.

4.3.7.3 Capacitance Probes and Buildup

Material formation or buildup on a capacitance probe is a serious problem in capacitive probe based level measurement applications. The extent of the problem is based on strength of the coat on the probe and conductivity of the probe. It can keep the point level systems from improper operations leading to wrong decisions. The same issue leads to an offset in measurement of continuous level instruments. The issue can be addressed using the following approaches in continuous level measurement applications.

- Condensation process ensues naturally in the tank nozzle or close to ceiling and thus influences the measurement. In order to avoid this problem, a dead section is used at the top couple of inches (among the sensing element and the process connection).
- Usage of high measuring frequency reduces the effect of buildup on the measurement accuracy if the sensing element of the probe is coated and if the buildup is conductive, capacitive measurement system with large frequencies are however generally restricted to shorter probes (rod probes more than cable probes).

If the buildup is anticipated to be extreme, then it is advised to consider alternative measurement technique as the capacitive level measurement system is prone to repeated measurement errors during built up. For capacitive LSs, buildup can also be taken care of in two ways:

- Using a dead section at the upper couple of inches (among the sensing element and the process connection) to restrict condensation, which naturally happens close to the tank ceiling or in nozzles, from influencing the measurement.
- By using a compensation electrode which is part of the measuring probe. This electrode aggressively equals for altering amounts of buildup, which allows the capacitance switch to work, though the probe is fully coated.

In a general situation where there is no buildup, for a normal LS, the calculating loop contains of a high-frequency (HF) oscillator, probe, and impedance of the product. A change in high (no product) to low impedance (product at the probe) causes a change in position of the switch. If there is high buildup on the probe which continues to be on the probe while there is no level or the LS is short-circuited but is still indicating the level, a probe with an active guard system (Figure 4.32) is used. A probe with an active guard consists of two HF loops—one for the actual probe and other one with a restricted signal for the guard. If any

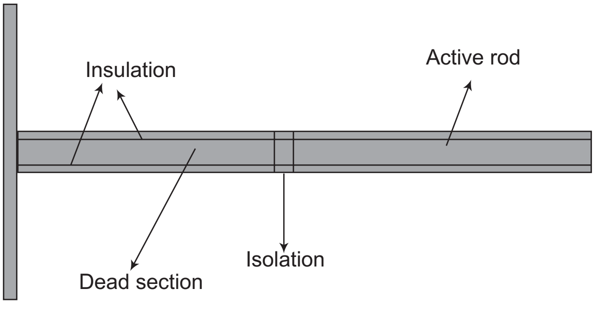


Figure 4.32: Capacitance probes with active guard

buildup is created, the LS keeps the signal (amplitude and phase) of the guard on the equal level as the signal at the probe. There is a current between the guard and ground, but no current between the probe and guard (as they are on equal potential); hence there is no level shown. If a real level is available, there is a current between the probe and ground, so the switch is turned on.

4.3.7.4 Installation and Application Considerations

Apart from some installation requirements discussed earlier such as dielectric constant, buildup in the tank, conductivity of the liquid, material of the tank, etc., other aspects should also be taken into account:

- The probe shall be mounted in a position in such a way that there is no obstruction until the lower range limit, the probe is not too close to the wall of the tank and is far away from inside the tank equipments such as internal tubes or agitators, etc.
- The probe shall be mounted with sufficient space between the wall of the tank especially when measuring liquids with more viscosity and high probability to build up. These installations if not taken care lead to erroneous measurement.
- The lateral force that applies to the probe are caused by the disturbances in the tank such as agitation speed and viscosity needs to be considered. These factors if not taken care, have the potential to damage the probe. Sometimes the probes are installed in a stilling well or built in ground tube for protection purpose.
- In case of liquid level measurements using capacitive probes in tanks made of plastic or glass, special considerations are needed—since glass or plastic cannot be used as reference. These tanks require a probe that is inbuilt or has an individual ground reference. The ground reference electrodes should be in galvanic isolation with the liquid to be measured because these tanks are generally used for chemically aggressive liquids, such as acids. This might pose a major problem with the chemical compatibility of the construction materials for the ground reference (costly special materials, like tantalum, may be used). It is not suggested to use a ground reference with insulation properties similar to the probe itself. Although such a system would technically work, both electrodes (probe and reference) might form a huge antenna that makes the system responsive to electromagnetic interference in the frequency range of the capacitance system. With no shield around the probe (grounded metal tank or grounded conductive liquid), the measurement is expected to become undependable.
- For capacitive level measurement applications for liquids with high viscosity and conductivity, delays can be expected to become accurate after draining a tank. It would take hours prior to run off the probe completely by the material; as long as there is any buildup left, the level is shown with a certain offset.

4.3.7.5 Advantages/Disadvantages

The main benefit of capacitance system is its wide range of application in various industries. Apart from this, other advantages include ease of installation, accessibility of many application-specific solutions, good accuracy (in appropriate applications), and proven technology. The drawbacks are basically dependent on changes in the material properties (dielectric constant, conductivity), material buildup, and capacitance systems being inferring system, i.e. measuring level based on changes in capacitances.

4.3.8 Level Detection and Measurement of Liquids and Solids Using Radar

Radar technology based level measurement is gaining wide acceptance for various applications in liquids and solids. Earlier the cost of the equipment and large power requirements were constraints in the adaptation of this technology. However, the current day technologies can provide solutions at a cost similar to other devices and can work with loop-powered methods with minimum power needs.

4.3.8.1 Point Level Measurement

The microwave pulse is transmitted from the top of the tank and reflections or echoes are sensed back. The reflections are generated from the top of the process materials such as liquids, solids or slurries. When the medium is filled with the content at the point of measurement, then a dielectric change occurs which is measured and sensed by the receiver to detect the presence of the material. In other words, the transmitted beam is reduced to the extent proportional to the dielectric constant at the receiving end. The radar-based LS are sensitive to light density liquids, solids and are insensitive to the variations in pressure and temperature in the tank. The disadvantage is susceptibility to build up of materials and moisture. The built up can be a source of erroneous LS operation.

4.3.8.2 Continuous Level Measurement

A radar level transmitter works on the principles such as PTOF or frequency modulated continuous wave (FMCW) and works in a frequency band accepted for industrial use. The beam power of the this type of transmitters is safe for installation in hazardous areas on metallic and nonmetallic tanks. The technology is proven safe for human beings and environment.

Microwave radar-based level measurement is used to calculate the volume of the liquid in storage tanks, process tanks, etc. The storage tanks can constitute different temperature gradients, inert-gas blankets, and vapors. Radar-based level measurement is insensitive to such harsh environment. Figure 4.33 depict various applications of microwave radar-based level measurements. Some installations have a stilling well as well which can reduce the turbulence in the measurement liquid and also reduce the formation of foam, etc., which are potential constraints for proper measurement.

4.3.8.3 Selection Criteria

Radar-based level measurement is insensitive to pressure and temperature in the tank and environment inside the tank such as dust and vapor. The measurement is reliable for a known dielectric constant of the measurand. These types of instruments are selected based on the application, and site and vessel conditions. The antenna size and configuration depends on the desired measuring range, process conditions, dielectric constant, agitation, and foam.

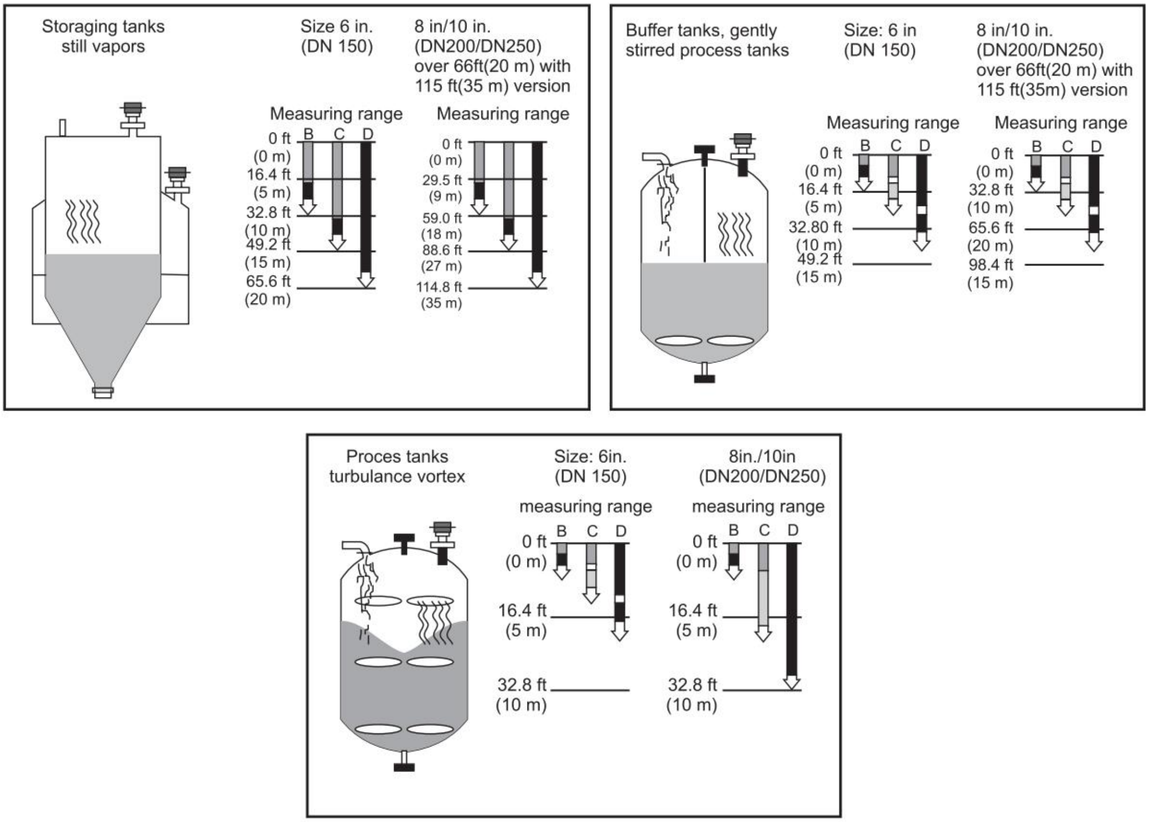


Figure 4.33: Radar device installed in a storage tank

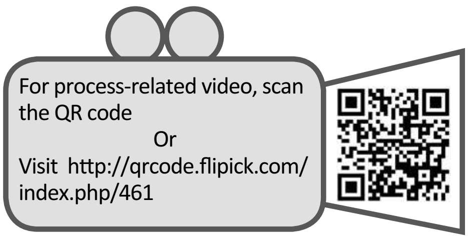
4.3.8.4 *Installation Guidelines*

The microwave pulse must, if feasible, turn up unhindered at the product surface. The subsequent guidelines must be considered:

- The transmitter axis should be at a 90° angle to the surface of the measurand, which is surface of the liquid or solid, etc.
- The edge or horn of the antenna shall be inserted inside the tank in such a way that the microwaves have undisturbed path to the surface of the liquid or solid.
- Installation of the antenna should be selected in a way which is away from piping's and fittings in the path of the beam.
- Avoid installation and mounting close to the filling steam or outlet as both these considerations create turbulence to the measurement.
- In synthetic tanks like fiberglass, PVC, polypropylene, or unleaded glass, the transmitter can be installed outside the tank, given the nonintrusive nature of measurement.
- Generally, the antenna is installed at a certain height above the maximum level range. This helps the transmitter to be away from harsh conditions such as high temperature

and material built up, etc. In some situations where the temperature is much more, a heat barrier is planned to avoid over heating of the electronics.

The advantage of using radar level measurement is its insensitivity to pressure, temperature, vapor and constant for a given dielectric constant. Radar level transmitters are also a good selection for interface level measurement applications. The disadvantages are erroneous and result in the presence of foam.



In this concept animation, the concept of operation of measurement of a level based on radar signals is explained. The radar signals are used and their time of flight on the surface of the liquid is also explained.

4.3.9 Level Detection and Measurement of Liquids and Solids Using Time-Domain Reflectometry

Microimpulse time-domain reflectometry, or MiTDR, is the technique used for measuring level in industrial applications. In this technique, a small microwave impulse is triggered on a wave guide, which can be a rod or cable. Figure 4.34 illustrate the conceptual view of the principle of operation. The signal is available in an area, wave guide, close to the cable or rod. Since the signal travels along the wave guide there is no deterioration of the signal quality and hence it is insensitive to the adverse process conditions inside the tank. In this technique, the time difference between the trigger of the microwave pulse and reflection response from the level surface is measured.

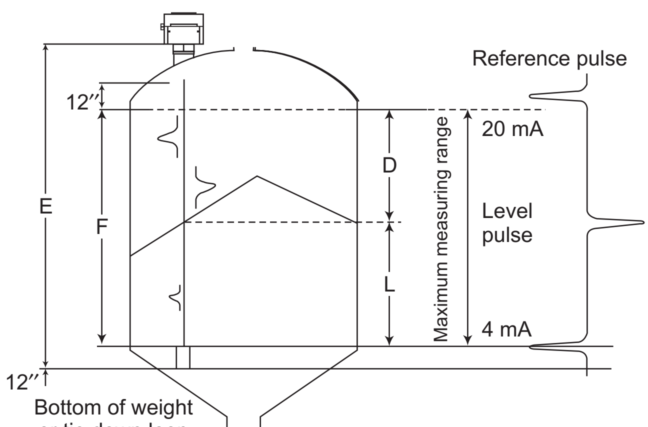


Figure 4.34: Time-domain reflectometry measuring principle

The reflection occurs if the signal around the wave guide or cable senses an area with a dielectric constant which is different from the dielectric of the area of its origination. For example, if the signal is triggered from the antenna in air which has a dielectric constant of 1 and as the wave propagates through the tank and senses a medium with dielectric constant of 1.8, the reflected signal is measured. The reflected pulse moves back up the probe to the pulse sampler. The same is reflected later to the electronics, and is detected and timed. The signal processing in the instrument calculates the time it takes to trigger the pulse to the time it senses a signal with different dielectric constant.

The pulse travels through the guide until the end and gives an empty signal if there is no process liquid to measure. Each time a sample or signal is triggered and reflections are measured across the wave guide. The received signal has a signature shape which is dependent on the dielectric of the material present around the wave guide. This can generate multiple reflections one each for change in dielectric at different layers. This is the primary reason for its ability to detect the interface levels.

Guided wave radar (GWR) or MiTDR is used in applications to measure the level of liquid in storage tanks for volume measurement. Careful evaluation is required to use these instruments for highly agitated liquids. Typical applications include measurement of solids in thin or tall bins with dusty and/or light materials.

The advantage of using MiTDR or GWR level is that the measurement is insensitive to the existence of vapor in the tank, steam, dust. The system also does not get affected by the changes in temperature, pressure and noise in the vessel, density, etc. For a known material with the given dielectric constant, the measurement will be stable and reliable in the calibrated range. The only drawback with this system is its invasive form of measurement and the associated constraints.

4.3.10 Level Measurement Using Nucleonic Gauging

Nucleonic gauging systems operate on a simple, noncontacting, nuclear principle—gamma radiation penetrates any material, but is absorbed in proportion to the amount of mass it penetrates. A small gamma source of radiation is safely housed in a shielded holder mounted outside the process vessel. When the shutter mechanism is opened, a collimated radiation beam is emitted. This gamma energy penetrates vessel walls, spans across the entire width of the vessel and is received by a detector—also externally mounted directly opposite the portion of the radiation beam. The detector senses this radiation change and produces a signal used to indicate an alarm, operate a recorder, or perform various control functions. Nuclear type devices work on the principle that process material absorbs (attenuates) radiation. On the outer side of one wall of the vessel, a nuclear source is installed which emits radiation while a nuclear detector is installed on the outer side of the opposite vessel wall. The nuclear source and detector are usually built in form of a strip. The type of radiation used is usually gamma rays (*X*-rays). As the radiation beams from source to detector, the process material absorbs some of the gamma rays. The amount of absorption is based upon the process material's density and the current process material volume within the vessel. As the liquid level rises, the liquid absorbs more of the radiation than the gas or air above the liquid. As the liquid level rises, the radiation detected decreases. The increase in level is determined from the decrease in detected radiation.

The design of nuclear radiation devices requires knowledge of the wall thickness of the vessel, vessel's dimensions, and materials of construction. From this information, the amount of radiation that will be absorbed when the vessel is empty can be determined. Then, the amount of radiation absorbed with the vessel full can be recalculated. The calculations may indicate that factors, such as wall thickness, can affect measurement resolution, since thick walls absorb more radiation.

4.3.10.1 Nuclear Devices

The measurement is truly "noncontacting" because all system components are external to the process. The systems are immune to effects of product temperature, pressure, corrosiveness, abrasiveness, or viscosity and also to vessel size, shape or construction (Figure 4.35).

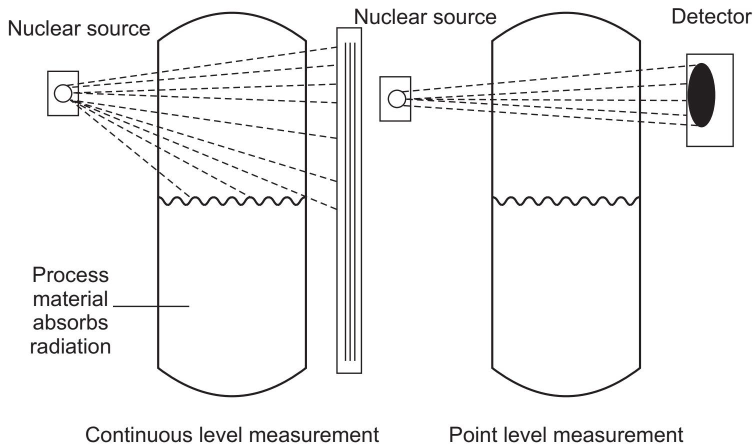


Figure 4.35: Level measurement using nucleonic gauging

There are two basic types of level measurements:

- **Single point:** This type of measurement is used for high/low conditions. Single point systems, utilizing a narrow conical radiation beam, are installed at one particular level. When the process material reaches that level, a relay is actuated.
- **Continuous:** This type of measurement is used for indicating exact material height within a designated span. Continuous systems use a fan-shaped radiation beam and a vertical ion chamber detector. As the process material rises, increasing amounts of radiation are blocked. The detector, sensing proportionally less radiation, produces an analog signal corresponding to material level.

4.3.10.2 Installation

A typical installation is one where a point or strip nuclear source is installed on one wall of the vessel, while on the outside of the opposite vessel wall a detector is installed. The devices are installed outside the tank—contact with the media is not an issue.

4.3.10.3 *Advantages*

- Performance of radiation devices is very good; reliability is excellent.
- Nuclear radiation devices are noncontact devices, and require very little maintenance.
- Nuclear radiation devices can be mounted outside the vessel.
- The devices can accommodate a number of tank geometries.
- Occasionally, nuclear radiation devices have automatic calibrations to account for the decay of the radioactive source.
- The devices are linear.

4.3.10.4 *Disadvantages*

- Radioactive material is on the process site, which requires meeting various regulatory and safety regulations.
- For industrial applications, the radiation source is usually cesium 137 or in some cases, cobalt 60.
- Nuclear radiation devices are usually under some form of governmental regulatory control.
- The regulations change frequently. The installation may require periodic checks for leakage.
- The user of the nuclear radiation device is responsible for obtaining the necessary approvals, not the vendor.
- Disposal of the device may require additional costs; the device cannot be simply thrown away.
- In summary, it requires an individual to assume personal responsibility for the device throughout its lifetime and stay current with nuclear radiation regulations.

4.3.10.5 *Applications*

Radiation devices find their main use in level and density measurements. In level measurements, two additional safety issues are worth mentioning. First, when a radiation device is used in a vessel, procedures must be established and followed to ensure that maintenance support personnel do not enter a vessel during a vessel shutdown or repair vessels while the radiation device is on. Second, radiation devices used for level measurement tend to be greater radioactive sources than those used for density measurements, so additional regulations may apply for nuclear devices used in level measurements. While the nuclear radiation devices have excellent performance results, users tend to look at nuclear devices as the measurement device of last resort, and may even then decide that the safety risks cannot be tolerated.

4.3.11 Load Cells for Level Measurement

Load cell level measuring devices actually measure mass, not level. Load cells are often installed on a vessel's structural steel supports. The structural steel support can be in the form of steel legs on a bin, skirted support structures, or chains suspending a small tank. Load cell sensors are mainly used for the measurement of dry dusty solids. When a vessel has an unusual, irregular shape, then load cells provide a suitable measurement solution.

4.3.11.1 Principles and Design

Load cells are either used as compression cells on vessel supports or used at the top of a suspended weighing pan. For example as shown in Figure 4.36, in a tank the support structures are at the bottom of the tank. Each support structure can be equipped with a load cell, called a compression type load cell. As material is added to the tank, the steel support structure begins to deflect. The deflection also implies that the compression on the load cells increases. The compression values are converted to a weight measurement. The other type of load cell system is the suspension system. The suspension system is used primarily for measuring solid weights. An example arrangement is one when the pan is suspended. Above the pan, a load cell is installed, which measures the force as the weight of material changes.

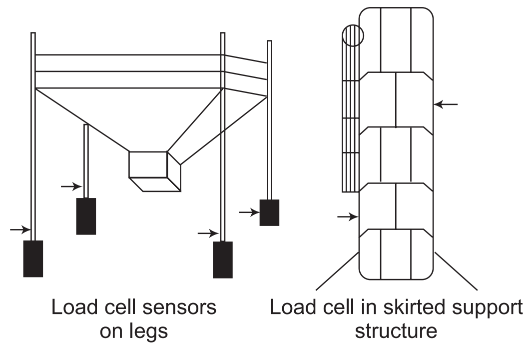


Figure 4.36: Load cell usage

4.3.11.2 Installation

The interface to a load cell is often through an RS 232 port. If there is more than one load cell, such as 16 load cells, the requirement for 16 RS 232 ports may be difficult to justify cost. Because a multidrug network arrangement is often needed to collect the data, the additional RS 232 ports become too costly. One approach is to take the RS 232 signal and convert it to an RS 485 signal. When the distributed control system (DCS) accesses data from one load cell the DCS designates a specific load cell. The load cell then responds to the request for current weight data. The requests, however, could be as slow as 10 requests per second. It is not unusual for users to write their own programs to access the data. When custom programs are written, maintenance personnel are often not familiar with what the program is trying to do.

4.3.11.3 Performance

The main consideration in compression load cells is that the weight should be applied vertically. Any side motions or forces on the tank can give erroneous readings. Any additional piping can have an adverse effect. In that case, flexible hosing is often recommended. Note that flexible hosing connections cause additional safety concerns as to whether it can withstand pressure, corrosive services, and flammable media. Load cells require little or no maintenance; however, some familiarity with RS 232 protocols may be required of the maintenance personnel.

4.3.11.4 *Applications*

Load cell sensors do provide an alternative to other level measuring devices when the goal is to measure how much of a dry dusty solid is present. Load cells are noncontacting with the process material. The noncontacting technology makes the load cell appropriate for materials that are corrosive, toxic, or viscous. Load cell sensors may be an alternative when a vessel connection or instrument ventilation is not possible. Load cells are a relatively expensive solution when compared to more conventional level measurement devices.

4.3.12 Level Switch

Level switches are often used in process interlocks, safety interlocks, and on/off (discrete) control applications. The use of level switches is especially important to applications that involve safety. Preferably, the level switch provides a point level measurement, which indicates whether a liquid is present or not present at a particular point in a vessel (Figure 4.37).

Figure 4.37 | Level switch installed in the bottom of the tank

For colored industry photograph visit http://highered.mheducation.com/sites/9385880527/student_view0/index.html

For example, if a pressure transmitter is installed at the bottom of the tank, the output of the transmitter can be taken to a pressure switch or on-off detectors. However, when safety is a consideration and the concern is a level exceeding a certain point, instead of using a pressure switch, one approach is to use a level switch. The level switch's purpose in this example is to determine whether a liquid level is there. Level switches can be used for liquid/gas, solid/gas, and liquid/liquid interface applications.

The technologies vary for level switches. The following discussion provides a brief description of technology as it applies to level switches:

- **Diaphragm:** The diaphragm is connected to a switch. When a level is present, it deflects the switch.
- **Float:** A float type could be inserted in the side or top of the tank when the level rises to the point level, the switch is tripped.
- **Displacer:** Displacer elements are usually short in length and have a narrow span.
- **Vibrating element:** Similar in concept to a tuning fork, an oscillating device on the outside of the tank vibrates the fork at certain amplitude of the vibration.
- **Ultrasonic:** Ultrasonic switches use a probe, inserted either on the top or at the side of the tank. The probe itself has a space. On one side of the space is a vibrating crystal; on another side of the space is a recipient. The signal reception decreases when liquid is in the gap.
- **Capacitance:** The capacitance probes are similar in design to the ultrasonic probes, except that they measure the capacitance in the gap.
- **Microwave:** Microwave level switches have a transmitter and receiver installed on opposite sides of the tank. If the vessel is empty, the signals are detected; if the vessel is full, the signals are not detected.
- **Conductivity:** A conductivity probe's electrode conduct current when level is sensed.
- **Paddle wheel:** Paddle wheels are reliable for detecting solid levels. The wheels move slowly and are able to detect when a solid is present.

For answers to checkpoint, scan the QR code

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Checkpoint

✦✦✦ **1.** In a servo level gauge, what happens in equilibrium condition?

✦✦✦ **2.** What is the principle of level measurement using pressure transmitters?

✦✦✦ **3.** In an open vessel level measurement, if the zero point is above transmitter, then why the zero suppression is to be made?

✦✦ **4.** The hydrostatic pressure from the liquid acts on which side of the pressure transmitter?

✦✦✦ **5.** What kind of pressure transmitter is suitable if a nitrogen blanket or vaporization pressure is present on the tank?

✦✦✦ **6.** What is a datum line?

✦✦ **7.** What is zero suppression?

✦✦ **8.** What are the other terminologies used for zero suppression?

✦✦✦ **9.** Explain why pressure transmitters for liquid level are not practical if there is constant change in specific gravity or density.

✦✦✦ **10.** In closed or pressurized tank applications, which transmitters are used to measure the level?

4.4 INTERFACE LEVEL MEASUREMENT

LO 4
Analyze interface level measurement

4.4.1 Definition of Interface

Process vessels such as separators permit immiscible liquids (i.e. liquids that are incapable of mixing) of different specific gravities to separate for further processing. The boundary between the immiscible liquids is called an "interface".

4.4.2 Purpose of Interface Measurement

Providing an accurate interface measurement is important because movement of the interface position or even reversal of one of the phase positions to the top or bottom of a vessel can cause lost production, increased operating costs, and even safety hazards. Interface measurements are frequently found in the crude oil cleanup steps of oil production. The cleanup of crude oil is essential in order for the oil to be transported properly and to be processed without causing fouling and corrosion of equipment. The interface measurements that are common in the cleanup of crude oil are usually one of the following:

- Field separation processes
- Crude oil desalting

4.4.3 Role of Interface Measurement in Field Separation

Field separation is one of the initial attempts to remove gases, water, and dirt that are contained in crude oil. Field separation is accomplished in large vessels that permit the crude oil to separate into three phases—gas, crude oil, and water. The separation process is often a function of gravity.

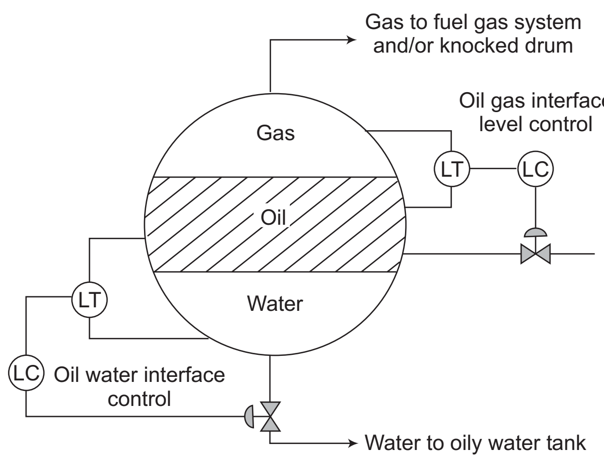


Figure 4.38: Interface in oil separation example

Because the crude oil is heavier than gas and lighter than water, field separations occur ideally into distinct layers of gas, oil, and water. The layer of crude oil appears within the vessel as a middle layer. The interface measurement in a separator (Figure 4.38) includes measuring the location of the gas/oil interface, as well as the location of the oil/water interface. It is important to measure the interface, because each layer within the separator is processed further. The gas layer is often pumped out for natural gas processing. The crude oil is pumped from the middle layer for more processing, such as stabilization. The water is pumped from the bottom of the separator to be disposed of at the well site.

4.4.3.1 Role of Interface Measurement in Crude Oil Desalters

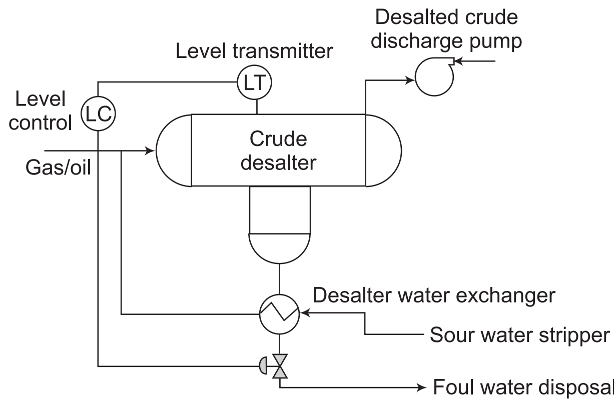


Figure 4.39: Crude oil desalting example

Crude oil desalting (Figure 4.39) is a water washing operation to treat crude oil for further processing. Crude oil from prior separation processes contains contaminants. These contaminants, if not removed, will plug equipment, dissociate at high temperatures and corrode equipment, and deactivate catalysts in refining processes. To prevent this from occurring, an important measurement that occurs within a crude oil desalter is the interface measurement. If the level is too high, then the electrostatic elements (voltage grid) within the desalter can short out. If the level is incorrectly measured as too low, then product is unnecessarily dumped. The oil/water interface must be tightly measured (and subsequently controlled) for the reasons previously mentioned. The challenge an engineer faces in this type of measurement is that a small change in level can make a very large change in volume. The reason for this is that crude oil desalted vessels are very large, containing large volumes of crude oil and water. Changes in crude oil and water densities by itself can cause erroneous interface measurements. These measurement considerations, along with the process operation objective of providing constant desalted throughput, create a measurement selection challenge for the engineer.

The role of interface measurements in plant operations again illustrates a consistent theme throughout this section—level measurement selection process is application dependent.

4.4.4 General Categories of Interface Measuring Devices

The following discussion describes general categories of interface measuring devices which include the following:

- Displacement devices
- Capacitance devices
- Hydrostatic head devices
- Other types of devices such as:
    - Float
    - Ultrasonic

4.4.4.1 Displacement Devices for Interface Level Measurement

The principles and design of the torque tube displacer is based on Archimedes buoyancy principle. In an interface application, however, the displacer is completely submerged. Selecting the proper diameter for the displacer is significant for interface applications. In an interface application, the upper liquid and lower liquid will have different specific gravities. In these applications, the lighter fluid surrounds the upper part of the displacer, while the heavier fluid surrounds the lower part of the displacer. The buoyant force that the displacer is trying to detect is dependent upon the difference in specific gravities, so larger diameter displacers are required when the specific gravity difference is small.

Performance For displacer units to detect an interface, a minimum difference in the liquid's specific gravities must exist. A reason for the added complexity is that in a typical process level measurement, liquid specific gravities of 0.5 or greater generate sufficient buoyant force. However, in an interface application, the differences in specific gravities between the liquid/liquid layers could be very slight. The need to measure a slight difference in specific gravity means that the sensitivity of the displacer must be very high. For example, one vendor's device requires that the minimum specific gravity between fluids must be 0.2 or greater. If the fluids are less than that 0.2 value, nonstandard displacers must be specified and selected.

Installation The displacer can either be installed inside the vessel or externally mounted for the interface application. When a displacer instrument is mounted internally in the vessel through a flanged opening, the displacer element remains inside the vessel. The displacer element actuates the switch or pilot mechanisms that are housed externally to the vessel. When a displacer is mounted externally (Figure 4.40), as is the case in many process applications, the displacer element is housed in an external chamber (also called a "float cage"). While this permits convenient maintenance without shutting down processes, some considerations should be noted.

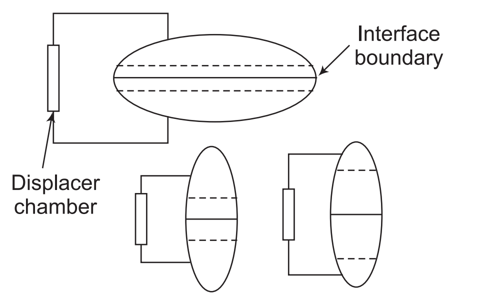


Figure 4.40: External displacer configuration

Some applications may require the following extra installation considerations:

- The displacer and connecting piping may need to be heated when the liquid is viscous.
- If the vessel temperature is high, the displacer chamber may require heating so that the liquid within the external chamber can be at the same specific gravity as the fluid within the vessel.

In a steam stripper application, the presence of water vapor and hydrocarbons creates the risk that hot droplets of condensed water vapor may fall on the hot hydrocarbon liquids inside the external displacer chamber. Boiling can occur, causing the displacer element to surge and provide false readings. To avoid this, a continuous flow of purge gas is necessary to minimize the amount of water vapor entering the chamber. Applications may require purging, diluting or limiting the fluid entering the external chamber to prevent material buildups on the displacer (Figure 4.41).

Applications Displacers are used in clean applications. Highly viscous material may cling to the displacer and affect the displacer's operation, requiring additional steps such as continuous purging of the external chamber.

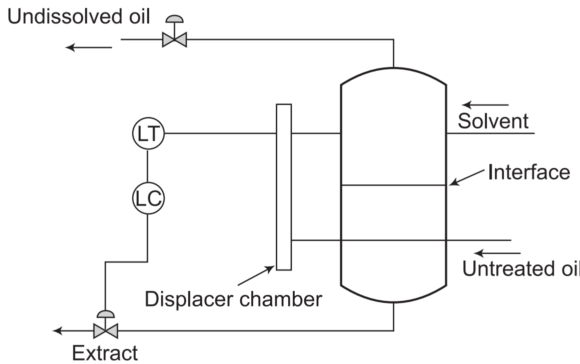


Figure 4.41: Interface measurement in settling tank

4.4.4.2 Capacitive Probes for Interface Level Measurement

Capacitance probes are well suited for interface measurements, as well as the process level measurements described earlier in the section. While a hydrostatic head device or displacer can be used to measure an interface, the measurement's sensitivity is often a function of the difference in specific gravities (densities). When a capacitance probe is used for an interface measurement, that device's sensitivity is a function of the difference in dielectric constants.

Principles and Design The principles and design, although described earlier in this chapter, are briefly reviewed to emphasize several concepts. Recall that the capacitance type probe measured the amount of capacitance between two plates of a capacitor. The vessel walls in most application became one plate; the capacitance probe became the other plate. The process material became the dielectric barrier to be measured between the two-capacitance plates. For interface measurements, it is very important to note that the capacitance probe is measuring only one variable. Therefore, in interface measurements, the capacitance probe can only measure one interface.

In an interface application, two interfaces may be present. The process may have a gas/upper liquid interface and upper liquid/lower liquid interface. The challenge for the engineer is to select a capacitance device or find a method that will ignore the gas/upper liquid interface. The goal is to measure only one interface, and there are two ways to accomplish this:

1. Design the vessel to be 100% full
2. Select a probe that ignores the gas/upper liquid layer.

Since it is not always practical for the vessel to be 100% full, the better option is to select a probe that ignores the gas/upper liquid layer. This is accomplished with capacitance probes that have inactive shields. The inactive shield covers the probes to a point that is below the gas/upper liquid interface. The inactive shield approach is a common method of solving the problem of applications that have two interfaces.

Performance If the interface is between oil and water, the dielectric constants for oil and water are much greater than the specific gravities for oil and water, giving the capacitance probe better sensitivity. However, if the interface involves measuring an acid, then the capacitance probe may not be as suitable if the material composition affects the dielectric constant.

Installation The small size and small process connections make the capacitance probe inexpensive and easy to install. The installation of the capacitance probe for an interface measurement has the same considerations as when it is used in measuring process level height. The considerations are listed as follows:

- Continuous level sensing probes are installed vertically. The probe should not come in contact with vessel walls or internal vessel structures.
- Point level sensing probes are installed horizontally. The goal is to provide a large change in the probe's wetted area for a small change in level.

If the tank walls and process media are non-conductive, additional ground reference electrodes may be necessary.

- The capacitance probe can be internally installed within the vessel or externally in an chamber. When used in an interface application, the installation of the capacitance probe also has the following consideration:
- The continuous level sensing capacitance probe's inactive sheath extends to a distance that is just below the interface (Figure 4.42).

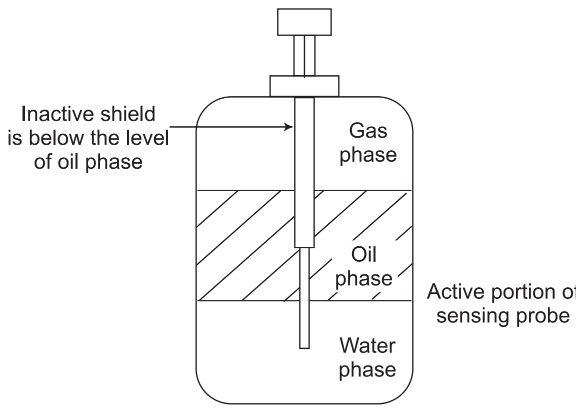


Figure 4.42: Probe installation

Applications Capacitance probes are best applied in relatively clean products that do not have heavy buildup problems. If buildups are anticipated, capacitance probes are available that include anticoating technology. Capacitance probes can be used in difficult applications, including those that have high temperatures and pressures.

When used to measure an oil/water interface (Figure 4.43), the water phase is measured since an aqueous phase is more conductive than an oil phase. The oil phase is often considered an insulating phase with relatively insignificant changes in capacitance. The following applications are also possible with capacitance probes:

- Point level sensing of water bottoms in an oil stock tank is accomplished through the use of a horizontal interface probe.
- Continuous level sensing of the interface level in a heater treater
- Point level sensing of the interface in a heater treater. The horizontal probe here is used as a backup to a continuous level sensing probe.
- Continuous level sensing of the interface in a skim oil tank.
- Point level sensing of the interface in a skim oil tank. The horizontal probe here is used as a backup to a continuous level sensing probe to provide a low interface alarm.

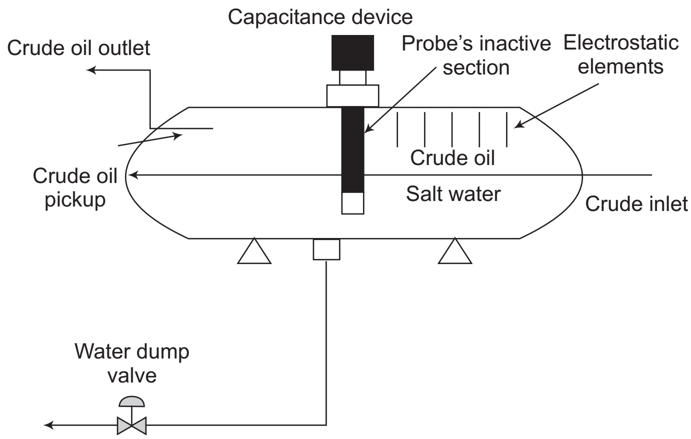


Figure 4.43: Application-crude oil desalter

4.4.4.3 Hydrostatic Head Devices for Interface Level Measurement

The following discussion refers to the use of microprocessor-based pressure transmitters to measure an interface position. An advantage of using this approach is that the hydrostatic head method provides a continuous measurement (as opposed to a point level detection) of the interface position.

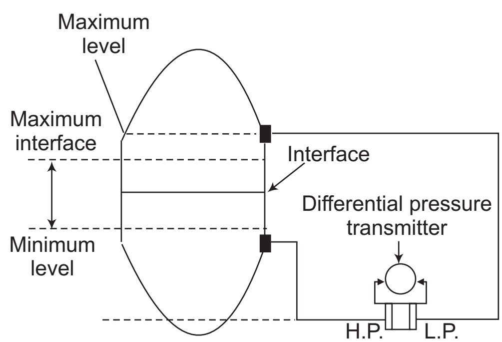


Figure 4.44: Hydrostatic method for interface detection

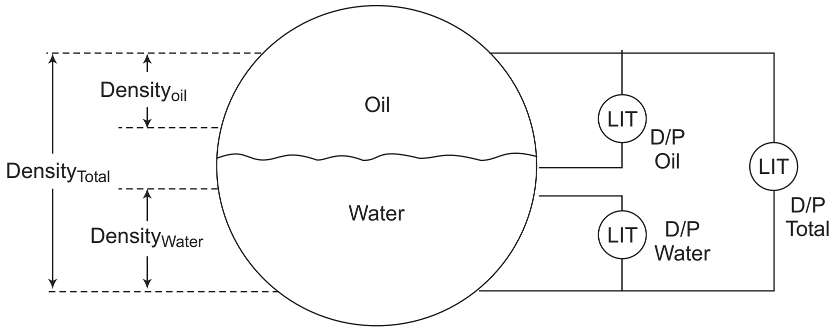
Principles and Design The span of the differential pressure transmitter in Figure 4.44 is configured to locate the interface level. The span is based on the difference between the liquid's specific gravities and the distance between the maximum and minimum interface levels. The following calculation is used to determine the span:

$$\text{Span} = H(SG_2 - SG_1), \tag{4.30}$$

where, H = distance between maximum and minimum interface levels, SG_1 = specific gravity of liquid 1, SG_2 = specific gravity of liquid 2

Additional calculations may be required for any range suppression or elevation.

Performance and Installation The measurement of an interface with less than a 0.1 difference in specific gravities is difficult when conventional 4–20 mA transmitters are used. When microprocessor-based transmitters are used, it is possible to measure down to smaller differences in specific gravities. For example, a 0.05 difference in specific gravity can be controlled within a 7.5% level change. A conventional transmitter would require a 20% change in level before it would detect this change. Microprocessor-based transmitters can better detect the shift in interface position. One assumption in the use of differential pressure transmitters is that the specific gravity of the two liquids does not change. The assumed specific gravity is then used to calibrate the differential pressure transmitter. The concern is that an unchanging specific gravity can cause undetected measurement errors. Interface positions are then incorrectly reported when the specific gravity of the liquids change. In Figure 4.45, several pressure transmitters are employed, two pressure transmitters are used to account for the specific gravity change in each liquid, one is used to measure total head pressure.



$$\% \text{ Level interface} = \frac{(\text{D/P Total/Density total}) - (\text{D/P water/Density water})}{(\text{D/P Oil/Density oil}) - (\text{D/P water/Density water})}$$

Figure 4.45: Multiple DPs for interface detection

Performance advantages are listed as follows:

- Continuous measurement is provided in this method
- Hydrostatic method is not susceptible to foaming and bubbles

Performance disadvantages are listed as follows:

- Movement of interface level position should be large enough to be detectable by differential pressure transmitters.
- Hydrostatic method can be susceptible to changing specific gravities

Applications Microprocessor-based pressure transmitters can continuously measure interface position for liquids whose specific gravities can change.

4.4.4.4 Other Types of Interface Devices

Other types of devices include the following:

- Float
- Ultrasonic

Float Floats are available for measurement of liquid interface. The float is weighted so that it floats on interface position. The floats used for interface measurement are larger than those used for level indication.

Ultrasonic Special transducers are available from manufacturers to permit ultrasonic detection of an interface. Usually this is a point level measurement. To operate properly, the device is installed at a 10° off horizontal angle. Another approach is to install the ultrasonic device at the bottom of the vessel and reflect signals off the interface position.

4.4.5 Selecting an Interface Device when Emulsions are Present

Of particular concern in separators is the occurrence of emulsions of crude oil and water (Figure 4.46). What makes an interface measurement particularly challenging is an emulsion layer, up to 1 or 2 meters thick, can appear. The thick emulsion layer can make it difficult to properly measure and control the interface. Capacitance devices perform best if you need a small percentage water in oil. However, if you need a small percentage of water oil in water, then the application becomes challenging. Under those requirements, the emulsion layer makes it difficult for level measurement devices to identify the interface. As a result, the controller does not get the proper measurement information of when to dump water from the separator. Ideally, you do not want to dump the emulsion.

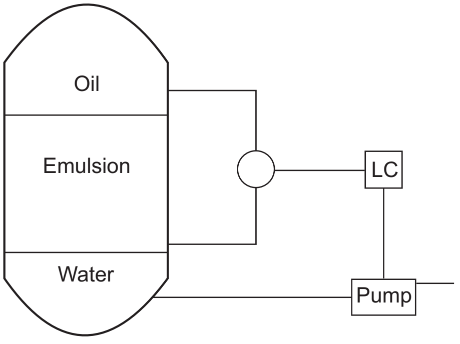


Figure 4.46: Emulsion presence in interface

Fortunately, some interface measurement approaches have had success in this approach, and are briefly listed. For this particular application, consulting with the instrument vendor is recommended. The intent of this brief overview is to illustrate that more than one level measuring device can be used for a difficult interface application. The devices are the following:

- **Microwave probe:** Some microwave probes are able to detect very small amounts of water in hydrocarbons. The probes are not temperature or salinity sensitive. Coatings such as paraffin or tar do not hinder probe operation.
- **RF admittance probe:** The RF admittance probe can be spanned across all liquid layers. Doing so creates a measurement that is the average of all three layers. The interface can be measured to an inch within a 3 ft diameter vessel. The probe has negligible effects from heavy bitumen asphaltic coatings and temperature extremes.
- **Differential pressure transmitters:** Two differential pressure transmitters installed slightly above the discharge line can measure the density. The varying density is measured as the emulsion layer travels within the vessel.
- **Conductivity sensors:** Installing two conductivity sensors that are sensitive to the low conductivity variances can be used. One sensor is installed at the interface level, while another is installed at the bottom of the vessel.

When emulsions occur in an interface measurement, processing methods are often used to minimize the emulsions. Some of the known methods of processing methods of emulsion are heat treatment, allowing the gravity to settle the emulsion or adding chemicals.

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✦✦✦ 1. Define "interface" in the context of industrial level measurement.

✦✦ 2. Which are the common applications of interface measurement in crude oil cleanup?

✦✦✦ 3. What is the minimum condition that must be met for the displacer to be used for interface measurement?

✦ 4. Explain the reason why the purging or diluting on external chamber of the displacer is required?

✦✦✦ 5. In capacitive probe, the interface level is sensitive to which physical property of the liquid?

✦✦✦ 6. When a capacitive probe is provided with anti-coating technology?

✦✦ 7. How span is calculated for the interface level measurement using hydrostatic head devices?

4.5 AUTOMATIC TANK GAUGING

LO 5
Analyze automatic tank gauging system

The term "automatic tank gauging" represents a measurement system that provides an accounting of hydrocarbon inventories. The accounting of inventories places demands that the process measurements be highly accurate so that the subsequent inventory calculations, which are in part based upon the level measurements, are also accurate. An ATG system may include level, temperature, and density measurements. Because level measurement plays an important role in the tank gauging system, the selection of a level measuring device or system places several unique challenges upon the engineer.

While tank gauging includes a variety of process measurements and calculations, it is often regarded as a separate measurement discipline and not just another form of process level measurement. For example, an ATG system may compensate the measured level quantity and calculate level data for changes in the tank structure itself as the tank fills and empties. Tank gauging measurements of level are used to derive mass and volume data.

The following discussion is mainly concerned with the level measurement aspect of tank gauging. What is important to note in determining whether a level measuring device meets tank gauging requirements is the purpose of a tank gauging application, how the level measurement data in a tank gauging application is derived, and how important the level measurement is to the end user. In order to have an adequate background and understanding of the role of level measurement in tank gauging, the following topics that influence level measurement device selection are discussed.

- Purposes of level measurement in tank gauging:
    - Differences between tank gauging and process level measurement
    - General comments about tank structures

- ATG techniques
- Float and tape devices
- Servo-driven displacers
- Radar devices
- Ultrasonic devices
- Hydrostatic tank gauging (HTG)

4.5.1 Purposes of ATG

Tank gauging has as its purposes one or both of the following—account for inventory and/or ownership transfer and provide effective process operations.

4.5.1.1 Account for Inventory and/or Ownership Transfer

Tank gauging provides measurement data that is often needed for inventory control purposes. Various departments, such as management, sales, and accounting, need to know what hydrocarbon inventories they have to successfully do their jobs. The inventory data includes gross volume, standard volume, mass, and level data. Many times the custody transfer operations are accomplished through flow metering; a significant amount of custody transfer is accomplished through ATG. When ATG is used for custody transfer, the accuracy of measurements becomes important. Before and after the product transfer, the level of the tank is read. The difference in level can be used to determine the amount of material delivered or received. Custody transfer information goes into billing, so accuracy of inventories is of considerable importance.

4.5.1.2 Provide Effective Process Operations

Note that not all tank-gauging measurements are just for the purposes of inventory management and custody transfer. Tank gauging is also important to process operations personnel whose foremost concern may not necessarily be inventory management. Operations personnel are concerned that they do not overfill a tank, or when discharging a tank, empty the tank dry. To provide safe operations, operations personnel need to know the level and volume-to-safe fill height so they can safely transfer product into and out of the tank.

Operations personnel can also use tank-gauging data for assessing feed rates and yields. As an industry example, tank-gauging measurements are sometimes used in blending operations. For example, the tank gauging system could have a role in the initial processing of crude oil. Crude oil streams from several tanks can be blended to a consistent density (API number), then charged to a surge tank before entering a crude distillation process. Blending to a consistent density has the effect of providing smoother process operations of the crude distillation process. These kinds of operations are dependent to some degree upon ATG, of which level measurement plays a role.

4.5.2 Differences Between ATG and Process Level Measurement

To have a better understanding of the differences between tank gauging and process level measurement, the following differences are briefly reviewed—accuracy requirements, data access intervals, communication path and types of data required.

4.5.2.1 Accuracy Requirements

One major difference between tank gauging and process level measurement is that the accuracy of tank gauging systems may approach the accuracy requirements of custody transfer systems. A reason for using highly accurate tank gauging systems is the concern that the increased yields in automating processes are often lost in less than accurate tank gauging systems. Additionally, highly accurate tank gauging systems provide better information on process performance.

4.5.2.2 Data Access Intervals

Tank gauging systems provide management information systems (MIS) departments measurements at scan rates of about every minute. Process level measurements have scan intervals of 1 second or less to continuously monitor and/or control a level.

4.5.2.3 Communication Path

Another difference between tank gauging systems and a typical process level measurement is that a different communication path is used between the storage tanks (tank farm) and the control system. The communication path for a typical process level measurement system is its 4–20 mA signal to a controller whereas for a tank gauging system, a separate data highway or network is used, where the control system get its data from a field interface unit. The field interface units consist of microprocessor-based technology that receives the process signals such as level, pressure, or temperature measurements. The field interface unit uses that data to make density and mass and volume calculations. The field interface unit then sends its data to a remote system.

4.5.2.4 Types of Data Required

The previous discussion about field interface units correctly implies that tank gauging supplies a variety of measurements and calculated data. The typical data that a tank gauging system provides often includes level, average temperature, water bottoms, density, gross volume, standard volume, and mass. The measurements can be provided by either of several tank-gauging techniques.

4.5.3 Tank Gauging Techniques

The distinction among the tank gauging techniques is that typical tank measurement data—such as level, volume, mass, and density—is derived differently. Depending upon the technique, data is derived through either direct measurement, inferential measurement, calculations, or some combination thereof. Thus, the accuracy of the data depends on how the data is derived.

Knowing how the data is derived and how important accuracy is to the end user influences the level measuring device selection. The tank gauging techniques are:

- Level-based techniques
- Pressure-based techniques
- Combined (hybrid) techniques

4.5.3.1 Level-based Techniques

Level-based techniques employ devices such as float and tape devices, servo-driven displacers, and radar as the level measuring devices for obtaining a direct level measurement. The techniques use one of these level-measuring devices to get the most accurate level measurement possible. Accuracies of tank gauging are to be 1/16″ or 1.6 mm according to some specifications from the plants. A rationale for such a high degree of accuracy is to have the most accurate level measurement for the subsequent volume and mass calculations. To arrive at mass, a lab sample is required to get the density value for the mass calculation. Level-based techniques provide the most accurate level measurement compared to pressure-based techniques. Some vendors claim accuracies up to ± 0.8 mm (±1/32″). However, the density measurement, because it is a lab sample, requires personnel to make the measurement. The lab sample itself may not necessarily be representative of the average density of the entire tank's hydrocarbon inventory.

4.5.3.2 Pressure-based Techniques

Pressure-based techniques employ a method called hydrostatic tank gauging. HTG uses highly accurate microprocessor-based pressure transmitters to arrive at a measure of the weight or mass of the product. HTG is sometimes referred to as a "mass-based system." HTG represents a fundamentally different approach to tank gauging. Pressure-based techniques provide the most accurate mass measurement, compared to level-based techniques. Because it is a mass-based approach, some users feel that HTG is inherently more accurate than level-based systems. If a level measurement is needed, an additional density measurement is made. The level measurement is calculated—the calculation is based upon the pressure and density measurements. The pressure-based technique of HTG is not new to tank gauging; it has been known for several decades. Only in recent years has accurate and stable technology been available to make HTG practical.

4.5.3.3 Combined (Hybrid) Techniques

Combined (hybrid) techniques employ a method that combines both level and pressure measurement technology. The rationale behind this approach is that the best of both level-based and pressure-based techniques are combined to make very accurate level, mass, and density measurements.

4.5.4 Tank Structure Considerations when Selecting Level Measuring Devices

To determine valid level, mass and volume data also requires an understanding of tank structures, which are beyond the scope of this learning objective. Nonetheless, some general comments about tank structures are made in order to place a sufficient perspective on level measuring device selection for tank gauging systems. The considerations can be summarized as follows—imperfections of tanks, fixed versus floating roof tanks, importance of reference point to level measurement.

4.5.4.1 Imperfections of Tanks

Tanks are imperfect objects, so level measurement errors are possible unless allowances are made for the imperfections (Figure 4.47). Current tank gauging systems often include technology, called correction or strapping tables that compensate for changing process conditions. While the objective of tank gauging is to measure level to 1/16 in or 1.6 mm, within a very large tank, 1/16 in or 1.6 mm is a small distance to measure. Tank imperfections by themselves can contribute to errors of a larger magnitude. Tanks are also elastic. Thermal stresses cause tanks to expand and contract with temperature. Tanks change shape as they fill and empty. The large quantities of liquid within the tank also present measurement challenges. For example, the liquid itself can experience temperature and density stratification. Stratification can cause the temperature and density measurements to not reflect current product conditions and as a result make the resulting mass and volume calculations suspect. Fortunately, many tanks have re-circulation equipment to reduce the effects of stratification.

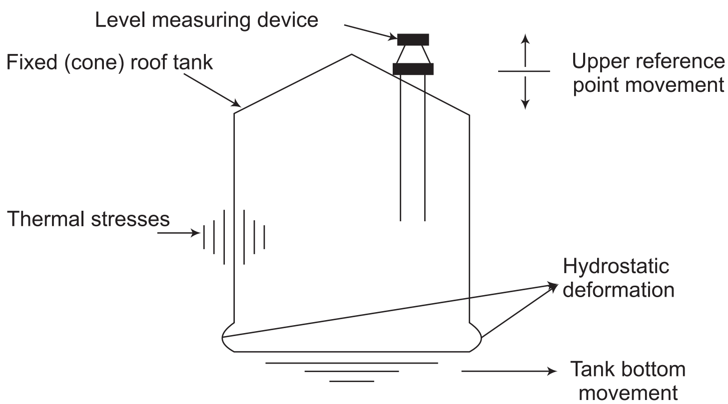

Figure 4.47: Tank imperfections that affect level measurement

4.5.4.2 Fixed Roof and Floating Roof Tanks

Fixed roof and floating roof tanks influence level measuring device selection for tank gauging systems. To minimize floating roof errors, one option is to install a still-pipe within the tank. The still-pipe, also referred to as a stilling well, is an independent structure within the tank. The still-pipe does not deform during the filling and emptying of a tank. Because the still-pipe is not a structural member of the tank, its rigidity is much better than the tank walls. Occasionally, the level measuring device is installed on top of the still-pipe structure in order to provide an accurate measurement.

4.5.4.3 Importance of Reference Point to Level Measurement

Regardless of how accurate or sophisticated a level-measuring device may be for a tank gauging application, movement of a tank gauging mounting or reference point always causes the largest measurement error. Addressing the movement of a tank gauging mounting or reference point should be the engineer's foremost concern whether the tank gauging is automatic or manual.

The imperfections and elasticity of tanks are such that selecting a level measuring system for a tank gauging application can indeed be very challenging. These challenges have led to tank gauging technologies that have evolved and continue to evolve. The types of ATG systems include:

- Float and tape
- Servo tank gauge (STG)
- Radar tank gauging (RTG)
- Hydrostatic tank gauging
- Ultrasonic

Note that industry literature often uses abbreviations ATG, FTG, STG, HTG, RTG to identify ATG systems. ATG encompasses all technologies, which include FTG, STG, HTG, and RTG. Acronyms FTG, STG, HTG, RTG identify a specific ATG technology. HTG is one of the more commonly used acronyms; less frequently used abbreviations are FTG, STG, and RTG.

Float and Tape Devices Float and tape devices, also referred to as "mechanical gauges", are perhaps the earliest tank gauging system and continue to be extensively used in many industrial applications.

Principle and Design The simplest description for a float element is that a float element is a buoyant object that rests directly on the liquid surface. The float element is guided along a set of wires to keep the float from shifting horizontally. A float must be kept in a vertical plane in order to provide an accurate measurement. The guide wires have anchors for them at the tank bottom, as well as spring mechanisms at the tank's top that maintain tension on the guide wires. The float element often has a wide diameter, about 381 mm (15 in), to minimize the potentially detrimental effects a product's changing specific gravity has on the level measurement. A float has a wide diameter because if there is a change in the liquid's specific gravity, the resultant change in the float's immersion depth is less for a wider diameter float than a smaller diameter float.

A perforated tape is connected to the float. The perforated tape is also connected to a gauge head assembly. The gauge head assembly provides the level indication. Within the gauge head assembly is a sprocketed counter drive and tape storage spool. The perforated tape is routed over the sprocketed counter drive and tape storage spool. The shaft of the sprocketed counter drive is connected to a level readout indicator. The tape storage spool inside the gauge head assembly is able to wind and unwind the tape as the float element rises and falls with the liquid level.

The gauge head assembly is either mounted on top of the tank directly above the float, or next to the tank at grade (ground level). When the gauge head assembly is attached to the top of the tank, the operator has to climb up to the top of the tank in order to view the readout indication. In a fixed roof tank (Figure 4.48) that has a

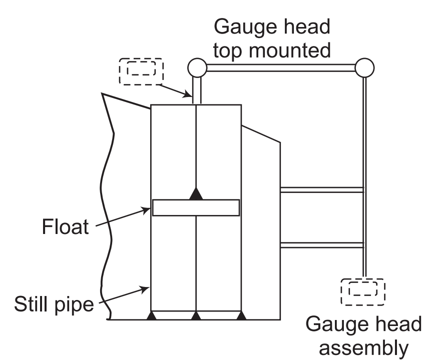

Figure 4.48: Float in fixed roof tank

still-pipe, the gauge head assembly is preferably mounted at the top of the still-pipe. The float element rests on the liquid level within the still pipe. Although the float is within a still-pipe, guide wire assembles are still present to keep the float in a vertical plane.

Performance Properly installed float and tape devices are capable of highly accurate measurements. Although float and tape devices represent one of the earliest tank gauging technologies, they can be accurate up to 1.6 mm (1/16 in). However, the installation (described later in this section) of a float and tape device has a major influence on its accuracy. Additionally, a tank builder may provide the float and tape device as a tank accessory (appurtenance). Note that if the float and tape device is purchased as a tank accessory, it may not have necessarily received the attention from the tank builder that a float and tape device requires to perform accurate measurements.

The performance advantages of float and tape devices include:

- Direct level measurement (not by inference)
- Relatively inexpensive device
- No limits to height of tank
- No limits to specific gravity

The performance disadvantages of float and tape devices include the following:

- Accuracy dependent upon installation (3.2 mm to 1.6 mm if installed on still-pipe, 254 mm or more if installed at grade).
- Accuracy may not be acceptable for custody transfer operations.
- Accuracy may be questionable for inventory operations, given the increasing value of petroleum products and desires for more precise inventory control.
- Over a period of time, float, and tape devices can become very maintenance intensive. Types of maintenance issues include:
    - Moving parts exposed to fluids
    - Tapes can bend or break
    - Tank obstructions interfere with float
    - Float must be kept clean
    - Floats can be difficult to repair if breakage occurs inside tank

Installation The installation of a float and tape device has a major influence on its measurement accuracy. A typical industry installation is to mount the gauge head assembly at grade on the side of the tank.

Installing the float and tape in this fashion can lead to measurement errors in the range of ±2.5 cm (±1 in). The error can be higher if the device is not properly maintained. A reason why the error is high is that the tape has to be routed from inside the tank from the float to the outside assembly at grade level. When a tank wall grows or shrinks because of thermal and/or hydrostatic influences, the tape also moves. Tape frictions and effects of corrosion also contribute to errors. Grade-mounted tape and float devices also experience the largest error when its top reference point moves down during tank filling, resulting in an under delivery of product. If float and tape devices are installed on the top of the right kind of still-pipes or stilling wells, they become inherently more accurate, with accuracies up to ± 3.2 mm (±1/8 in).

However, a typical industry practice is that floating roof tanks rarely have float and tape devices mounted on top of a still-pipe. Instead, the float and tape device pulleys are supported from the side of a tank. The exposed tape can experience errors due to windage.

Applications Generally, float and tape devices represent a mature technology that is being replaced with level measuring devices, such as improved STG, HTG and RTG. Float and tape devices are used in tank farm applications, primarily in liquid services.

Servo Tank Gauge A servo-driven displacer (Figure 4.49) can eliminate many of the problems experienced with a float and tape device. STGs are expensive and regarded as precision instruments. They are popular with users today because manufacturers based the design on the automation of a manual tank gauging process called hand dipping.

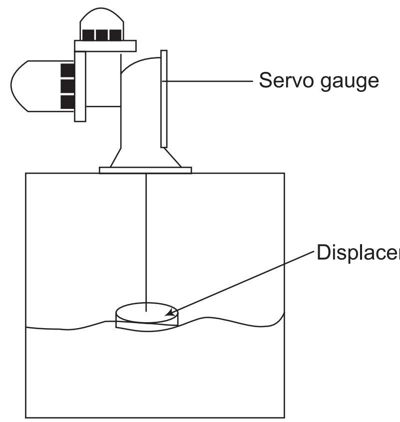

Figure 4.49: Servo-driven displacer

Principles and design The difference between a float element and a displacer element is that the displacer element is heavier than the liquid it is immersed in, while a float element rests on a liquid surface. Refer Figure 4.50 for internals of the displacer. The displacer element sinks into the liquid unless it is restrained by a cable connected to a servo assembly. The servo winds and unwinds a cable so that it is always supporting the displacer. The displacer, because it is denser than the liquid, has fixed weight. The combination of the fixed weight of the displacer and the weight of the cable means that a known amount of tension should be on the cable when the displacer is immersed in the liquid. The servo assembly maintains that constant tension on the cable, and uses that tension (along with the length of cable extension) to determine the level surface. As the level changes, the servo senses changes in the cable tension. The servo assembly winds or unwinds a cable accordingly to change in the displacer position so that an equilibrium tension is always maintained. In effect, the displacer is continuously weighed, and as a result, the level is constantly monitored. The servo-driven displacer uses precision force transducers and microprocessor based technology to make highly accurate measurements and 0.004 in repeatability.

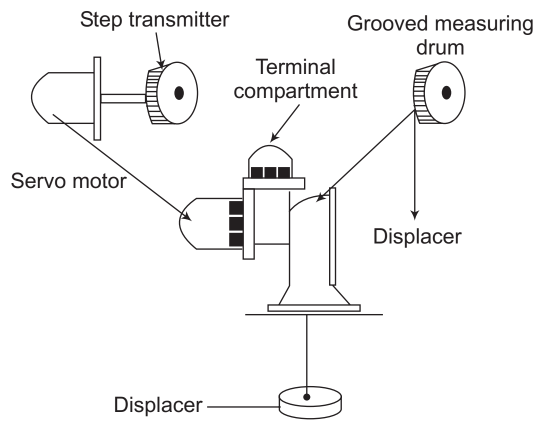

Figure 4.50: Principle of servo-driven displacer

Performance Because currently manufactured servo-driven displacers have less moving parts, currently manufactured servo-driven displacers have better reliability than earlier servo devices. For example, one manufacturer reduced the number of parts from nearly 100 parts to essentially three parts (the servo spool, the cable, the displacer element). Some vendors claim measurement accuracies to ±0.8 mm (± 1/32 in). The advanced servo-driven displacers have accuracies that are approved for use in custody transfer operations.

Installation In addition to the references listed in Figure 4.51, the following references apply to servo-type displacer installation. Review these references (as well as the vendor's supporting documentation) for additional detail when determining a device's suitability for an application.

Applications Servo-driven displacers are best suited for clean applications, such as finished products like gasoline and diesel fuel. Because the displacer element is denser than the liquid, STG also find usage in measuring liquid interfaces. Some tanks operate with water at the bottom of a tank (also called "water bottoms" or "swimming pools"). STGs can also be used to detect the interface in those applications. Additionally, in an interface application, the same STG that is used to measure surface level can be programmed to periodically descend and locate the interface. Density measurements are also possible with STGs.

Radar Devices Radar devices have been described in detail in the previous sections of this chapter. Several additional comments are made in this section as they apply to tank gauging and level measurement device selection.

Principles and Design The basic principle described earlier is that a radar device, mounted on top of a tank (Figure 4.51), simultaneously sends a signal to the surface, and senses the reflected echo signal. The time it takes for the reflected signal to return becomes the theoretical basis for calculating product level. Radar devices provide a direct level measurement reading. Most RTGs have temperature measurement capabilities as options.

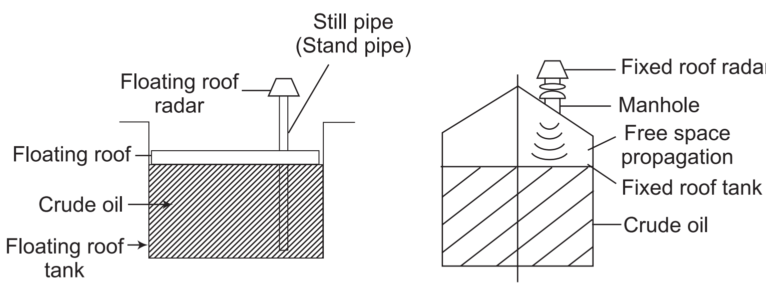

Figure 4.51: Tank radar operations

Performance and Applications The performance and application of radar devices is described in detail in an earlier part of learning objectives. An additional comment regarding performance is that radar devices are available from vendors in performance tiers. In other words, radar devices are available from vendors that are designed just for ATG applications. The more accurate radar devices, which are those that provide ±1 to 3 mm (±0.04 to 0.125 in) accuracies for tank gauging, are more expensive than radar devices used in process level measurements.

Performance considerations of radar devices are:

- Smoothness of liquid surface
- Foaming, moisture, error due to internal tank pressures, and internal tank structures

Hydrostatic Tank Gauging Hydrostatic tank gauging systems use pressure measurements to derive (calculate) values for level, mass, density, and volume. Of the HTG derived values, mass measurement is the most accurate. Because HTG measures the hydrostatic pressure at the bottom of a tank, it is best to think of HTG as a method of measuring oil mass. The HTG method represents a fundamentally different approach to tank gauging. Unlike direct level measuring systems, HTG systems infer the level measurement. The level measurement is inferred from a pressure measurement. The density measurement unlike float, radar, and servo-driven displacers is a current density measurement.

Principles and Design An HTG system (Figure 4.52) consists of one to three highly accurate pressure transmitters, a resistance temperature detector (RTD), and an optional hydrostatic interface unit (HIU). The HIU converts the measured pressures and temperature into product density, mass, volume, and level. The HIU also takes into account the changing physical shape of the tank. In an HTG system, one pressure transmitter must always be installed at the bottom of the tank.

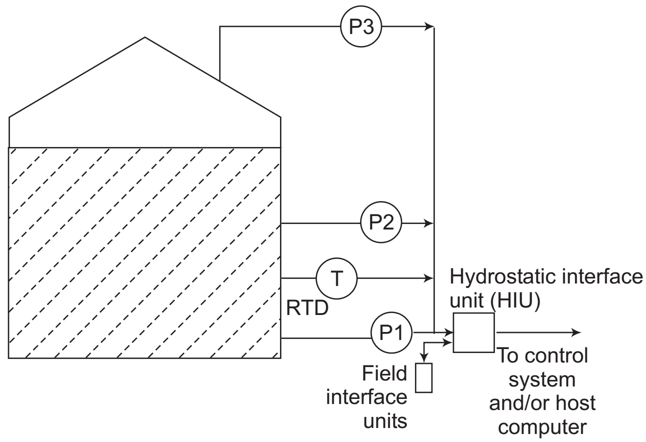

Figure 4.52: HTG system

If direct measurement of density is needed, a second pressure transmitter is installed. The second transmitter is installed at a short distance (usually about 8 ft) above the lower pressure transmitter. The pressure difference between the two transmitters provides the data for a density calculation. The density value is then used to calculate level and standard volume. A third pressure transmitter is located at or near the top of the tank if the tank is pressurized. The third pressure transmitter reads pressure in the tank vapor space. The pressure reading from the third transmitter is subtracted from the first pressure transmitter at the bottom of the tank. If the tank is an open tank or is at atmospheric pressure, then the third pressure transmitter at the top of the tank is not necessary (Figure 4.53).

Table 4.2: HTG calculation	
Measurement	*Calculation*
Density	Density = (P1 – P2)/Distance between P1 and P2
Level	Level = (P1 – P3)/Density
Mass	Mass = (P1 – P3) × Area
Area	Equivalent area from tank strapping table, determined by dividing volume by level, area = volume/level
Standard volume	Standard Volume = Mass/Density$_{\text{at reference temperature}}$

An RTD is normally provided in HTG systems. The RTD is installed in between the two lower P1 and P2 transmitters. The RTD provides the temperature of the liquid between the two lower P1 and P2 transmitters. The temperature reading from the RTD is necessary for calculating inventories at standard conditions (Table 4.2). Note that liquid temperature is not needed for the mass calculation. The purpose of the temperature reading is to take current density value derived from the two pressure transmitters, P1 and P2, and reference the current density back to standard conditions. The current density and temperature are used to derive the standard density (or API gravity at 60°F), often referred to as "D_{ref}". The reference density, D_{ref}, is used in the calculation of net standard volume.

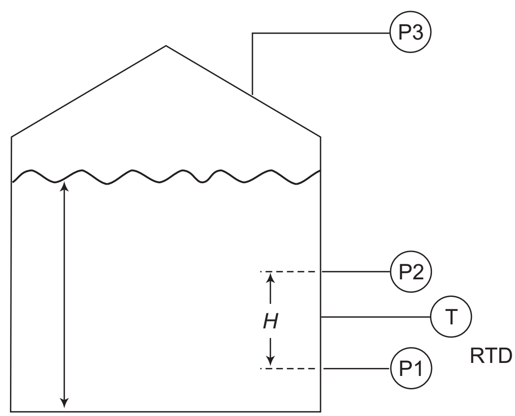

Figure 4.53: HTG measurement

Performance Performance advantages of HTG include the following:

- Provides a noncontacting measurement
- No moving parts, no tank internals, grade accessible
- Easier and less maintenance
- Installation possible while tank in service (hot-tapping)
- Direct density and mass measurement (as opposed to density from a lab sample).
- Provides an inherently more accurate mass measurement than level-based systems.

Performance disadvantages of HTG are listed as follows:

- Density and/or temperature stratification may affect HTG calculations. For example, the density measured between P1 and P2 may not necessarily represent the product density throughout the tank. The distance between P1 and P2 may only represent 20% of the total tank height, so it is possible the density between P1 and P2 may not be representative of the whole tank.
- Provides less accurate level measurement compared to currently manufactured servo-driven displacers, radar, and properly installed float and tape devices.

- Although an HTG system may provide a level measurement accuracy of 1/4 to 1/2 in, it does not mean that HTG is inferior to currently manufactured servo-driven displacers, radar, and properly installed float and tape devices. As the general comments on tank structures suggest, any level measurement accuracy should not be assumed constant for all level measuring devices given fixed reference point movements. Whether the level measuring device is servo-driven displacer, radar, float and tape, HTG, or ultrasonic, accuracy is dependent on product type, tank size and geometry, and other installation factors.
- Proper installation is important in HTG systems because the hydrostatic deformations that occur when a tank is filling can literally cause movement in the upper reference point, as well as movement in the distance between P1 and P2. Fortunately, microprocessor-based technology provides compensation algorithms for tank deformations. A standard recommendation for pressure transmitter installation (when the vessel is a spheroid or bullet) is to have the bottom pressure transmitter, P1, installed as close to the bottom as possible. The second pressure transmitter, P2, should be installed at about 20% of the tank height above P1 (Figure 4.54). Minimum distance between P1 and P2 is 2 ft maximum distance is 8 ft. An installation with P1 and P2 following these distance guidelines are less likely to have the P2 transmitter uncovered. The P2 transmitter should not become uncovered by process media because the HTG system needs readings from both the P1 and P2 transmitters to calculate density. Applications where the tank height contains products that will always be at a height much greater than the 20% of tank height recommendation can have the P2 transmitter installed at a higher height. The higher height for the P2 mounting provides a more accurate density calculation at the risk of the P2 transmitter becoming uncovered.

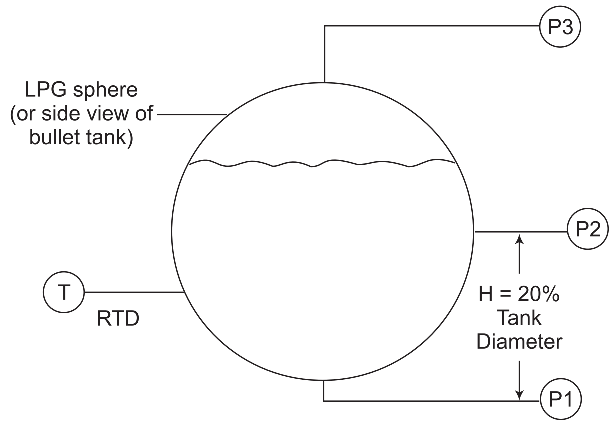

Figure 4.54: HTG measurement when vessel is spherical

Common tank equipment such as mixers, blowers, or agitators cause random pressure effects and does affect HTG operation. The effects of tank equipment are minimized by placing a transmitter in a position that is not directly across from the tank equipment. In such cases, the ideal position is at 90° from the equipment.

Applications HTG is suitable for applications for products such as LPG (liquefied petroleum gas) to asphalt. HTG is usable with various tank geometries such as vertical, spherical and bullet shapes that would eliminate other devices.

In conclusion, again note that accurate volume or mass data is not necessarily a concern of operations personnel, who are concerned with safely filling and emptying a tank. Regardless of the level-measuring device selected for a tank gauging application, the concern of safely filling and emptying a tank is often met by providing level switches in addition to the level-measuring device. For example, in the event a float and tape device is stuck, a false level reading occurs, leading to a potential accident. A separate high-level switch could be installed and configured to prevent an overflow of the tank.

Although the level measurement may meet the 1/16 in or 1.6 mm level requirement for tank gauging, personnel concerned with inventory management may express doubt about the accuracy of the volume or mass calculation, because of valid concerns about variables such as temperature and density as well as concerns about the tank structural deformations. The selection of a level measuring device for a tank gauging application, then, is often determined by how critical the measurement data is to the end user and how to best provide that data.

Checkpoint

✦✦✦ **1.** What does automatic tank gauging represents?

✦✦✦ **2.** What are the different parameters measured in automatic tank gauging systems?

✦✦✦ **3.** Explain how tank guaging is different from level measurement in process industries?

✦✦✦ **4.** List three differences between automatic tank gauging and process level measurement.

✦ **5.** What is the data access interval difference between a tank gauging and process level instrument?

✦✦✦ **6.** What is the communication path between automatic tank gauging system and process level instruments?

✦✦✦ **7.** What are the various data provided by the tank gauging systems?

✦✦✦ **8.** List the tank gauging techniques.

✦✦ **9.** What is the hybrid technique of tank gauging?

For answers to checkpoint, scan the QR code

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4.6 GENERAL CONSIDERATIONS IN SELECTING LEVEL MEASUREMENT TECHNOLOGY

LO 6
Review general considerations in selecting level measurement technology

The choice of measurement technology, the application, and installation requirements are some of the important considerations while selecting the right level measurement solution. There is no single universal technology that can address all level measurement requirements. Level measurement needs are addressed from a broad array of technologies.

It is important to review the ability of the instrument to measure the level with the required accuracy, but also suitability of the same for the environment in which it will be operated. Based on the principle of operation some instruments needs a direct contact with the process, whereas some other are noninvasive in nature. Some equipment has the mechanical rotating equipment and some are purely based on the physics of nature. In either case, every instrument is associated with certain amount of maintained cost and hence the life cycle cost of the instrument becomes another attribute in the selection process. In cases where the instrument is used for custody transfer applications, the accuracy of the instrument directly impacts the commercial transactions of the firms and hence the cost of the instrument is seen of less importance compared to the loss going to be incurred in case of inaccurate measurement. Frequently the cost of a particular technology is dissimilar if viewed from a total lifetime cost of ownership viewpoint. Purchase, installation, maintenance, and training costs all occupy a part in shaping this.

It is also equally important to review the quality of level information required. There are cases in which the level is measured to provide a control in a tank or vessel or in a distillation column, etc. In some cases, the level is used to gain information that helps to take commercial decisions. The type of instrument is important based on the quality of level information required. The accuracy of the measurement is not only from the specifications of the manufacturer, but also depends on the type of the installation, environment and area of the application, etc.

It is recommended to take into account the following general considerations when selecting a level measurement device.

4.6.1 An Initial Selection Approach

Given the widespread choices available for level measurement technology, an engineer would benefit from an approach that narrows the selection choice to several technologies. The selection applies the general philosophy of the petroleum industry which is to select a device best suited to the process in which it is to be used. After reviewing the initial selection approach, the selection criteria for level measurement devices also includes—application characteristics, process conditions affecting measurement, safety considerations, metallurgy, installation considerations, maintenance and calibration, compatibility with existing process instrumentation, economic considerations and technical direction.

4.6.1.1 Application Characteristics

The engineer narrows the selection choice by identifying the following application data—type of application measurements, type of vessel, point versus continuous measurement, accuracy and span requirements, contacting or noncontacting technology requirements, temperature and pressure conditions, maximum and minimum safe heights of process material.

Type of Application Measurements The type of application often narrows the available number of level measurement devices. Each application may have its own requirements and restrictions that influence the selection of the level measuring device. The type of application measurements that influence level measuring device selection are the following—process level measurements, interface level measurements, specific gravity or density measurements and ATG.

Process Level Measurements Process level measurements are used either to provide a measured quantity to a level controller or simply an on/off indication of current level for monitoring purposes. In addition, the measurement of an interface with respect to a reference or datum line can be applied to all process level measurements. For example, measuring the water level in an open-air tank can be defined as the measurement of the liquid (water) interface (position) with a gas (air). Describing the previous example in abstract terms helps you regard all process level measurements as interface measurements. However, the term “interface” is more commonly understood to represent the position where two nonmixing fluids meet.

Interface Level Measurements Interface level measurements identify the position or location where two nonmixing (immiscible) liquids meet. Interface measurements can take several forms—liquid/gas, liquid/liquid, or liquid/liquid/gas. Process vessels such as separators permit immiscible liquids of different specific gravities to separate for further processing. The boundary between the immiscible liquids is called an “interface.” Providing an accurate interface measurement is important because movement of the interface position or even reversal of one of the phase positions to the top or bottom of a vessel can cause lost production, increased operating costs, and even safety hazards.

Specific Gravity or Density Measurements Specific gravity or density measurements as performed by level measurement devices, frequently use hydrostatic approaches to help determine the weight of materials or volume of materials in a vessel. Instrument engineers to represent the same type of measurement use the terms “specific gravity” and “density” often. Common usage of the terms specific gravity and density have led even experienced personnel to think of the terms as being synonymous. However, “specific gravity” and “density” are not the same. The following brief discussion clarifies what is meant by the terms specific gravity and density. Specific gravity represents the ratio of the density of a substance to the density of a reference fluid to specified conditions. Because specific gravity represents a ratio of densities, specific gravity is also referred to as “relative density.” The most frequently given specific gravity reference for a liquid is the density of water at standard conditions of 15.6°C (60°F). Specific gravity of liquids can be expressed as follows:

$$\text{Specific gravity} = \text{Density liquid}/\text{Density water at standard conditions}$$

While density measurements are often made using special analytical instruments, a requirement can exist for a density measurement within an ATG system. The density measurement is necessary in order to calculate mass and volumes at standard reference conditions. Frequently, the density measurement is made in HTG systems, using pressure transmitters to measure density. Another example of measuring density or specific gravity to infer level is the use of differential pressure transmitters to identify an interface. The span of the differential pressure transmitter is configured to locate the interface level. The span is based on the difference between the liquid's specific gravities and the distance between the maximum and minimum interface levels. This type of approach requires the more accurate microprocessor pressure transmitters.

Automatic Tank Gauging ATG refers to a measurement system that employs level measuring devices, and possibly temperature and density measurements. Inventory accounting and custody transfer is often the goal of tank gauging. Note that process level control is also critical to tank gauging since personnel use level measurements to perform safe tank operations.

Type of Vessel The type of tank or vessel often narrows the available number of level measurement devices. Each vessel has its own requirements and restrictions. The type of tanks or vessels that influences level measuring device selection is—buried tanks, vented or atmospheric tanks, pressurized tanks, elevated tanks, cryogenic tanks, boilers, chlorine tanks, and accounting grade tanks.

Buried Tanks Buried tanks usually contain oil or gas at atmospheric pressure. Suitable level measuring devices include devices ranging from the simple dipstick to hydrostatic head devices. Because the access to a buried tank is through the top of the tank, level measuring devices with probes (capacitance, ultrasonic) are also a possible selection choice.

Vented or Atmospheric Tanks Vented or atmospheric tanks generally can be accommodated with any of the level measuring devices.

Pressurized Tanks Pressurized tanks have a pressure range of operations that determines which level measuring device is suitable. Displacers, differential pressure, capacitance, and ultrasonic type devices are examples of suitable level measuring devices. Each device would have an acceptable working pressure identified on its vendor data sheets.

Elevated Tanks Elevated tanks typically use hydrostatic or differential pressure devices to accomplish level measurements.

Cryogenic Tanks Cryogenic tanks include tanks used for liquefied natural gas (LNG) and carbon dioxide level measurements. A differential pressure device is often used to measure the fluid's level.

Boilers Boilers contain both high pressures and high temperatures that place demands upon the level measuring device. A differential pressure device is often used to measure the level.

Chlorine Tanks Chlorine tanks represent a hard to handle liquid level measurement because of the pressures involved, safety hazards, and corrosiveness. A differential pressure device is often used to measure the level.

Accounting grade Tanks Accounting grade tanks refer to vessels used for inventory management or custody transfer purposes. The level measuring devices used include floats, displacers, differential head, ultrasonic, and microwave radar devices. When employed in an accounting grade tank, the level measuring devices become part of an ATG system.

Point versus Continuous Measurement The type of level measurement such as a point level or continuous level measurement influence the selection procedures. Recall that point level measurements provide an on/off, true/false type of representation of level presence, while continuous level measurement provides a numeric representation of the level. Quite frequently, a level measurement application requires both point and continuous level measurement devices. For example, a level controller may rely on a continuous level measurement. The same application may have, as an added safeguard, point level measurements in the form of level switches to provide alarms or shutdowns.

Accuracy and Span Requirements The application's accuracy and span of level change requirement has an influence on which level measurement device is selected. In tank gauging systems, accuracy is very important, because the engineer is concerned with proper inventory reporting. In process level measurement applications (point level and continuous), accuracy is important, but repeatability is considered more important than accuracy. The reason that repeatability is important is that the engineer is concerned about controlling a process more than how accurately the level is measured. The engineer also considers the span of level change requirements when selecting a device. A typical industry procedure for level measurement selection is to use differential pressure transmitters for measuring large span levels, and select displacers for smaller ranges.

Contacting or Noncontacting Technology Requirements Hard-to-handle fluids are best measured with devices that do not come in contact with the process material, through the use of devices that are called "noncontacting" technologies. Examples of noncontacting technologies are radar, ultrasonic, and laser devices. For example, measuring the level of hot asphalt, which must be constantly mixed, is accomplished with microwave radar devices that can best withstand this type of hostile environment. The radar device is mounted on top of the vessel. Although the radar device is exposed to internal tank atmospheres, the device is still considered "noncontacting". When noncontacting technology is installed outside a vessel without making an opening or tap in the vessel the technology is called "noninvasive." For example, noninvasive technology is fastened or clamped externally to the pipe or vessel itself in difficult to measure applications. Determining level presence in a pipe is one use for noninvasive technology. What determines whether noninvasive technology is selected is the practicality of measuring the process material level.

Temperature and Pressure Conditions Temperature and pressure conditions may determine whether a level measuring device is able to operate within that environment. Each level-measuring device has its temperature and pressure operating conditions identified on their respective vendor sheets. The temperature conditions may be as low as 60° C (140° F) for the electronics of some differential pressure transmitters.

Other level measuring devices, such as some capacitance probes, may work in temperatures up to 1128° C (2000° F). Pressure operating conditions for some level measuring devices, such as bubblers, may be as low as atmospheric pressure. Other level measuring devices, such as differential pressure level detectors, are usable in conditions up to 69 MPa (10,000 PSIG).

Maximum and Minimum Safe Heights of Process Material The engineer selects these devices to accommodate the maximum and minimum safe heights of process material within the vessel. Regardless of whether the level measurement is a process level measurement or an ATG system, operations personnel's foremost concern is to avoid overfilling a tank or emptying it dry. The concern for safely filling or emptying is usually addressed with level measurement devices that meet the necessary level measurement safety shutdown and alarming requirements.

4.6.1.2 Process Conditions Affecting Measurement

The process operating conditions that bear on level measuring device selection are—process material characteristics and vessel operating conditions.

Process Material Characteristics Process material characteristics are considered when selecting a level measuring device because the process media itself can eliminate a device from the application. Several examples of process material and how they affect level measuring device selection are listed as follows—material buildups from process media, changing specific gravity, changing dielectric constant and coatings.

Material Buildups from Process Media When level measuring devices experience exposure to process media, one concern is whether material buildups will occur. For example, when a float or displacer is exposed to process media, then material buildups are a potential possibility. Excess material buildups can change the weight of the float or displacer, and as a result, create errors in the level measurement.

Changing Specific Gravity Level measurements may be based upon an assumed specific gravity value. When hydrostatic methods are used to measure the level of the fluid, then an undetected changing specific gravity can cause the level measurement to be erroneous. If the application is likely to experience undetected specific gravity changes, then the level measurement device selected for that application would be needed to be the one that is unaffected by specific gravity changes. Pressure type devices and displacers are susceptible to measurement errors if an undetected specific gravity change should occur.

Changing Dielectric Constant Changing dielectric constants affect the level measurement accuracy of a capacitance probe. Some wave generation devices, such as radar, depend on the reflectivity of process material Reflectivity is influenced by the dielectric constant of process material. Several vendors provide compensation technologies to overcome effects of changing dielectric constants.

Coatings When level measuring devices experience coatings from process material, false level readings can occur. For example, when the level in a vessel decreases, a process material coating may remain on the capacitance probe, creating a false level reading. Early capacitance probes are susceptible to this coating problem. Newer capacitance probes use anticoating technologies to prevent the coating from giving a false level indication when a material level has fallen below the capacitance probe.

Vessel Operating Conditions Vessel operating conditions are considered when selecting a level measuring device because the vessel conditions often eliminate a device from use in the application. Several examples of vessel conditions are listed below and how they affect level measuring device selection. Vessel conditions that influence level measuring device selection are—turbulence and agitation, steam and other vapors, foaming, interference from internal tank structures.

Turbulence and Agitation Vessels often contain some kind of mixing equipment to keep the materials mixed. Mixing the materials helps avoid density and temperature stratification of the material, which leads to erroneous level and volume measurement results. The engineer may have to specify an instrument for use in this kind of environment based upon the presence and strength of the agitation.

Steam and Other Vapors The presence of steam and other vapors within the vessel has detrimental effects on the performance of some level measuring devices. For example, vapors can affect the ultrasonic device's level measurement reading by altering the timing of the return signal. Compensation approaches are sometimes available on the level measurement device to overcome unwanted affects from steam and other vapors.

Foaming The generally undesirable effects of foaming create level measurement errors for some level measuring devices. The goal of the measurement may have been to ignore the effects of foaming and measure liquid levels only. However, the goal can be to measure both the level of foaming and the liquid level. Level measuring devices are available that can measure both the liquid level and the amount of foaming that is occurring.

Interference from Internal Tank Structures The choice of a level measuring device is often restricted by how much open space is inside the vessel for a measurement device. Presence of internal tank structures determines which level measuring device is chosen. For example, wave generation devices, such as radar and ultrasonic, are affected by reflections from internal vessel structures. Radar and ultrasonic devices have options that minimize or ignore the effects of internal tank structures.

4.6.1.3 Safety Considerations

The safety considerations that influence level measuring device selection are whether the device is used in an environment where there is a possible occurrence of one or more of the following—explosion hazard, lethal material measurement, and regulatory requirements.

Explosion Hazard Many of the gases and liquids measured are inflammable or explosive in nature. Level measuring instruments often state whether they can meet the intrinsic safety or other low energy requirements for these types of measurement. The low energy requirements of a level measuring device are recognized and approved by agencies such as Factory Mutual (FM), Canadian Standards Institute (CSA), and British Approvals Service for Electrical Equipment in Flammable Atmospheres (BASEEFA).

Lethal Material Measurement Lethal materials, such as hydrogen sulfide, can be fatal even in small quantities. Devices that are sealed properly will not let lethal process material escape through the measuring unit.

Regulatory Requirements Some level measurement devices, mainly nuclear devices, have regulatory concerns about proper use, record keeping, and disposal. Because of the regulations and potential risk to personnel, nuclear devices tend to be devices of last choice and selected when no other device is found suitable for the application.

4.6.1.4 Metallurgy

When the process material is corrosive to the level measuring device, then metallurgy becomes an important selection criterion. Devices that make contact with the process material can often be covered with an inert insulating material such as Teflon.

4.6.1.5 Installation Considerations

External versus internal mounting is a decision that has several tradeoffs. Typical installation considerations that bear on level measuring device selection are:

- Internal vessel mounting
- External cage mounting to vessel, standpipe, or stilling well
- Connection to process taps

Internal Vessel Mounting When a vessel can be taken out of service for scheduled level measurement device maintenance and not interrupt the process, then internal vessel mounting may be considered. Level measurement devices are sometimes mounted internally if the process liquid is highly viscous.

However, internal mounting decisions are not quickly made. For example, the mounting location of a noncontacting device is not necessarily at the apex of a vessel—vessel vapors can accumulate there and cause measurement errors. If the process connection is to the side of a vessel, then the process connection is one where the effects of process material plugging and accumulating would be avoided or, at best, has negligible effects upon measurement. An additional consideration about internal vessel mounting is whether the device requires some type of guides or rods to keep sensing element in place, as in the case of some floats and displacers. A valid concern about internal mountings is the risk of device breakage within the vessel and the difficulty of making repairs if breakage occurs. To summarize, internal mountings have to take into account internal obstructions, proximity to product inlets, and potential signal interference from process equipment, location of mounting, the risk of breakage and difficulty of subsequent repair, and potential process material accumulations at the mounting location.

External Cage Mounting to Vessel Standpipe, or Stilling Well Some level measuring devices require an external cage, standpipe, or stilling well to provide the best conditions for level measurement (Figure 4.55). When an external cage is used to house the level-measuring device, the external cage permits the level-measuring device to be removed for service or calibration. When a vessel standpipe is used, more than one level-measuring device may be connected to the standpipe (a notable exception here is a shutdown device, which requires its own vessel connection). In the real world, the location and number of nozzles on a vessel are the determining factor.

When a stilling well is used, as in the case of a floating roof tank (Figure 4.56), the installation provides more stable level measurement conditions. When a stilling well is inserted into a tank, it is often called a "still pipe." External cages, standpipes, still pipes, and stilling wells provide the following:

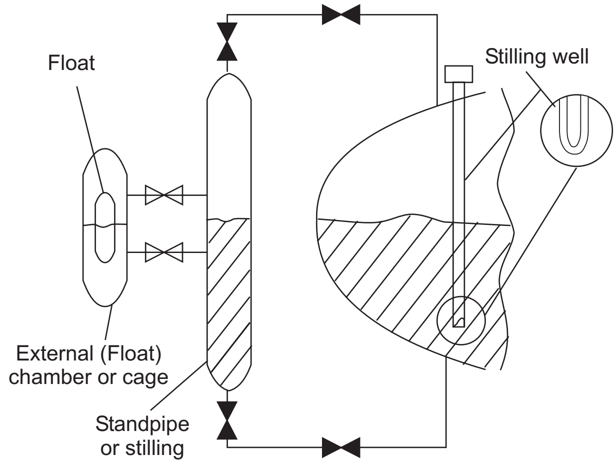

Figure 4.55: Standpipe example

- Liquid waves do not bounce the sensing element. The bouncing waves would cause erroneous level measurements.
- The sensing element is easier to keep free from material buildups, scale, and dirt.
- The connections to an external standpipe are less likely to plug than if they were connected to the process vessel.

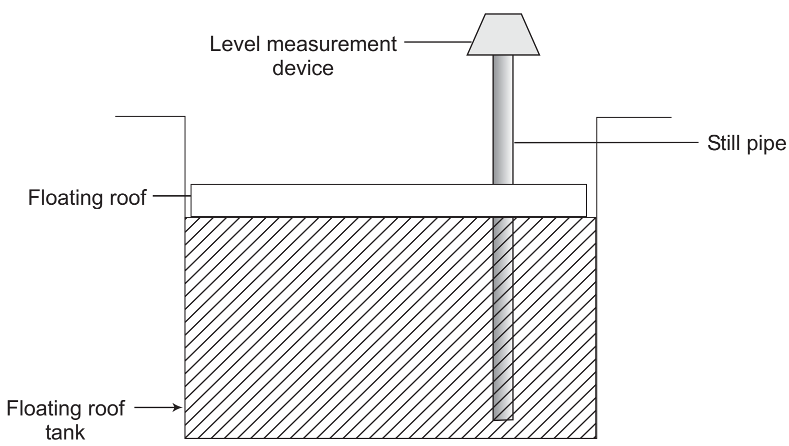

Figure 4.56: Still pipe example

Connection to Process Taps Instruments may be connected to process connections called "taps" that allow connection directly to the tank. Differential pressure transmitters, for example, have tap location considerations. In a level measurement application, the top tap must be positioned so that the maximum high level is always below the top tap. If the process material flows into the top tap, the low side pressure measurement will be incorrect. In a density measurement application, the top tap must be positioned so that the maximum high level is always above the top tap. If the process material is below the top tap, a density measurement is not possible.

4.6.1.6 Maintenance and Calibration

The primary maintenance and calibration consideration in selecting a level measuring device is the calibration device's ease of use. An instrument is often bench-calibrated before installation.

Other level measuring devices can be calibrated in the field while connected to a still-pipe or standpipe. As a rule, the best calibration results are obtained from the simplest calibration devices. For example, water can be used to calibrate a displacer. Squeeze bulbs can be used for calibrating pressure instruments. More complex devices, such as nuclear devices, require sheets of lead for proper calibration. When you calibrate a level measuring system, a question arises as to what standard the level measuring system is calibrated against. In some cases, you may have to rely on the visual indication from a sight glass and calibrate the level-measuring device after it is installed. Some users state that calibrating a sophisticated level measurement device with a sight glass is the equivalent of calibrating a micrometer with a wooden ruler. Thus, the calibration requirements may influence level measuring device selection in that an accurate calibration standard must also be available to ensure proper calibration and traceability.

4.6.1.7 Compatibility with Existing Process Instrumentation

Compatibility considerations that can influence the selection of the level instrumentation are the other devices that coexist in the same loop and there is a need to communicate. The typical example of such are types of output signals, output indicators and relay contact specifications, etc. output indication, types of output signals and relay connections.

Output Indication Output indication refers to a configuration choice of either direct or reverse indication for the level measuring device's output signal. Direct output indication means that the level-measuring device outputs a low signal, such as a 4 mA signal, representing a low level, and high signal, such as a 20 mA signal, representing the highest level. Reverse output indication refers to a choice for the level measuring device to output a low signal representing a high level, and high signal representing the lowest level.

Types of Output Signals Output signals from level measuring devices could be pneumatic, electronic (4 to 20 mA), or proprietary digital signal (Hart, Honeywell DE, Foxboro IA). Some level measuring systems, such as load cells, have to communicate with various commercial communication networks, such as RS232. An additional network interface is required to support the device.

Relay Connections Relay connections on a point level-measuring device are used for alarming, shutdown, or control configurations. The relay's specifications state whether they are compatible with the alarming, shutdown, or control configurations.

4.6.1.8 Economic Considerations

Economic considerations that influence level measuring device selection are—purchase price, installation costs, calibration costs, training costs, maintenance costs and spares inventory.

Purchase Price The vast majority of simple point level measuring devices is less costly, while continuous level measuring devices are about moderately costly. More sophisticated devices, such as Radar, can be high. Purchase prices, however, do not often provide an indication of what the installation costs are.

Installation Costs Installation costs are dependent upon where the device is installed in the vessel. Devices such as a capacitance or ultrasonic probe can easily be installed from a single vessel opening above the process material level. Other devices require an additional external measuring chamber or standpipe. Some devices, such as differential pressure devices, have to be installed below the material level. In summary, note that devices can require costly modifications of the vessel in order to properly install.

Calibration Costs Microprocessor-based instruments often do not require field calibration—the calibration can be accomplished from the control room. Less sophisticated devices may require personnel to empty and fill vessels in order to calibrate the device.

Training Costs With a large variety of level measuring technologies available, the costs for training personnel can become significant. Newer, costlier technologies require adequately trained personnel to support the installation and maintenance of such devices.

Maintenance Costs Maintenance costs can be inherently high in devices that use mechanical parts. Devices such as floats, displacers, and paddle wheels require periodic maintenance. More sophisticated devices, such as radar, require little or no scheduled maintenance.

Spares Inventory One argument for standardizing on a particular level measuring device is that the number of spare parts inventory can be reduced. The main goal of the spares inventory is to reduce downtime in the event of system failure. Some level measuring devices can be adapted, such as shortening a probe length, to meet different level measurement needs.

4.6.1.9 Technical Direction

The following discussion provides an overview of the technical direction of level measurement technology. The discussion briefly describes several ongoing trends that may influence future selections of level measuring devices. The following trends are briefly described as—advances in hardware and software, point level switch trends, RF admittance versatility, growing acceptance of HTG, increasing usage of microwave radar, and potential usage of time domain reflectometry.

Advances in Hardware and Software Advances in software permit users to configure their own systems without reliance on vendors and third parties. Hardware improvements such as application specific integrated circuits (ASICs) reduce the size of the devices and improve their reliability.

Point Level Switch Trends Ultrasonic switches have increased the temperature operating ranges from 250°F to 300°F. Usage of frequency shift tuning fork level switches is gaining acceptance. Frequency shift tuning fork level switches are only slightly affected when density, viscosity, solids buildup, and material composition changes.

RF Admittance Versatility RF admittance versatility or capacitance/admittance continuous level measuring systems are claimed to represent a universal level measurement technology. The technology is usable in a wide range of applications such as slurries, volatile chemicals, and interface applications. The technology is operational in temperature and pressure extremes.

Growing Acceptance of HTG Highly accurate pressure transmitters have led to the growing acceptance of HTG as a solution for the more difficult level measurement applications.

Increasing Usage of Microwave Radar Although costly compared to other level measuring devices, microwave radar has solved many difficult, hostile level-measuring applications. In Europe, radar is approved for custody transfer applications because of its proven accuracy in ATG operations.

Potential Usage of Time Domain Reflectometry Time domain reflectometry is based upon the principle that reflections from an electrical signal can be used to identify the location of signal disconnection. For process measurement, the "disconnection" is used to identify the level position. Time domain reflectometry has evolved to a level where it now has become a technology that is independent of a process material's capacitance, specific gravity, temperature, and capacitance. Time domain reflectometry technology is relatively stable and intrinsically safe.

Below are the process characteristics that need to be investigated before selecting the level measurement device.

4.6.2 Process Characteristics

4.6.2.1 Density and Viscosity

The density and visocity of the liquids in which the level measurement instrument is applied plays an important role. An example of such a situation is that if the level switch is used for a high viscous liquid, the switch may get stick or hangup. Another case is that the switch may get damaged due to the force on the probes by high density materials. In a tank with agitated liquids, high lateral forces are generated inside as the density and viscosity increase which can damage the measurement probes.

Some of the measurement technologies are dependent on the density of the liquid. If there is a change in density, the instrument may need a recalibration. Some examples of such instruments are based on technologies such as bubblers, displacers, and hydrostatic instruments measuring hydrostatic head of a liquid. For such instrument, if there is change in density, for the same level, instrument may represent an incorrect reading which is higher than the previous reading.

Changes in density and viscosity have no influence in the noncontacting types of instruments as there is no direct contact with the process.

4.6.2.2 *Chemical Composition*

Chemical composition of the liquid is one of the attribute in the selection of the level measurement instrument. In addition to measuring the level accurately for a particular liquid, the chemical composition and properties, such as dielectric constant, conductivity and pH, palys a role in the measurement. For example a capacitance probe that measures the level is dependent on conductivity and dielectric constant of the liquid and any variations in these properties has an impact on the measurement. Even for the instruments that are noncontact in nature such as ultrasonic level measurement instruments, the corrosive vapors if any in the vessel can damage the instrument over a period of time and hence calls for necessary precautions during the selection of the instrument and its material of constructions etc. Having said that, in general the non-contacting measuring instruments have less dependency on the composition of the liquid.

4.6.2.3 *Ambient Temperature*

The ambient temperature in which the instrument is installed is one of the parameter to consider during the selection of the instrument. Note that the ambient temperature is different from the process temperature. Process temperature can be high based on the process conditions, but the instrument may have to be selected keeping ambient temperature also into consideration. If the ambient temperature is outside the specifications of the instrument, it may potentially damage the electronics and/or erroneous measurements. Similarly the accuracy of level instrument from a differential pressure transmitter may be accepted if remote seals or impulse lines are used to contact the process material. If the variation in ambient temperature has an impact on the fill fluid of the remote seal or impulse line, then the measured differential pressure may change and hence the calculated level will change. In other words, the ambient temperature can cause a change in the accuracy of the level measured.

4.6.2.4 *Process Temperature*

The process temperature is an important attribute to consider during the selection of the level measurement application and technology. The process temperature of the instrument is used to select the material of the construction which can sustain such temperature. In some applications, the changes in the process temperature can affect the accuracy of the measurement. For example, a hydrostatic level measuring instrument may report an error in reading for a sudden increase in temperature can cause change in density of the fill fluid and hence a change in pressure. If the temperature of the process is not measured and compensated in the electronics, the results may look erroneous.

4.6.2.5 Process Pressure

The process pressure of the vessel is an attribute in the selection of the level measuring instrument. The pressure ratings on the instrument connections, such as flanges or tubes should match with the process connection of the equipment or vessel. Similarly for the vacuum measurement, the ratings on both sides should match. In case of hydrostatic pressure instrument used for level application, the pressure on the top of the vessel has an impact on the measurement. Generally a different pressure transmitter is used to compensate the pressure on the top of the vessel for actual head measurement.

4.6.2.6 Regulated Environments

The level measurement in an industrial environment requires to be complied with special regulations. Installations in hazardous location where gas and dust can create an ignition needs to be carefully assessed and appropriate instrument needs to be classified and selected. The instruments should also be selected based on the national and international codes and safety practices, certificates from recognized agencies such as Factory Mutual (FM), Underwriters Laboratories (UL), and Canadian Standards Association (CSA), etc.

4.6.2.7 Process Agitation

The selection of the level instrument should also be based on the vessel conditions such as agitation and vertices, etc., sometimes these are localized to some part or to complete vessel based on the process conditions. Sometimes these agitators become an obstruction to the capacitance probes meant for level measurement. Process agitation makes the reflections off to the receiving transducer in the case of noncontacting type level measurement such as ultrasonic and radar type level measurement which results to unreliable measurement.

4.6.2.8 Vapor, Mist and Dust

The area over the surface of the liquid and solids constitutes some vapor, dust or mist, etc. This is important parameter to consider especially if the noncontact type measurement technologies are used such as ultrasonic, radar, microwave, etc. These vapors can create measurement uncertainty because a change in temperature of the vapor can influence the speed of sound and hence the ultrasonic level measurement. Similarly the dust and mist can contribute to the reduction in the acoustic and electromagnetic signals meant for measuring the level of the surface of the liquid.

4.6.2.9 Interfaces or Gradients

Measuring the level of process for the interface applications is an important consideration in the selection of the instrument. The interface applications range from two different liquids, liquids and foams, liquids and solids, etc. In general, oil and water is mostly used application for interface level. Radar and guided wave radar instruments, time domain reflectometry instruments are used to measure the interface of two liquids where there is a change in dielectric constant. Capacitance-based level instruments are used for interface level applications where the interface can be detected between the liquids with conductive/high dielectric to nonconductive/low dielectric properties. There are some ultrasonic level instruments that can detect the speed of sound and acoustic reflection at the transition of liquids in the interface locations.

If the measurement technology is to be less affected by the physical properties such as density and conductivity, then gamma and magneto strictive is a possibility. Many times the interface between two liquids is not very distinct, with some emulsion layers or gradient in the middle. The major challenge in these measurements is the characteristic if the individual liquids are not fixed and keeps changing from source to source. These practical problems limit our ability to select the right instrument for the application. The characteristics of the liquids such as conductivity, dielectric constants, acoustic, optical, and density variations may be challenging to different measurement technologies. In the presence of foam in the interface, ultrasonic and radar technologies can be used on a liquid if too little acoustic or microwave energy is reflected from the surface.

4.6.2.10 Process Conductivity and Dielectric Constants

Process conductivity and dielectric constant are important parameters to consider in choosing the level measurement application. These parameters are the basis for the measurement and hence the material of the construction of the probe is critical. If the parameters are not in line for using some technologies, then an alternative technology is to be considered.

4.6.2.11 Vibration

Vibrations are a common situation in an industrial environment, primarily generated from engines, pumps and agitators, etc. Even though vibration do not have a direct impact on the measurement, certain precautions and considerations need to be taken care to avoid issues.

If the vibrations add any additional force to the sensor and generates an erroneous readings, then some appropriate corrections need to be done otherwise it may impact the electronics or the mounting structure of the level instrument.

4.6.2.12 Material Buildup or Stickiness

In level measurement applications, material built up or stickiness causes significant errors and causes most of the maintenance. Knowing such situations, the engineer should be able to anticipate the kind of built up that can come up in such processes and proper mitigation steps should be considered. The buildup should not become a coating on the rod or other process measuring items. Similarly the material can also built up on the walls of the tank which results in erroneous results. Knowing the risk of the buildup or sickness mitigation plans needs to be devised or an alternative technology has to be selected.

4.6.2.13 Static Charge

Electrostatic charges are produced in nonconductive materials during the movement of the material from one equipment to another through pumping, etc. These charges can become sufficiently large that a sudden discharge though a sensor such as capacitance probe can damage the electronics. These problems can be minimized by selecting a suitable principle where the possibility of discharge is minimum or by taking mitigation steps in which the tanks and vessels are properly grounded.

4.6.2.14 *Humidity/Moisture*

The humidity and moisture content will be there in solids which are based on the composition of the material, sometimes related to the season, etc. The level measurement in bulk solids in silos can be affected by the presence of humidity and moisture. Level measurement using capacitance, for example, can be affected as changes in the moisture can change the conductivity and dielectric constant of the material. Based on process temperatures, moisture may also make condensation at the coldest point in the tank such as vessel ceiling, etc. In such a case, the measurement technique selected should be insensitive to the condensation and changes to the material characteristics.

4.6.2.15 *Repeatability, Stability, and Accuracy Requirements*

Sometimes in process control applications, the repeatability and stability of the measurement takes more priority than the accuracy of the signal. The major challenge for the suppliers is to design products in such a way that the output is stable over the specified range and insensitive to all possible external influences in the process. A small drift from the actual value is acceptable unless it is a custody transfer application. The bottom line still remains that a right principle is essential for the right application. A good instrument for a bad application is as good as bad measurement and results will not meet the expectations from the process control systems and process operators.

4.6.3 Protection for Instruments

Every instrument needs some protection as they are used in outdoor or semi outdoor settings. The degree of protection varies from instrument to instrument and is also based on the type of application for which it is employed. The degree of protection is divided into several classes as per IEC 60529 and/or DIN EN 60529.

Figure 4.57, Tables 4.3 and 4.4 explains the meaning of each letter in the class of protection provided to the instrumentation systems.

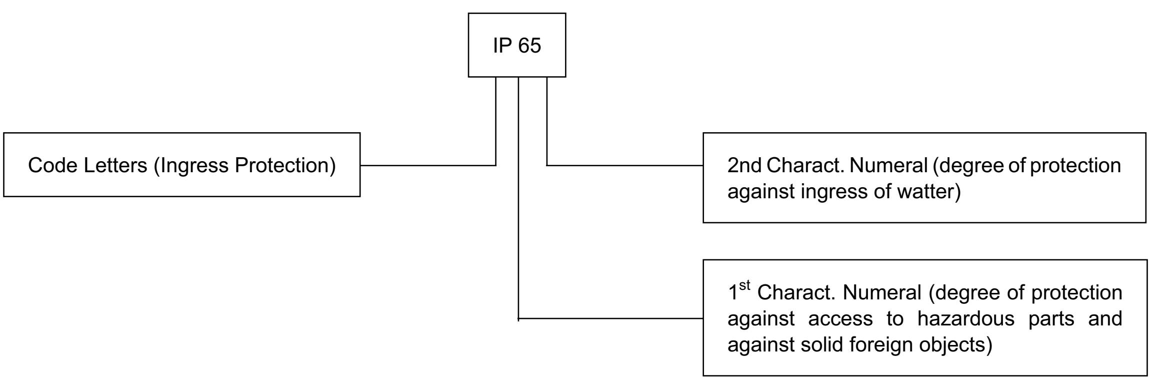

Figure 4.57: Representation of IP codes

Table 4.3: Description of first character in the IP Code		
First Character Numeral	*Brief Description*	*Definition*
0	Non protected	--
1	Protected against access to hazardous parts with the back of a hand. Protected against solid foreign objects of more than 50 mm diameter.	The probe, sphere of 50 mm diameter, shall not fully penetrate and shall have adequate clearance from hazardous parts.
2	Protected against access to hazardous parts with a finger. Protected against solid foreign objects of more than 12.5 mm diameter.	The jointed test finger of 12mm diameter, 80 mm length shall have adequate clearance from hazardous parts. The probe, sphere at 12.5 mm diameter shall not fully penetrate.
3	Protected against access to hazardous parts with a tool. Protected against solid foreign objects of more than 2.5 mm diameter.	The probe of 2.5 mm diameter shall not penetrate at all
4	Protected against access to hazardous parts with a wire. Protected against solid foreign objects of more than 1mm diameter.	The probe of 1mm diameter shall not penetrate at all.
5	Protected against access to hazardous parts with a wire and dust-protected.	The probe of 1 mm diameter shall not penetrate. Intrusion of dust is not totally prevented, but dust shall not penetrate in a quantity to interfere with satisfactory operation of the device or to impair safety.
6	Protected against access to hazardous parts with a wire, dust tight.	The probe of 1 mm diameter shall not penetrate. No intrusion of dust.

Table 4.4: Description of second character in the IP Code		
Second Character Numeral	*Brief Description*	*Definition*
0	Non protected	--
1	Protected against vertically falling water drops	Vertically falling drops shall have no harmful effects.
2	Protected against vertically falling water drops when enclosure tilted up to 15°.	Vertically falling drops shall have no harmful effects when the enclosure is tilted at any angle up to 15° on either side of the vertical.
3	Protected against spraying water	Water sprayed at an angle up to 60° on either side of the vertical shall have no harmful effects.

(Contd.)

4	Protected against splashing water	Water splashed against the enclosure from any direction shall have no harmful effects.
5	Protected against water jets	Water projected in jets against the enclosure from any direction shall have no harmful effects.
6	Protected against powerful water jets	Water projected in powerful jets against the enclosure from any direction shall have no harmful effects.
7	Protected against the effects of temporary immersion in water	Intrusion of water in quantities causing harmful effects shall not be possible when the enclosure is temporally immersed in water for 30 min in 1 m depth.
8	Protected against the effects of continuous immersion in water	Intrusion of water in quantities causing harmful effects shall not be possible when the enclosure is continuously immersed in water under conditions which shall be agreed between manufacturer and user but which are more severe than for numeral 7
9K	Protected against water during high pressure/steam jet cleaning	Water projected in powerful jets with high pressure against the enclosure from any direction shall have no harmful effects.

4.6.4 Intrinsic Safety in Instrumentation

Intrinsic safety (IS) is an instrumentation design methodology for electrical equipment in flammable atmosphere areas. It is a mechanism or method to ensure safety of electrical equipment if flammable situations are existent. The areas which are prone for risk are called hazardous areas. The situations that can cause the flame is presence of materials such as crude oil and their derivatives, alcohol, gas and dust, etc. Safety is most priority item in the operations of the industrial facilities and enough precautions should be taken to ensure the safety of the personal and equipment and does not ignite irrespective of the conditions in the environment.

There are various techniques used to mitigate the risk of ignition. Firstly the instruments are installed in a heavy, flame proof, explosion proof enclosure which can contain any ignition inside itself when occurs. Secondly using sand and oil filling the access to the ignition to reach the instrument itself is restricted. Thirdly, the instrument is enclosed in a resin or pressurizing the instrument such that ignition or flammable gases does not enter to the instrument. From the above three solutions, it is clear that the resultant solution is heavy in size and maintenance and repair is difficult or not possible while the instrument is in the same area of its operation. Instruments have to be brought to safe area for any maintenance or repair activities.

In addition to the above approaches, intrinsic safety follows a method which provides safety intrinsically. As the name suggest, in this approach the flammable atmosphere can be allowed to be in contact with the instrument. However, the power and current levels and surface heating on the instrument is restricted to a level that does not create any spark in the specified zone in its normal operating conditions.

This methodology is realized by designing the instrument and apparatus that connects to the process is not capable to cause an ignition in these specific zones. This condition is not only for the instrument of the discussion but also extends to all the associated apparatus connected to it. The electrical energy generated due to faults, sparks or hot surfaces in these zones are so low to create the ignition. Unlike earlier methodologies, this approach allows the equipment to be opened in the area of operation with suitable precautions and approved test equipment. In a similar way, the instrument can be removed or replaced while the remaining system is operating at normal condition. This situation helps instrument to be maintained and repaired without disturbing the remaining plant operations which has a significant economic benefit. Unlike earlier approaches, intrinsic safety is standardized internationally in addition to the national standards and the instruments certified in one standard is eligible to be installed in most areas of the world.

Hazardous areas are classified as area classifications (degree of hazard) and Gas Group (the gases present in that area). Area classification informs areas in accordance to the probability of an explosive atmosphere present and the suitability of a specific protection technique. There are two major standards in use for area classification. These are the zone-based classification, as defined by IEC 60079-10, and the division-based classification, as defined by the North American and Canadian national electrical codes. The European CENELEC standards follow the IEC 60079 approach. The zone-based classifications are also recognized in North America and Canada as an alternative to division based classifications.

The two area categorizations are summarized in Table 4.5.

Table 4.5: Hazardous area categorization

IEC and CENELEC	*NEC (USA and Canada)*
Zone 0 Explosive gas-air mixture continuously present, or present for long periods. Common Understanding more than 1000 hazardous area (h/a). **Zone 1:** Explosive gas-air mixture is likely to occur in normal operation. Common understanding 10 to 1000 h/a	**Division 1:** Hazardous concentration of flammable gases or vapors—or combustible dusts in suspensions—continuously, intermittently or periodically present under normal operating conditions.
Zone 2: Explosives, gas-air mixture not likely to occur and, if it occurs it will exist only for a short time. Common understanding: less than 10 h/a	**Division 2:** Volatile flammable liquids or flammable gases present but normally confined within closed containers or systems from which they can escape. Only under abnormal operating or fault conditions. Combustible dusts not normally in suspension nor likely to be thrown into suspension.

The IEC defined the IS systems in to two categories based on the number of components or other faults (1 or 2) that can be present while the equipment remains safe. The north American standards defined only a single category of equipment that is safe with up to two independent faults introduced. The two equipment categories are summarized in Table 4.6.

Table 4.6: Hazardous area equipment categorization

IEC and CENELEC	*USA and Canada*
Ex ia: Explosion protection maintained with up to two faults in components upon which the safety depends. IS apparatus may be located in and associated apparatus may be connected into zone 0, 1 and 2 hazardous areas. **Ex ib:** Explosion protection maintained with up to one fault in components upon which the safety depends. IS apparatus may be located in, and associated apparatus may be connected into zone 1 and 2 hazardous areas.	**One category only:** Safety maintained with up to two faults in components in which the safety depends. IS apparatus may be located in, and associated apparatus may be connected into division 1 and 2 hazardous locations.

Gases are classified based on the energy required to ignite. All IS equipment is designed and certified as being safe for operation in the presence of a specific group of gases. However in practice most IS systems are designed to be safe with all the gas groups. There is a different classification of gases between IEC and North America which is listed in Table 4.7.

Table 4.7: Classification of gases in hazardous areas

Flammable gases, vapors and mists are classified according to the spark energy required to ignite the most easily ignitable mixture with air. Apparatus is grouped according to the gases that it may be used with. Surface industries: Groups IIC: acetylene Group IIC, hydrogen Group IIB: ethylene Group IIA: Propane Dusts, metals, flour, starch, fibers, flying, grain Mining Industry Group 1: methane	Flammable gases, vapors and mists and ignitable dusts, fibers and flying are classified according to the spark energy required to ignite the most easily ignitable mixture with air. Surface industries: Class I, Group A, acetylene Class I, Group B: hydrogen Class I, Group C: ethylene Class I , Group D, propane Class II, Group E, metal dust Class ii, Group F: carbon dust Class II, GROUP G, flour , starch, grain Class III, Fibers and flying, mining Industry Unclassified : methane

The temperature classification on IS instrument can be defined as highest temperature reached with in any part of it when a specific power is supplied under fault conditions. Temperature classification of the instruments in intrinsic safety is common across all the regions of the world (Table 4.8).

Table 4.8: Temperature classification

Class	*Temperature*
T1	450°C
T2	300°C
T3	200°C
T4	135°C
T5	100°C
T6	85°C

4.6.4.1 Ignition Curves

The minimum ignition energy of a gas can be defined as the energy required to ignite the most easily ignitable mixture of gas with air. However, the current required to sustain the ignition varies with the voltage levels in the circuit. Each of the intrinsic safety standards publish the curves of permitted voltage and current for each gas group. Typically these are the results from experiments and are accepted internationally. Typical example of such curve is shown in Figure 4.58.

In the circuits with inductance and conductance involved, additional curves are supplied. The curves described earlier are linear in nature and applied to the loads which are resistive, i.e. a resistor is used to limit the current. However, in industrial practice nonlinear circuits are also used for voltage and current limitation (Figure 4.58). In such cases there are several possible ways to determine the permitted values of voltage and current for a given circuit. Typically the permitted voltage and current is determined through computer simulation or ignition tests. Sometimes it is well advised to contact the local certification authority for the accepted method of specifying the limited values.

These factors typically restrict the operating region to about 30 V and 300 mA as shown in Figure 4.59. Capacitance is treated as a lumped parameter and its permitted value reduces sharply as the system voltage is increased. This proves to be a stronger defining effect than the reduction

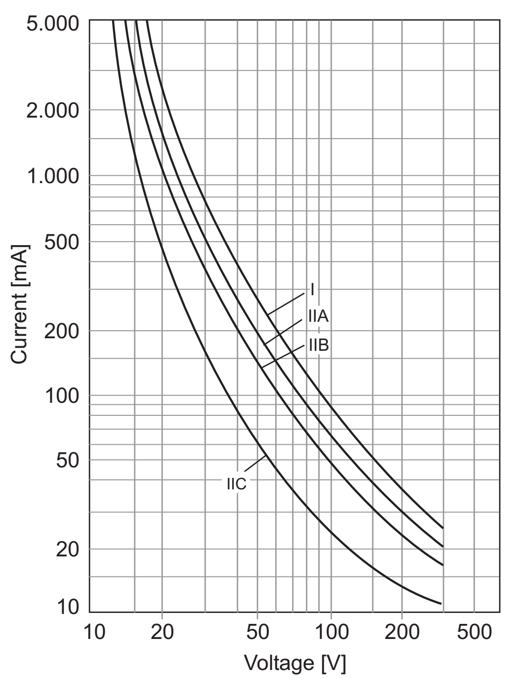

Figure 4.58: Ignition curves

of permitted inductance as the current increases. This is because the increased inductance of system is always accompanied by an increased series resistance which reduces its effect. Any item of IS associated apparatus normally has maximum specified values for permitted capacitance, inductance and inductance to resistance (L/R) ratio that may be safely connected to it IS terminals.

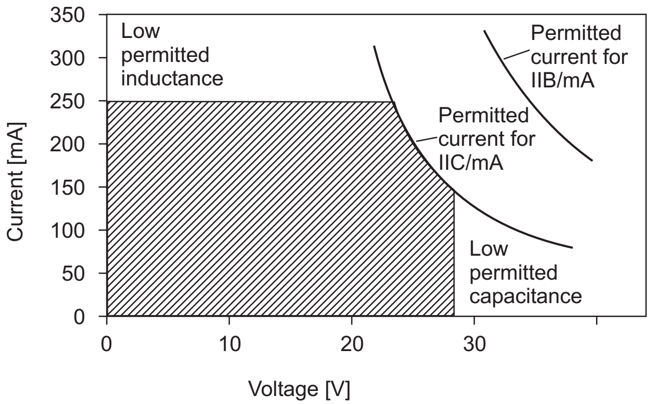

Figure 4.59: Practical operating region

Most of the devices and barriers for operations in the IS areas are designed in such a way that the energy released by an electrical fault is not enough to cause an ignition even for single or double faults conditions. This ignition point is a function of power, determined by voltage and current.

For answers to checkpoint, scan the QR code

Or

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Checkpoint

✦✦✦ 1. Which level measurement method is used for specific gravity or density measurement?

✦ 2. Define specific gravity.

✦ 3. Define relative density.

✦✦✦ 4. Explain the role of measuring density in interface level measurement.

✦✦✦ 5. What are the possible options of level measurement in buried tanks?

✦✦✦ 6. Explain why repeatability is more important than accuracy in process control applications of level measurement.

✦ 7. Give examples of noncontacting level transmitters.

✦✦✦ 8. Explain how an excess material build up can create errors in level measurement using float or displacer type level instruments.

✦✦✦ 9. Explain how a coating can have an impact on the level measurement device.

✦✦✦ 10. Explain how vapors can affect the ultrasonic level measurement readings.

4.7 CALIBRATION OF LEVEL TRANSMITTERS

LO 7
Illustrate calibration of level transmitters

There are various types of measurement techniques used in the industrial process measurement and some of them are based on direct measurement of the physical quantity and some other are indirect in nature, which means they measure a physical parameter and the actual parameter is inferred based on the original measurement. One of the classical example of the indirect measurement is differential pressure measurement which is used to measure the pressure, flow and level. It is also used to measure density and viscosity of the liquids. In all these cases the transmitter measures only differential pressure whereas the actual measurement is derived and calculated from the differential pressure. This means the differential pressure transmitter can be calibrated to different values based on the type of the actual parameters to be measured. There are different methods of calibration for the differential pressure transmitters such as re-ranging, dry calibration and wet calibration. The type of the calibration is decided based on the application of the DP transmitter to the type of the measurement. Let us discuss the difference among these three calibration procedures in the context of a DP transmitter.

4.7.1 Re-ranging a Differential Pressure Transmitter

Differential Pressure Transmitters are two-wire, loop powered transmitters with 4–20 mA current output. The lower range value (LRV) is calibrated for 4 mA, and the upper range value (URV) is calibrated for 20mA. The difference between lower range value and upper range value is called as span of the transmitter. The range of the measurement required for the application becomes the span of the transmitter. The transmitter reading is more precise while it uses most of its span during measurement.

For example, the 4 and 20 mA points of a DP transmitter are set to 10 and 100 H_2O as real calibration. In this case, the span will be 100–10 = 90 H_2O as shown in Figure 4.60. Now there is some change in the process and the process pressure need the minimum to be 50 H_2O. In this case, the minimum 4mA is to be re-ranged to 50 H_2O. Once this re-ranging is finished, the span will change to 50 H_2O.

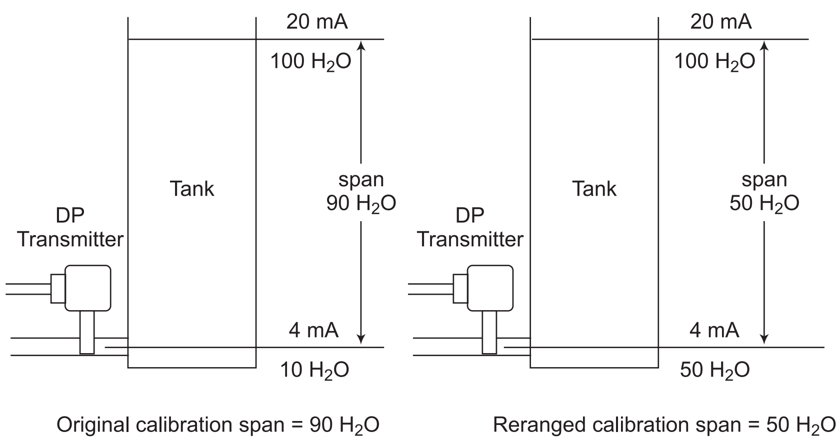


Figure 4.60: Re-ranging of differential pressure transmitter

4.7.2 Dry Calibration of a Differential Pressure Transmitter

Dry calibration or dry leg calibration technique of a DP transmitter is applicable in a closed and pressurized tank. This is most commonly used method and one of the simplest. The technique is almost alike to open tank level calibration. In a closed tank, the bottom most point is the high pressure (HP) point and the top most point is the low pressure (LP) point. The transmitter is fixed near the HP or bottom most position, and the HP inlet of the transmitter is linked to the bottom most position of the vessel by an isolation valve (Figure 4.61). The LP inlet of the transmitter is linked by a pipe to the topmost point.

The calibration procedure is as follows. Make both the inlet pressures at HP and LP equivalent to the atmospheric pressure by opening both the valves V1 and V2. The 4 mA (Minimum span) calibration is made. Now, close valve V1 and V2, open the isolation valve V3 and V4. The HP inlet is made to maximum span and calibrates the transmitter to 20mA. Now, open the dry reference leg valve, the LP side will be made to the minimum span. Re-range the transmitter. The dry technique of calibration is absolute.

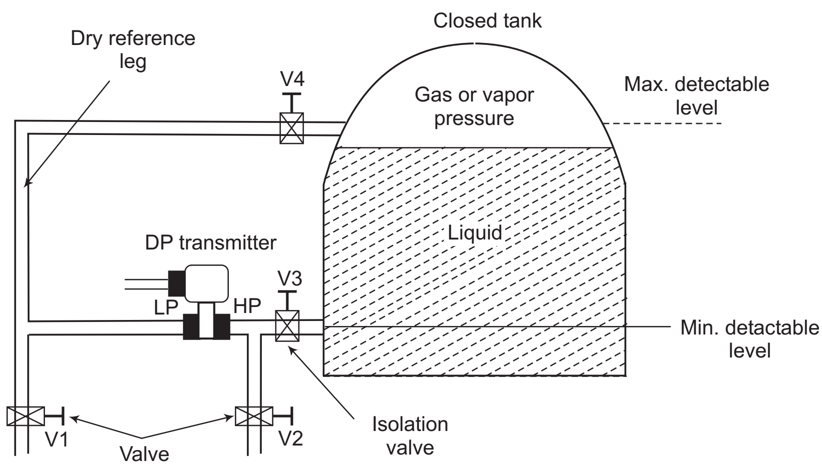


Figure 4.61: Dry calibration of differential pressure transmitter

4.7.3 Wet Calibration of Differential Pressure Transmitter

As discussed earlier, the dry leg calibration is suitable for the tanks where the temperature of the liquid in the tank is at ambient temperature. If the liquid in the tank is at higher temperature or lower temperatures, then condensate will fill the dry leg of the transmitter. Hence it is named as wet leg calibration and previous method of dry leg calibration is not applicable in such scenarios.

The low pressure side of the transmitter is filled with some fill fluid and generally, the fill fluids used in industry are diesel, glycol or glycerin, etc. At this point the procedure outlined earlier in the dry leg calibration needs to be performed on this wet leg as shown in Figure 4.62.

Dry leg calibration is used only for level measurement in open tank systems for liquids at ambient temperatures while wet leg calibration technique is used for level measurement in closed tank systems for hot and cold liquids. The general calibration procedure for level transmitters is depicted in Figure 4.63.

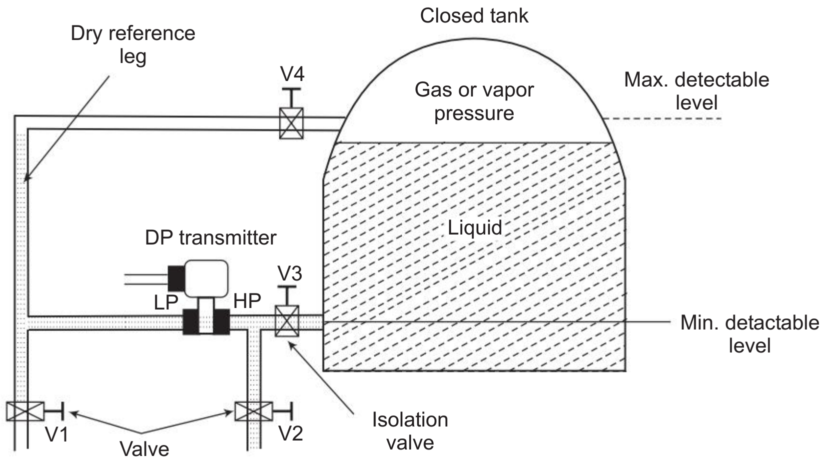


Figure 4.62: Wet calibration of differential pressure transmitter

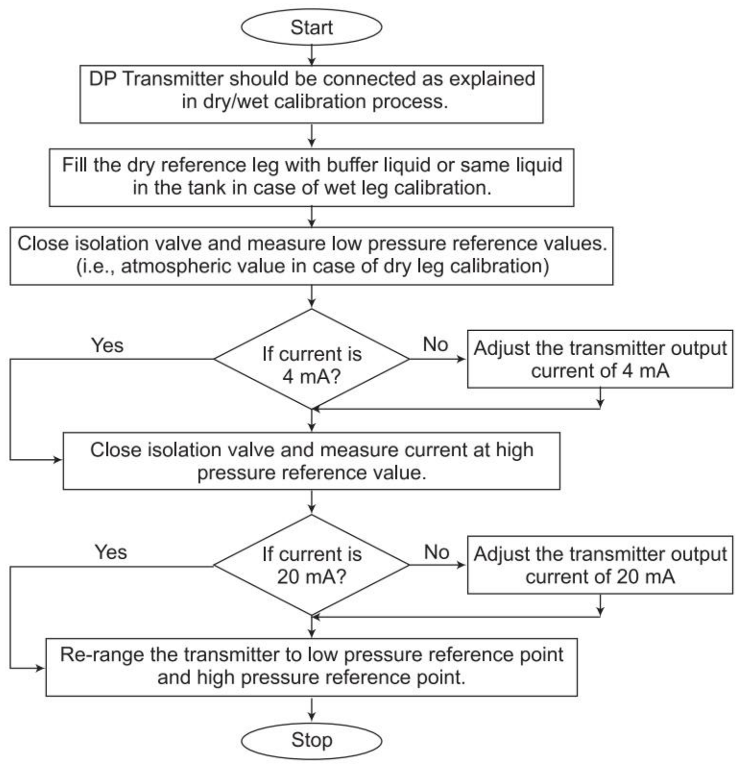


Figure 4.63: Flowchart for the calibration of level transmitter

4.7.3.1 Calibration of Ultrasonic Level Instrument

There are numerous types of level sensors and instrumentation. The sensor type used in a particular application depends on many factors including the process fluid measured, density, vented/pressurized, direct or indirect detection, agitated, continuous or point measurement, accessibility, maintenance requirements, etc. For example, calibrating an ultrasonic level instrument has two methods. Method 1 is used when the instrument can be removed and the cabling has enough slack to move to an open area with an unobstructed path to a smooth surface. If this is not the case, use second method.

Method 1

1. Determine the distance from the face of the ultrasonic transducer to the 100% level. This should already be documented as part of the instrument setup.
2. Determine the test point distance. Realize the distance from the test surface by simulating the distance from the top of the liquid level and take into an account the distance determined in step 1.
3. Turn off the transducer.
4. Use appropriate safety precautions, remove the instrument from the top of the tank.
5. Use a tape measured to mark off the distances from the test surface at each desired test point determined in step 2 above.
6. Place the instrument at a distance equal to the first test point from the wall or floor that will be used to bounce the signal back.
7. Turn the transducer on and record the level reading.
8. Move to the next distance and record the level reading. Repeat until all “as found” readings have been obtained.
9. If necessary, adjust the instrument in accordance with the manufacturer’s instructions in the instrument technical manual.
10. If adjustments were made, repeat steps 6 to 8 above to obtain “as left” readings.
11. Return the instrument to operational condition.

Method 2

1. Establish an independent method for determining the actual liquid level in the tank.
2. Adjust the level in the tank to each of the desired set points throughout the range of the instrument and record the reading from the ultrasonic instrument at each tests point.
3. If necessary, adjust the instrument in accordance with the manufacturer’s instructions in the instrument technical manual.
4. If adjustments were made, repeat step 2 above to obtain “as left” readings
5. Return the system to operational condition.

Summary

LO 1: Describe level instrumentation in process industry

- Point level process measurements often are accomplished with level switches.
- A single-point level alarm, such as a vessel level high alarm limit, is an example of point-level process indication.
- In continuous-level process measurements, a level measurement system can provide numeric representation of the current position (height) of the process material's surface.
- When level is inferred from a pressure measurement, the units of measure are often in either millimeters or inches of water column.
- Vessel deformations can occur during level measurement. Deformations may occur when the vessel is filled. For example, walls stretch in a crude oil storage tank because of the increasing hydrostatic pressure on the walls as the vessel fills.
- An important conclusion, then, is that depending upon the vessel's shape and length, a small level change can represent a large change in volume. From this example, one can observe that a vessel's shape can influence level measurement device selection.
- Level measuring instruments can be classified into two ways on a broader level. Direct measuring devices that provides the level as a direct visual indication using mechanical instruments without much instrumentation involved; indirect measuring devices provides a level indication by measuring a primary parameters such as pressure and so on and converting it to indicate level reading into a usable format.

LO 2: Explain direct methods of level measurement

- Level measurement consists of a wire of a corrosion-resisting alloy, about 6 mm in diameter, bent into a U-shape with one arm longer than the other does.
- Sight glass is a simple device used to determine the level within a boiler in steam boilers and similar applications.
- Float actuated mechanisms are recommended for use in tanks storing water, fuel oil, chemicals or other liquid products where operations do not require extreme accuracy.

LO 3: Explain inferential methods of level measurement

- In an equilibrium condition, the weight of the displacer partly immersed in the product, balances against the force of a balance spring.
- In an open vessel level measurement. If the zero point of the desired level range is above the transmitter, zero suppression of the range must be made.
- When a pressure transmitter (level or gauge) is installed in an open tank application, the transmitter's high side connection is made to a tank nozzle for the process connection. The pressure transmitter's low side connection is vented to atmospheric pressure. The effect of atmospheric pressure is cancelled because the atmospheric pressure acts upon both the high and low side of the pressure transmitter. Thus, the hydrostatic pressure from the liquid acts upon the high side of the pressure transmitter, and becomes an inferred measurement of level height.
- For the transmitter to output a signal representing just the level from its maximum height to the lower process tap, the effect of the fluid in the high side connection must be "suppressed." In this situation it is desirable that a 4 mA signal, representing 0 differential pressure and thus the minimum level, is output when the liquid level is at the lower process tap connection. A suppressed-zero range must be configured for the transmitter.
- According to accepted practice, suppressed-zero range is the preferred terminology. Note that terms such as "elevation," "elevated range," and "elevated span" are also used to express this condition. Some companies also uses the term "range elevation."

- Pressure transmitters are not practical for liquid level measurements whose specific gravity or density is changing.
- Transmitters with diaphragm seals may be used for extremely viscous materials, for materials containing solids or in hot service.
- The filled capillaries contain oil that does not readily transfer heat so that the transmitter can be located away from the process.
- Displacement devices are based upon Archimedes principle, which states that a body immersed in a liquid is buoyed up by a force equal to the weight of the liquid that is displaced.
- The displacer is usually installed in an external chamber outside of the vessel. A reason for using an external chamber is to keep displacer element vertical at all times.
- External cage mountings have advantages. For maintenance purposes, it is often desirable for maintenance to be able to access the device for cleaning. When the displacer is externally mounted, the process does not have to be shut down for repair and cleaning.
- Displacement devices are recommended for liquid-liquid interface level measurement.
- Ultrasonic level measurement technology is based on the fact that sound travels through a medium with a known propagation speed, depending on the density and the temperature of that medium.
- The time it takes from emitting the signal to receiving the reflection is measured and then used (based on the known propagation speed of the sound wave) to calculate the distance to the level surface and the level height (based on the programmed calibration values of the system).
- The noncontacting principle is the main advantages of an ultrasonic system; it is not influenced by changes of the material properties, its sensor is not subject to wear and tear, and it has a wide range of applications.
- A capacitive probe works in most liquids (and solids), as it relies on the dielectric constant of the liquid to operate. As the liquid rises in the space between two electrodes, which are in effect the two plates of a capacitor, the variation in capacitance can be monitored and set to alarm.
- The only variable left is the dielectric constant of the medium. When the process material replaces the empty space or air (dielectric constant 1) in the vessel, the capacitance of the capacitor increases (the higher the level, the bigger the capacitance).
- The main advantages of capacitance systems are easy installation, broad application range, availability of many application-specific solutions, good accuracy (in suitable applications), and proven technology.
- The disadvantage of radar-based level measurement is the requirement for nonmetallic vessel walls or windows and vulnerability to buildup of material or moisture, which can cause false level indications.
- A microwave level transmitter, sometimes referred to as a radar level gauge, uses a Pulse Time of Flight (PTOF) radar or frequency modulated continuous wave (FMCW) measurement methods and operates in a frequency band approved for industrial use.
- Radar-based level measurement provides reliable measurement under difficult conditions, such as when the dielectric constant of the medium is less than 1.9 or vortices are present.
- The advantages of MiTDR (Microimpulse Time Domain Reflectometry) is that level measurements are disregard of the presence of vapors, steam, dust, gas layers, buildup, temperature changes, pressure changes, acoustic noise, changing density of the material to be measured, changing dielectric constant of the material to be measured, and changing conductivity of the material to be measured.
- Load cell sensors are mainly used for the measurement of dry dusty solids. When a vessel has an unusual, irregular shape, then load cells provide a suitable measurement solution.

LO 4: Analyze interface level measurement

- Process vessels such as separators permit immiscible liquids (i.e. liquids that are incapable of mixing) of different specific gravities to separate for further processing. The boundary between the immiscible liquids is called an "interface."
- For displacer units to detect an interface, a minimum difference in the liquid's specific gravities must exist. A reason for the added complexity is that in a typical process level measurement, liquid specific gravities of 0.5 or greater generate sufficient buoyant force.
- Applications may require purging, diluting or limiting the fluid entering the external chamber to prevent material buildups on the displacer.
- When a capacitance probe is used for an interface measurement, that device's sensitivity is a function of the difference in dielectric constants.
- If buildups are anticipated, capacitance probes are available that include anti-coating technology.

LO 5: Analyze automatic tank gauging system

- The terms "automatic tank gauging" represents a measurement system that provides an accounting of hydrocarbon inventories.
- An ATG system may include level, temperature, and density measurements.
- An ATG system may compensate the measured level quantity and calculate level data for changes in the tank structure itself as the tank fills and empties. Tank gauging measurements of level are used to derive mass and volume data.
- Tank gauging systems provide MIS departments measurements at scan rates of about every minute. Process level measurements have scan intervals of 1 second or less to continuously monitor and/or control a level.
- The communication path for a typical process level measurement system is its 4 to 20 mA signal to a controller. For a tank gauging system, a separate data highway or network is used, where the control system get its data from a field interface unit.
- The typical data that a tank gauging system provides often includes level, average temperature, water bottoms, density, gross volume, standard volume, and mass.
- Current tank gauging systems often include technology, called correction or strapping tables that compensate for changing process conditions.
- Stratification can cause the temperature and density measurements to not reflect current product conditions and, as a result, make the resulting mass and volume calculations suspect.
- The still-pipe, also referred to as a stilling well, is an independent structure within the tank. The still-pipe does not deform during the filling and emptying of a tank.
- The difference between a float element and a displacer element is that the displacer element is heavier than the liquid it is immersed in, while a float element rests on a liquid surface.
- Density measurements are also possible with servo-driven displacers.
- An HTG system consists of one to three highly accurate pressure transmitters, an RTD, and an optional HIU.
- The temperature reading from the RTD is necessary for calculating inventories at standard conditions.

LO 6: Review general considerations in selecting level measurement technology

- Specific gravity or density measurements, as performed by level measurement devices, frequently use hydrostatic approaches to help determine the weight of materials or volume of materials in a vessel.

- Another example of measuring density or specific gravity to infer level is the use of a differential pressure transmitter to identify an interface.
- Buried tanks usually contain oil or gas at atmospheric pressure. Suitable level measuring devices include devices ranging from the simple dipstick to hydrostatic head devices. Because the access to a buried tank is through the top of the tank, level measuring devices with probes (capacitance, ultrasonic) are also a possible selection choice.
- In tank gauging systems, accuracy is very important, because the engineer is concerned with proper inventory reporting. In process level measurement applications (point level and continuous), accuracy is important, but repeatability is considered more important than accuracy.
- Hard-to-handle fluids are best measured with devices that do not come in contact with the process material, through the use of devices that are called "noncontacting" technologies. Examples of noncontacting technologies are radar, ultrasonic, and laser devices.
- When level measuring devices experience exposure to process media, one concern is whether material buildups will occur. For example, when a float or displacer is exposed to process media, then material buildups are a potential possibility. Excess material buildups can change the weight of the float or displacer, and as a result, create errors in the level measurement.
- When level measuring devices experience coatings from process material, false level readings can occur. For example, when the level in a vessel decreases, a process material coating may remain on the capacitance probe, creating a false level reading.
- The presence of steam and other vapors within the vessel has detrimental effects on the performance of some level measuring devices. For example, vapors can affect the ultrasonic device's level measurement reading by altering the timing of the return signal.
- Some level measuring devices require an external cage, standpipe, or stilling well to provide the best conditions for level measurement. When an external cage is used to house the level-measuring device, the external cage permits the level-measuring device to be removed for service or calibration.
- Instruments may be connected to process connections called "taps" that allow connection directly to the tank. Differential pressure transmitters, for example, have tap location considerations.
- Calibration requirements may influence level measuring device selection in that an accurate calibration standard must also be available to ensure proper calibration and traceability.
- The expansion and the contraction of fill fluids within capillaries/impulse tubes connecting the process seal with the pressure sensor may cause level changes with change in ambient temperature.
- Ultrasonic measurements can be affected by the presence of vapor and/or changes in temperature of the vapor if the speed of sound is changed.
- Ultrasonic and radar measurements can be compromised by the presence of foam on a liquid if too little acoustic or microwave energy is reflected off the surface.

LO 7: Illustrate calibration of level transmitters

- Dry calibration holds true only when the liquid in the tank is at ambient temperature. When the liquid is hot or much colder than the ambient temperature, the liquid vapor or the condensate will fill the dry-leg. Under this condition, the dry calibration does not hold true. In such a situation, wet calibration method is to be adopted.

Questions

I. Objective-type questions

✦✦ **1.** Tank mapping is required for which type of level measurement?
- (a) Ultrasonic type level measurement
- (b) Float type level measurement
- (c) Bubble type level measurement
- (d) Capacitance type level measurement

✦✦ **2.** Ultrasonic level transmitter works well where tank is subjected to vacuum.
- (a) True (b) False

✦✦ **3.** Temperature of gases surrounding the measured components effects accuracy of level measurement in ultrasonic level transmitter.
- (a) True (b) False

✦✦✦ **4.** False readings can creep in for radar level measurement if atmosphere surrounding the measured components has dust.
- (a) True (b) False

✦✦ **5.** In a 4–20 mA signal that corresponds to a 0 to 100% scale, what would the current be at 50%?
- (a) 4 mA (b) 8 mA
- (c) 12 mA (d) 16 mA

✦✦ **6.** In pneumatic signaling, which of the following is true regarding a live zero?
- (a) Keeping the air supply at least 5 psi above the 100% signal allows enough pressure to keep a 0% reading from being underpowered and therefore variable.
- (b) Mechanical pneumatic entities such as tubes cannot operate for long in vacuum or constant pressure, so 0% must be at 0 psi and not a negative or positive quantity.
- (c) To get accurate readings that are continuously variable, the 0% reading must be set at 0 psi.
- (d) Representing 0% at 0 psi could result in a pressure failure being mistaken as a lower range value.

✦✦✦ **7.** Which of the following measurement methods is most cost-effective for measuring the level of highly corrosive media?
- (a) Ultrasonic (b) Radioactive
- (c) Float (d) Capacitance

✦✦ **8.** Which of the following will eliminate potential problems when using a pressure differential transmitter?
- (a) Changing density of the stored liquid
- (b) Replenishing tubing liquid with a purge flow
- (c) Increasing the pressure in the vapor space at the top of the tank
- (d) Evaporating liquid from filled tubing

✦✦ **9.** Which of the following causes a constant offset for any measurement?
(a) Turndown ratio (b) Zero error
(c) Field calibration (d) Span error

✦✦ **10.** Which of the following is an example of zero suppression?
(a) Calibrating a sensor to read 4 mA when a sensor reads a holding tank as being empty when the tank has 0 gallons of fluid.
(b) Convection keeps a fluid flowing through a system very slowly even when the process is not active and the sensor is set to read this level of flow as 0 gpm.
(c) A sensor set to monitor a fluid level and triggering automatic refill when the tank reads it is approaching 0 gallons so that the tank is never allowed to be empty.
(d) Changing the gain on a pressure sensor to read 3 psi even when the pressure within the system is at 0 psi.

✦ **11.** Which control measurement is generally expressed as the ratio of the error to the full-scale output?
(a) Response (b) Accuracy
(c) Linearity (d) Repeatability

✦✦ **12.** Which of the following methods of inferring level from head measurement is widely used in water/wastewater vessels and sumps?
(a) Displacer (b) Differential pressure transmitter
(c) Level switches (d) Bubbler

✦✦ **13.** If you set the instrument zero to a negative value, what is this called?
(a) Live zero (b) Zero based
(c) Zero elevation (d) Zero suppression

✦✦ **14.** Can we use pressure sensor to measure tank level and what type of sensor is used?
(a) No (b) No, Level sensor has to be used only
(c) Yes, absolute pressure sensor (d) Yes, Differential Pressure sensor

For Interactive Quiz with answers, scan the QR code

Or

Visit **http://qrcode.flipick.com/index.php/403**

II. Short-answer questions

✦ **1.** What is the abbreviation for level transmitter and level switch?

✦✦ **2.** How level measurement can be classified at a broader level?

✦✦ **3.** List any two categories of level measurement systems.

✦ **4.** What does hook type level measurement consists of?

✦ **5.** What is a sight glass measurement?

✦✦ **6.** How a bubbler level sensor measures the level?

✦✦✦ **7.** What is the principle of operation of the displacer?

✦✦✦ **8.** What is a torque tube displacer?

✦✦✦ **9.** Explain the principle of level measurement using ultrasonic technology.

✦ **10.** List three advantages of ultrasonic measurement systems.

✦✦ **11.** Explain the principle of operation of capacitive probes?

✦✦ **12.** Explain why a built in or external ground reference is required for capacitive probe with nonconductive materials?

✦✦✦ **13.** What are the two types of methods used in radar based level measurement?

✦✦ **14.** What are the advantages of using radar methods in level measurement?

✦✦✦ **15.** What is the principle of operation of measuring level using time domain reflectometry?

✦✦ **16.** What are the advantages of MITDR level measurement?

✦✦✦ **17.** List the disadvantages of nucleonic level gauges.

✦✦ **18.** Explain the applications in which load cells are used for level measurement.

✦✦✦ **19.** List few technologies used in level switches?

✦✦ **20.** List the advantages of float type tank gauging systems.

✦✦✦ **21.** List the disadvantages of float type tank gauging systems.

✦✦ **22.** What is the difference between a displacer and float type tank gauging system?

✦✦ **23.** List the advantages of HTG based tank gauging systems.

✦✦✦ **24.** What are the advantages of external cage mounted installation.

✦✦ **25.** Give an example of connection to process taps in level measurement.

✦✦✦ **26.** List three economic considerations in the selection of the level transmitters.

✦✦ **27.** Explain how a hydrostatic sensor exposure to large process temperature change can have temporary offset?

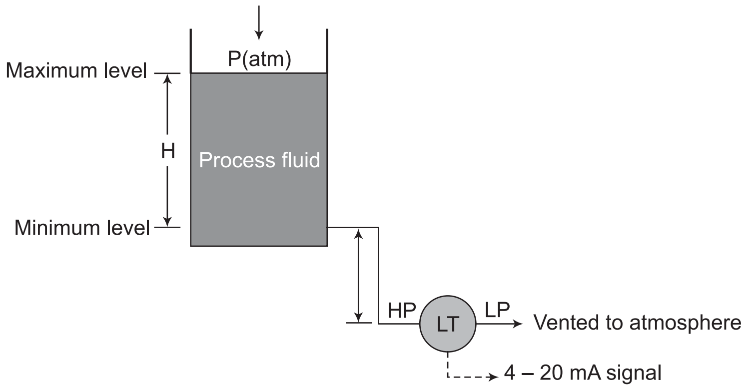
✦✦✦ **28.** How an ESD can be minimized in a level measurement system?

✦✦ **29.** When a dry calibration is performed on a DP transmitter?

III. Unsolved problems

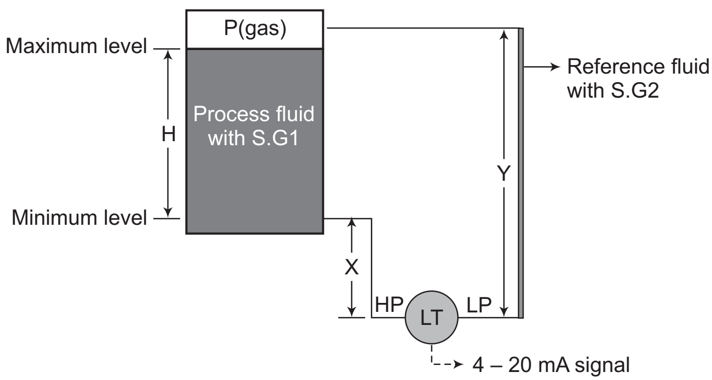
✦✦ **1.** A tank contains liquid which is measured by a pressure transmitter for its level. What is the level of a liquid, if the pressure measured is 127 kPa and the liquid density is 1.2 g/cm^3?

✦✦✦ **2.** Consider the following level measurement arrangement:



Suppose the maximum level of the liquid in the tank is 40 ft, the specific gravity of the liquid is 0.9. If the level transmitter is mounted 6 ft below the base of the tank, what should be the calibration range of the transmitter?

✦✦ **3.** Consider the following level measurement arrangement:

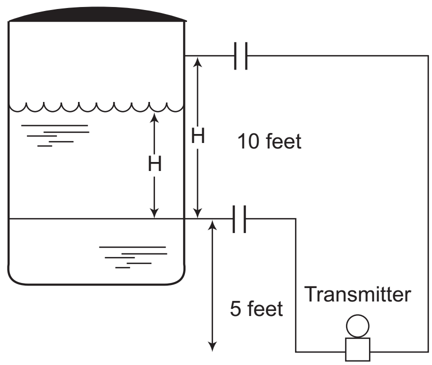


Suppose the maximum level of the liquid in the tank (H) is 550 in, X = 60 in and Y = 650 in the specific gravity of the liquid and the fill fluid is 1.0. If the level transmitter is mounted what should be the calibration range of the transmitter?

✦✦✦ **4.** What is the level of liquid with a density of 0.9 g/cm^3 in a round vertical flat bottom tank that is 2 m in diameter when the pressure at the bottom of the tank is 4 m of water column?

✦✦ **5.** What is the volume of liquid with a density of 0.9 g/cm^3 in a round vertical flat bottom tank that is 2 m in diameter when the weight of the liquid is 12 MT?

✦✦✦ **6.** For Figure, consider the h (range) is 0–10 feet and a factory calibrated (4–20 mA corresponding to 0–10 feet) differential pressure transmitter is mounted but not calibrated for the application which measures the level of the water in the tank, calculate how much mA the transmitter would send when the tank is once filled and emptied. Consider that the Low Pressure LP side is connected to the top of the tank.



IV. Critical-thinking questions

✦✦ **1.** How weight is measured using level measurement?

✦✦ **2.** What is vessel deformation and why it occurs?

✦✦ **3.** Why a vessel shape is important in level measurement to infer volume?

✦ **4.** Explain the reasons why a vessel's shape can influence level measurement device selection.

✦ **5.** What are the level measurement applications where in the float actuated mechanism is recommended?

✦ **6.** Explain the reason why the low pressure port of a differential pressure transmitter is equipped with 90° fitting and is turned down with a mesh?

✦✦✦ **7.** What are the conditions in which the DP transmitters with diaphragm seals are recommended?

✦✦✦ **8.** What is the purpose of filled capillaries in remote seal models of DP transmitters?

✦✦✦ **9.** Explain the reason for the displacer installed outside the vessel?

✦✦ **10.** What is the main contributor for the error in a displacer?

✦✦✦ **11.** What is the advantage of external cage mounted displacer from maintenance perspective?

✦✦ **12.** Displacers are recommended for which type of interface level measurement?

✦✦✦ **13.** What is echo suppression or tank mapping in ultrasonic technology?

✦✦✦ **14.** How variations in temperature affect the measurement of level using ultrasonic technology?

✦✦✦ **15.** How variations in gas composition affect the measurement of flow using ultrasonic technology?

✦✦ **16.** What is blocking distance in ultrasonic sensors?

✦✦ **17.** How the variations in dielectric constant of the medium contribute to the measurement of level using capacitive probes?

✦✦ **18.** List the advantage of capacitive level probes.

✦✦✦ **19.** What are the disadvantages of radar point level measurement?

✦✦ **20.** List two advantages of using hydrostatic head method for interface measurement?

✦✦ **21.** List two disadvantages of using hydrostatic head method for interface measurement?

✦✦ **22.** How ultrasonic transducers are installed to measure the interface level in the vessels?

✦✦ **23.** List at least three methods of measuring interface in the presence of emulsions.

✦✦ **24.** What is the purpose of correction or strapping in tank gauging systems?

✦✦✦ **25.** What is the purpose of stratification in tank gauging systems?

✦✦ **26.** What is the purpose of stilling well in floating roof tanks in tank gauging systems?

✦✦✦ **27.** Explain how the displacer be used for density measurement?

✦✦ **28.** List the instruments of a hydrostatic tank gauging system.

✦✦ **29.** Explain how the calibration requirements influence the level measurement device selection.

✦✦✦ **30.** Explain how the ambient temperature has an impact on the level measurement.

✦✦ **31.** Explain how ultrasonic measurement can be affected by the presence of vapor or changes in temperature of the vapor?

✦✦✦ **32.** Explain how ultrasonic or radar technologies might be influenced by the occurrence of foam?

✦✦✦ **33.** When a wet calibration is performed in a DP transmitter?

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Flow

5

Flow measurement is one of the complex and critical application of instrumentation in process control. Flow measurements are classified based on the technique such as the direct measurement or inferential methods. Within these categories various methods and technologies are discussed. Flow measurement requires the basic understanding on the hydraulics engineering and hence a short introduction to the nomenclature and basic principles are discussed. Some of the old, still widely used techniques like orifice, venturi and flow nozzles are introduced with their principles of operation. The differential pressure instruments in the application of flow measurement for gas, liquid and steam are discussed in detail. The flow computer applications and custody transfer applications are discussed in terms of their applications and different principles of operations as used in today's industry. Like other instrumentation, flow measurement has advantages of using smart instrumentation. The flow characterizations, and critical parameters that indicate the flow profile over the digital bus are discussed. Selection of the right instrument technique, proper design and installation is critical for accurate measurement. In this context, various selection guidelines are also discussed in detail. Various calibration methods used in the industry for the flow instrumentation as well as detailed procedures are introduced.

Keywords:
Magnetic flow meter, Coriolis meters, vortex meters, orifice, nozzle, Venturi, ultrasonic meters, Doppler effect, time domain reflectometry

LEARNING OBJECTIVES

After reading this chapter, you will be able to:

1. Describe the purpose of flow measurement, terminology, symbols, categories, and units of measure
2. Explain the restriction flow meters with primary devices and differential pressure transmitters
3. Elaborate the applications of variable area flow meters
4. Analyze the applications of magnetic flow meters
5. Demonstrate the applications of turbine flow meters
6. Explain the applications of oscillatory flow meters
7. Analyze the applications of Coriolis flow meters
8. Elaborate the applications of ultrasonic flow meters
9. Demonstrate the applications of positive-displacement flow meters, flow indicators and totalizers
10. Summarize the flow-measurement device selection criteria
11. Illustrate the calibration procedures for flow meters

"Every line is of perfect length if you cannot measure it"
Marty Rubin

5.1 FLOW MEASUREMENT

LO 1

Describe the purpose of flow measurement, terminology, symbols, categories, and units of measure

Flow measurement in industrial instrumentation means a range of practices from the selection of the flow measurement devices through the installation, application and interpretation of the results. This chapter covers purpose of flow measurement, terminology and symbols, general categories of flow instruments, units of measure and the hydrodynamic principles of the flow measurement.

5.1.1 Purpose of Measuring Flow

One important aspect of process control is measuring fluid flow. Accurate measurement of flow is essential in many process control applications. It is often the most frequently measured process variable. The measurements are used to monitor and control the flow rates at various process facilities. The flow measurement, along with measurement of temperature, pressure, and composition, are used to develop material and energy balances on processes. In addition, in some applications, controlling the flow rate in a particular upstream process helps to sustain the efficiency and to minimize the waste on downstream processing operations.

In general, oil-processing plants require material flows through successive operations, flow measurement is central to oil-processing equipment design and operation. Accurate flow measurements are fundamental to:

- Conversion and yield determination
- Material balances in separation processes
- Pumps and compressor operations
- Custody transfer operations

5.1.2 Terminology and Symbols

Let us understand the terminology and symbols in flow measurement applications in industrial instrumentation.

- Definitions and terminologies
- Drawing symbols
- Flow loop examples

5.1.2.1 Definitions and Terminologies

Flow meter is defined as a device that measures the rate of flow or quantity of a moving fluid in an open or closed pipe. It usually consists of a primary device and a secondary device. Flow is generally measured inferentially by measuring velocity through a known area.

- **Primary device:** A primary devices is the instrument installed internally or external to the pipe or conduit whose defined characteristics are in accordance to the flow of the fluid."
- **Secondary device:** A secondary device is defined as "Device that responds to the signal from the primary device and converts it to a display or to an output signal that can be translated relative to flow rate or quantity" .The secondary device constitutes

one or more elements that translates the signals from the primary device and translates to a signal which is standard for communication and also provides the signals for information to the user.

- **Meter run:** Meter run or meter tube is defined as upstream and downstream length of pipe containing the orifice flanges and orifice plate or orifice plate with or without quick-change fittings. No other pipe connections should be made within the normal meter tube dimensions except for pressure taps and thermowells. A meter tube is an important part of a flow meter installation. The meter run must create an acceptable flow pattern (velocity profile) for the fluid when it reaches the primary device. For example, orifice plate. Distortions occurring in the flow pattern result in pressure drop errors.
- **Pipe diameter:** It represents the inside diameter of a pipe. To calculate the inside diameter of a pipe, use the outside diameter of a pipe minus two times the wall thickness of the pipe. Pipe data tables give the inside diameter (I.D.) as a function of nominal pipe size, pipe material, and schedule.
- **Flow straighteners:** Flow straighteners are also sometimes referred as flow conditioners. Flow straighteners help to provide accurate measurement when a distorted flow pattern is expected. The flow pattern, called a flow profile, is distorted by sources such as pipe area changes, partially open valves, or valve and elbow combinations. When flow straighteners are installed in the pipe, a predictable flow pattern (flow profile) occurs at the outlet of the flow straightener. Flow straighteners are installed in the upstream section of meter tube. Flow straightening vanes reduce the upstream meter tube length requirement.
- **Flow rate:** Flow rate is an indication of how fast a substance moves through a conduit from one place to another. Flow rate can also be used to determine the distance a substance moves over a period of time. Flow rate is usually expressed as
  - **Volume flow rate:** It represents the volume of fluid that passes a measurement point over a period of time. An example measurement unit is barrels per day. The volume flow rate can be calculated if the average flow velocity and inside pipe diameter are known. The calculation is based on the formula:

    $$Q = A \times v$$

    where, Q = volumetric flow rate, A = cross-sectional area of the pipe, v = average flow velocity (flow rate).
  - **Mass flow rate:** It represents the amount of mass that passes a specific point over a period. Mass flow rates are used to measure the weight or mass of a substance flowing through a process operation. If the volumetric flow rate and density are known, the calculation is based on the formula equation 5.1:

    $$W = Q \times r \tag{5.1}$$

    where, W = mass flow rate, Q = volumetric flow rate, r = density (r = density "rho").
- **Compressible versus incompressible flow:** Temperature and pressure changes cause the volume of a fluid to change. The change in volume is extreme in gases than in

liquids. Compressibility represents the change per unit volume of a fluid caused by a unit change in pressure at constant temperature. When accurate gas flow measurements are needed, a factor for compressibility is often included in the measurement. The ratio of volume of the gas for a given temperature and pressure to the volume of the gas at base conditions, i.e. ideal gas law is called compressibility factor):

$$z = PV/nRT \tag{5.2}$$

The shapes of the compressibility factor curves for methane, propane, and isobutene gases at constant temperature are widely available in the datasheets. Methane has a lower boiling point than propane. Propane has a lower boiling point then isobutene. Methane shows the least deviation of the three for an ideal gas effect.

- **Viscosity:** Viscosity is frequently described as a fluid's resistance to flow. Viscosity can have a dramatic effect on the accuracy of flow measurement. Viscosity has a role in flow measurement when a fluid is in motion, but not when a fluid is at rest. Resistance to flow occurs because fluids have combined actions of cohesion and adhesion that create internal friction between layers in the fluid. Water, for example, having low viscosity has less resistance to flow. While viscosity is often described as a fluid's stickiness or thick appearance (or lack of either stickiness or thickness), those descriptions do not fully describe viscosity. Viscosity is a subject of a scientific discipline called fluid mechanics. Fluid mechanics deals with fluids in motion, which includes the property of viscosity. When a fluid is in motion, layers of fluid are subject to tangential shearing forces, causing the fluid to deform. Viscosity, then, is more accurately defined as the property of a fluid that resists the rate at which deformation occurs when tangential shearing forces act upon the fluid. Using the example of water's low viscosity, one can imagine that when a fluid has low viscosity (i.e. low ability to resist deformation), it would not be worthwhile to consider its low viscosity in a flow measurement. That is, a fluid's low viscosity does not become an influential property of the fluid upon flow measurement. However, when measuring the flow rate of a fluid with high viscosity, the viscosity does become an influential property in flow measurement.
- **Accuracy reference:** Accuracy is measured in terms of maximum positive and negative deviation observed in the testing of a device under a specified condition and specified procedure. The accuracy rating includes the total effect of conformity, repeatability, dead-band, and hysteresis errors. The accuracy of a flow meter is expressed in several ways. Flow meter accuracy is expressed as one of the following:
    - **Percent of rate accuracy:** It refers to an accuracy that is based upon the actual flow rate. The accuracy applies to meters such as turbine meters, DC magnetic meters, vortex meters, and Coriolis meters. The accuracy can be expressed as:

      $$\%\text{ of rate accuracy} = =\pm(\text{flow uncertainty}/\text{Instantaneous flow rate}) \times 100 \tag{5.3}$$

    - **Percent of full scale flow:** It refers to the accuracy of primary meters such as rotameters and AC magnetic meters. The accuracy can be expressed as:

      $$\%\text{ of full scale accuracy} = \pm(\text{flow uncertainty}/\text{full scale flow rate}) \times 100 \tag{5.4}$$

- **Percent of maximum differential pressure:** It applies to differential pressure flow transmitters. The accuracy can be expressed as:

$$\% \text{ maximum } \Delta P \text{ accuracy} = \pm (\Delta P \text{ uncertainty/maximum } \Delta P) \times 100 \quad (5.5)$$

As one may observe from the accuracy reference, it is important to know in what terms the accuracy reference is made. An accuracy reference of simply 2% is incomplete. One would have to know if that accuracy reference is in terms of instantaneous flow rate, full-scale flow rate, or maximum ΔP.

- **System accuracy:** In order to combine the component's accuracy statements to arrive at a system accuracy statement, it is first necessary to determine that all component statements are of the same type, i.e. % of maximum flow, % of rate, etc. This usually means that at least some of the components will have varying accuracy at different flow rates. Then the system accuracy must be calculated at various flow rates to produce a useful statement. A common method to combine accuracies of series connected components is to calculate the square root of the sum of their squares as:

$$\text{Syst. Acc.} = \pm \text{Sqrt}((\text{Acc.1})^2 + (\text{Acc.2})^2 + (\text{Acc.3})^3 \cdots) \quad (5.6)$$

- This method takes into account, in part, the fact that the various errors will probably not all be either positive or negative at one time and that the resulting uncertainty should not reflect the "Worst case" of arithmetic addition of errors.
- **Totalization:** Totalization represents the process of counting the amount of fluid that has passed through a flow meter. The purpose of totalization is to have periodic (daily or monthly) readings of the material usage or production. The totalization data is used for billings for material usage or production.
- **Custody transfer:** Flow measurement for custody transfer, where ownership of a product transfers, is on occasion regarded as a separate flow measurement topic. Usually the custody transfer flow meters are used for legal applications such as weights and measures compliance and contact applications where there is a commercial transaction between two companies or departments, etc.

  One reason for that distinction is that custody transfer flow measurement becomes essentially a money measurement. Because the purpose is primarily for billing, the perspective on flow measurement changes to one where accuracy becomes very important. In process control applications, the accuracy requirement may be several percent, but for custody transfer operations the accuracy requirement may be in tenths of a percent.

5.1.2.2 Drawing Symbols

Below are some of the commonly used symbols to represent various elements used in flow measurement systems and applications. The symbols are being standardized by ISA for the benefit of whole instrumentation engineers, whereas still we can see the symbols used on per company basis. Various sample symbols are shown in Figure 5.1 and Figure 5.2. The students are encouraged to refer to the ISA standards for the actual symbols.

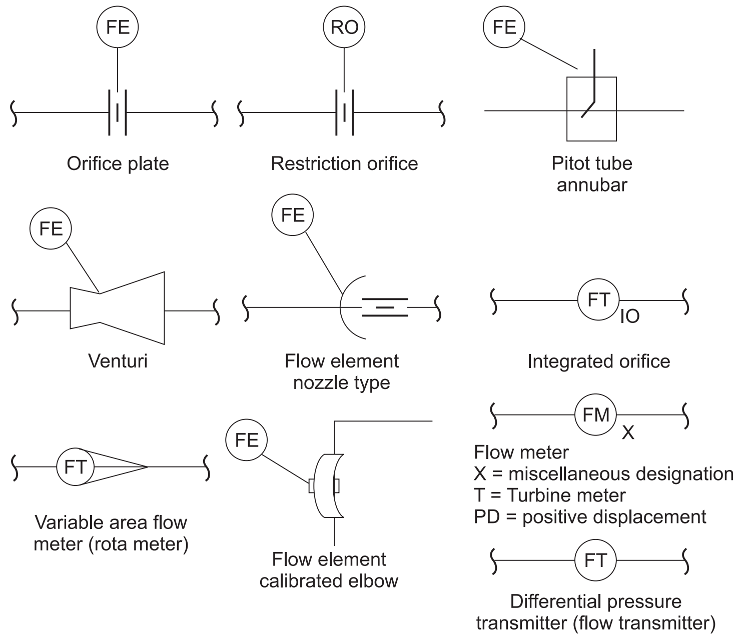

Figure 5.1: Flow drawing symbols-1

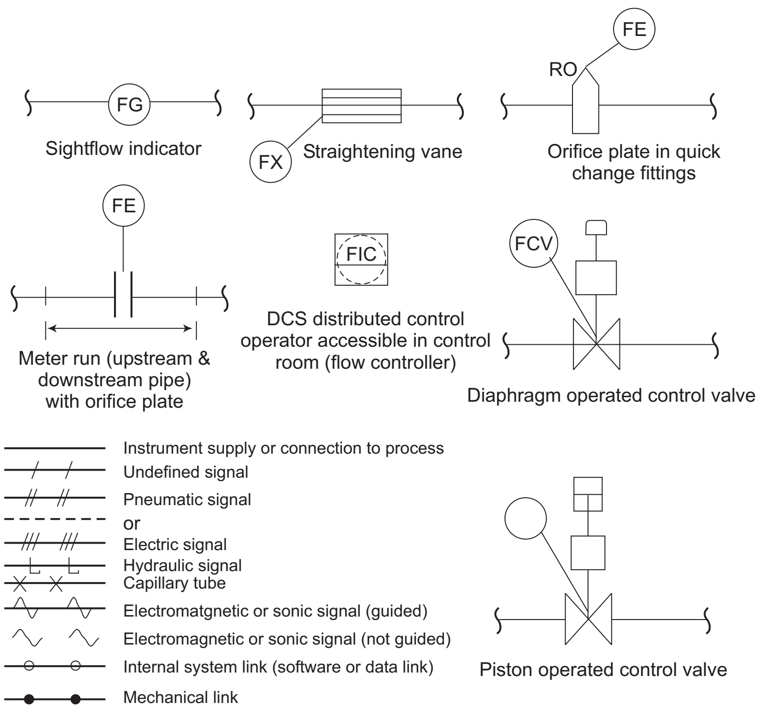

Figure 5.2 Flow drawing symbols-2

5.1.2.3 Flow Loop Examples

An orifice meter is one of the most common of flow meter installation (The details of the orifice meter can be seen in next section). In the orifice meter installation as shown in Figure 5.3, the primary device consists of the meter tubing (also called a meter run) and a constricting element. The constrictive element in this flow meter is the orifice plate. The secondary device measures the pressure drop caused by the primary element. The secondary device in this example is a pressure-sensing device such as a differential pressure transmitter (flow transmitter). Similarly, in place of orifice plate with flange, a venture or flow nozzle may be used.

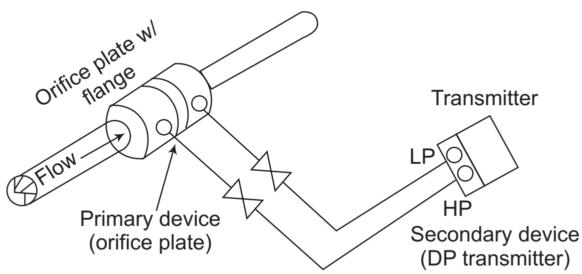

Figure 5.3: Flow meter setup

The example Figure 5.4 show a typical flow control loop on a refinery. Using the definitions and symbols provided above, the various elements should be understood.

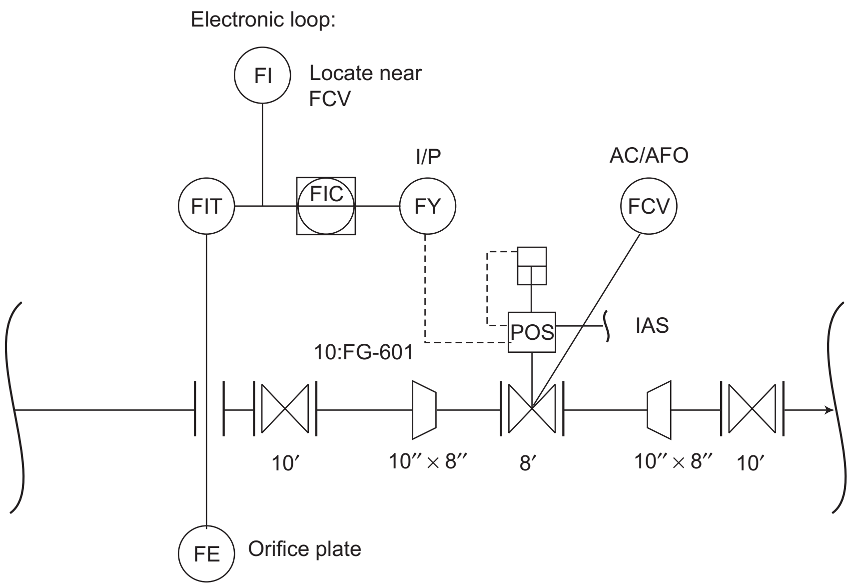

Figure 5.4: A sample electronic flow loop diagram

Similarly, a pneumatic flow loop is represented in the Figure 5.5.

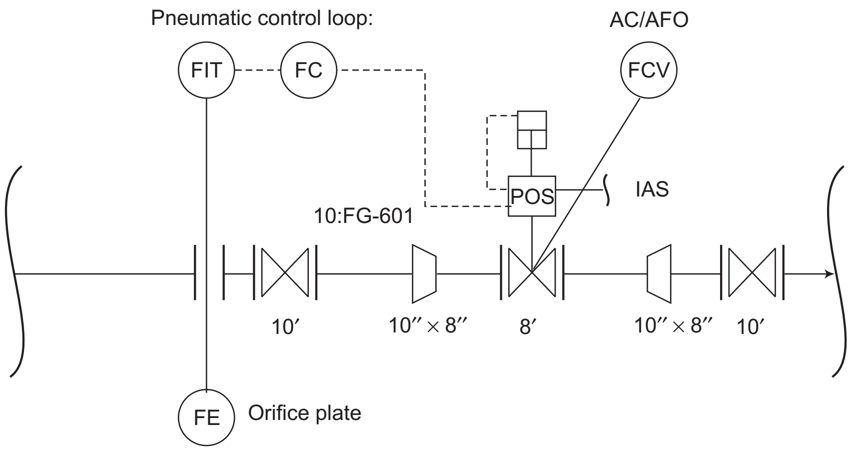

Figure 5.5: A sample pneumatic flow loop diagram

5.1.3 General Categories

Flow instrument categorization can vary and is not usual to see up to nine categories of flow meters. Two approaches to meter categorization are to describe flow meters in terms of rate or quantity type, and energy usage type.

5.1.3.1 Rate or Quantity Type

Rate meters are the most common classification of flow meters. Rate meters measure the process fluid's velocity. Velocity is expressed in terms of distance per time, such as m/s or ft/s. Because a pipe is cross sectional area is known, the velocity is then used to calculate the flow rate. A flow rate, such as m^3/s or ft^3/second, represents the amount of fluid volume at a particular location and at a particular time during which the measurement is taken.

A rate meter can either infer the flow rate or measure the velocity of the flowing fluid to determine the flow rate. For example, a differential pressure flow meter infers the flow rate from the differential pressure across a restriction in a line. The flow rate in this case is inferred from the measured differential pressure and accepted correlations to rate. A velocity measurement, as in the case of a turbine meter, uses the velocity of the fluid times the area through which the fluid is flowing to determine the flow rate.

Quantity meters continuously divide the flowing material into predetermined volume segments. Quantity meters count and keep track of the number of these volume segments. An example of a quantity meter is a positive displacement meter. Whenever you refill your car with petrol or diesel, the liquid flows through a positive displacement meter that counts the number of liters of petrol or diesel that you have purchased. Meters that directly measure mass can also be considered either as a quantity meter or as a mass flow rate meter. Table 5.1 provides various types of meters and their categorization.

Table 5.1: Classification of various flow meters			
Type of Device	*Quantity*		
	Direct Mass Measurement	*Direct volume Measurement*	*Flow Rate*
Positive displacement • Rotating paddle • Oscillating piston • Fluted rotor • Oval shaped gear		✓	
Turbine meter			✓
Differential pressure • Orifice • Venturi • Flow nozzle • Pitot			✓
Magnetic flow meters			✓
Mass flow meters (Coriolis and thermal)	✓		✓
Ultrasonic flow			✓
Vortex			✓
Variable area flow meters (rotameters)			✓

5.1.3.2 *Energy Usage Type*

Another way of categorizing flow meters is to use a method called the energy approach. Flow meters either take from or introduce energy to the process media, which leads to the following two sub classifications—extractive energy approach and additive energy approach.

Extractive Energy Approach In this approach, flow meters take energy from the fluid flow. These flow meters, because they are intrusive, often introduce pressure losses into the fluid flow. An orifice plate is an example of an extractive type device.

Additive Energy Approach In this approach, flow meters introduce some form of energy into the fluid flow. These flow meters, because they are nonintrusive, do not produce pressure losses in the fluid flow. The energy—electromagnetic, acoustic, or mechanical—is required for the flow meter to operate. A magnetic flow meter is an example of an additive type device.

5.1.4 Units of Measure

The flow measurement can be measured in different units like any other process variables. Table 5.2 provides some of the units used in process industries.

Table 5.2: Units of measure for flow		
Fluid	*SI Metric Units*	*English Units*
Water	m^3/h (cubic meters per hour) m^3/d (cubic meters per day)	GPM (Gallons per minute) BPD (Barrels per day)
Oil, in plant process liquids, steam condensate, gas	m^3/h (cubic meters per hour) m^3/d (cubic meters per day) kg/h (kilograms per hour)	BPH (Barrels per hour), BPD (Barrels per day) LB/HR (Pounds per hour) SCFH (Standard cubic feet per hour) SCFD (Standard cubic feet per day) MMSCFD (Millions of standard cubic feet per day)
Gas, crude oil products	m^3/d (cubic meters per day)	SCFD (Standard cubic feet per day MMSCFD (Millions of standard cubic feet per day) BPD (Barrels per day)

5.2 PRINCIPLES OF FLOW MEASUREMENT

LO 1

In order to choose the proper measurement instrument, one must have an understanding of fluid's properties, particularly when that fluid is in motion. The study of fluids in motion is called hydrodynamics. It is important to consider a fluid's properties as being unique prior to flow measurement device selection. Hydrodynamic principles that bear on flow measurement are: device selection are described as: Bernoulli and basic hydraulic equations, relationships governing Newtonian versus non-Newtonian fluids, and viscosity.

5.2.1 Bernoulli and Basic Hydraulic Equations

When a liquid flows from one place to another it may undergo a change in potential energy or in kinetic energy, but if it moves without waste of energy caused by friction, the unit's total energy remains unchanged, in accordance with the law of conservation of energy. Consider a liquid flow steadily through a tube of any section as illustrated in Figure 5.6, and imagine that the liquid is incompressible and frictionless and that its velocity at any cross-section is uniform throughout that section. During a short interval of time, particles of liquid at section 1 and at

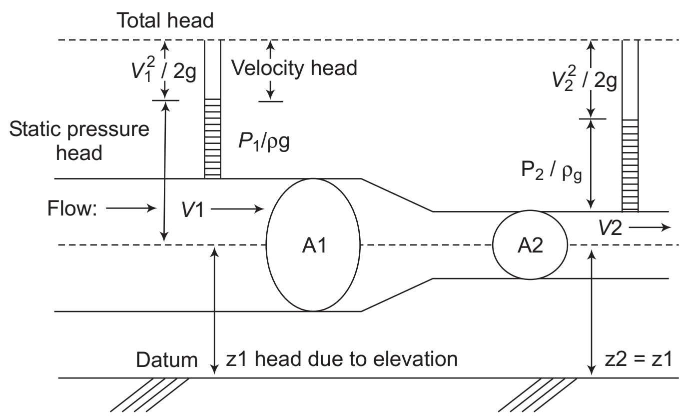

Figure 5.6: Bernoulli and hydraulic equations

section 2 will move as indicated by the arrows. Let the cross-sectional areas at these sections be respectively A_1 and A_2, the corresponding velocities of the liquid be v_1 and v_2, the elevations of the sections above a convenient datum plane are respectively Z_1 and Z_2, and the pressures of the liquid are respectively p_1 and p_2.

Then because the liquid is incompressible, the same mass "*m*" will pass any section of the tube in a given time (t) the volume of this mass will be $V = m/\rho$, where ρ is the density of the liquid. The work that must have been done on this mass of liquid to bring it to the conditions existing at section 1 consists of three parts: mgZ_1 to elevate it to the height Z_1 above the datum plane; ½ mv_1^2 to give it the velocity v_1; and p_1V or $p_1\ m/\rho$ to force it into a region of pressure p_1. Because the liquid is frictionless, the same amount of work would be required to bring this mass of liquid to the conditions existing at section 2; consequently:

$$mgZ_1 + 1/2mv_1^2 + p_1m/\rho = mgZ_2 + 1/2\ mv_2^2 + p_2m/\rho \qquad (5.7)$$

The corresponding expression for the total work per unit weight of liquid at any section is obtained here from by dividing each term by the weight mg, thus:

$$Z_1 + v_1^2/2g + p_1/\rho g = Z_2 + v_2^2/2g + p_2/\rho g \qquad (5.8)$$

This summation is referred as *total head*, the respective terms being called:

$$Z = \text{elevation head, } v^2/2g = \text{velocity head, and } p/\rho g = \text{pressure head.} \qquad (5.9)$$

Daniel Bernoulli's total head equation, above, says "If there is a constant sum of energy the components can be varied, with each contributing more or less depending upon their condition. A change in velocity will result in an inverse change in pressure. If the flow area is reduced, the velocity will increase. This velocity increase through a narrowed flow area is the basis for all variable differential pressure types of flow meters.

P = Static Pressure (pounds force per sq. ft)

ρ = Density (rho) (pounds mass per cubic ft)

v = Velocity (feet per second)

g = Acceleration of Gravity (feet per second^2)

Z = Elevation Head Above a Reference Datum (feet) (5.10)

Other basic hydraulic concepts that describe fluid flow characteristics are: equation of continuity and Reynolds numbers.

5.2.2 Equation of Continuity

The equation of continuity is the basis for describing how all velocity-type flow instruments operate. It states that the volumetric flow rate can be calculated by multiplying the cross sectional area of the pipe at a given point by the average velocity at that point. The equation is based on the formula:

$$Q = A \times v \qquad (5.11)$$

where, Q = volume flow rate (ft^3/min), A = pipe cross-sectional area (ft^2), v = average fluid velocity (ft/min).

5.2.3 Reynolds Number

In 1882, Sir Osborne Reynolds wrote the seminal paper on flowing fluid characteristics. He defined the major distinctive quality of fluid flow as the ratio of inertial forces to viscous forces. When two samples of flowing fluid have the same no dimensional ratio value, they have similar flow characteristics.

Low Reynolds numbers defines laminar flow with the largest flowing fluid moving coherently without intermixing. High Reynolds number with much mixing defines turbulent flow. Both flow extremes are beneficial depending upon requirements. Turbulent flow is best when high heat transfer is wanted, while laminar flow is best when flowing fluid is to be delivered through a pipe with low friction losses. Flow is considered laminar when the Reynolds number is below 2,000. Turbulent flow occurs when the Reynolds number is above 4,000. Between these numbers, the flow characteristics have not been defined.

When choosing flow meters, the flow's Reynolds number must be within the range of the meter's design. If not, the measurement will be suspect. Reynolds number is defined by the following equations:

For liquid flow:

$$Re = 50.7\ \rho Q/D\mu \quad \text{or} \quad Re = 6.32\ W/D\mu \tag{5.12}$$

where, Re = Reynolds number (dimensionless), ρ = density (lb/ft^3) at current temperature, Q = flow rate (gal/min), D = internal tube diameter (in), μ = viscosity of flowing temperature (centipoise), W = flow rate (lb/h).

For gas flow:

$$Re = 6.32\ \rho Q/D\mu \quad \text{or} \quad Re = 6.32\ W/D\mu$$

where, ρ = density at standard conditions (lb/ft^3), Q = flow rate (scfh) and other units are defined the same as for liquid.

Example

What is the Reynolds number for 68°F water flowing in a 6 inch schedule 40 pipe at 50 ft/s?

$$\begin{aligned}\text{Re} &= 6.32\ W/D\mu \\ &= 6.32\ (50)\ \text{ft/sec}\ (6.065/12)2 \times \pi/4\ \text{ft}^2 \times 3600\ \text{sec/h} \times 62.4\ \text{lb/ft}^3/\ (6.065\ \text{in} \times 1\ \text{cp}) \\ &= 6.32 \times 50 \times 6.065 \times \pi \times 3600 \times 62.4/12^2 \times 4 \\ &= 6.32 \times 6.065 \times \pi \times 3.750 \times 62.4/12 \\ &= 2{,}350{,}000\end{aligned}$$

Because the Reynolds number is greater than 10,000, the flow is turbulent.

5.2.4 Incompressible Flow

Fluids are materials that flow. Liquids are fluids that flow without changes in density. The previous development of a Bernoulli theorem considered a flowing liquid with other simplifying assumptions. That primitive analysis can be expanded by considering real life deviations from the simplifying assumptions.

An example of an incompressible fluid is water. In theory, water does change density in its temperature excursion from ice (solid) to steam (vapor or gas), but ever so slightly. Water is most dense at 4°C. Ice floats on water, as ice is less dense than water at freezing temperatures and below. Water is a Newtonian fluid that shows certain fluid mechanics' properties. Hydrocarbons, generally, are non-Newtonian in their flowing characteristics. Liquids tend to hug the bottom of any container in which they are placed. Gases, compressible fluids, tend to distribute uniformly throughout the enclosing container.

5.2.5 Compressible Flow

Gases are fluids that have variable densities because of the pressure and temperature conditions. The Ideal Gas Law correlates these conditions, incorporating Boyle and Charles laws:

$$PV = nRT \tag{5.13}$$

where, P = Absolute pressure, V = Volume, n = Mass (number of molecules), R = Universal gas constant, T = Absolute temperature.

The ideal gas law is not always true. The compressibility factor, Z, which has been introduced previously, can recognize a deviation. As another example, consider the flow of a gas through a meter. At low velocities, the gas may behave as an incompressible fluid and the Reynolds number may provide a suitable parameter for correlating data. At high velocities, however, compressibility effects may be present and it may be necessary to use the Mach number in order to correlate the data.

Laminar flow refers to a smooth, streamlined flow pattern (Figure 5.7). The flow pattern appears as if there are several plates or laminations of flowing particles that flow parallel to each other. Consider the growth rings of a tree. Each layer or ring flows at a constant speed. The flow pattern nearest the pipe walls is slower than the flow pattern in the center of the fluid because of friction that occurs between a fluid and the pipe's walls.

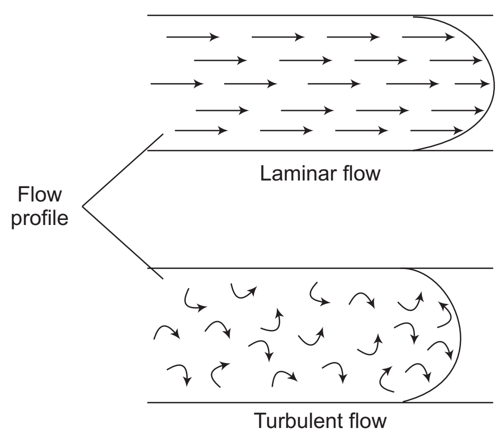

Figure 5.7: Flow profiles

Turbulent flow refers to a flow pattern that is the opposite of laminar flow. The flow pattern is distorted, rough, and irregular. A turbulent flow pattern has small whirlpool-type eddy currents that appear to go in all directions.

5.2.6 Relationships Governing Newtonian and Non-Newtonian Fluids

In Newtonian fluids, the resistance to deformation when subjected to shear (consistency of fluid) is constant if temperature and pressure are fixed. Whereas, in a non-Newtonian fluid, resistance to deformation is dependent on shear stress even though the pressure and temperature are fixed. The relationship is further described in the following terms: Hagen-Poiseuille Law, rheograms, Newtonian fluids, and non-Newtonian fluids.

5.2.7 Hagen-Poiseuille Law

Hagen-Poiseuille law defines viscosity in terms that are more practical. Newton's definition of viscosity is the ratio of shear stress divided by shear rate. Hagen-Poiseuille defines it as the ratio of shear stress divided by shear rate at the wall of a capillary tube as shown:

$$\mu = \text{shear stress/shear rate} = (PR/2L)/(4Q/\pi R^3) = (\pi PR^4)/(8QL) \qquad (5.14)$$

where, μ = absolute (dynamic) viscosity (pounds/foot-second), P = pressure differential across liquid in the tube (pounds/square foot), R = inside radius of the tube (ft), L = length of the tube (ft), Q = volume rate of flow of liquid (ft^3/s)

Rheograms can be used to determine the characteristics of any fluid. Rheograms evolved from the science of rheology, which studies flow. "Rheo," derived from the Greek language, means, "flowing". Rheograms are useful as an aid to interpret viscosity measurements.

5.2.8 Newtonian Fluids

A Newtonian fluid exhibits the constant ratio of shear stress to shear rate (flow velocity) when subjected to shear and continuous deformation. When a fluid's temperature is fixed, the fluid exhibits the same viscosity through changing shear rates. Viscosity is not affected by shear rate (flow velocity). The relationship is linear between the shear stress (force) and velocity (resulting flow). Newtonian fluids are generally homogeneous fluids. Gasoline, kerosene, mineral oil, water, and salt solutions in water are examples of Newtonian fluids.

5.2.9 Non-Newtonian Fluids

Fluids that do not show a constant ratio of shear stress to shear rate are defined as non-Newtonian fluids. Fluids exhibit different viscosity at different shear rates. In non-Newtonian fluids, there is a nonlinear relation between the magnitude of applied shear stress and the rate of angular deformation. Non-Newtonian fluids, which have different classifications, tend to be liquid mixtures of suspended particles. Thick hydrocarbon fluids are considered non-Newtonian fluids. Figure 5.8 represents the graphical difference between the fluids.

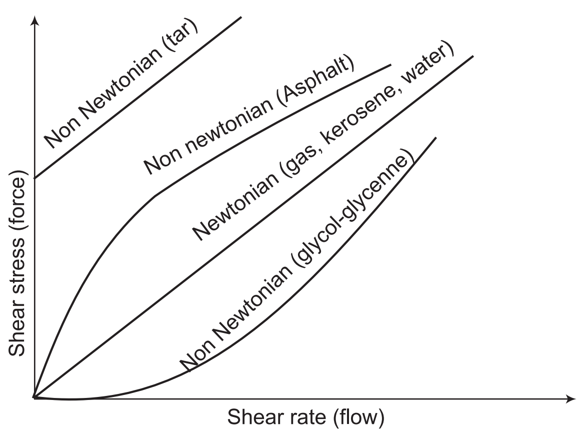

Figure 5.8: Newtonian vs non-Newtonian flow

5.2.10 Viscosity

Viscosity is a property of a fluid, which affects the fluid's behavior. Viscosity is defined as a fluid's internal resistance to flow. If a fluid undergoes continuous deformation when subjected to a shear stress, than the resistance (consistency) offered by the fluid can be stated for such deformation. Viscosity is often expressed in terms of the following—dynamic viscosity, kinematic viscosity, viscosity index , and viscosity scales.

5.2.10.1 Dynamic Viscosity (Absolute Viscosity)

It represents a fundamental viscosity measurement of a fluid. Density of fluid does not play a part in the viscosity measurement. The ratio of shear stress applied to the flowing velocity and the resistance offered by the liquid may be termed as viscosity. If all the other characteristics of the liquids such as static pressure and temperature are fixed at a constant density for the gases and non-Newtonian liquids, the same viscosity may be termed as absolute viscosity (μ). One method to measure viscosity is to rotate a disk in the fluid at a particular rotational speed. The rotational torque required keeping the disk rotating divided by the speed of rotation and by the disk contacting surface area is a measure of absolute viscosity. The measurement units for dynamic (absolute) viscosity are centipoise, Pascal-seconds, or lb/ft s. Another viscosity measurement that can be used for liquids and gases is the falling sphere viscometer (viscosimeter).

5.2.10.2 Kinematic Viscosity

It represents a ratio of dynamic (absolute) viscosity to the density of the fluid and is expressed in stokes ($\nu = \mu/\rho$). In liquids, an increasing temperature usually results in lowering the kinematic viscosity. In gases, an increasing temperature increases the kinematic viscosity. The method for determining kinematic viscosity involves measuring the time to drain a certain volume of liquid by gravity out of a container through a capillary tube or some type of restriction. The time it takes to drain a liquid is directly related to viscosity and is recorded in seconds. The flow rate of fluids by gravity, which is the force causing the flow, depends upon the density of the fluids. Viscosity measured by this method is called the kinematic viscosity. The measurement units for kinematic viscosity are either centistokes, m^2/s, or ft^2/s. The centipoise (cP) is equal to centistokes multiplied by the density of the fluid.

5.2.10.3 Viscosity Index

It represents the change in viscosity with respect to temperature. Viscosity index is used with reference to petroleum products. A high viscosity index number means that the fluid's viscosity does not change very much for a given temperature. A low viscosity index number indicates that the fluid's viscosity does change significantly for a given temperature.

5.2.10.4 Viscosity Scales

It presents viscosity measurements in time units. Viscosity scales that are commonly used include the following:

- Saybolt Furol scales

- Redwood scales
- Engler scales

The three scales express kinematic viscosity in time units rather than centistokes. For example, if the kinematic viscosity of a fluid at 122°F is 900 cs, on the Saybolt Furol scale the equivalent viscosity is expressed as 424.5 s (centistokes × 0.4717). Flow engineering reference manuals often provide conversion formulas between centistokes and the respective viscosity scale. Note that dynamic viscosity can be derived from the kinematic viscosity.

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Checkpoint

✦✦ 1. Which measurement is critical for oil processing equipment design and operations due to the material movement?

✦✦ 2. A flow meter is a device that measures ____________ or ____________ of a moving fluid in an open or closed conduit.

✦ 3. Flow is generally measured inferentially by measuring ____________ through a known area.

✦✦ 4. Define primary device.

✦ 5. Define secondary device.

✦✦✦ 6. Define meter run.

✦✦✦ 7. Why a user must create an acceptable flow pattern (velocity profile) for the fluid when it reaches the primary device?

✦✦ 8. What is flow rate?

✦✦ 9. Define mass flow rate.

5.3 RESTRICTION FLOW METERS WITH PRIMARY DEVICES AND DP TRANSMITTERS

LO 2

Explain the restriction flow meters with primary devices and differential pressure transmitters

In this learning objective, various types of restriction flow meters are discussed along with their merits and demerits, installation practices and selection and application criteria.

5.3.1 Orifice Plate

The oldest known method of metering flow is by using the orifice plate. During the Roman Empire, viaducts were used to supply water to homes in the city of Rome. An orifice was

Note: ✦ Level 1 & Level 2 category
✦✦ Level 3 & Level 4 category
✦✦✦ Level 5 & Level 6 category

installed in the water line going into the house and the resident had to pay a tax proportional to the size of the orifice. The size of the orifice in the line regulated the amount of water received. This was the earliest water meter. Today the orifice/differential pressure meter is still the most widely used flow meter technology. Like any other measurement of any process parameter, the flow measurement device selected depends on the nature of the liquid/solids and the process, environmental conditions. In general, flow is measured by an indirect means either by measuring the differential pressure across a restriction or by measuring the velocity of the stream. The indirectly measured variables such as differential pressure or volume is electronically converted to rate of volume, also called as flow.

The most common type of measuring the flow rate in a pipe is to create an obstruction in its path and measure the pressure differential across the same. The relation between the flows rates to the type of the obstruction to the differential pressure are correlated to known correction constants, known as pipe diameters. In any closed pipe, the flow of liquid passing though the obstruction or restriction in the pipe creates a momentary loss of pressure. This loss of pressure is mathematically related to the flow and in general, the flow is directly proportional to the square root of differential pressure. Orifice is one of the restricting elements in the flow path that can be used to infer the flow in the path.

An orifice plate is the main element within an orifice meter tube. An orifice plate is the simplest and most economical type of all differential pressure flow meters. An orifice plate is constructed as a thin, concentric, flat metal plate. The plate has an opening or "orifice." An orifice plate is installed perpendicular to the fluid flow between the two flanges of a pipe. When the fluid passes thorough the restriction, there is an increase in velocity and decrease in pressure as the static pressure (potential energy) is converted into velocity (kinetic energy). Similarly as the fluid exits the plate, the velocity reduces with an increase in pressure, which is nothing but the kinetic energy is converted back to potential energy (with some loss). Orifice plates always experience some energy loss, i.e. a permanent pressure loss caused by the friction in the plate. The beta ratio is defined as the ratio of the diameter of orifice bore to internal pipe diameter. The most common holding system for an orifice plate is a pair of flanges, upstream and downstream piping, and a pressure tap. The pressure taps are located either on orifice flanges or upstream and downstream of the pipe from the orifice plate.

Several types of orifice bore designs are available for orifice plates; concentric, segmental, and eccentric orifice plates. The plates are used for a wide range of applications. For precise measurement, various types of fittings are used junior fittings, senior fittings, and simplex fittings. The fittings provide easy installation of an orifice plate, removal of the plate for changes in flow rate services, and convenient removal for inspection and maintenance. Limitations of orifice plates include a high irrecoverable pressure and a deterioration in accuracy and long-term repeatability because of edge wear. Two types of orifice plate designs are available—paddle type and universal type. The paddle type orifice plate, used with an orifice flange, has a handle for easy installation between flanges. On the paddle type plate, the orifice bore, pressure rating (flange rating), bore diameter, beta ratio (β), and nominal line size are stamped on the upstream face of the plate. The outside diameter of a paddle plate varies with the pressure rating of the flanges. The universal orifice plate is designed for use in quick-change fittings, or in the plate holder of the ring type joint (RTJ) orifice flanges. The universal plate is placed in a plate holder; the outside diameter is the same for all pressure ratings for any given size. When using orifice fittings, the internal diameter of the meter tube must be specified because the orifice plate is held in an orifice plate-sealing unit. The sealing unit is made of metal, Viton, or rubber material.

Some orifice plates have a small hole in the orifice plate besides an orifice bore, either above or below the center of the plate that is called a weep hole. The purpose of the weep hole is to allow the passage of any condensate in a gas application or passage of gas in liquid service applications. The area of the weep hole must be considered when sizing an orifice plate. An orifice plate with a weep hole should not be used when accurate measurement is required in a flow measurement application, such as in gas sales service such as custody transfer applications.

5.3.1.1 Basic Orifice Plate Types

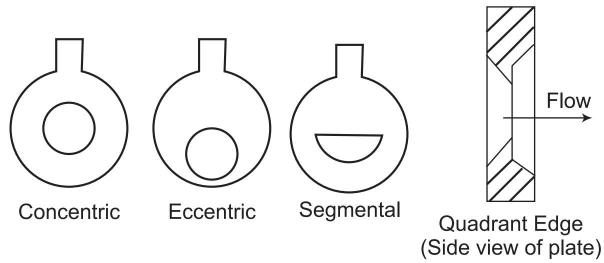
The orifice plate with a bevel edge and concentric bore is used for general applications. Four basic types of orifice plate bores as shown in Figure 5.9 are concentric, eccentric, segmental, and quadrant or conical edge.

Concentric Plates The concentric orifice bore plates are used in general flow measurement applications. The concentric orifice plate has an orifice bore in the center of the plate. The center of bore is either beveled or straight. The beta ratio for the concentric plate is between 0.1 to 0.75. The beta ratios of the plate are "d/D" where "d" is the diameter of the bore and "D" is the diameter of the plate or internal diameter of the pipe. The concentric bore plate is used for clean fluid services, as well as for applications requiring accurate flow measurement.

Eccentric Plates The eccentric orifice plate is similar to a concentric plate, but the eccentric plate has the bore in an offset position. The eccentric orifice plate is used when dirty fluids are measured, to avoid the tendency of completely plugging if a concentric plate were used. Flow coefficient data is limited for eccentric orifices; therefore, it provides less accurate measurement. In eccentric office plates, the hole is provided inside the pipe wall tangentially. The tangential bore is concentric with a diameter not smaller than 98% of internal diameter of the pipe. When lacking specific process data for the eccentric orifice plate, the concentric orifice plate data may be applied as long as accuracy is not a major issue. During the installation of an eccentric plate, make sure that flanges or gaskets do not interfere with the plate hole. In an eccentric orifice plate, the line size ranges from 4 inches minimum to 14 inches maximum. The eccentric plate can be made smaller than a 4 inch size as long as the orifice bore does not require a beveling edge. Beta ratio is limited between 0.3 to 0.8. Flange taps are recommended for eccentric orifice plate installations. In an eccentric plate, the pressure taps should be located in the quadrants directly opposite the hole. The tabs on this plate should be stamped after installation to indicate the type of bore that the plate has.

Segmental Plates The segmental orifice plates bore looks like a segment of a circle. The segmented circle hole is offset from the plate's center. In a segmental orifice plate, the hole is provided inside the pipe wall tangentially. The tangential bore is concentric with a diameter

Figure 5.9 **Types of orifice plates**



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not smaller than 98% of internal diameter of the pipe. The plate arc is parallel to the pipe wall. During the installation of the segmental plate, make sure that the flange or gasket does not interfere with the plate hole. The beta ratio (β) for the segmental orifice plate is expressed as a/A, where "a" is the area of the hole segment and "A" is the area of the internal pipe. Beta ratio is limited between 0.3 to 0.8. In a segmental orifice plate, the line size ranges from 4 inches minimum to a maximum of 14 inches. Reynolds number for segmental plate is limited to 20,000 D, where "D" is the diameter of the pipe. However, the Reynolds number should not be less than 10,000. Flange taps are recommended for segmental orifice plate installations. The taps for the segmental orifice plate should always be in the line with the maximum dam height. The tabs on this plate should be stamped after installation to indicate the plate's type of bore.

Quadrant Edge Plates Quadrant edge bore (quarter circle) orifice plates are used for pipes with the liquids with low Reynolds number. The flow coefficients for sharp edge orifice plates for liquids with low Reynolds number is largely variable. In general, the Reynolds numbers can range from 500 to 10,000. The stability of flow coefficient will be increased by a factor of 10. The quadrant edge orifice plate is used for viscous clean liquid applications. Nominal pipe size ranges between 1 in and 6 in.

5.3.1.2 Orifice Plate Parameters

The orifice plate is a simple and accurate flow-measuring device. The accuracy of measurement depends on the quality, installation, and maintenance of the orifice plate. The following are the main parameters of an orifice plate:

- **Orifice flow rate**: The orifice flow rate represents the mass or volume of flow through an orifice meter per unit of time.
- **Pipe line size and pressure rating**: When sizing or specifying the orifice plate, the pipeline size, schedule, and pressure rating need to be specified. For example, 4 inches, schedule 40, and pressure or flange rating 300#RFSF are example specifications. For a pipe size of 4 inches, schedule 40, the internal diameter of pipe is 4.026 in. The internal diameter of pipe is specified as parameter "D".
- **Thickness of orifice plate**: It is important to specify the thickness of the plate. The thickness of the plate is from 1/4 inch to 1/2 inch in size. The specified thickness depends on the size of the plate, the operating pressure, and the differential pressure across the orifice plate.
- **Orifice bore (d):** The orifice bore is simply the hole opening in the plate. An orifice bore is either in the center of the plate or offset from the center of the plate. The orifice plate bore diameter (d) is calculated at flowing temperatures under physical and chemical conditions. The orifice bore is calculated either manually or with commercially available orifice sizing programs.
- **Orifice plate holders**: The orifice plate holder includes orifice flanges, orifice fittings (simplex, junior, or senior fittings), or regular flanges (if it is a restriction orifice plate).
- **Beta ratio:** The beta ratio is also called a diameter ratio. The beta ratio defined as the calculated orifice bore's diameter to the internal pipe's diameter.
- **Differential pressure (ΔP):** The differential pressure represents the static pressure difference upstream and downstream of the plate. Generally differential pressures across the plate range from 0 to 50, 0 to 100, 0 to 200 inches of water column. Note that the differential pressure is used in calculations for the orifice plate bore or flow rate.
- **Temperature**: The temperature represents the fluid temperature flowing through a pipe. The flowing fluid temperature is measured in degrees Fahrenheit or degrees

Celsius. Temperature is used to determine the density of the fluid. The temperature of the fluid value can be converted to an absolute temperature value in degrees Rankine or Kelvin.

- **Reynolds number (Re)**: In an ideal condition fluid with no viscosity, the velocity profile of the fluid in a pipe would be uniform. In a real condition fluid with a viscosity, the fluid slows down near the pipe wall and velocity is zero. The flow profile is nonuniform across the pipe wall. The pipe Reynolds number represents a dimensionless ratio of density of fluid times the internal diameter of the pipe times the velocity of the fluid to the viscosity of the fluid.

$$Re = v\,D\rho\mu$$

  At low Reynolds numbers below 2,000, the flow is laminar. The flow can be visualized into group of concentric shells where each shell reacts in a viscous manner on adjacent shells; the velocity profile across the diameter is substantially parabolic. At higher Reynolds numbers, flow is turbulent. Turbulent flow produces eddy currents between the body of the flowing fluid and the boundary layer, and propagates through the flowing stream pattern. For Reynolds numbers above 10,000, flow is turbulent. The coefficient of discharge of the various head type flow meters changes as the Reynolds number changes.

- **Pressure Taps**: Taps are holes drilled radially in the wall of the pipe or in a pair of orifice flanges. A differential pressure-measuring device is piped to an orifice plate through the taps. The following parameters are required to calculate the orifice bore:
  - **Flow rate**: The rate of the flow flowing through a pipe per unit of times at a flowing temperature. Normal and maximum flow rate are required. If the normal flow rate is not available, then use 80 % of the maximum design flow rate.
  - **Temperature**: The temperature of a flowing fluid is required at flowing and base conditions. The unit of temperature is in degrees F or degrees C. The temperature can be converted into absolute temperature in degrees Rankine or Kelvin.
  - **Pipe diameter**: The internal pipe diameter equals the outside nominal pipe diameter minus twice the wall thickness (ID = OD - 2 x wall thickness).
  - **Pressure rating**: Pressure ratings are important because selection of the thickness of the plate depends on the pressure rating. For example, specifications can be in terms of 150#, 300#, 600#, 1500#, and 2500# class ratings.
  - **Operating pressure**: The operating pressure of fluid flowing through a pipe can be expressed in psia (pounds per square inch absolute) or Kilopascal units.
  - **Differential pressure (ΔP)**: The differential pressure represents the static pressure difference across the upstream and downstream of the plate. Typical units of differential pressure are inches of water column for the orifice plate, Venturi, flow nozzles, annubar, or Pitot tube and psia or Kilopascal for the restriction orifice plate.
  - **Density of fluids**: The density of homogeneous fluid represents the ratio of its mass to its volume. The density varies with temperature changes. The density

of fluid is expressed in mass per unit volume at a specified temperature and its units are lb/ft^3, or kg/m^3.

- **Viscosity**: Viscosity represents the fluid's property of shearing stress on fluid velocity at a flowing temperature. Units of viscosity are centistokes (Cs) or centipoise (Cp).
- **Specific gravity**: The specific gravities of fluid at operating temperature and base temperature are required for the calculation.
- **Super compressibility**: Compressibility is defined as the delta in volume per unit volume of fluid caused by a unit change in pressure at a constant temperature. The ideal gas law does not fully explain gas behavior when pressures are above 100 psig. In order to explain gas behavior, super compressibility factors are required for gas flow measurements when pressures over 100 psig are encountered.
- **Molecular weight (Mw)/Specific heat ratio (Cp/Cv)**: Molecular weight of gas is required as an input for the calculation. Specific heat represents the ratio of specific heat at constant pressure Cp to specific heat at constant volumes at operating temperature (i.e. k = Cp/Cv).
- **Base conditions**: Also called standard conditions, base conditions represent pressure and temperature conditions to which measured volumes are referenced to. For example: Base pressure and base temperature: 14.7 PSIA @ 60°F, Base pressure and temperature in SI unit 100 kPa @ 15.6°C.
- **Plate thickness**: Thickness of the plate specified in inches.
- **Vent or drain hole**: Also called a weep hole, the engineer determines whether it is required or not on the orifice plate.

- **Differential pressure range (ΔP):** It represents the drop in pressure across a head device at specified pressure tap locations. The pressure drop is generally measured in inches or millimeters of water column. The differential pressure is the most important variable factor for differential head meters, because it is used to calculate flow rate. When errors in flow measurement occur with a differential head meter, the error is seen in this measurement. Differential pressure for orifice meter tubes, Venturi and flow nozzles, is typically 0–100 inches of water column (0 to 25 kPa) for a full-scale flow. The 100 inches span permits a 2:1 flow rate change in either direction to accommodate changes in operating conditions. The pressure loss in an orifice is about 65% when a beta ratio of 0.75 is used. The higher the differential pressure, the lower the beta ratio. An application where the pressure loss is up to 3.5 psi becomes expensive. If a high-range differential pressure transmitter is not available, it can be handled by the selection of a lower differential pressure or Venturi tube.
- **Orifice meter tube and straight pipe parameters:** The meter tube assembly consists of an orifice plate, orifice plate holders (such as orifice flanges or simplex, junior, or senior fittings), straight pipes runs (upstream and downstream from orifice plate), straightening vanes (at upstream side if required), pressure taps, and temperature taps. The length of the straight upstream pipe and straight downstream pipe of the same diameter depends on beta ratio and configuration of piping layout. To assure accurate

flow measurement, fluid flow should be free from swirl or vortices. To achieve the best flow free from swirl or vortices, designers use flow conditioners and adequate lengths of straight pipe runs upstream and downstream from the orifice plate. Normally, upstream straight pipe runs are from 20 to 25 times the diameter of pipe (20 D to 25 D) and downstream straight pipe runs are from 5 to 7 times the diameter of pipe (5 D to 7 D) from the orifice plate. Requirements for a straight upstream pipe will be reduced by use of straightening vanes. No pipe connections should be within these distances other than the orifice pressure taps or temperature connection. Thermowell connections may be installed in the meter tube upstream of the straightening vanes if required. The selection of the meter tube is determined by the volume of the fluid to be measured. For sizing of the meter tube, first determine what range of differential pressure instruments will be used. The beta ratio (β) should be within a range of 0.20 to 0.7 for flange taps, 0.25 to 0.67 for pipe taps. Refer to the manufacturer's catalogue or AGA Report Number 3 for more information on requirements for straight upstream and downstream pipe based upon beta ratio calculations and piping configuration layout.

5.3.1.3 Four Common Types of Pressure Taps

A tap hole is a hole drilled in the wall of a meter tube or flange of an orifice plate. Four common types of pressure taps are—flange taps, pipe taps, corner taps, vena contracta taps.

Pressure tap holes are drilled radially to meter tube wall or in the flanges for the orifice plate. Generally, differential pressure instruments are connected to the pressure taps in an integrated mode or a large impulse lines are connected to provide a connectivity between the pressure taps to the instrument taps. These impulse lines filled with "fill fluid" or condensate for transporting the pressure.

Flange Taps Flange taps are holes drilled into a pair of flanges. The location of the tap hole center is 1 in upstream and downstream from the face of the orifice plate. Tap holes are drilled radially into the meter tube. The diameters of pressure tap holes are 3/8 in 1/64 in for a pipe size of nominal diameter 2 and 3 in. Tap hole sizes are 1/2 inch ±1/64 inch for a pipe size of nominal diameter of 4 in or larger. Flange tap holes are not recommended when the pipe size is below 2 in.

Pipe Taps Pipe taps are located at 2 1/2 pipe diameters upstream and 8 diameters downstream from the orifice plate. Exact location of the taps is not critical. However, the effect of pipe roughness and dimensional inconsistencies can be severe. The error with the pipe taps can be more than 50% than the other options if enough care is not considered and the pipes are closer to the orifice. Pipe taps are not used normally unless there is a need to install the orifice meter on other taps or on an existing pipe.

Corner Taps Corner taps are a style of flange taps, with only difference that the pressure is measured at the corner between orifice plate and pipe wall. Corner taps are most commonly used in Europe for all sizes of pipe diameters. Some tests indicate inconsistencies with high beta (β) ratio installations that have some instability of flow upstream of the orifice plate. For this situation, an upstream tap is at one pipe diameter upstream of the orifice plate. Corner taps are used when the pipe size is 2 in or less.

Vena Contracta Taps When an orifice plate is inserted into the flow line, it creates an increase in flow velocity and a decrease in pressure. The section downstream of an orifice bore shows an increase in velocity and decrease in a pressure at a point called a "vena contracta point." The location of the vena contracta point is between 0.35 to 0.85 of pipe diameters downstream of the plate, depending on the beta ratio and Reynolds number. Vena contracta taps are located 1D upstream and at the vena contracta location downstream. Vena contracta taps are the optimum location for measurement accuracy. They are not used for pipes less than 6 in in diameter.

Pressure Profile As shown in Figure 5.10, the flow approaches the orifice plate, there is a slight increase in pressure on the upstream side of the orifice plate. After passing through the orifice bore restriction, the flow velocity increases and the pressure drops. This is a conversion of pressure head energy to velocity head energy. As the flow leaves the orifice, the velocity decreases, and the pressure increases. Although the flow velocity downstream of the orifice recovers to the velocity upstream of the orifice plate, there is a permanent pressure loss across the flow meter.

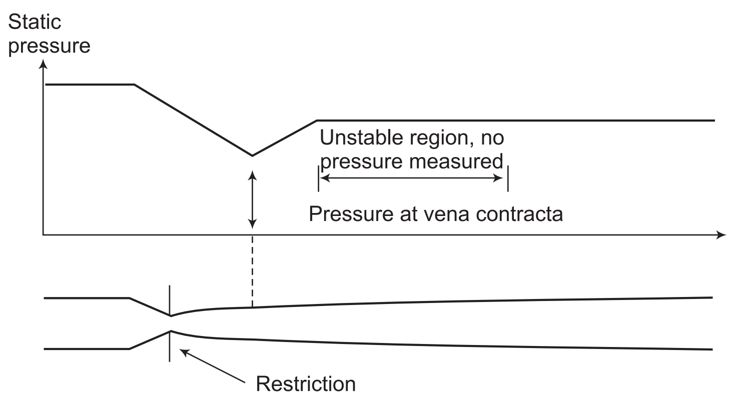


Figure 5.10 Pressure and flow profile

5.3.1.4 Temperature Measurement

The temperature of the flowing fluid is measured either upstream or downstream of the orifice plate. When the velocity of the fluid is well below sonic levels, you can insert a temperature-sensing device in the flowing stream to measure the temperature of a flowing fluid. In meter tube assembly, thermowell connections are upstream of straightening vanes. Temperature is measured in either degrees Fahrenheit or degrees Celsius. In practice, the temperature is assumed a static temperature for the flowing fluid. In measurement calculations, the flowing temperature is used to determine the density of fluid at flowing conditions. Temperature units can be converted from degrees F or degrees C to degrees Rankine or absolute temperature in Kelvin using the following conversions as:

$$°R = °F + 459.6$$

$$K = °C + 273.15 \tag{5.15}$$

5.3.1.5 *Integral Orifice Meter*

The integral orifice meter consists of a primary device (orifice plate) and a secondary device (transmitter) combined in a single unit. The meter is designed for application with small flow rates. The integrally mounted restriction consists of an orifice, fittings, and mounting devices. Either a pneumatic or electronic differential pressure transmitter senses the differential pressure produced. The complete assembly is referred to as an integral orifice flow meter. The flow restrictor plates are interchangeable to support a wide range flow rate measurements. The integral orifice meter is used in laboratory, pilot plant, or refinery small flow measurements. To avoid plugging the small hole in an integral orifice assembly, the meter is generally used for clean fluid flow measurements. The integral orifice meter is a proprietary product. Specific performance data is available from the respective manufacturer.

5.3.1.6 *Secondary Instrumentation for Orifice Metering*

Secondary instruments that are used in orifice metering to measure the flow rate are most often differential pressure transmitters. In this application, a differential pressure transmitter is either a pneumatic type or an electronic type. Other secondary instruments that measure the flow rate in conjunction with the orifice plate are differential pressure indicators, flow recorders, flow switches, flow totalizers (flow computer), and flow controllers.

5.3.2 Differential Pressure Transmitters

As mentioned above, two types of differential pressure transmitters are often used for measuring the flow—pneumatic transmitters and electronic transmitters. The differential pressure flow meters output a nonlinear signal that corresponds to the square of the flow rate. A change in flow at a low rate produces a very small signal change. A change in a large flow rate produces a much larger signal change. For example, a small flow rate from 0% to 10% outputs a signal from 0% to 1%; for a large flow rate, a 90% to 100% flow rate change outputs an 81% to 100 % signal. A transducer called a square root extractor is often used with transmitters. A transducer converts a square root signal to a linear signal. The differential pressure transmitter outputs a signal that is used for control, indication, or totalization. Pneumatic differential pressure transmitters output a signal of 3–15 psig, and electronic differential pressure transmitters output a signal of 4–20 mA dc. Differential pressure transmitters are calibrated in ranges from 0–50 to 0–400 inches of water column depending upon the delta $P(\Delta P)$ used in calculating the orifice bore at full-scale flow with 0 to 100 being the most common. To determine the flow rate, it is necessary to take the square root.

5.3.2.1 Restriction Flow Measurement with Primary Devices and Differential Pressure Transmitters

The flow rate in a pipe across an orifice, nozzle or venture generates a proportional pressure differential across them. The pressure drop varies exponentially with an increase or decrease in flow rate. The relationship is a suareroor direct proportion. The pressure drop increases by four times for an increase in flow by two times. Similarly if the flow reduces by half, the pressure drop reduces by four times. In this method, by measuring the pressure drop, the flow rate is implied in a pipe lines. Earlier, when the technologies were in the initial stages, a U tube manometer is used to measure the differential pressure across an orifice as shown (Figure 5.11). The U-tube manometers are generally filled with water and the delta in the height of the water in the legs is indicated pressure differential. Generally the difference is water column is measured in inches of water column (in WC). The U-tube comes with filled in mercury as well and is applied based on need and preferences. The U-tube with filled in water is naturally was very long and takes more space. A differential of 100 inches are still common phenomenon. A simplified formula for determining pressure drop versus flow is:

$$\left(\frac{Q_x}{Q_k}\right)^2 \times P_k = P_x \tag{5.16}$$

where, Q_x is the unknown flow rate, Q_k is the known flow rate that generates a known pressure drop, P_k is the known pressure drop produced at flow rate Q_k, and P_x is the pressure drop that is produced at flow rate Q_x.

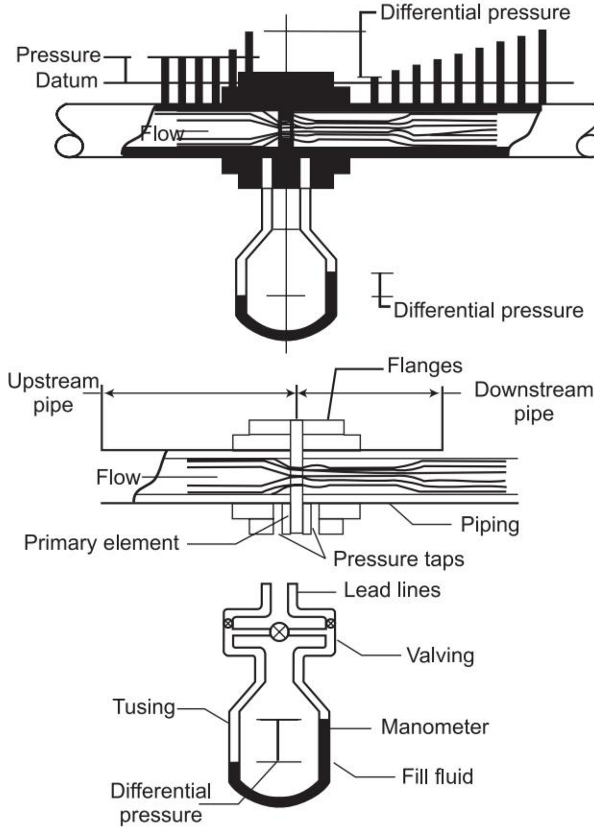
As the technology moved forward, the U-tube based head measurement is replaced with the differential pressure transmitters. The impulse lines will be connected to both sides of the diaphragm of the transmitter. The high pressure side of the transmitter creates the pressure on the diaphragm such that it deflects towards the low pressure side. This deflection causes a change in the transmitter output which is square root proportional to the differential pressure.

The output signals were initially in the range of 3–15 psi which has naturally got moved to 4–20 mA when pneumatic technologies were migrated to electronics. The pressure drop has a geometric relationship with flow, such that the pressure drop varies with the square of the flow. Either an internal or external square root extractor is used to linearize the current.

Due to the square root relationship of the differential pressure to the flow rate, the graduations on the resultant scale are also scaled accordingly. The scale so generated will have markings too close at the lower ranges and gets wider at the upper scale ranges. This was one of the reasons for the rangeability of differential pressure transmitter is generally considered to be 3:1 (33–100%).

The orifice bore is calculated at a certain operating conditions such as temperature, pressure, density and viscosity and the same has be within certain range of threshold for the differential pressure to be consistent and reliable for the same flow. Major changes in these operating conditions require the instrument for a recalibration or an alternative bore for the orifice. The most widely used DP transmitters use pneumatic and electronic signals for the output parameters. The base transmitter is used for measuring either pressure, flow or level which

Figure 5.11 Differential pressure flow meter



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makes it more flexible option for the selection. The transmitter can measure the differential pressure across any type of the restrictions such as orifice, venture, etc., irrespective of the size of the pipe and type of the fluid. The basic transmitter may be used to meter flow, level, or pressure variables, which makes it very versatile. Similarly the same type of instrument can be used for measuring the flow of liquids, steam and gases. The transmitter is generally calibrated to measure a differential of 100 in WC which means it generates 20 mA when the differential reaches 100 in WC.

The proper selection and installation of the differential producer—mostly the orifice plate plays an important role in making a DP transmitter effective for a given application. The calculation of the orifice bore is important; a wrong orifice bore could provide inaccurate flow measurement. Restrictions on how large the hole may be, must be accounted for, when the orifice bore is calculated. The orifice bore is represented in the form of "beta ratio", which is the ratio of orifice bore (hole) to the inner diameter of the pipe. Most commonly used applications have a beta ratio of 0.7 which means for a pipe of 4 in schedule pipe with an inner diameter of 4.12 in inner diameter, the bore will be 3.6 in usually the pressure drop in the pipe is an important consideration in the design of the overall plant system and hence the pipe sizes and the restrictions across the pipes and associated loss of pressure plays a vital decision making inputs.

Apart from the installation of the flow restricting primary element and the differential pressure transmitter, an impulse lines needs to be installed for the measurement. The impulse lines are meant to transport the pressure from the primary element to the transmitter. The impulse lines are generally a quarter inch or half inch tubes and are installed based on the type of the application of the measurement. Generally they are kept as short as possible to keep the lag of the measurement to a minimum while not compromising the safety and accessibility of the instrument for the technicians. In case of installing the metering system outdoors, it is necessary to protect the sensing lines from freezing in cold weather. Generally heat jackets or heat tracings are provided to the impulse lines with the steam lines to avoid the freezing of the fill fluid in the tubes and creating noise in the measured value. The impulse lines are provided with manifolds and draining valves to remove and clean the tubes as and when necessary. If the process measured is liquids at high temperature or steam, then it is necessary to keep the impulse lines filled with either water or another fill fluid which can isolate the temperature of the process to the pressure sensor and its electronics.

In addition to the above, the impulse lines are connected to the three way manifold which in turn connects to the transmitter. The three way manifold enables to balance the pressure in high and low side of the transmitter. This activity is required if the transmitter zero is to be established and calibrated accordingly. Some plants have a maintenance procedure to verify the transmitter zero on a periodic basis.

In most of the installations of the transmitter, it is essential to provide isolation valves from the transmitters to the process connections (both on high pressure and low pressure sides). These valves enable the removal of the transmitter for maintenance, calibration or replacement without disturbing the process.

The orifice flange is yet another high-cost part of the DP system. If the pipeline is small, most users opt to use orifice flanges. These typically special 300 flanges enable the sensing lines to be attached to the process through the two holes bored through the side. For the applications of orifice based flow measurement in large pipes where the orifice is installed between two flanges, the impulse lines will be tapped at the pipe wall itself. In general there are various ways of tapping the impulse lines and most common among them is radius tap (D and Half D) wherein the upstream tap is one pipe diameter before the orifice plant and the downstream tap is 1/2 pipe diameter before the orifice plate. The other types being Vena Contracta taps and pipe taps where in the tap is far from the orifice plate, rendering permanent pressure loss the highest as shown in Figure 5.12. Even though there will be some pressure drop after the restriction type instruments, there will be some recovery from the loss after the fluid passes the restriction. Once the flow slows down, the pressure energy is recovered from the velocity energy. See Figure 5.12 for the locations of the various types of taps. The corner tap, a variation of the flange tap is another type of tap that is rarely used in the U.S, but is sometimes used in Europe and other parts of world. It is tapped in the flange such that the pressure is measured at the point where the orifice plate contacts the flange surface. It is done with a technique such that the pressure tap is from all the sides of the pipe (circumference). The corner tap orifices are more expensive than the other due to additional mechanical machining needs.

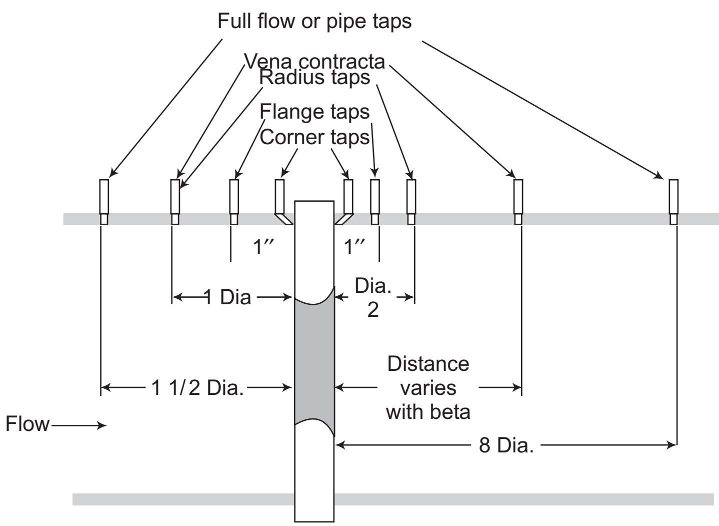

Figure 5.12: Various tap locations

5.3.2.2 *Orifice Application and Device Selection*

The major difference in the application of the orifice comes from different states of the media such as gas, liquid and steam. The installation requirements are different for each of the media type. Ideally the impulse pipes should be installed horizontally at the same height from the process tap to the transmitter such that the same head is applied at the transmitter end. However modern say transmitter can have bias as much as 100% for any installation deviations. In order to remove the permanent bubbles in liquid flow measurements and liquid stoppers in gas measurement applications, a minimum of 4^0 angle is maintained and sometimes at 10^0 is recommended.

Steam As shown in Figure 5.13 in steam flow measurement applications, the pipe tapings are maintained at the same height of the orifice. However, the transmitter is installed below the process pipe such that sufficient steam can condense and impulse line are transmitter are filled with condensate.

Gas In gas flow measurement applications using orifice plate, the impulse lines should be projected above the process pipe as shown in Figure 5.14. The differential pressure transmitter is installed above the process pipe, which helps the impulse pipes and the transmitter from being filled with condensate. The condensate in the impulse lines if not taken care leads to a DP zero error. For some gas measurement applications, the manifold and transmitter can be directly installed onto the orifice tapings which can reduce the cost of installation significantly. However, the temperature of the gas should be less such that the transmitter electronics does not get damaged.

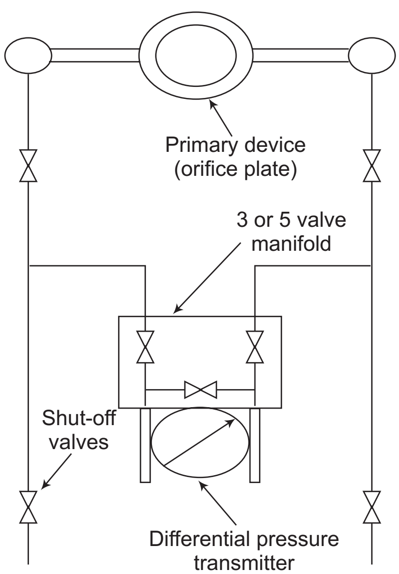

Figure 5.13: Steam flow installation

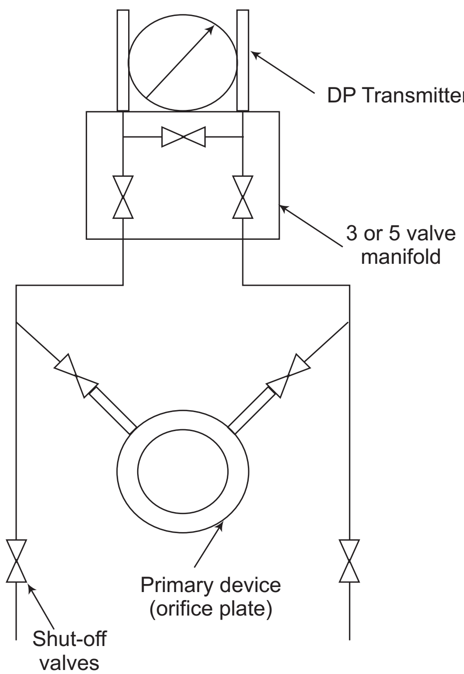

Figure 5.14: Gas flow installation

Liquid For the liquid measurement applications, the impulse lines must be dropped downwards below the process pipe and orifice. This installation prevents the gas bubbles from entering the impulse pipe and creates measurement errors and noise in the output. The schematic of the connection is shown in Figure 5.15.

Wet Gas Figure 5.16 is the recommended installation practice for measuring wet gas using orifice based flow rate measurement. Deposition chambers are maintained, which can be emptied regularly to prevent the impulse pipes from filling with condensate.

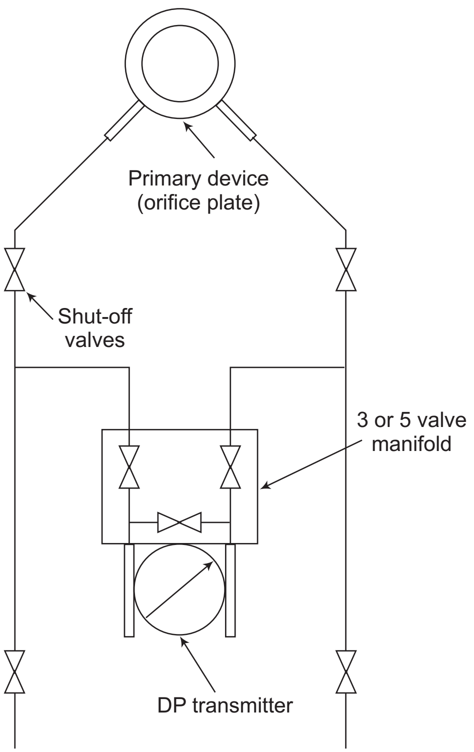

Figure 5.15: Liquid installation

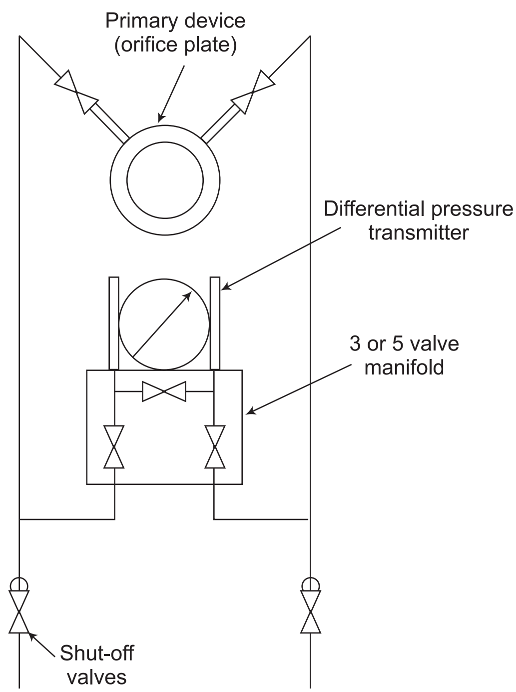

Figure 5.16: Wet gas installation

Factors Affecting Flow Rate in Pipes The major factors affecting the flow of fluids through pipes are:

- **Fluid velocity:** Fluid velocity in a pipe depends on the head pressure that is forcing the fluid in the pipe. More the head pressure, the greater the fluid flow rate (all other factors remaining constant), and consequently, the greater the volume of flow. Pipe size also affects the flow rate.
- **Fluid viscosity:** Viscosity (μ), or the molecular friction is another factor that negatively affects the flow rate of liquids.
- **Friction of the fluid in contact with the pipe:** Pipe friction works together with Viscosity to further decrease the flow rate of a fluid near the walls of a pipe.

Advantages The advantages of differential pressure/orifice-based flow measurement have the following advantages:

- The differential pressure and orifice-plate based measurement is used for many years and skills required to select, use and maintain is decently high at engineering and technicians level.

- The flexibility of instrument to measure various parameters such as level, flow and pressure is a great advantage. The instrument can also be changes to measure the flow in different pipe lines just by changing the orifice plate with different bore. The differential cost for one size pipe versus another is relatively small. A 100 in WC differential is the same for any pipe size.

Disadvantages Following are some of the disadvantages of the differential pressure/orifice system:

- The accuracy of the system is highly dependent on the installation and maintenance.
- Long straight pipe runs are required, which limits the location of the meter.
- Solids in a flow stream may cause clogging of the meter.
- The impulse lines must be provided with heat jackets or heat traces with steam lines in winter if the meter is installed outside.
- The accuracy is affected by wear and tear and damage to orifice plate.

5.3.3 Flow Nozzles, Pitot Tube and Venturi

Flow nozzles and flow tubes are some other types of differential producers. Flow nozzles can be fabricated at the job site itself as they often needs to be calibrated at side for proper measurement. Flow nozzles are preferred restriction to the path of the flow, if there is an anticipated solids to pass on downstream and should not be clogged liked an orifice plate. Flow nozzles may be considered as a variation of the Venturi tube. The flow nozzle is a high velocity flow meter used where turbulence is high such as in steam flow at high temperature.

5.3.3.1 Flow Nozzle

The flow nozzle as shown in Figure 5.17 is another type of differential-producing device that follows Bernoulli's theorem. The permanent pressure loss produced by the flow-nozzle device is approximately the same as the permanent pressure loss produced by the orifice plates. The flow nozzle can handle dirty and abrasive fluids better than can an orifice plate. In a flow nozzle with the same line size, flow rate, and beta ratio as an orifice meter, the differential pressure is lower, and the permanent pressure loss is less.

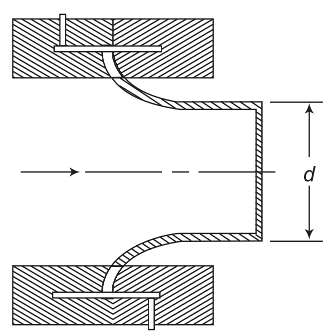

Figure 5.17: Example of nozzles

The flow nozzle design is one that has a smooth entry and sharp exit. Several configurations are available, but the most important flow nozzles are ASME long radius nozzle, high or low beta ratio series, and the throat tap nozzle for gas and liquid applications. High beta ratio nozzles are acceptable for a diameter ratio that ranges between 0.45 to 0.80. Low beta ratio nozzles range from 0.25 to 0.50. For best accuracy, beta values between 0.25 and 0.8 are used. The nozzles can be welded in the pipeline, or mounted in a holding ring between flanges. If frequent maintenance inspection of the nozzle is required, then the holding ring design is preferred for flow nozzle mounting. Flow nozzles can be fabricated from any material such as aluminum, fiberglass, stainless steel, or chrome-moly steel. The outlet or discharge side of the nozzle is beveled and is the most critical part of the flow nozzle to manufacture

5.3.3.2 Pitot Tube

A Pitot tube consists of two hollow tubes that measure the pressure at different places in the pipe as shown in Figure 5.18. The application of Pitot tubes is same as other restricting type instrument principles such as orifice and is installed in the same manner. In general, the Pitot tubes are used in gas and liquid applications where the pipe diameter is high and less fluid pressures. The previously discussed primary differential pressure flow metering devices utilized the difference in static pressure perpendicular to the direction of flow as a basis for inferring velocity. The actual velocity was not measured, but was calculated after many experimental laboratory measurements and correlations.

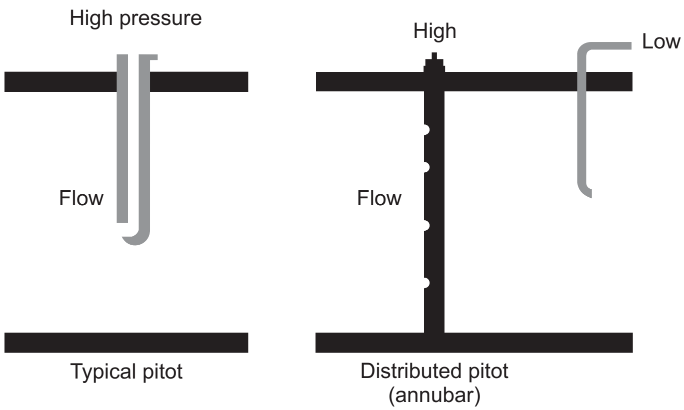

Figure 5.18: Pitot tube

The Pitot tube senses total pressure in the direction of flow and static pressure perpendicular to the flow. The Pitot tube sensing effects are used to derive velocity pressure from which the flowing fluid velocity can be inferred. The pressure relationship is:

$$P_T = P_s + P_v \tag{5.17}$$

where, P_T = Total, Impact, or Stagnation Pressure, lbf/ft^2, P_s = Static Pressure, lbf/ft^2, P_v = Velocity Pressure, lbf/ft^2

From energy considerations:

$$P_T - P_s = P_v = \frac{\rho(V_P)^2}{2gc} \tag{5.18}$$

And by algebra:

$$V_P = \frac{C(P_T - P_S)^{0.5}}{\rho} = \frac{C(P_V)^{0.5}}{\rho} \tag{5.19}$$

where, V_P = Approach velocity at the probe, ft/sec, ρ = Fluid density, lbm/ft^3, gc = Dimensional constant = 32.2 lbm ft/lbf sec^2, C = Dimensional constant = 1,096.5 when P_v is in inches of water.

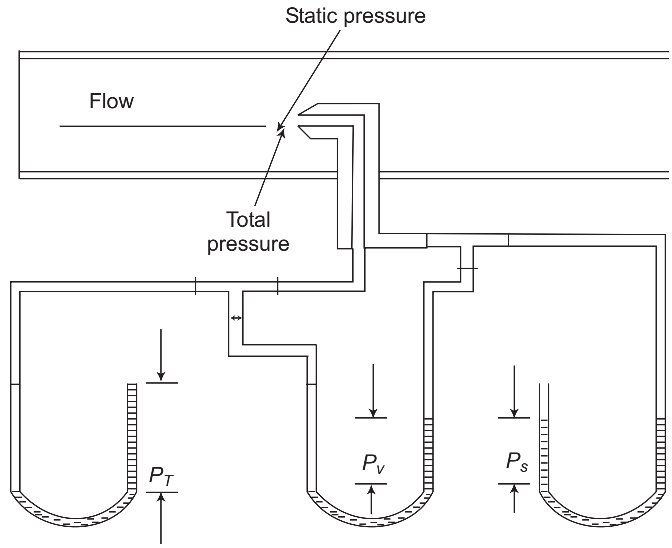

Figure 5.19: Pitot tube principles

A Pitot tube is designed to sense pressures in an enclosed moving fluid stream. It is frequently used in traversing a duct determining average fluid velocity across the duct as shown in Figure 5.19. It must be light and portable so that it can be moved to sense in more than a single location. It must be long enough to push in for adequate insertion length. It must be capable of connecting to pressure measurement devices. The static connection must be in the same extended plane as the nose. All pressure sensing holes must be free from nicks and burrs.

Advantages

- A Pitot tube has a major advantage in that it creates very little permanent pressure drop and, as a result, is less expensive to operate.
- A Pitot tube can be installed on 4 in and larger pipe sizes.
- Performance of the Pitot tube is historically proven.
- A Pitot tube's installation and operation costs are low.
- A Pitot tube can be a standard differential producing device for all pipe sizes.

Disadvantages

- Point-type Pitot tubes require traversing the flow stream for average velocity.
- Poor rangeability.
- Nonlinear square root characteristic.
- Difficulty of use in dirty flow streams

Applications The Pitot tube is used for flow measurements of liquids, gases, and low flow measurements. A Pitot tube is used for control purposes and not for custody transfer purposes. When a single point's flow velocity is measured, accuracy generally ranges to ±5% unless specifically calibrated for higher accuracy. Generally, Pitot tubes are considered alternative flow meters and alternative flow meters should be considered when it is evident that orifice plates, or precision flow metering devices are not suitable nor practical for metering process fluids caused by process constraints, short meter run lengths, or specified accuracy requirements. Additionally, Pitot tubes and Pitot Venturi tubes are considered only for flow metering applications involving clean liquids or dry gases where a substantial pressure drop cannot be tolerated and where accuracy is of minimal concern.

Additionally, the following installation practices are used.

- **Gas**: For gas flow measurement applications, the impulse lines must be installed to above the process pipe and the Pitot tube. The differential pressure transmitter must also be mounted above. This method helps the impulse pipes do not fill with condensate and therefore cannot introduce an error in measurement. For lower gas temperatures, the manifold block and differential transmitter can be mounted directly onto the flanged Pitot tube tapings. These versions has reduced installation costs, but with the limitations that instruments cannot be removed without disturbing the process.
- **Wet gas**: If the flow rate of a wet gas is being measured, then a deposition chamber must be installed. These chambers should be emptied regularly to prevent the impulse pipes from filling with condensate.

5.3.3.3 Venturi

A Venturi meter is a flow-measuring device whose principle of operation is based upon Bernoulli's theorem. A Venturi design can be described as a restriction with a long passage with smooth entry and exit. Venturi tubes produce less permanent pressure loss and more pressure recovery than the other meters. Refer to Figure 5.20 for a Venturi tube. It is one of the more expensive head meters. Whenever low-pressure drops are required for nonviscous fluids, the amount of pressure drop becomes dependent on the angle of the downstream cone and the beta ratio of the Venturi. A Venturi consists of a cylindrical inlet section, converging conical section, throat section, and diverging section. The diverging section is called the recovery section. A converging conical section, in which the cross-sectional area decreases, causes an increase in the velocity and decrease in pressure head. The decrease in pressure head is measured where the velocity of the fluid is constant, this occurs in the cylindrical throat section of the Venturi. Similarly, the diverging recovery cone is where the fluid velocity decreases and most of the pressure is recovered. The unrecovered pressure head is called head loss. Two types of venturi meter designs are available—classic Venturi (long form venture) and short-form Venturi.

Classic Venturi The classic Venturi is manufactured as a cast iron body, while the throat is made from stainless steel or bronze. Several pressure taps, typically 4–6 taps, are at the midpoint of throat. These multiple taps connecting to the throat will measure the average pressure of the chamber of the annubar. Generally the cross section of the annubar chamber is one and half times the cross sectional area of the tap. The throat pressure is measured through the internal taps. The diverging cone (that is, the recovery cone) sets at an angle of 7 degrees. The classic Venturi is limited to clean, noncorrosive liquid and gas applications. If the Venturi should be used in a dirty service, the taps can plug up with dirt. If the taps clog up with dirt, it is impossible to clean or flush out the pressure taps. The flow coefficient for the classic long form Venturi is 0.984. The overall length of the Venturi is 8 times the diameter of pipe.

Short-form Venturi Because of cost and the longer length of the classic Venturi, manufacturers have developed new designs for the Venturi called the short form Venturi. The internal annular chamber is replaced by single pressure taps. The recovery of cone is redesigned from 7° to 21°. The material of the construction of the venture can be made of cast iron or some stainesless steel etc. The discharge flow coefficient is 0.985 with an accuracy of 1.5% of the range. Usually based on the pipe diameter of the inlet pipe, the pressure taps are located at one half to one quarter of the inlet cone. The low pressure point tap is arranged at the center of the throat. Usually a piezo ring consisting of number holes in the plane of tap locations, which when connected together generates the average pressure. This pressure is used for measuring the differential pressure of the short form Venturi tubes. Piezometer ring connections are used for large tubes or when a more accurate average measurement is desired. A piezometer connection is not advisable for a dirty fluid or slurry service. In a modified short form Venturi, all of the cones are shortened. In a short form Venturi, the converging cone angle is 21° and the diverging cone angle is 15°.

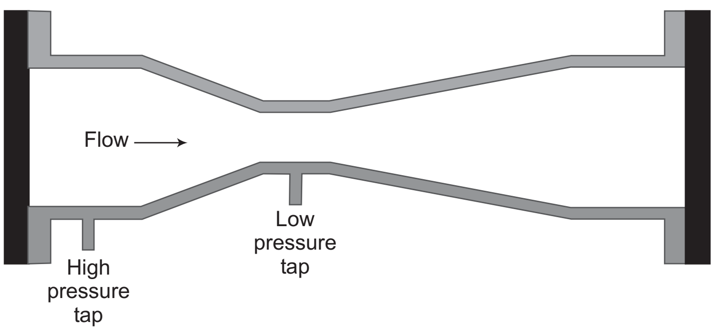

Figure 5.20: Venturi flow meter

Advantages

- The long form Venturi develops up to 89% pressure recovery for a 0.75 beta ratio and decreases to 86% recovery for a 0.25 beta ratio.
- The short form Venturi develops up to 85% recovery at 0.75 beta ratio and decreases to 7 % at 0.25 beta ratio.
- A Venturi meter has a low permanent pressure loss and high recovery at higher beta ratios.
- A Venturi meter can be used for dirty fluids and slurries.
- Higher accuracy (better than orifice)

Disadvantages

- A Venturi meter is a very expensive measuring device to use.
- A Venturi meter has limited rangeability and is only installed when flow rate's rangeability is less than 3:1.

Applications A Venturi can be used for dirty fluids and slurry services. A Venturi meter experiences less permanent loss and exhibits high recovery. In general, Venturi tubes will be considered for special flow measurement applications where higher instrument costs can be economically justified by a lower unrecoverable pressure loss, enhanced flow meter accuracy, or the ability to meter fluids containing suspended solids, for example, measuring inlet flow rates to gas compressors.

The differential pressure transmitters are most widely used principle for measurement of flow and level. The video explains the principle of operation of a differential pressure transmitter measuring the flow using the orifice as the restriction mechanism.

For process-related video, scan the QR code
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5.3.4 Open Channel Flow Meters

5.3.4.1 Weir for Flow Rate Measurement

In open channels, the restriction across the path of the flow is called as weir. The restruction weir will increase the depth of the water as the water flows over it. It also means the increase in flow rate will increase the depth of the flow. The height of the water above the top of the weir is used for measuring and computing the flow rate (Figure 5.21).

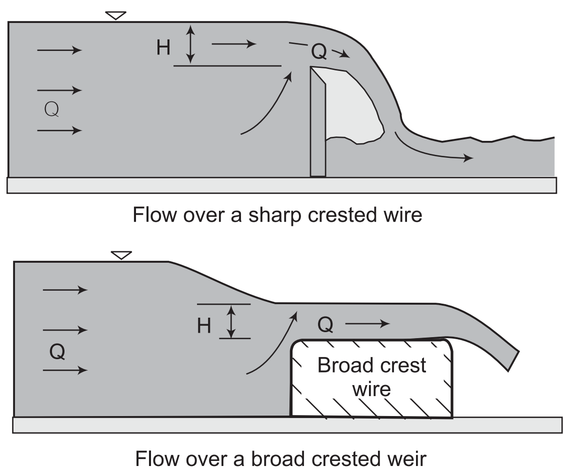

Figure 5.21: Weir for flow measurement

The weirs are generally categorized as sharp crested and broad crested. Here crest means the top of the weir on which the liquid flows downwards. The representative images of the weirs are shown below. The sharp crested weir has a sharp edge at the crest and broad crested has a broad surface at its crest. Here the height of the water above the weir is called as "head" and represented with letter "H" in the image. The head H, is the basis for measuring the flow rate in the open channels.

The sharp crested weirs can be of two types which are called V notch weir and rectangular weir. The types of the sharp crested weirs is shown in Figure 5.22. If the rectangle goes all the way through the channel, then it is called suppressed rectangular weir and if the rectangle is created in a part of the weir, then it is called contracted rectangular weir.

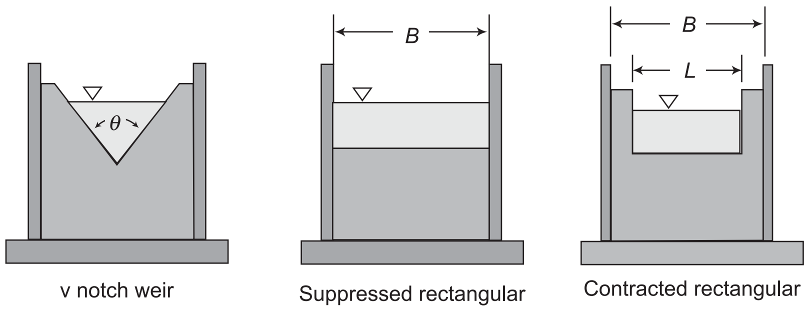

Figure 5.22: Types of sharp crested weirs

5.3.4.2 Flume for Flow Rate Measurement

A flume is a specifically shaped open channel flow section that provides a limit in channel area and/or a modification in channel slope. The flow rate in the channel is obtained by calculating the liquid depth at a definite point in the flume.

A Parshall flume, the much known and generally used flume today, is a fixed hydraulic structure established to calculate surface waters and irrigation flow. It is presently used to measure volumetric flow rate in municipal sewer lines, industrial discharges, and influent/effluent flows in wastewater treatment plants (Figure 5.23).

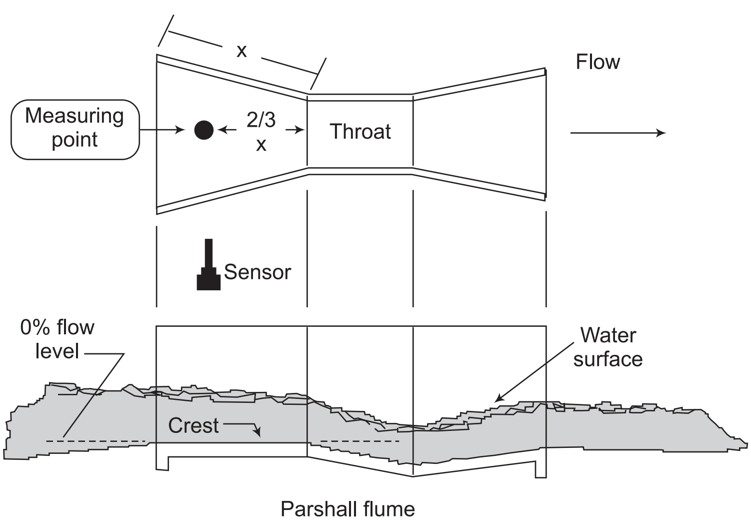

Figure 5.23: Parshall flume in flow measurement

Checkpoint

✦ 1. Which is the oldest known method of measuring flow?

✦✦ 2. What are the ways in which orifice plate is installed in the path of flow?

✦✦ 3. How an orifice plate converts potential energy (static pressure) into kinetic energy (velocity)?

✦✦ 4. What causes permanent loss of pressure in orifice plate?

✦ 5. What is the purpose of weep hole in orifice plate?

✦✦ 6. What is the typical usage of the concentric bore orifice plates?

✦✦✦ 7. What is the typical usage of eccentric bore orifice plates?

✦✦ 8. Define beta ratio and its application in the selection of the orifice plate.

✦✦✦ 9. Define a vena contracta point?

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5.4 APPLICATIONS OF VARIABLE AREA FLOW METERS

LO 3

Elaborate the applications of variable area flow meters

As discussed in earlier sections, the use of restrictions such as orifice, Venturi, etc., creates a differential pressure across the same. The same principle is used in variable area flow meters where there is an variable orifice and a relatively constant pressure drop. Therefore, the area of the annular opening through which the liquids pass is indicated as flow rate. This position of restrictions is read as float or obstruction in orifice.

Variable area flow meters, also known as glass-tube flow meters or rotameters (Figure 5.24) are designed in three general configurations:

- **Tapered tube meter:** In a tapered tube meter, the float with density more than the liquid being measured is positioned in a vertical glass tube with a tapered bottom. Tapered bottom means the diameter of the tube at the bottom is smaller than at the top. The overall area of liquid passage or concentric orifice through which the liquid passes will rise in the tube as the flow increases. The float is raised to a position in the tube where the gravity acting downwards and force due to the liquid flow acting upwards are in equilibrium. The maturity in the technologies at a later point in time bought rod or rib guided nonrotating floats to the market.

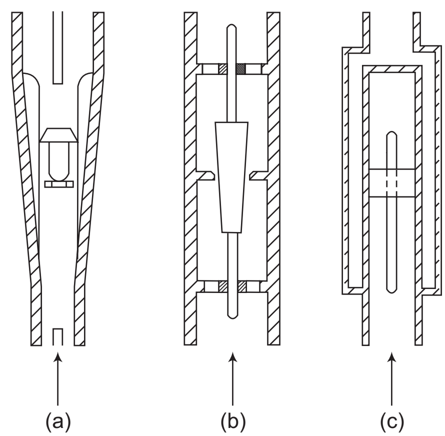

Figure 5.24: Schematic views of three basic types of variable area flow meters. (a) Tapered tube (rotameter); (b) Orifice and tapered plug; (c) Cylinder and piston

- **Orifice and tapered plug meter:** In orifice and tapered plug meters, a fixed orifice is created in a vertical enclosure. In this case, unlike earlier, the float is tapered at the bottom and moves vertically in the enclosure. The fluid passing through the fixed orifice will create an upward force which will be balanced by the gravitational force on the float and the position of the float on the enclosure is calibrated to measure the flow rate.
- **Piston-type meter:** In a piston-type meter, a piston is installed inside a sleeve and is enclosed to permit the passage of fluid. The position of the piston inside the tube indicates the flow rate.

Different types of corrosion-resistant materials are used to make floats. For general applications, the rotameter tubes are made of borosilicate glass.

In hard industrial environments with high pressure lines and hazardous areas, the rotameters are made of metal tubes. These metal tube rotameters are provided with magnetic coupling to the float to know the position outside the tube. The magnetic position is used to indicate the flow rate. The designs of the floats have matured over the year making them insensitive to changes in the viscosity of the fluid through the sharper edges. Most of the rotameters are available with advanced technologies, digital communication capabilities and calibration capabilities. These advanced capabilities are very much similar to any other smart transmitters.

The principal characteristics of variable area flow meters are summarized in Table 5.3.

Table 5.3: Characteristics of a variable area flow meter

Attributes	*Range of Values*
Flow rate: liquids, gases	0.2 to 23 gal/min (0.6 to 87 L/min) 0.9 to 106 scfm (26 to 2993 L/min)
Rangeability	10:1
Accuracy	Depends on model High accuracy designs: ±1% of reading from 100 to 10% (full-scale) Purge meters: ±10% (full-scale)
Repeatability	Depends on model; average 0.5% (full-scale)
Configurations	Full view; armored for high pressure; glass and metal tubes (magnetically coupled indicator); alarms
Operating temperature (maximum)	Glass tube: 400°F (204°C) Metal tube: 1000°F (583°C)
Operating pressure (maximum)	Glass tube: 350 psig (2.4 MPa) Metal tube: 720 psig (4.9 MPa)
Floats	Rod-guided, rib-guided, tube-guided glass or sapphire spheres
Construction materials	Metering tubes: borosilicate glass High pressure: stainless steel, Hastelloy, Mone Depending on service, floats are glass, sapphire, tantalum, Carboloy, stainless steel, aluminum, Hastelloy, CPVC, Teflon, PVC

(*Contd.*)

Advantages	Relatively low cost; direct indicating; minimum piping required
Limitations	Must be vertically mounted; need minimum back pressure (gases); usually limited to direct viewing

5.4.1 Performance

In general the rotameters are rugged, simple to operate and available with an error of 1% to 5% of the full scale range. Some meters are available with the better accuracy of 1% at the measured value. Logarithm scale meters are intended to provide the same accuracy percentage at all scale positions over a 10:1 range of the meter. The high accuracy type meters find the greatest application in laboratory testing, development, and production where the highest accuracy is required. The capacity of the rotameters is changed by changing the float. Rotameters typically deviate from linearity by approximately 5%. When the meter is equipped with a transmitter, linearity adjustments are generally supplied to guarantee linearity of the output versus flow rate. The linearity of transmitters is usually rated at ±1 % full scale.

5.4.2 Installation

Rotameters are limited to vertical installations. Rotameter installation includes a small needle valve that regulates the flow. The bottom portion of the tube is connected to the pipe inlet where the fluid enters and the upper portion of the tube is connected to the pipe outlet where the fluid leaves after metering the flow. The meter is not affected by an upstream piping effect. The meter can handle any configuration of upstream piping.

Always install some safety device to ensure that the line pressure cannot exceed the pressure rating of the flow meter. A pressure gauge can be used for gas pressure indication and should be located as close to the outlet of the meter as possible. No valve or any kind of restriction should be present between the meter and pressure gauge. For a gas service application, a throttling device such as valve or pressure regulator should be installed close to the meter outlet. In that case, follow the manufacturer's installation guidelines.

The general industrial guidelines state that rotameters should be mounted vertically in vibration-free locations with sufficient clearance available for occasional float removal at the time of service or inspection. Meters shall be located so that they are visible and readily accessible for operation and maintenance. Usually, a meter which is to be used for regulating service, is placed close to the throttling point with the valve located at the outlet fitting.

5.4.3 Applications

Flow meters can be used for liquid, slurries, some gas applications, or two-phase flow applications. Meters can also be used for flow rate measurement with limited supply pressure for a liquid and gas. Rotameters are also used for purging application. In general, rotameters are considered an alternative flow meter and alternative flow meters should be considered when it is evident that orifice plates, or precision flow metering devices are not suitable nor practical for metering process fluids caused by process constraints, short meter run lengths, or specified accuracy requirements. Additionally, rotameters are recommended for metering applications requiring wide rangeability, linear output, measurement of low flows, or where indication is required only. Rotameters are available as indicators, transmitters, recorders, local pneumatic controllers, and totalizers with or without alarm functions.

Typical applications include purge rotameter with integral needle control valve for the measurement of inert gases or liquids, seal liquids, small volumes of chemicals, chlorinator flow rates, and air purges for instruments, analyzers, or sample flow streams.

Glass taper tube rotameters for flow indication of liquid streams with or without suspended solids or other volatile liquids in nonhazardous services.

Armored: Metal taper tube rotameters for measurement of hot liquid flows above 40°C, (104°F), strong alkalies or acids, steam or slurry services, high pressure fluids, freezing or congealing liquids such as strong chemicals, waxes and asphalts, liquid streams with or without suspended solids, and liquefied petroleum gas (LPG) or other volatile liquids.

Changing a flow nozzle is more difficult than changing an orifice plate when there is a change in flow rate requirements. Flow nozzles are used for steam, high velocity, no viscous, erosive fluids, and fluids with some solids, wet gases, and similar materials. The flow nozzles pass 60% more flow than the orifice plate of the same diameter and differential pressure. A flow nozzle's inaccuracy of ±1% of rate is standard with ±0.25% of rate flow calibrated. In general, flow nozzles are considered an alternative flow meter and alternative flow meters should be considered when it is evident that orifice plates, or precision flow metering devices are not suitable nor practical for metering process fluids caused by process constraints, short meter run lengths, or specified accuracy requirements. It is also recommended that ASME wall-tap flow nozzles or ISA type flow nozzles should be considered for flow metering applications involving:

- The measurement of wet gases (e.g. saturated steam with condensate in suspension)
- Entrainment in gas, liquid, or vapor streams (e.g. metering liquids with suspended solids).

When metering liquids with suspended solids the flow of liquids should be oriented vertically downward so that all suspended solids can be swept through the throat of a flow nozzle. Flow nozzles are not recommended for highly viscous fluids or fluids containing large amounts of sticky solids.

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Checkpoint

✦ **1.** What is variable area meter?

✦✦ **2.** Explain the reason for magnetic coupling in variable area rotameters?

5.5 APPLICATIONS OF MAGNETIC FLOW METERS

LO 4
Analyze the applications of magnetic flow meters

Father Bonaventura Thurlemann of Switzerland was the first to develop a magnetic flow measuring system for closed pipes in 1939. The technology has been used for many years close to half century now and is considered suitable for flow measurements of aqueous liquids. The instrument offers several advantages that are beneficial for many operations in an in industrial processing.

Over the period, due to the maturity in the technologies in electronics, materials and manufacturing, new features, advanced electrodes, better lining, etc., were commercialized. These technologies made the magnetic meters suitable for many types of liquids and different process conditions.

Like any other transmitter, the magnetic flow meter constitutes a sensor that senses the flow of the liquid and generates a signal, and transmitter electronics that concerts the received signal into a pulse per unit of volume or time and/or current output based on the flow rate in the specified range.

The recent magnetic flow meters are available at a cost point that was similar to an orifice-based flow measurement meters. The magnetic flow meters are also available in a compact version where the sensor and the electronics are packaged in a common enclosure and the output signals (pulse or current) are available at the measuring point itself.

The magnetic flow meters are available with the microprocessors with many input and output modules surrounding it. The processor provides flexibility to the user where in the parameters such as range, time constants and alarm limits can be configurable. For example, using the front panel push buttons itself, the use can change the output from 0–20 mA or 4–20 mA or a pulse signal from 10 L/pulse to 20 L/pulse, etc. These features provide flexibility and also reduce the spare inventory as the same unit can be used across multiple such instruments.

5.5.1 Measuring Principle

Magnetic flow measurement operates on the principle of Faraday's law of induction. The law states that when a conductor moves in a magnetic field in a direction perpendicular to the field, then a voltage is generated in this conductor in a direction perpendicular to both.

$$U_e = B \times L \times V \qquad (5.20)$$

where, B = the strength of the magnetic field (induction), L = the length of the conductor (distance of electrodes), V = velocity of the conductor (average flow velocity)

In magnetic flow measurement as shown in Figure 5.25, relating to the Faraday's law, the liquid conductor flowing in the pipe is electrically

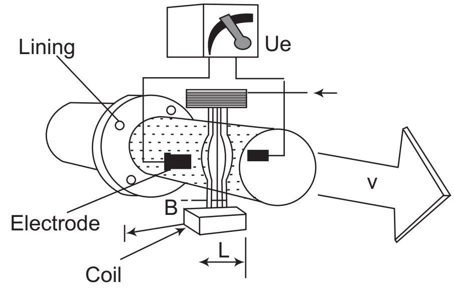

Figure 5.25 Magnetic flow meter principle

conductive. There will be no specific velocity at the outer cross-section of the liquid. However, the effect of the velocity profile on the voltage generated in negligible and hence an average velocity V is taken into consideration.

Two coils either energized by an ac power line voltage or by pulsed dc voltage generate a magnetic field. Two insulated electrodes receive the induced voltage U_e. A lining material is used to insulate the fluid being measured from the metal pipe as per equation 5.32:

Since $$V = \frac{\text{Flow }(V)}{\text{Area }(A)}$$

$$U_e = B \times \frac{V \times 4}{D^2 \times \pi} \tag{5.21}$$

where, D = Pipe internal diameter

Therefore, U_e is proportional to V.

As mentioned earlier, the axis of the electrodes to measure voltage, the direction of the coils to generate magnetic field, and direction of flow are perpendicular to each other. The voltage generated is directly proportional to the induction due to the magnetic field, velocity of the liquid (flow) and also the distance between the electrodes (L). Since the induction and distance between the electrodes is constant, the flow of the liquid is directly proportional to the voltage generated as shown in Figure 5.25.

5.5.2 Sensor

The sensor of the magnetic flow meter constitutes a pipe which is nonferromagnetic (magnetically nonconductive). The pipe is enclosed inside with a lining material and two coils to generate magnetic field, it also constitutes two measuring electrodes for generated voltage as shown in Figure 5.26.

5.5.3 Construction

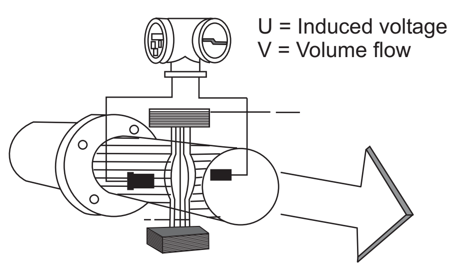

Figure 5.26: Measuring system

The nonferromagnetic pipe (for magnetic flow meter) is generally made of stainless steel (SS304, 316)) with flanges to comply with various standards such as ANSI, DIN, JIS, etc. The pipe and the liquid flowing through the pipe are separated by the lining material which is made of soft rubber teflon, etc. The selection of the lining material depends on the type of application and process conditions and type of the liquid flowing through it. In case of applications where the pipe is made of plastic, then the lining may not be required. The electrodes are in contact with the liquid being measured but insulated from the pipe, and receive the signals. The electrodes are made of corrosion-resistant materials such as stainless steel, hastelloy, tantalum, titanium, platinum/rhodium, and plastics or graphite. The material used for the electrode can have a significant impact on the meter's price. Magnetic flow meters do an excellent job of averaging the voltage combination across the metering cross-section. The voltage developed at the electrodes has an extremely low-level signal. In order to use this low-level signal, a transmitter or signal conditioner must provide amplification of the signal in the range of 4–20 mA dc. A 0–1000 Hz frequency output signal is also used in magnetic flow meters that totalize flow. Magnetic flow meters are available with remote or integral type transmitters. Each device is individually calibrated. There are two types of magnetic flow meters:

- ac excitation
- dc pulse excitation

5.5.3.1 AC Excitation

In an AC type magnetic flow meter, line voltage (120 or 240 V ac) is applied directly to the magnetic coils. This generates a magnetic field in the outer body that varies with the frequency of the applied voltage. An ac meter's signal has a sine wave pattern. The flow signal at a constant flow velocity also looks like a sine wave. The magnitude of the sine wave is directly proportional to the flow velocity. The system produces an accurate, reliable, fast responding meter. The ac-type meters needs periodical maintenance by stopping the flow through the same and perform zero offset. An ac-type system is normally considered as a percentage of full scale flow system.

5.5.3.2 DC Pulse Excitation

In a dc-type magnetic flow meter, line voltage is the main source of power, but instead of applying it directly to the coils, it is first applied to a magnet driver circuit. The magnet driver circuit sends low frequency pulses to the coils to generate a magnetic field.

While many forms of excitation are in use, on/off excitation and plus/minus excitation are the main types used. The dc pulse system eliminates the zero shift problem that occurs in an ac system. In a dc pulse system, a reading of induced voltage is taken and stored when the coils are excited. Similarly a second reading of the voltage is taken while the coils are not excited. The earlier reading is nothing but a combination of signal and noise and the second one is noise only. The result of these two signals becomes the final output signal for the flow meter.

5.5.4 Rangeability and Accuracy

Magnetic flow meters have excellent rangeability. The ac-type meter has 100:1 rangeability and an accuracy of ±1% of full scale. A pulse dc-type meter has an accuracy of ±1% rate applicable to 10:1 rangeability or, for higher accuracy, ±0.5% of rate over a 2:1 to 5:1 range.

5.5.5 Installation

Proper magnetic flow meter operation is dependent upon the installation. Indeed, the warranty could become void if the flow meter is improperly installed. Installation considerations for a magnetic flow meter primarily involve the following:

- Meter orientation
- Minimum piping requirement
- Grounding

Meter Orientation A vertically installed flow meter, with the fluid flowing upwards, is the preferred installation for a magnetic flow meter. The preference for a vertical installation is that the meter remains full of liquid at all times. A vertical installation also minimizes wear from abrasive particles. A sloping installation, with flow moving upward through the meter, is also acceptable. Horizontal installations, which are very common, are also considered acceptable for most typical process industry flow measurements. A magnetic flow meter can measure the flow of conductive liquid in both the forward and reverse directions. Flow in the forward direction develops a voltage opposite in phase or polarity from the flow in the reverse direction. If the system is designed for bidirectional flow, it cannot detect this difference. Many meters are built with flow direction arrows to indicate the proper direction for the flow through the meter. If the unidirectional meter is installed in the bidirectional flow line, the flow through the opposite direction remains zero.

Minimum Piping Requirements General guidelines regarding piping requirements include locating elbows, pumps, and control valves a certain distance from the magnetic meter. Elbows are usually located 3 pipe diameters upstream of the magnetic meter, pumps, and control valves are usually located 10 pipe diameters downstream of the meter. The reason for locating valves and pumps downstream of the meter is to minimize turbulence as well as to provide enough backpressure to keep the magnetic meter full of liquid. If higher accuracy of a magnetic meter is required, the distances should be doubled for those previously mentioned.

Grounding Grounding is extremely important—both for the safety of personnel and for satisfactory flow measurement. Stray electrical currents often develop as leakage from capacitive motor insulation’s ages, or currents develop from inductive coupling from other motor conductors. The currents are carried by the pipe or process fluid. The magnetic meter thus becomes a path for the current. To provide safety and proper measurement, magnetic meter grounding rings and piping grounding are implemented. Grounding practices are explained in more detail in vendor literature. Electronics should be oriented properly so that they are not at the top of the pipe in a horizontal and sloping installation. This prevents air from coming into contact with the electrode, causing errors in the flow signal.

5.5.6 Advantages

- The magnetic flow meter is nonobstructive and has no moving parts.
- Pressure drop is very little, so pumping costs are minimized.
- DC pulse-type meter electrical power requirements can be as low as 15–20 W.
- The magnetic meter is suitable for acid, bases, water, and aqueous solutions. The lining materials provide good electric insulation and corrosion resistance.
- The magnetic meter can handle extremely low flow rates and can be used for bidirectional flow measurements.

5.5.7 Disadvantages

- The meters only measure conductive fluid flows. Hydrocarbons, gases, and pure substances cannot be measured by these meters.

- Proper electrical installation care is required.
- Conventional meters are heavy and larger.
- Meters are expensive, but the cost of the meters can be justified by the accurate performance over a wider turndown ratio.

5.5.8 Applications

Magnetic flow meters are well-suited for flow measurement of slurries and dirty fluids because magnetic flow meters do not have sensors that enter the flowing stream of fluids. However, the fluid must be conductive, or have some minimal amount of conductivity (20 µS/cm or more) for the flow meters to work properly. The magnetic flow meters limitation of usage on conductive materials means that magnetic flow meters are not used in the measurement of hydrocarbon fluids. In general, magnetic flow meters are recommended for measurement of conductive fluids, i.e. corrosive acids, sewage, abrasive slurries, and crude oil that contains salt water. This type of meter is well suited for bidirectional flow streams requiring virtually no pressure drop. Magnetic flow meters are not affected by viscosity or the consistency of Newtonian or non-Newtonian fluids. The resulting change in flow profile caused by a change in Reynolds number or upstream configuration piping does not change the meter's performance or accuracy. It is recommended to follow the manufacturer's instruction when calibrating flow meters.

Magnetic flow meters are used for measurement of flow and are based on electromagnetic principle. The flow measurement is animated in a way to explain the concept including the installation considerations.

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Checkpoint

✦✦ 1. Explain the reason why magmeters construction and measuring feature make them ideal for flow measurement of aqueous liquids.

✦✦✦ 2. Which type of liquid is used in magnetic flow meters?

✦✦ 3. Explain the construction of a magnetic flow meter.

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5.6 ANALYZE THE APPLICATIONS OF TURBINE FLOW METERS

LO 5
Demonstrate the applications of turbine flow meters

In this learning objective, we shall deal with flow meters that are based on rotating mechanical equipment to measure the flow.

5.6.1 Static Vane Systems

Static vane is a simple mechanical way of measuring the flow rate, a vane is inserted in the direction of flow and it is connected to an indicator which provides a view of the flow rate outside the pipe, the angle by which indicator varies shows the rate of flow, however the relationship between the indicator and flow is nonlinear. In addition, a large number of datasheets need to be provided based on the nature of fluid for calibrating the instrument accordingly. In addition, due to the obstructing nature of the vane, lifespan of this meter may be relatively low calling for more maintenance. Hence, for better performance a slight modification is made for the static vane by making it rotary, where a wheel containing vanes is made to sit on a spindle and rotation of a vane from one end to the other gives the rate of flow and as we see it provides a mass flow rate indication. This is a basic design and by using a pickup to read the pulses generated is another indication of flow rate. By bettering this design turbine flow meter has evolved which is discussed next.

5.6.2 Turbine Flow

Turbine flow meter constitutes a rotor which is the rotating part, installed in perpendicular direction to the path of the fluid in a known cross-sectional area of a pipe. For a given pipe with known cross-sectional area, fluid velocity and volumetric flow rate can be inferred by counting the number of turbine-wheel revolutions per unit of time.

The following equation relates the conversion from fluid velocity (ft/s) to volumetric flow rate (gallons per minute):

$$Q = v \times A \times C \tag{5.22}$$

where, Q = volumetric flow rate, v = fluid velocity, A = cross-sectional area, C = constant.

5.6.2.1 k-factor

The turbine meter's k-factor is determined by the supplier by moving a known volume of fluid through the meter and the number of pulses generated. The total number of pulses divided by the volume of the fluid moved through the pipe is calculated as k-factor. The k-factor of the turbine meters are linear with in a rangeability of 10:1. Extended flow ranges are restricted to the fluids with specific parameters.

5.6.2.2 Reynolds Numbers

The fluid parameter that has a major effect on the flow measurement is Reynolds number. The Reynolds number is the ratio of fluid's inertial force to the drag force. Here the inertial forces are caused by the fluid flow rate and specific gravity, whereas the drag forces are caused by pipe diameter and viscosity.

For a given fluid and for a given meter, the specific gravity and the pipe diameter are constant. For a liquid with low Reynolds numbers represent a low fluid flow rate or a high fluid viscosity. The issue of measuring the flow rate of liquid with low Reynolds number using turbine meter is that the fluid has a higher velocity at the center of the pipe and lower along the inside diameter of the pipe. This parameter makes the *k*-factor not to be constant over the entire flow rate range of the meter. The Reynolds number equation relating these forces is:

$$R = \frac{3160 \times Q \times G_t}{D} \tag{5.23}$$

where, R = Reynolds number; Q = fluid flow rate, gal/min; G_t = fluid specific gravity; D = inside pipe diameter, in; μ = liquid viscosity, centipoise (cP)

The performance characteristics of the flow meters with reference to various variables are shown in Figure 5.27.

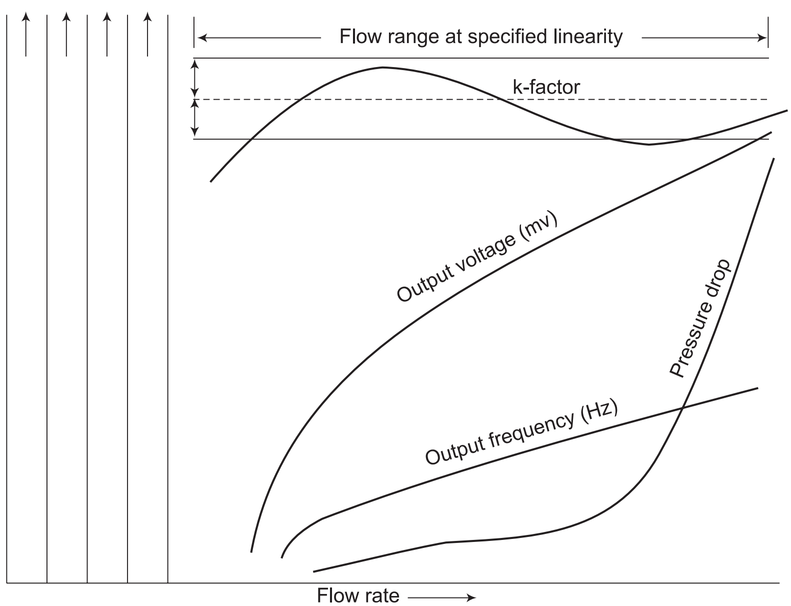

Figure 5.27 Turbine flow meter performance characteristics

5.6.3 Turbine Flow Meter Construction

The rotors of turbine flow meters are made of permeable metal and are used for housing in a nonmagnetic body as in Figure 5.28. These materials allows the proximity sensors to sense the blades of the rotor through the body of the meter directly. There are various designs of the rotors available in different products, but most generally used rotors are with tangential axis type for flow less than 20 L/m etc. and axial type rotors for higher flow rates. In general, the rotors are designed to be of low mass with respect to the fluid momentum. This design and the dependency reduces the response time of the turbine flow meter by decreasing the rotational inertia required to accelerate the rotor. The bearings of the turbine flow meters are of ball or sleeve type and they provide more life with minimum frictional losses.

The turbine flow meters are provided with straightening vanes at the inlet and outlet to stabilize the flow of the fluid in a uniform manner in the rotor area. The general installation practices are to have 10 times the diameter at inlet and 5 times at the outlet. However, the user needs to consult and follow the recommendations of the suppliers. These installation practices enable an accurate measurement.

Various methods are used to sense the speed of the rotor through the body. The most common among them is the variable reluctance pick up type sensor. This device generates a magnetic field through a coil and the nonmagnetic flow meter body into the rotor area. As the rotor blades enter the magnetic field, a discontinuity created excites a voltage in the coil, producing an electrical sine wave current with the frequency and voltage proportional to the velocity.

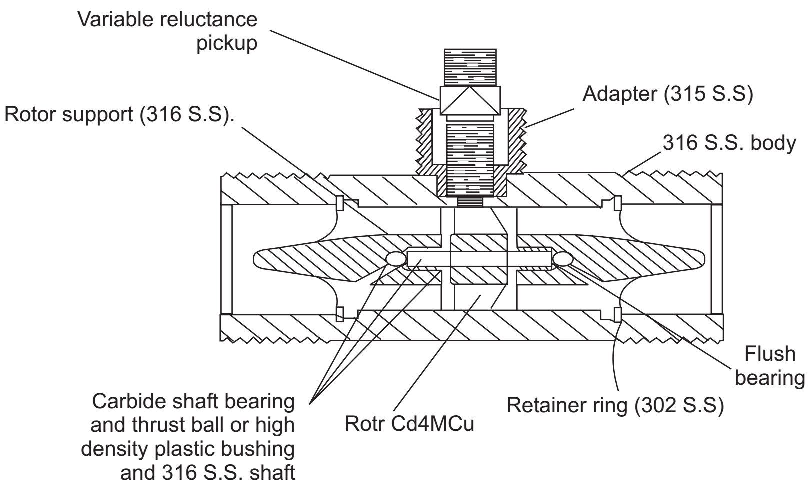

Figure 5.28: Typical axial-rotor turbine flow meter construction

Various characteristics of the turbine meter are listed in the Table 5.4.

Table 5.4: Characteristics of turbine flow meters

Attribute	*Range / Description*
Accuracy	± 0.5% (reading) over 10:1 flow range; depends on specific designs; on average as quoted in literature, ± 0.25% (rate) for liquids, ± 1% (rate) for gases; factory calibration should include viscosity and lubricity factors for liquids.
Repeatability	± 0.05% (reading) over 10:1 flow range
Sizes	Generally, 0.5–24 inches (12.7–610 mm), flanged or threaded connections
Rangeability	10:1 (generally); can be extended to 50:1, but with restricted flow parameters
Scale	Nominally linear, especially for Reynolds number higher than 10,000

(*Contd.*)

Flow ranges	Extremely low flow rates claimed; depends on design; generally, for liquids, 5 gal/min (19 L/min) to 50,000 gal/min (11.400 m^3/h); gases, 10 mil ft^3/h (285,000 m^3/h)
Pressure	Up to 3000 psig (20 MPa)
Temperature	Up to 400°F (204°C), but can be extended to 800°F (427°C) on special order; installations and maintenance relatively easy; can be used as bypass meter around pipeline orifice
Limitations	Problems may be encountered with two-phase flows; upstream straight piping required, including straighteners

5.6.4 Sizing and Selection

Turbine flow meters are available in a wide variety of sizes and flow capacities. The smallest flow a liquid turbine meter can measure is as low as 0.001 GPM; gas turbine meters can measure as low as 0.001 CFM. Turbine meters also measure high flow rates. The operating pressure and temperature should be considered in the selection of meter sizes. Pressure drop is also considered when selecting a turbine flow meter. A high-pressure drop could damage the blade of rotor. High velocity can damage the bearings. The following are the equations for the gas and liquid turbine meters.

Equation for gas applications is given as:

$$q^b = q^f M^f (P^f/P^b)\,(T^b/T^f)(Z^b/Z^f) \tag{5.24}$$

where, q^b = Flow rate at base conditions, SCFM @ 14.73 psia & 60°F; q^f = Flow rate operating conditions (meter reading), SCFM; M^f = Meter factor to correct meter output based on calibration; P^f = Pressure at flowing conditions, psia; P^b = Base pressure set by agreement near atmosphere pressure,14.73 psia; T^b = Base temperature by agreement near ambient (60 °F), 520°R; T^f = Temperature at flowing conditions, °R; Z^b = Compressibility at base pressure and temperature; Z^f = Compressibility at flowing pressure and temperature

Equation for liquid applications is given as:

$$q^b = q^f M^f Ft Fp \tag{5.25}$$

where, q^b = Flow rate at base conditions, GPM; q^f = Flow rate at flowing conditions, GPM; M^f = Meter factor to correct output based on calibration; Ft = Correction from flowing temperature to base temperature; Fp = Correction from flowing pressure to base pressure

5.6.5 Typical Industry Installations

Installation of gas turbine meter must be according to AGA-7 or ISO 9951. For custody transfer, installation of liquid turbine meter should be according to the API Manual of Petroleum Measurement Standards. A common installation practice is to install 10 pipe diameters of straight pipe upstream of the meter to minimize flow velocity profile disturbances for 2 in and greater pipe size. However, swirl is the most sensitive external influence on a turbine meter, and swirl can exist for up to 100 pipe diameters. Thus, flow straighteners are also installed to minimize swirl. For a pipe, size 2 in and under, 20 pipe diameters of straight pipe run upstream of the meter is required. If there is not enough space upstream of the meter for straightening vanes, and the meter must be installed in a large flow disturbance, it is advisable to install a perforated plate or screen to provide the normal turbulent flow. An obvious installation mistake is not observing the direction arrow on the turbine flow meter. If the meter is installed backwards, it provides incorrect flow meter readings. In order to minimize the cavitation in the turbine meter, make sure that there is sufficient backpressure in the system. If there is not sufficient backpressure in the system, then installation of a backpressure regulator is necessary at the downstream side of the meter. For turbine meter installations, a common practice is to purge the flow lines before installation of turbine meter to avoid debris damage to the turbine rotor and rotor blades. The turbine meter is a precision meter and should be treated with the care that a precision device needs. For example, one should avoid blowing compressed air across the blades because it could easily over speed the meter; over speeding could damage the bearings.

5.6.5.1 Electrical Connections to Turbine Meter

The electrical connection to the meter itself is made to the "pick-off" sensor. Meters are supplied with pigtail wire or connectors. Amplifiers are available for ac or dc power types. Always put the amplifier as close to meter as possible to minimize the signal noise. Always keep the power line and signal lines separate from each other. The shield cable or ground wire is grounded at one point in the system to prevent ground loops. The signal from a turbine meter is typically a low-level sinusoidal or square wave pulse that makes it especially susceptible to electrical noise interference. All electrical installations should comply with the requirements listed in the API Manual of Petroleum Measurement Standards.

5.6.6 Performance

Performance of the turbine meter is described in terms of:

- **Accuracy:** Turbine meters are highly accurate devices, with accuracy of ±0.5% of readings typical, ±0.25% when measuring rate liquids, and ±1% when measuring rate gas. However, one should note that accuracy is often stated under ideal conditions. Any calibration accuracy should simulate operating conditions for viscosity and lubricity. The calibration accuracy is not dependent upon the meter itself as much as it is a matter of how traceable the standard is for the meter.
- **Rangeability:** Rangeability of a turbine gas meter depends upon pressure. Typically, rangeability is from 10:1 for a gas at atmospheric pressure and from 100:1 when gas pressure is greater than 1000 psig. Rangeability on a liquid turbine meter is about 10:1, but changes caused by viscosity, density, or meter size. If the viscosity of a fluid goes above the viscosity of water, then the meter range drops to as low as 3 to 1.
- **Repeatability:** Repeatability for a precision turbine meter can be as low as ±0.02%. When turbine meters are used over an extended range, note that the low flow rates may not have good repeatability. Additionally, the type of service can affect repeatability. For example, gas service repeatability can be 0.25%.

- **Application effects:** Although turbine meters are highly accurate, application effects can impact measurement accuracy. Improper or missing straightening sections, or operations of the meter at Reynolds numbers different from conditions at calibration, can cause failure. Temperature conditions also affect the performance of the meters. When a turbine meter uses a fixed *k*-factor in an extended range, it is possible to add a percentage error into the meter reading. Linearity of a turbine meter is defined as the maximum deviation in *k*-factor:

$$\text{Percentage linearity} = (k_{\text{max}} - k_{\text{aver}}) \times 100/k_{\text{aver}}$$

The linearity of a turbine flow meter in liquid measurement is typically ±0.05 % of the measured value over a range 10 to 1 at fixed viscosity and temperature. Linearity also depends upon the viscosity of the fluid. A gas turbine meter is linear in gas than in liquid. The linearity of a gas turbine is expressed as the percentage of a full scale as opposed to an absolute percentage. Linearity is also affected by viscosity, density, and type of electronic sensors.

5.6.7 Advantages

- Excellent accuracy and good rangeability over the full linear range of a meter.
- Low flow rate designs are available.
- Some versions do not require electrical power.
- Overall meter cost is not high. Overall meter cost is considered nominal because a turbine meter can support high flow rate for a given pipe size.
- Output signal from the meter is at a high-resolution rate, which helps reduce meter proving.

5.6.8 Disadvantages

- Sensitive to fluids with increasing viscosity.
- Two-phase fluids can create usage problems.
- Straight upstream piping or straightening vanes are required in a turbine meter
- Installation to eliminate the flow turbulence into the meter.

5.6.9 Applications

Applications for turbine meters are dependent upon whether the turbine meter is one of the two types:

- Insertion type turbine meters
- Full bore (also called line size or reduced bore) turbine meters

Insertion type turbine meters are only recommended for applications where a nominal accuracy ±5% to ±10% of a flow rate is required. The insertion type meter is used when the pipe has more than a 4 inch diameter. Turbine meters (full bore types) are considered for fluid flow measurement when rangeability (10:1), accuracy, and process dynamics of installation parameters suggest their use. Services include the metering of hydrocarbon liquids and gases as well as metering cryogenic fluids.

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Turbine flow meters are used for measurement of flow and are based on velocity/turbine principle. The flow measurement is animated in a way to explain the concept including the installation considerations.

For answers to checkpoint, scan the QR code
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Visit http://qrcode.flipick.com/index.php/414

Checkpoint

✦✦✦ 1. Define the k-factor in turbine meters.

✦✦✦ 2. Explain the reason for not using turbine meters for fluids with low Reynolds numbers.

✦✦ 3. What is the recommended upstream and downstream meter run for turbine meters?

✦✦ 4. A high-pressure drop could damage the blade of rotor; high velocity can damage the bearings. Explain why?

✦✦✦ 5. What is the advantage of installing flow straighteners?

5.7 VORTEX SHEDDING FLOW METERS

LO 6
Explain the applications of oscillatory flow meters

Similar to the turbine flow meters, the oscillatory flow meters reacts to the moving fluid. The velocity of the moving fluid is measured based on the physical properties of the fluids. The oscillatory flow meters can be classified into the following two broad categories:

- Vortex meters
- Fluidic meters

The vortex meters or vortex flow meters can be again subdivided into:

- Vortex shedding flow meters
- Vortex precision flow meters

The simple principle on which the vortex shedding operates is a simple non streamlined object or obstruction makes the liquid to separate itself and moves around while moving downwards as shown in Figure 5.29. At the point of contact with the obstruction, the vortex swirls gets formed on alternative sides. This process creates an increase in pressure and decrease in velocity in one side and vice

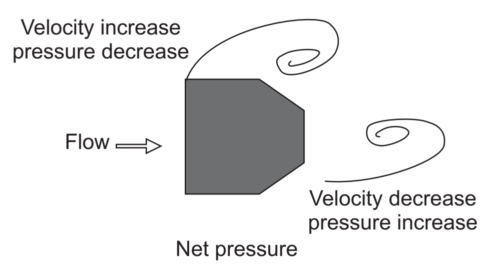

Figure 5.29: Vortex diagram

versa on the other side. After the formation of the shedding at one side and reversal at the other side, the obstruction becomes a measure of the velocity. The obstruction sometimes is also called shedder bar.

In a way the vortex swirls are shed continuously as they are 180 degrees (out of phase) to each other. The velocity of the material flowing past the bluff body or shedder bar determines the frequency of the shedding process. Each vortex swirl is of the same volume, regardless of the flowing medium.

During the manufacturing, a test with the liquid is performed to determine the *k*-factor of the meter for the specific liquid. The *k*-factor will be the multiplication constant which informs the number of pulses per unit volume such as liter, etc., *k*-factor which is a constant for a meter and is determined or designed based on meter body, size of the obstruction, etc. The general experience is that the meter remains accurate until the dimensions of the shedder or obstruction are significantly changed due to corrosion, erosion, etc. The meter also requires periodic calibration, but not as frequently as some other principle-based flow meters.

The frequencies for the vortexes range from 2 s to 1000 s based on the design of the meter, velocity of the fluid, medium of the liquid, size of the meter, etc. The frequency of the pulses generated while measuring flow is more than 10 times for gas compared to the liquids. This is largely due to the velocities of the gas being much higher than liquids for the similar conditions such as same pipe sizes. In general the smaller meters have higher shedding frequencies than large meters. The output of the meter is linear to the vortex frequency. The output of the meters is generally either a 4–20 ma analog signals or a pulse or frequency as needed. Most meters can come with an accuracy of better than +1% of the full scale.

5.7.1 Application Guidelines

The general selection criteria is to use the vortex meters for relatively clean liquids, gas, and steam, which does not contain significant amount of solids. In addition to the above, the fluids with low viscosity and low Reynolds numbers. The vortex meters are tested and found to be linear below Re = 20,000. The applications are also used for the liquids as low as Re = 4000 with some loss in accuracy.

Density of the gas is also an important consideration in the selection process. For the gases with low density and low flowing velocity the swirls created are small. The swirls are too small to detect for a pressure sensor to detect the presence of the flow or to distinguish between the presence of flow and zero condition. Most of the applications can be seen similar to the traditionally applied situations where orifice plates, differential pressure meters for many years such as clean liquids such as gas, steam or liquids with low viscosity.

5.7.2 Vortex Meter Advantages

When it comes to the selection of the vortex meters, the accuracy and rangeability becomes major advantage. The rangeability of the vortex meters are available from 20:1 to 45:1 The rangeability of the typical vortex meter is 20:1 and sometimes even higher depending on the viscosity or density.

Ensure proper installation of the vortex meter as that could affect the accuracy of the meter. In most cases of inaccuracy of a vortex meter, the cause is traceable to improper installation or the presence of a foreign object causing unwanted turbulence in the flow stream.

5.7.3 Installation

The vortex shedding flow meter is not altitude sensitive. Flow can be upward or horizontal without affecting meter performance. However, recommended vortex meters should be installed in horizontal meter runs. The line must be kept full of liquid at all times when metering is required. The vortex-shedding meter requires the same straight run as the orifice meter run. The flow stream should be smooth for better accuracy. If the flow stream is not smooth and does not have enough upstream piping run, then straightening vanes are required on upstream of the meter.

When mounting the vortex-shedding meter on-line, correct installation is important. The mating pipe should be the same diameter as the meter bore. Most manufacturers indicate that the pipe size should be used to mate with meter bore. The pipe sizes are generally schedule 40 or 80.

Some vortex shedding meters may be able to function properly in other pipe schedule with or without some adjustments to the meter *k*-factor (For more installation details review the manufacturer's guidelines). The characteristic of oscillatory flow meters is described in Table 5.5.

Table 5.5: Characteristics of oscillatory flow meters

Attribute	*Range / Description*
Flow range: Vortex shedding	3–5000 gal/min (11–19,000 L/min) for liquids 10 mil scfh (283,200 m^3/h) for gases
Fluidic	1–1000 gal/min (4–4000 L/min) for liquids
Accuracy: Vortex shedding	±1% (rate) or better for liquids ±2% (rate) for gases
Rangeability: Vortex shedding	20:1 or greater Fluidic (Coanda) up to 30:1
Scale: Vortex shedding Fluidic (Coanda)	Linear (high Reynolds numbers) Linear (high Reynolds numbers)
Operating pressure: Vortex shedding	Up to 3600 psig (25 MPa) up to 600 psig (4 MPa)
Advantages and limitations: Vortex shedding	Requires straight piping Sensitive to viscosity below minimum Reynolds number No moving parts Handles wide range of fluids, including steam Relatively good cost/performance ratio

(*Contd.*)

Fluidic (Coanda)	Requires straight piping Sensitive to viscosity below minimum Reynolds number No moving parts Handles wide range of liquids Relatively good cost/performance ratio Bypass types available
Size ranges: Vortex shedding	0.5–12 in (15–300 mm) 1–4 in (25–100 mm)

5.7.4 Performance

The vortex shedding meter provides a linear output signal (digital or analog) without the use of a separate transmitter or converter. Meter accuracy is good over a potentially wide flow range. The meter does not have any moving or wearing components, provides improved reliability, and reduces maintenance. Vortex meters have no valves or manifolds that could cause leakage problems. The same meter can be used for a gas or a liquid application.

The general instrumentation designers describe vortex meter performance constraints in the following manner. The minimum number of straight upstream and downstream pipe diameters must be maintained to ensure maximum flow meter accuracy. Oscillatory type flow meters are sensitive to increases in fluid viscosity, density, and solids entrainment. It is difficult to calibrate vortex meters in the field. Electronic calibrations are easily performed, but actual flow calibrations are difficult to achieve unless a comparison test is made against a turbine, PD, or D/P meter. Avoid using vortex meters for metering laminar flows or streams with Reynolds numbers below 10,000. Avoid using insertion type vortex meters where full line-size vortex meters can be used. Potential insertion vortex meters installations must undergo careful investigation and user surveys to determine if they are applicable to process situations and environmental constraints.

5.7.5 Applications

The vortex shedding flow meter can be used for liquid as well as gas applications. The flow meters are not recommended for viscous and dirty fluid applications. If two-phase fluid flows are present, the vortex-shedding meter will not provide accurate flow measurement.

When the meter is measuring a gas flow, the operating density becomes very important to measurement accuracy. At some point, the density/velocity relation becomes so low that the meter cannot detect the flow signal. At the no flow point, the meter should be calibrated to indicate a no flow condition. When the meter is measuring a liquid flow, the fluid's Reynolds number becomes very important to measurement accuracy. Refer to manufacturer's guidelines for how low a Reynolds number can be for a particular application. Pressure drop and fluid velocity also must be considered when selecting a vortex meter.

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The vortex flow meters are based on the formation of vertices in the flow by the restriction. The concept is very old, and tough to understand unless seen practically. The concept animation, explains the principle of operation in a dynamic view.

For answers to checkpoint, scan the QR code
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Checkpoint

✦✦ 1. What is a shedder bar?

✦✦ 2. How much is the phase shift of the vertices that shed in swirl?

✦✦ 3. What is the characteristic of the fluid for application of vortex meters?

✦✦ 4. What is the major advantages of using vortex meters?

5.8 MASS FLOW METERS

LO 7
Analyze the applications of Coriolis flow meters

Mass flow meters measure the mass flow rate of the liquid flowing though the device. Unlike other flow measurement devices which measure the flow of liquids in volume per unit time such as liters/sec, etc., the mass flow meters measure the flow in mass per unit time such as kilograms per second, etc.

5.8.1 Impeller-Turbine Mass Flow Meters

In an impeller turbine type mass flow meter, as the name indicates an impeller and turbine are housed in the same enclosure through which the fluid is passed. Using a synchronous motor with a magnetic coupling, the impeller is maintained at a constant speed. The impeller creates an angular momentum to the flowing fluid which is now passed through the turbine. The angular momentum generates a torque on the turbine which is measured using the deflection of the spring attached to it. The deflection of the spring is directly proportional to the torque applied and the torque is directly proportional to the mass flow of the fluid (Figure 5.30).

5.8.2 Twin Turbine Mass Flow Meter

Similar to the impeller turbine, the twin turbines operates on using the angular momentum to measure the mass flow rate of the fluid. In this mass flow meter, two turbines are attached to a common shaft and are connected through a calibrated torsion element. The magnetic pickup coils are arranged to measure the speed of the turbines as shown in Figure 5.31.

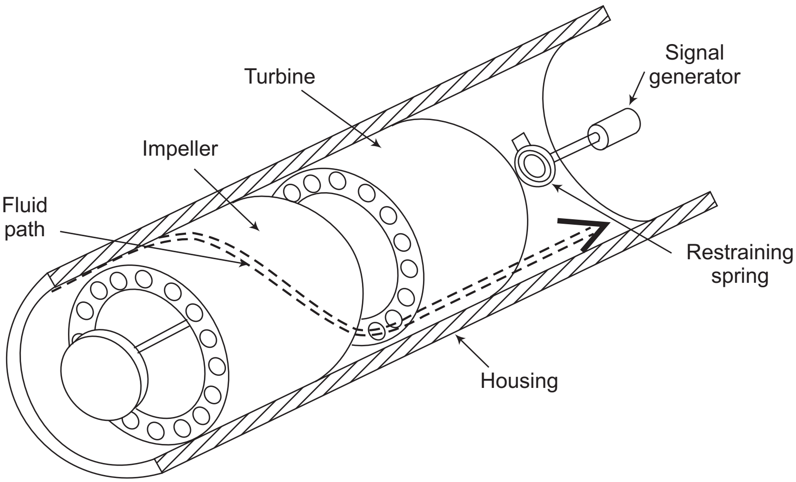


Figure 5.30: Impeller turbine mass flow meter

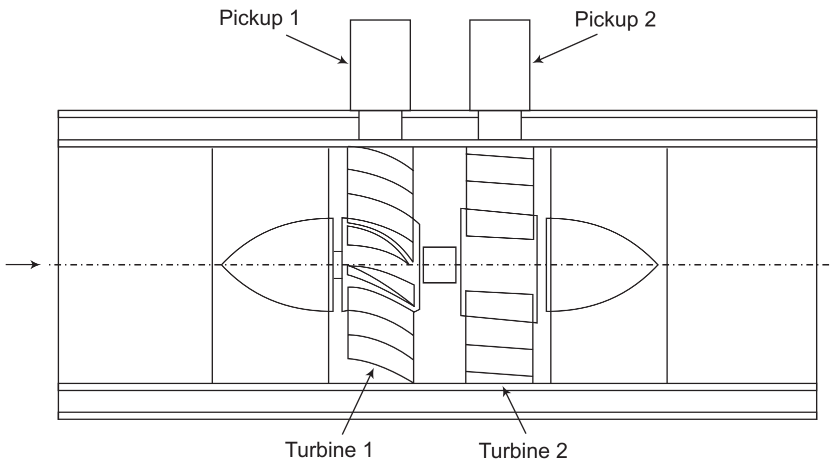


Figure 5.31: Twin turbine mass flow meter

The turbines are designed with different blade angles and hence for the same flow, they rotate at different angular velocities. However, the torsion element restricts the speed of the both the turbines and hence the complete assembly will have a common average velocity with an angular phase shift between the turbines. This angular phase shift is directly proportional to the angular momentum and angular momentum is directly proportional to the mass flow of the liquid flowing. In twin turbine assembly, the torsion element is twisted to a degree proportional to the torque applied by the liquid on the turbines assembly.

5.8.3 Gyroscopic Mass Flow Meter

This angular momentum mass flow meter operates on the principle of Gyroscope. The gyroscopic mass flow meter employs a C-shaped pipe and a T-shaped leaf-spring as opposite legs of a tuning fork. An electromagnetic forcer excites the tuning fork, thereby subjecting every moving particle inside the pipe to a Coriolis kind of acceleration. The subsequent forces angularly deflect the C-shaped pipe to an amount that is proportional to the toughness of the pipe and equal to the mass flow rate inside the pipe. The angular bend of the pipe may be optically calculated two times through every cycle of the tuning-fork oscillation. The productivity of the optical sensor is a pulse that is width-modified equal to the mass flow rate.

Gyroscopic mass flow meters are applied for measuring slurries at medium pressure and temperature limits; however it is limited in its application for industrial measurement due to the limited flow ranges (Figure 5.32).

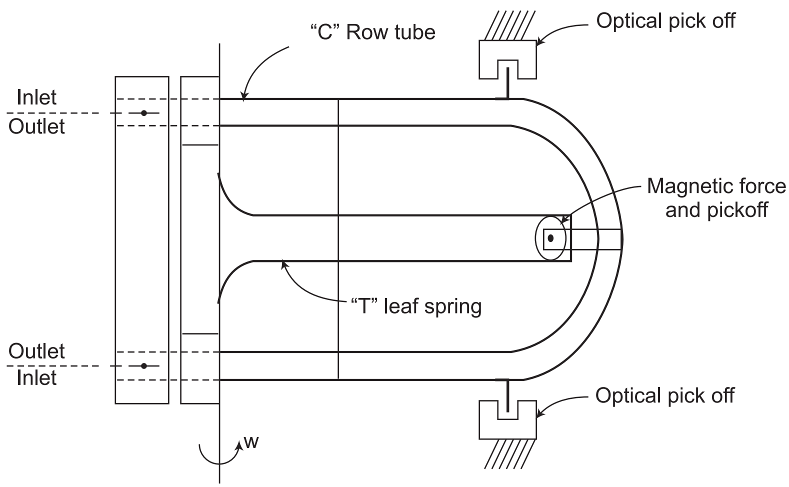


Figure 5.32: Gyroscopic mass flow meter

5.8.4 Thermal Mass Flow Meter

Thermal properties of the flowing fluid that are used to measure the flow in a pipe are called thermal mass flow meters. Most commonly, a known amount of heat is sent to the heater of the sensor which is placed in the flowing fluid. A temperature element is also embedded in the same sensor to measure the temperature. The heat is dissipated in the flowing fluid and amount of heat dissipated is directly proportional to the rate of flow. The dissipated heat is measured by the reduction in the temperature. Hence a heater and temperature element enclosed in one housing can measure the flow rate. The thermal mass flow meters are mostly applied in gas measurement applications (Figure 5.33).

While all thermal flow meters use heat to calculate the flow measurements, there are two methods for determining the amount of heat released.

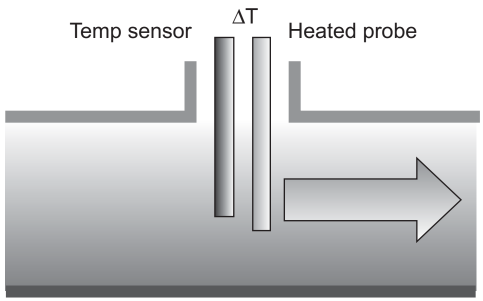


Figure 5.33: Thermal Mass Flow Meter

5.8.4.1 Constant Temperature Differential Method

In a constant temperature differential method a heated sensor and the actual sensor that measures the temperature of the gas are maintained at a constant difference. The electrical power required to maintain the constant difference is inferred as mass flow of the fluid.

5.8.4.2 Constant Current Method

In a constant current method a heated sensor and measuring sensor are used as in constant temperature differential method. In this case, the power to the heated sensor is kept constant and mass flow rate is inferred by the difference in the temperature between the two sensors. However the concept of an increase in flow rate proportional to the reduction in the temperature remains similar in both the cases.

5.8.5 Radiation-type Mass Flow Meters

In earlier applications, in order to measure the mass flow of the flowing liquid, multiple sensors were installed and the computations are performed outside the system. In the case of mass flow applications, one sensor for measuring the volumetric flow and other for measuring the density were used. Using these two signals the mass flow was computed. If the accuracy needs are more and variations in the fluid are frequent, then additional sensors to measure temperature, pressure viscosity, etc., are installed and computations were performed with more accurate correction factors. Figure 5.34 illustrates the multi input mass flow measurement system. In this case a radiation type density meter is used to measure the density of the liquid and a different sensor is used to measure the volumetric flow. These two inputs were computed to generate an output signal proportional to the mass flow of the liquid.

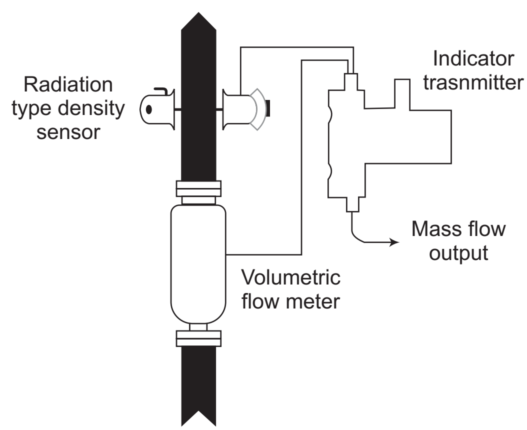


Figure 5.34: Volume flow meter with density

Advances in the technologies helped to package these multiple sensor units in a single enclosure and finally they became single instruments (Figure 5.35).

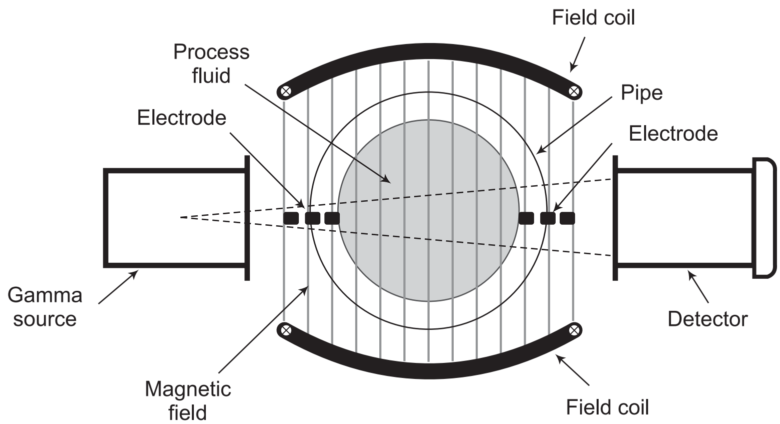


Figure 5.35: Radiation type flow meters

Generally, these single units constitute a magnetic flow meter coupled with a radiation type density meter along with a processor unit. These meters in general do not require compensating for the changes in the pressure and temperature. These meters are made of materials similar to any magnetic flow meters except that they are large in size due to multiple sensors being packed in one.

5.8.6 Coriolis Flow Meters

A relatively new technology has emerged that uses the Coriolis effect in an industrial flow meter to measure the mass flow directly as opposed to the differential pressure meters or positive displacement meters. The first industrial Coriolis mass flow meter introduced in 1972, which was very bulky, not very accurate, not reliable, application sensitive, and very expensive.

With advances in the technology, many designs of Coriolis meters with single, double tubes which are straight and also single and double bend tubes are available. The recent offerings in Coriolis meters are available with an accuracy of 0.1% to 0.2% and are much more reliable than their predecessors. The technology has matured enough to package them into small units for even the bigger pipe sizes and also become insensitive to the type of the liquids used. However, the Coriolis mass flow meters are most frequently used in liquids, slurries and gas and steam applications.

The primary reason for its widespread adaptation is its ability to measure the mass flow in a direct measurement which is also insensitive to the fluid characteristics and process conditions such as pressure, temperature and density, etc. The cost of the meter is medium and with many benefits such as ease of installation, maintenance, etc.

5.8.6.1 *Principle of Operation*

The mass of a body can be measured only by measuring weight and then dividing with the gravity of earth. The mass of a body can also be measured by measuring the acceleration of the body with a known force as derived from the Newton's second law of motion: force = mass × acceleration.

The Coriolis mass flow meter is based on the generation of the controlled generation of the Coriolis forces which are present when a translations forces and rotational movements occur in a tube simultaneously as shown in Figure 5.36.

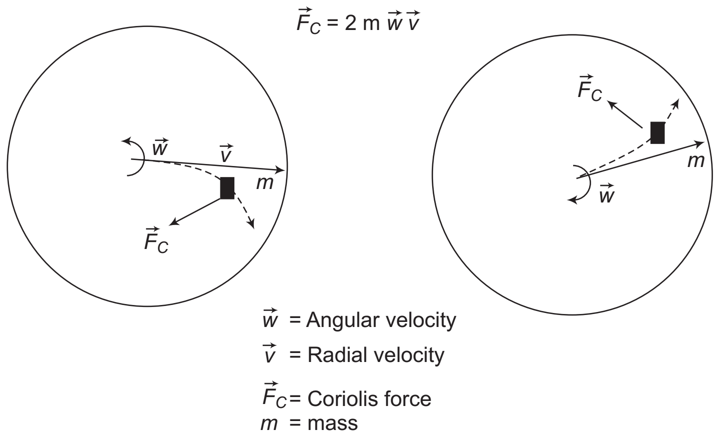


Figure 5.36: Principle of mass flow

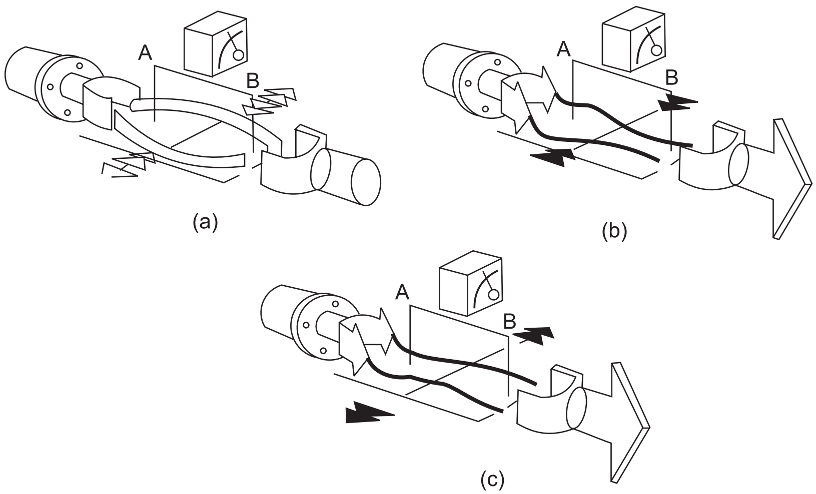
The sensor in the Coriolis mass flow meter constitutes a tube with flexibility. The tube is arranged to vibrate in a same phase while there is no liquid flowing. Such sensor arrangement when filled with flowing fluid will experience a change in phase of the vibrations. The phase difference is directly proportional to the mass flow of the liquid flowing through the tube. The amplitude of the vibrations is proportional to the mass of the fluid and its flow velocity which is the mass flow of the liquid.

$$\begin{aligned}
\overrightarrow{F_c} &= 2 \times \vec{\omega} \times \vec{v} \\
\overrightarrow{F_c} &= 2 \times \Delta m(\vec{\omega} \times \vec{v}) \\
\overrightarrow{F_c} &= \text{Coriolis force} \\
\Delta m &= \text{Mass of moving body} \\
\vec{\omega} &= \text{Angular velocity} \\
\vec{v} &= \text{Radial velocity in a rotating oscillating system}
\end{aligned} \tag{5.26}$$

The amplitude of the Coriolis force depends on the moving mass Δm, its velocity $\vec{v}$ in the system and therefore it is mass flow.

There are multiple designs used by the suppliers even though the underlying concept remains the same. Some designs has two tubes carrying the liquid and they both will be vibrating at some frequency. If there is no flow in the tubes, the phase shift will be zero and if there is liquid flowing through them, then the oscillation frequency will change and also the phase of the oscillations. These changes are detected by means of position sensors.

As described above, refer to Figure 5.37 for illustration. When there is no flow, both the phases are equal as shown in Figure 5.37(a), there will be no phase difference. If there is a flow in the tubes, the tube oscillations gets decelerated at the inlet and accelerated at the outlet [Figures 5.37 (b) and (c)]. With the increase in the flow, the oscillations and phase difference will also increase. Electrodynamics sensors, fitted at the inlet and the outlet determine the oscillations of the measuring tube(s). The measuring principle operates independently of temperature, density, pressure, viscosity, conductivity, or flow profile.



Figures 5.37: Oscillations at mass flow meter

Coriolis flow meters are applicable to single-phase liquid metering installations which are not susceptible to gas entrapment problems. Coriolis flow meters eliminate many of the problems commonly encountered in mass flow measurements. The output of the meter is directly proportional to mass flow rate. Therefore, there is no need to measure the critical parameters of pressure, velocity, temperature, viscosity, or density. Also, it is a nonintrusive meter, i.e. there are no moving parts in the flowing fluid, and the meter is unaffected by erosion, corrosion, or scale buildup in the flow sensor.

5.8.7 Advantages

- **Density measurement:** As discussed earlier the tubes in the Coriolis meter will be at their resonant frequency and is a function of the density of the liquid flowing through the tube. In this way, along with the mass flow, the meter can measure the density of the liquid which is supplied as an additional measurement parameter. Since the tubes are excited to oscillate at their resonant frequencies, a change in density or mass will change the oscillations and hence the vibration frequencies are readjusted.

- **Temperature measurement:** The meter measures the temperature of the fluid flowing though the tube for compensation purpose and the same is available as an output parameter.
- Even though the Coriolis mass flow meter is a direct measurement of mass, it is insensitive to the variations in the fluid properties.
- The Coriolis mass flow meter measures multiple process parameters such as mass flow, pressure, temperature and density with the same instrument. In addition to the above parameters some calculated parameters can be derived such as percent mass flow, percent volume flow, standard density, etc.
- The Coriolis flow meter provides high accuracy (typical: ±0.1% to ±0.3%)
- The flow meter has no moving parts: any rotating components.
- The flow meter is easy to maintain
- It is available in a range of corrosion-resistant measuring tube material. Coriolis flow meters can handle difficult applications that could, for example, plug an orifice plate. The Coriolis flow meters are suitable for a large number of fluids, whether Newtonian or non-Newtonian, high or low viscosity that would create problems for other flow meters.
- Flow meters can be used on liquids, slurries, gases, and two-phase gas and liquid flows.
- The nonintrusive design means less susceptibility to damage, wear, and maintenance.
- Coriolis flow meters can measure bidirectional flow.
- Accuracy is very good, typically ± 0.2% of rate or better.
- The linearity is usually over the entire flow range. The rangeability is typically 20:1 or better with Coriolis meters.
- The operation of these flow meters is independent of a fluid's property characteristics. The Coriolis flow meters are independent of a fluid's Reynolds number, as well as a fluid's turbulence and flow profile.
- The Coriolis meter has a very high turndown ratio.

5.8.8 Disadvantages

- Purchase cost for a Coriolis mass flow meter can be categorized as medium to high.
- The initial size used to be large such as 6 in. However, the latest offerings are available at much smaller sizes as small as 2 in.
- The process temperature range for its operations is limited upto 200°C
- Due to the tubes which are bent and multiple tubes in the sensor, the pressure drop across the meter is high compared to others designs.
- Traditionally Coriolis meters were considered large and bulky, whereas the latest offerings overcame such limitations and they are in a comparable size as any other meters.
- The Coriolis meters are sensitive to the vibrations in the pipe as the core principle is based on the vibrations of the tubes inside the meter. The sensitivity to vibrations make it sensitive to installations as well.

- Some earlier versions of Coriolis flow meters were susceptible to external vibrations.
- The durability of contoured sensor tubes should be considered if a corrosive fluid is used at high velocities.
- Pressure-drop requirements can be a factor in performance of Coriolis meters.
- Some Coriolis meters may require, for example, a 10 psi pressure drop. Others may require higher velocities and pressure drops to have an accurate measurement.
- A Coriolis meter is available only up to a maximum 6 in in size.
- Special installation requirements are followed to isolate the Coriolis meter from mechanical vibration.
- Avoid using Coriolis meters in piping or meter runs, which are prone to substantial vibration, shock, or extreme temperature gradients. External meter piping must be well supported. Avoid using Coriolis meters in liquid services prone to gas entrainment or slugs.
- Coriolis meters cannot be used in gas service.

5.8.9 Applications

The Coriolis flow meter is a versatile flow meter. Applications range from process control, inventory control, blending, and custody transfer. For example, mass flow applications include boiler control applications, where accurate measurements of combustion and preheat flows, along with fuel gas flows, are used for greater heating efficiencies. Other gas flow examples include metering natural gas in pipeline, and gas flow to flare stacks. Crude oil, asphalt, gasoline, and fuel oil applications are just several examples of process media that are usable with Coriolis meters.

Note

Not all Coriolis meters support gas measurement.

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Coriolis flow meters are the mass flow meters used most widely for accurate measurement of flow and are complex to understand. In this concept animation, the principle of operation, the dynamic conditions of the sensors and the concept of Coriolis effects used for measurement of flow are explained.

Checkpoint

✦✦ 1. What are the key factors that contribute the successful usage of the mass flow meters?

✦ 2. Explain the principle of operation of Coriolis mass flow.

For answers to checkpoint, scan the QR code

Or

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5.9 APPLICATIONS OF ULTRASONIC FLOW METERS

LO 8

Elaborate the applications of ultrasonic flow meters

Ultrasonic or acoustic flow meters are of four principal types:

- Doppler-effect meters
- Transit-time meters
- Cross-correlation
- Swept-beam meters

The ultrasonic flow meters measure the flow of the fluid by measuring the effect of flowing liquid on the sound waves injected into the pipe. These flow meters are also called noninvasive flow meters because in clamp-on designs, these meters measure the flow rate without intruding into the stream. These flow meters are essentially nonintrusive even in configurations in which transducers are contained in shallow wells.

5.9.1 Principle of Operation

The principles of ultrasonic flow measurement have been known for many years, but they have made remarkable penetration into the flow meter field only in the past few decades. The sluggish acceptance is mostly attributed to too many designs being introduced too soon, prematurely and without testing them against adverse plant environments. Initial days of the introduction of these technologies were not widely accepted due to the limitations in the accuracy. However, over a period of time the advancements in technology led to advantages such as better linearity, good rangeability, little or no pressure drop across the meter. The additional benefits as seen by the users is its ability to measure the flow rate in both directions, clamp on type installation where there is no need to open the pipes and at a cost range medium compared to others. In the last few years, ultrasonic flow measurement technology has found a firm foundation, and these meters are expected to occupy a prominent place in the future of flow metering.

5.9.2 Doppler-Effect (Frequency-Shift) Flow Meters

In mid-eighteenth century, Christian Doppler observed that the frequency and amplitude of the sound waves depend on the motion of the source or observer relative to the medium. The concepts were proven those days on a railroad where the sound from the trains are observer are placed in different directions and the theory was proven. The same concept is used by the ultrasonic flow meters to measure the flow rate.

The principle operates well if the medium of propagation has some material that can reflect the sound waves, for example solid particles or air bubbles, etc. However this may not be required in the transit-time ultrasonic flow meter which will be discussed immediately after this topic.

The basic equations of a Doppler flow meter are:

$$\frac{\sin\theta_T}{V_T} = \frac{\sin\theta}{V_s} \tag{5.27}$$

Simultaneously solving equation gives:

$$V_F = \frac{FV_T}{f_T \sin\theta_T} = kF \tag{5.28}$$

where, V_T = sonic velocity of transmitter material, θ_T = angle of transmitter sonic beam, k = calibration factor, V_F = flow velocity, F = Doppler frequency change, V_S = sonic velocity of fluid, f_T = transmission frequency, θ = angle of f_T = entry in liquid.

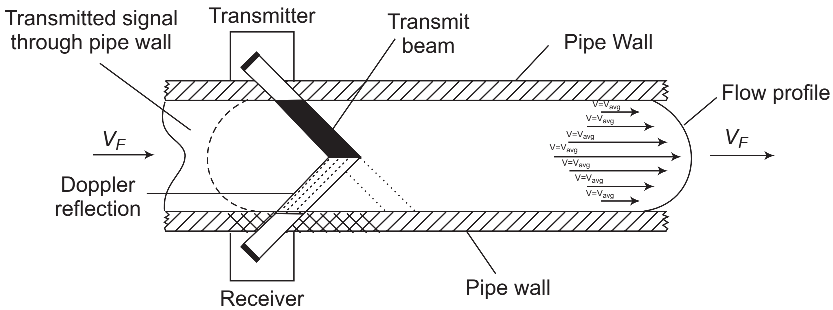
In the ultrasonic meters with the Doppler effect principle, a transmitter is attached to the pipe which emits sonic waves at about 50 kHz. The waves pass through the liquid and also gets reflected by the flowing stream. The receivers in the pipe sense the frequency of the received wave pulses. The difference in the frequency of the signals is proportional to the rate of fluid in the pipe. Figure 5.38 is represented with multiple positions of the receivers which depends on the design of the meter.

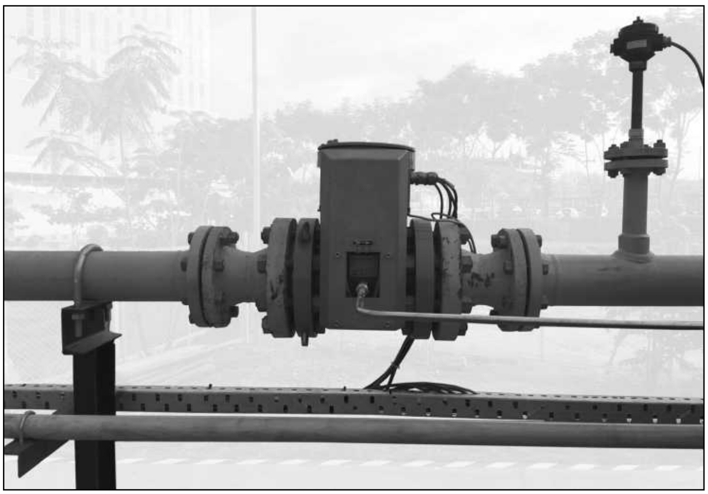
In essence, the Doppler-effect meter measures the beat frequency of two signals. The beat frequency is the differential frequency obtained when two different frequencies (transmitted and reflected) are combined.

A fluid is said to be sonically opaque when the fluid contains a large concentration of particles or air bubbles. The number of reflections that originate near the pipe wall is directly proportional to the opaqueness of the liquid, a situation exemplified by heavy slurries. It can be noted from the flow profile of the figure that these reflectors are in the low-flow-rate region. In contrast, the prevalence of particle reflectors occurs in the center of the pipe (where the flow rate is highest) when the fluid is less sonically opaque (Figure 5.39).

One limitation with the technology is if there are few particles in the stream which can reflect the beam, then the beam will cross the center of the stream without reflection back to the receiver. The penetrated beam will detect the slow moving particles in the inner side of the pipe in opposite side resulting in erroneous readings. Factory calibration is normally difficult, because it is difficult to predict the sonic opacity of the fluid in advance.

Figure 5.38 Principle of Doppler-effect ultrasonic flow meter





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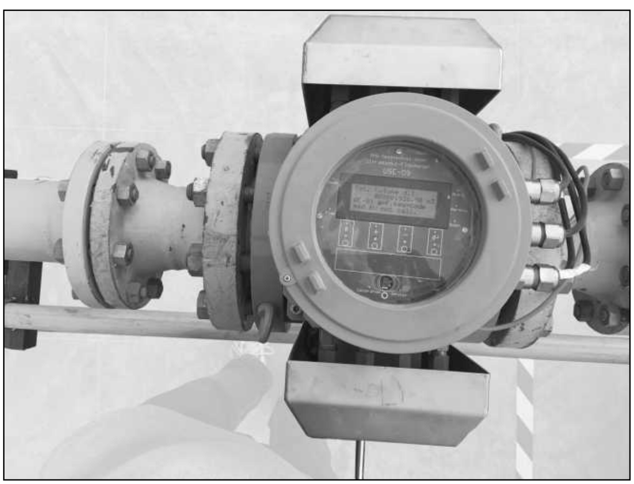

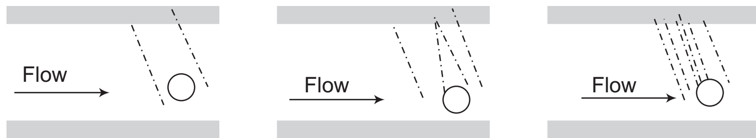

Figure 5.39: Configurations of Doppler-effect ultrasonic flow meter: (a) Single transducer, (b) Tandem dual transducer, (c) Separate dual transducers installed on same side of pipe

In general the fluid velocity is high at the center of the pipe and low at the edge of the pipe. The average velocity will fall somewhere in the middle, and hence the type of fluid and its characteristics, the type and size of the pipe play a critical role in the accuracy of the meter and hence also plays a role in the selection of the instrument. The fundamental precision of measurement increases when a measured fluid has a relatively consistent flow profile and includes an ideal concentration and distribution of particles and therefore simplifies calibration. There are various improvements in the designs to reduce the sensitivity of the meters with the type of fluid and pipe etc.

5.9.3 Transit-time Ultrasonic Flow Meters

Air bubbles and particles in the flowing stream are undesirable in transit-time flow meters (T flow meters) because their presence (as reflectors) interferes with the transmission and receipt of the ultrasonic radiation applied as depicted in Figure 5.40. In this case, the fluid is a conductor of sound waves. For a given temperature and pressure, the ultrasonic sound waves travels at a specific speed in the flowing fluid. In this case, the sound waves travel faster in the direction of flow and slower in the direction opposite to the direction of flow. By measuring the difference in the time of reaching by the pulses both upwards and downwards, the calculations can infer the fluid velocity or flow rate. The above said principle of operation is illustrated by the following equations:

$$V_F = \frac{(T_U - T_D V_s)}{\sin\theta}\frac{V_s\cos\theta}{d} = \frac{tV_s}{\sin\theta}\frac{1}{T_L} \tag{5.29}$$

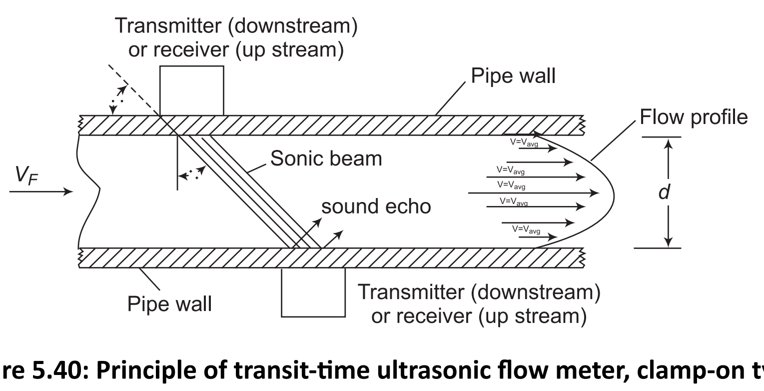

Figure 5.40: Principle of transit-time ultrasonic flow meter, clamp-on type

By Snell's law,

$$\frac{V_s}{\sin\theta} = \frac{V_c}{\sin\theta}\alpha = K$$

$$V_F = \frac{K\Delta t}{T_L}$$

where, T_U = upstream transit time, T_D = downstream transit time, T_L = zero-flow transit time, V_s = liquid sonic velocity, d = pipe inside diameter, V_F = liquid flow velocity, θ = angle between transducer and pipe wall, V_C = transducer sonic velocity.

In the clamp-on flow meter, the transducers are strapped to the outside of the pipe, and the sonic echo is away from the receiver enabling the device to retransmit earlier and operate faster. Ultrasonic meters with clamp on type installations are useful where there is difficulty to cut the pipe or for the retrofit applications. Some more designs have the transducers inserted inside the pipe and they will be in contact with the process fluid. In either case, the transducers are installed diagonally opposite or perpendicular to each side. Some designs have a small well inside the pipe in which the transducers are installed. Such installations provide better contact with the process while still being noninvasive to the process fluid.

In dual path flow meters, four transducers form two paths and are installed on the pipe at fixed locations. Each path is used for measuring the time in upstream and downstream and the electronic signal processing is used to derive the velocity of the fluid based on these time differences.

5.9.4 Installation

Ultrasonic flow meters can be installed on either horizontal or vertical pipe. Depending upon the type of meter, a manufacturer specifies the minimum distance from valves, tee, pumps, or other process equipment in order to ensure accurate flow meter performance. Typically, 10 to 20 diameters are required on the upstream side and 5 diameters required on the downstream side of the meter. Since the ultrasonic meters are based on sound wave propagation in a flowing fluid, the fluid is expected to be clean with non-air bubbles. Generally, bubbles in the fluid stream cause more alteration of the sonic signal than solid particles.

Large or complex installations of multiple transducers are mounted in the wall of the conduit. The transducers are held in place within the pipe wall by a series of expansion rings kept inside the pipe. Each transducer pair makes an independent measuring path. Each measuring path is mathematically calculated to produce flow measurement independent of the velocity. A special calibration is required for that particular installation, and is usually provided by the meter's manufacturer.

Depending on the process fluid, transducer material must be selected carefully and protection must be taken to prevent the transducer damage caused by the chemical action. A wide variety of pipe sizes and flow conditions are encountered. Several different sensor configurations are available—axial-type, radial-type and clamp-on-type.

5.9.4.1 Axial-type Configuration

When pipes of small diameters are encountered, it becomes necessary to pass the sound directly down the axis of the pipe and ensure that there is a sufficient path length to measure the transit time. A path less than 3 inches does not provide adequate time difference for an accurate measurement.

5.9.4.2 Radial-type Configuration

In a radial type installation, sonic transducer sensors are placed on the either side of the spool section and normally inclined at 45° to the pipe axis to measure a vector component of the flow. In a radial-type configuration, the lower pipe size limit is about two inches and with an upper limit in excess of 10 ft.

5.9.4.3 Clamp-on-type Configuration

Clamp-on-type meters are desirable to have when the pipe wall cannot be penetrated. Clamp-on-type meters can be installed without shutting down the process. Installation of a clamp-on-type meter is very convenient and has an accuracy that is similar to the accuracy of direct wetted transducers. The clamp on type meter is more complex to calibrate. The transducers are mounted on a calibration device and affixed to the pipe wall with grease or epoxy.

5.9.5 Performance

In ultrasonic meters with transit-time principle, the fluid flowing through the pipe should be full always, whereas Doppler-type flow meters can handle the partially full pipes as well as long pipes as the sensor is mounted below the pipe. The meter has large turndown ratio with higher accuracy for multiple designs compared to other meters. Accuracy is usually specified as a percent of rate; typically, for a single pulse meter accuracy is about 1–2% of full-scale rate. To increase accuracy for a larger pipe, manufacturers suggest installing another pair of sensors arranged to interrogate multiple acoustic path. While some ultrasonic flow meters can be used to measure gas flow rates, most are used to measure liquids. Ultrasonic flow meters do not require a pressure drop to measure flow rate because they are nonintrusive. Following are some advantages and disadvantages to ultrasonic flow meters.

5.9.6 Advantages

- Clamp-on versions are convenient for retrofits; process downtime is avoided.
- Ultrasonic flow meters are usually nonintrusive; no pressure drop is required to operate the flow meter.
- Ultrasonic flow meters have accuracy comparable to orifice plates. For transit time ultrasonic flow meters, this can be ±1% to ±2% of full scale.
- Ultrasonic flow meters have high rangeability; rangeability can be up to 40:1.
- An ultrasonic flow meter's high frequency pulse rate output minimizes errors from the effects of pulsation and fluctuating flow.

5.9.7 Disadvantages

- Applications normally are limited to clean, single-phase liquids.
- Straight piping is required for uniform flow profile.
- Sound wave attenuation may limit transmission path length.
- Averaging methods for large pipes are marginally cost-effective.
- An ultrasonic flow meter requires power to operate.

5.9.8 Applications

The ultrasonic meters are considered an alternative flow meter and alternative flow meters should be considered when it is evident that orifice plates, or precision flow metering devices are not suitable nor practical for metering process fluids caused by process constraints, short meter run lengths, or specified accuracy requirements. Additionally, ultrasonic flow meters are suitable for services involving either clean or entrained liquids. They are best suited however, for applications involving large line sizes where noninvasive flow measurement is desired, where low-pressure losses are required, or where fluid properties require an ultrasonic-type meter.

Potential ultrasonic meter applications include wastewater streams, slurries, viscous fluids, liquids containing suspended solids or entrained gas bubbles, crude oil measurement, and flare gas flow metering.

The measurement of flow based on the Doppler principle on sound waves, which measures the ultrasonic signals on both directions of the flow. The concept animation provides an overview of the operation and installation considerations..

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Checkpoint

✦✦ **1.** How flow rate is inferred in ultrasonic flow meters?

✦✦ **2.** What are the characteristics of the liquid for the acoustic Doppler?

✦ **3.** Does the reflectors are needed for transit time ultrasonic flow meters?

✦ **4.** Explain the principle of operation of ultrasonic Doppler flow meters?

For answers to checkpoint, scan the QR code
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Visit http://qrcode.flipick.com/index.php/417

5.10 POSITIVE-DISPLACEMENT FLOW METERS

LO 9

Demonstrate the applications of positive-displacement flow meters, flow indicators and totalizers

Positive-displacement (PD) flow meters measure flow directly in quantity (volume) terms by repeatedly trapping a sample of the fluid. The positive displacement meter fills the flowing fluid into small volume portions and each of these volume portions is counted to sum up the total flow rate. The total volume of liquid passing through the meter in a given period is the product of the volume of the sample and the number of samples. The fundamental principle of the PD meter does not have a time reference in the counting, but the sum of volume in a given amount of time can be used to infer the rate of flow as shown in Figure 5.41.

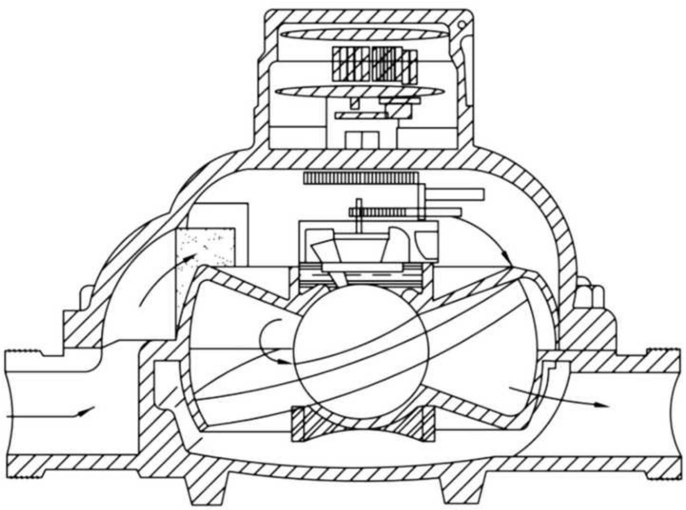

Figure 5.41: Sectional view of representative nutating disk flow meter

PD meters indicate flow in terms of weight and mass by making appropriate corrective changes in the density resulting from changes in temperature, pressure and composition. PD meters are best choice of selection where there is an accounting process involved such as receivables, sales, distribution, etc., whereas the inferential type flow meters discussed in rest of the topics are used in process control for monitoring and control.

The other major segment of usage for the PD meters is in utilities for the measurement for flow, such as water, gas, etc. Whenever a PD meter is used for metering application, they come under the preview of the weights and measures departments and they needs period testing, calibration and certification from the government authorities and agencies. The accuracy of the PD meters varies based on the type of the service such for water meters, usually comes with an accuracy of +2% whereas the gas meters has +1% accuracy.

Positive displacement meters precisely separate a flowing stream into discrete volume, count them, and then return the discrete volume to the flowing stream. The meter shows a count of volume, rather than flow rate. For the rotation of the volume-measuring element within the meter to occur, there must be a pressure drop. The pressure drop, or pressure difference, between the inlet flow and outlet flow, causes the rotation of the measuring element.

Positive displacement meters come in several varieties. Positive displacement meters include rotating paddle meters, oscillating piston meters, oval gear meters, sliding vane meters, and birotor meters. The term "displacement" refers to a discrete volume that is flowing through the meter, displacing (replacing) a previously counted volume. PD meters are mechanically driven meters and have one or more moving parts. The energy required to drive the meter's mechanical components is generated from the flow stream. The energy to drive the meter creates a pressure loss between inlet and outlet of the meter. A PD meter has output hardware can convert each unit of volume displacement into an electrical pulse. In a PD meter, there will be only one mechanically rotating part in the tube meant for measuring. The process fluid fills the chamber around the disk and leaves the port of chamber after the rotation. The movement or rotation of the disk is controlled by a cam in one side with bottom face in contact with measuring chamber and upper side is in contact with other chamber. In this way, the chamber is sealed in one side while the other is open. In a normal operation, the chamber fills, rotates and releases while the other chamber is filling successfully. The movements of the chambers is measured using the pulses. Each of the rotation movement is attached to a fixed volume which is measured based on the number of pulses or rotational movement. Although positive displacement meters come in several varieties, all positive displacement meters have the following in common:

- **Measuring element:** The most important part of a positive displacement meter design is the measuring element. The measuring element consists of a measuring chamber and displacement mechanism. The function of the measuring element is to precisely separate a flowing fluid into discrete volumes. In order to do that, vendors use precision manufacturing techniques to ensure that metal-to-metal seals are maintained and any distortions are minimized.
- **Meter housing:** The housing of the meter is designed to absorb system-piping stresses so that critical clearances are maintained in the measuring element. The housing also maintains a pressure balance between inlet and outlet flow so that pressure distortions do not affect measurement accuracy.
- **Counter drive train:** The counter drive train transfers the displacement motion occurring within the measuring chamber into a meter's output signal. The counter drive train is typically a mechanical gear arrangement that correspond mechanical revolutions to volumes of fluid.

5.10.1 Performance

Performance of the positive displacement meter is described in terms of:

- **Accuracy** for a positive displacement meter in terms of percentage registration is based upon the calculation or percentage variation of the flow meter factor.

$$\% \text{ registration} = \text{actual quantity}/\text{metered quantity} \times 100$$

At high flow rates, the increase in pressure drop (differential pressure) increases the flow slippage rate, reducing the meter's accuracy. At low flow rates, the meter has low energy because of the lower pressure drop, so the flow is undercounted, again reducing the accuracy. Accuracy of the meter is in the range of ± 0.1 to ± 2% of the actual flow.

- **Rangeability** of PD meters typically is 5:1, although 10:1 and greater flow ranges are possible. Maximum-rated capacities often apply to intermittent flow rates. Maximum capacities are sometimes derated if continuous flow is anticipated. The minimum and maximum range of flow meter depends on flow meter design and viscosity of the products.
- **Repeatability** is the ability to repeat the accuracy of measurement, specifications are typically ± 0.05% or better.
- **Pressure drop** represents the energy loss in driving the flow meter and its accessories. The pressure drop across the internal of flow meter creates an unbalanced pressure, which causes the rotation of the rotor.
- **Output signals** are obtained from the gear driven train. Output signals are available either in mechanical or electrical form as digital pulses or analog sinusoidal signals. Signal compatibility with other meter accessories should be verified. Following are some advantage and disadvantages of using positive displacement meters.

5.10.2 Advantages

- Ideal for viscous liquids
- Upstream piping requirements are minimal
- Some versions do not require electrical power
- High rangeability in liquid and gas meter without loss of accuracy
- Operating principle is simple to understand

5.10.3 Disadvantages

- Not ideal for liquids with suspended particles. Requires filtration or strainer to minimize the damage to the meter.
- Mechanical wear susceptibility reduces accuracy and repeatability.
- Larger meters require extra installation care.
- Some meters can be damaged by over speeding.
- PD meters have a substantial pressure head loss that is unrecoverable. They also have a limited product throughput for a given meter size.

5.10.4 Applications

Positive-displacement meters are used primarily in applications where the goal is to measure volume and not a flow rate. Although fluid viscosity must be accounted for when selecting a positive-displacement meter, viscosity differences do not have a significant effect on measurement accuracy. Positive displacement meters are often considered ideal for viscous liquids. Positive displacement meters have limited use when the application is one where the liquid contains solid particles. Positive displacement meters are often used in combination with other devices, such as pumps and control valves. Because the positive-displacement meter must interact with other devices, it must not be viewed as a standalone device. For example, a control valve would have to provide proper flow rate and back pressure for the positive displacement meter to work properly. Interaction with other equipment is described in more detail in the vendor's supporting documentation. Applications include pipeline metering, oil field production, fuel oil metering including gasoline, asphalt plants, additive metering, and tank truck metering. Positive displacement meters are normally limited to higher viscosity fluids.

5.11 SIGHT-FLOW INDICATORS

LO 9

A sight-flow indicator is a mechanically driven device. Sight-flow indicators are used for visual inspection of the process. Three types of sight flow indicators are available: paddle, flapper and drip.

5.11.1 Paddle

The paddle type sight-flow indicator design has a propeller inside its body. The paddle-type indicator is only used for high flow rate applications because the propeller will not turn into a low flow rate. A pressure drop in the paddle-type indicator is higher than the pressure in a drip or flapper type indicator. Paddle-type sight-flow indicators can be installed for flow directions that are horizontal or vertical upward. The paddle type design is used when dark process fluids are present.

5.11.2 Flapper

The flapper-type sight-flow indicator design has a flapper hinged in the body's center. Bidirectional flappers are also available. The flapper-type sight-flow indicators are used for transparent or opaque solutions and gas services. Flow direction can be horizontal or vertically upward.

5.11.3 Drip

The drip-type design is used when there is a dripping of fluid in a vertically downward direction. The drip-type design is used for vertically downward flows that are intermittent. Sight-flow indicators can be installed in an either horizontal or vertical flow direction. Assembly of a sight-flow indicator consists of a chamber, glass, gasket, end covers, and bolts. Sight-flow indicators are available in sizes ranging from 1/4 in to 6 in. Note, however, that it is very difficult to estimate the amount of flow rate from a sight-flow indicator.

5.12 TOTALIZATION

LO 9

The process of totalization means to totalize or to determine the total amount of fluid flow passing through a flow meter. Devices used for totalizing flow or indicating the total flow are mechanical or microprocessor-based units that track process material usage of chemicals and final products, and provide data for billing purposes. In an electronic device, the volumetric flow is transmitted as electrical pulses that are proportional to the flow rate. The electrical pulses are converted to a digital readout of total flow. A totalizer is often built into flow controllers and recorders. It is very difficult to determine the accuracy of the flow totalizer, because accuracy of the totalizer depends upon the accuracy of the flow meter. Generally, accuracy is expressed as a percentage. Accuracy is higher at high flow rates than at low flow rates. Microprocessor-based equipment, often used in a flow computer, has the capability of addition, averaging, division, integration, lead/lag signal, signal limiting, square root extraction, subtraction, and more.

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Checkpoint

✦✦ 1. Explain the principle of operation of positive-displacement flow meter?

✦✦ 2. What is the major application of PD meters?

✦✦✦ 3. Explain how the positive displacement meters are used for measuring volume?

5.13 FLOW MEASUREMENT DEVICE SELECTION CRITERIA

LO 10

Summarize the flow-measurement device selection criteria

Flow meter selection can be a very complex task, given the wide range of technologies and application requirements that must be accommodated. Several approaches to flow meter selection begin by a process of elimination—the number of flow meters is narrowed to a few acceptable choices. That does not mean that the "acceptable" choices are necessarily the "perfect" choice.

The meters that have been selected as suitable for the application often represent a tradeoff between meter service, process conditions, and a company's policy on instrumentation. A flow meter selection process takes into account the following:

- Application fundamentals
- Specifications
- Safety considerations
- Metallurgy
- Installation considerations
- Maintenance and calibration
- Compatibility with existing process instrumentation
- Custody transfer concerns

- Economic considerations
- Technical direction

5.13.1 Application Fundamentals

All flow meter selection begins with a rather simple, though understated, premise—what is the instrument expected to do? From that simple question, however, one can use approaches to flow meter selection that, to a large degree, require an understanding of the intended application. Two common approaches embed application fundamentals in their selection approach. The approaches use one of the following:

- Flowchart
- Checklist of selection criteria

5.13.1.1 Flowchart

A structured flowchart approach is shown in Figure 5.42. The selection process begins with determining the process fluid characteristics through comparing costs and performance.

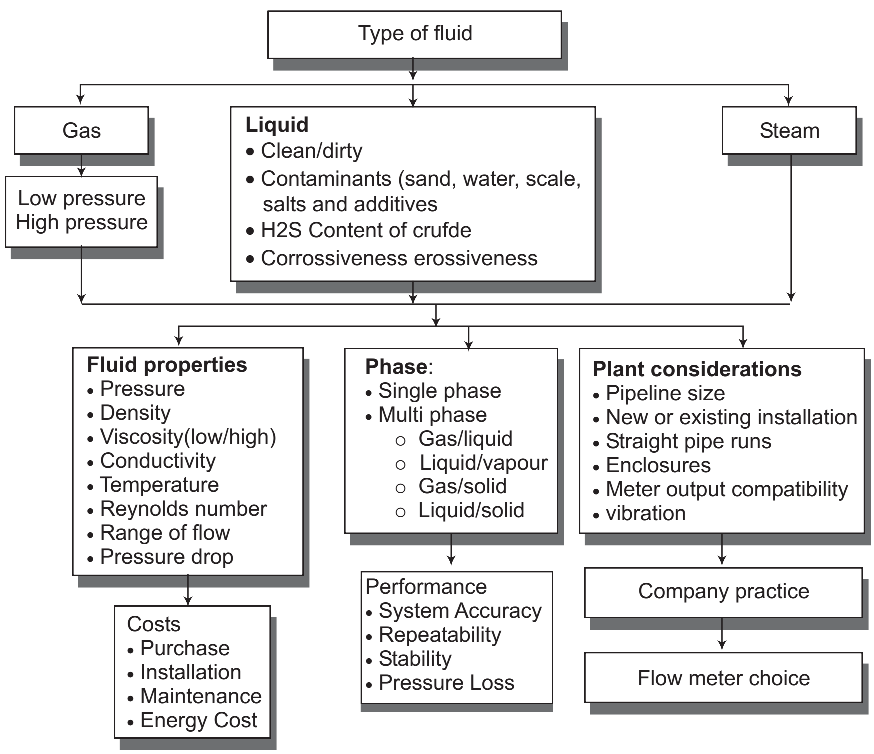

Figure 5.42 Flowchart approach to meter selection

5.13.1.2 Checklist of Selection Criteria

Vendors also provide flow meter checklists that assist an engineer in the selection process. A checklist, like the sample list that follows, may include the following items:

- Flow stream conditions:
    - Volume
    - Temperature
    - Pressure
    - Density
    - Viscosity
    - Flow velocity
- Flow measurement goals
- Accuracy requirements
- Range requirements
- Acceptable pressure drops
- Display and system requirements
- Potential problems (vibration)
- Flow stream erosive/corrosive materials, entrained gases and solids (if any)
- Available installation space and pipe geometry
- Economic factors (cost of ownership)

5.13.2 Specifications

Specifications for individual flow meter selections are listed in Tables 5.6 and 5.7. The specifications include:

- Type of service
- Accuracy
- Rangeability
- Pipe size
- Reynolds number limits
- Temperature
- Pressure
- Cost

Table 5.6: Flow meter applications											
Meter Type	*Service*										
Differential Pressure	Clean liquids	Dirty liquids	Corrosive liquids	Viscous liquids	Abrasive slurries	Low velocity flows	Vapor or gas	Dirty gas or vapor	High temperature service	Cryogenic service	Non-Newtonian
Orifice	D	C	A	A	C	D	D	C	D	D	C
Venturi	D	A	C	C	C	C	D	NA	C	C	C
Flow nozzle	D	C	C	C	C	C	D	NA	C	C	C
Pitot tubes	D	C	A	C	NA	C	D	NA	C	C	NA
Magnetic	D	D	D	A	D	A	NA	NA	C	C	NA
Mass Coriolis	D	D	A	D	D	A	C	NA	C	C	D
Thermal	D	C	C	C	C	A	D	NA	C	NA	C
Oscillatory Vortex Shedding	D	A	A	C	NA	NA	D	NA	C	C	NA
Positive-displacement	D	NA	C	D	NA	D	D	NA	C	C	NA
Target	D	A	A	A	C	C	D	NA	C	C	C
Turbine	D	C	C	C	NA	C	D	NA	C	C	NA
Ultrasonic Transit –T	D	C	C	C	NA	C	C	C	NA	C	NA
Doppler	NA	D	C	C	A	C	NA	NA	NA	NA	C
Variable area	D	C	A	A	NA	C	D	NA	A	NA	NA

D: Designed for service; A: Normally applicable for this service; C: Conditional usage, NA: Not applicable

Table 5.7: Flow meter applications

Flow Meter	*Accuracy*	*Range-ability*	*Pipe Sizes*	*Reynolds Number Limits*	*Temperature (F)*	*Pressure (psig)*
Orifice Square Edge	±2% FS	3:1	> 2.0	R > 2000	Process: 1000°F Transmitter: –20 to 250°F	Pipe Rating to 6000
Quadrant Edge	±2% FS	3:1	> 2.0	300 < R > 3300		
Segmental	±2% FS	3:1	> 4	R > 10000		
Integral	±2–5% FS	3:1	<= 0.5	R > 100		
Target	±2–5% FS	3:1	0.5–4	R >100		
Venturi	±1–2% FS	3:1	> 2	R > 75000		
Flow nozzle	±1–2% FS	3:1	> 2	R > 10000		
Pitot	±5% FS	3:1	> 3	No limit		
Positive-displacement	Liq ±0.25% (rate) Gas ±1% FS	10:1	Liq 2 to 16 Gas 1 to 16	Cs < 8000	Liquid 600; Gas 250	< 1440
Turbine Inline Insertion	Liq ±0.25–1.0% Gas ±0.5% (rate) ±0.5–1.0% FS	10:1	0.25 –24 0.25 –24	2 to 15 Cs	–300–500; –50–500	< 3000 < 1440
Ultrasonic Transit Time Doppler	±1% rate–5% FS ±5% FS	> 10:1 10:1	> 0.5 > 0.25	No limit No limit	300–500;	Pipe rating
Magnetic	±1% FS	10:1	0.1 to 12	No limit	Up to 300	Pipe rating
Mass Flow Coriolis Thermal	±0.5% (rate) ±1% FS	> 10:1 > 10:1	1/16 to 6 > 1	No limit No limit	–400–400 –50–350	Pipe rating
Variable area	±0.5% (rate) to ±10% FS	5:1–12:1	< 6	To highly viscous fluids	Glass < 400; Metal < 1000	Glass:350 Metal:720
Vortex Shedding	±0.75–1.5% rate	8:1 to 5:1	0.5–16	R = 10000	-300–400	Pipe rating

5.13.3 Safety Considerations

Safety considerations that influence flow meter selection are described in terms of:

- **Providing protection to the flow meter**: Flow meters can be protected with:
  - **Strainers** are used to protect meters from debris in a liquid stream. Strainers are not intended for filtering a liquid. Strainers should be carefully selected to ensure that they have a low-pressure drop when used with high velocity flow meters.
  - **Deaerators** are air elimination devices that protect the meter from receiving a large slug of air. The air elimination device separates that air from the liquid with special baffles. In the case of some positive displacement meters, a large slug of air can completely damage the meter. In the case of a turbine meter, air may not cause damage, but will cause errors in readings (registrations).
  - **Isolation valves** are typically provided at a meter inlet to permit meter reparability without shutting down the process.
  - **Block and bleed valves** are used in meter runs to provide a means for calibration. These valves divert the flow to the meter prover loop.
  - **Control valves** provide a means of controlling flow rate and/or backpressure. For example, flow rate control is necessary to prevent a positive displacement meter from over speeding.
- **Hazardous area requirements**
  - When a flow meter is installed in a hazardous location or used to measure an explosive fluid, various safety standards specify the necessary precautions. Vendors provide designs that are approved by third party agencies such as UL (Underwriters Laboratories), FM (Factory Mutual), and CSA (Canadian Standards Association). The hazardous atmospheres are defined in the National Electric Code (NEC) Articles 500 through 503. The NEC articles indicate the types of required protection and precautions.
- **Personal protection:** Personnel protection is provided through:
  - **Good design practices** include proper selection of materials of construction, which if not properly selected, can present hazards in applications where the metal reacts with the process media. An additional safety concern is the avoidance of toxic leakage, which increases as the number of manifolds, taps, and other meter components increases. Practices may also include designing in an extra margin of safety. For example, a vortex meter with a flanged body is safer than a vortex meter with a wafer body, especially if hazardous fluids are measured.
  - **Proper installation practices** are defined in the vendor's documentation and should be closely followed. Several common scenarios illustrate the need for safe practices. For example, flow meters have their pressure ratings stamped on the outside of the meter. Likewise, flange ratings also are stamped with their pressure ratings. Users must not mistake the flange rating which can be significantly different from the meter, for the meter body rating. Otherwise, meter damage and possible harm to personnel will result. Another example of safe installation

practices involves grounding. In the case of the magnetic flow meter (magmeter), proper grounding is necessary to avoid shocking personnel.

- **Proper maintenance procedures** include wearing protective clothing, opening valves slowly and carefully, de-energizing electric circuits to prevent shocks, using proper tools, and following vendor guidelines for their equipment. In summary, safety begins with good design and installation practices.

5.13.4 Metallurgy

Metallurgy considerations involve selecting meter materials of construction that provide chemical resistance, avoid reaction with process media, provide corrosion/erosion resistance, and meet special requirements for hydrogen sulfides.

5.13.4.1 Provide Chemical Resistance

Chemical resistance charts are available that describe how well a material resists chemical attack. Charts generally use a format similar to the one shown in Table 5.8. Additionally, vendors provide charts that summarize metal resistance to environmental conditions.

Table 5.8: Chemical resistance chart

	Carbon Steel	*304 Stainless Steel*	*316 Stainless Steel*	*Hastelloy*
Benzene	+	×	×	+
Carbon dioxide (Dry)	×	×	×	×
Carbon dioxide (Wet)	–	×	×	×
Water distilled	0	×	×	

×: Very good service; +: Moderate service; –: Limited service; : (Blank) No Data available

5.13.4.2 Avoid Reaction with Process Media

The meter's materials of construction must not react with the process media. Fluids such as oxygen can present explosive hazards if they chemically react with certain materials. Steels, for example, can present hazards if they are not clean and polished when used in oxygen-enriched, high-pressure, and high flow rate applications.

5.13.4.3 Provide Corrosion/Erosion Resistance

The meter's material of construction must also resist corrosion and erosion. Corrosive and erosive factors prevalent in applications include sulfur compounds, hydrocarbons, chlorides, dust, etc. Chemicals tend to have corrosive effects, while particulates have erosive effects. High temperature sulfur corrosion is very common in oil processing environments. Carpenter 20, an alloy of nickel and chromium, and Hastelloy B2 provide excellent corrosion protection from sulfuric acids.

5.13.4.4 Special Requirements for Hydrogen Sulfides

When wet, sour fluids are to be metered, proper standards shall be used as a reference for determining the type of materials to be used for the wetted flow meter elements. Careful attention must be given to the selection of orifice metering components to ensure that they are compatible with process fluids. Standards cover the metallic requirements for resistance to sulfide stress cracking. Sulfide stress cracking refers to the fracturing of metal in response to pressure and a corrosive fluid. If sulfides, such as H_2S, are present in a fluid, then carbon and low alloy steels are susceptible to sulfide stress cracking. For example, if crude oil is too sour (over 3% H_2S), then a typical industry approach is to provide a meter, such as positive displacement meter, with special iron trim, bearings, seals, and gear shaft.

5.13.5 Installation Considerations

Installation considerations are described in terms of upstream and downstream piping requirements, meter orientation, pipe supports, and piping and flow conditioners.

5.13.5.1 Upstream and Downstream Piping Requirements

Upstream piping length requirements are often specified by meter type. The upstream pipe must also be straight. Less obvious are the downstream piping requirements. Downstream piping may encounter control valves or obstructions that can create effects opposite to the flow direction.

- The effects can be large enough to back up to the meter, enter the meter, and alter the measurement. Piping requirements that have an influence on flow measurement also include:
- **Correct use of gaskets:** Gaskets should not protrude into or be recessed from the flow streams. If gaskets are not flush with the piping, they can create a flow disturbance.
- **Centering the pipe with the meter:** Vendors often provide centering devices to ensure that the meter body is centered in the piping.

5.13.5.2 Meter Orientation

The meter's orientation is important so that the flow meter can make an accurate measurement. For example, the electrodes of magnetic flow meters should be in the horizontal plane. If a flow is likely to have a large amount of air, the magmeter can be installed vertically. The vertical installation helps ensure that the pipes and meter are kept full of liquid. The vertical installation also helps keep the electrode from fouling. Note that some meters, such as variable area type meters, must be installed in vertical runs of pipe. Need to think in terms of whether the fluid is homogeneous; i.e. single or two-phase flow and whether the pipeline is full. If the pipe is partially full, the conditions under which the primary element was originally considered are not met and the results will be spurious.

5.13.5.3 Pipe Supports

Flow meters are not intended to be piping supports. Although smaller meters may be able to handle pipe stresses, larger meters do not handle stresses well. Large meters are often mounted upon concrete slabs at ground level. Larger meters, such as Coriolis, magmeter, turbine, positive-displacement, may require supports and anchors to limit piping stresses.

5.13.5.4 Piping and Flow Conditioners

Upstream piping should provide enough fluid mixing so that the flow profile at the meter is close to the flow profile used to calibrate the meter. Some flowing fluids experience jets and swirls that affect the flow profile. The two approaches to get the right profile are to use either longer length of pipe or flow conditioners. Flow conditioners reshape a swirling profile. Flow conditioners are available that can handle a full range of flow profiles.

Note

An engineer should be aware that flow conditioners contribute to a pressure (head) loss.

5.13.6 Maintenance and Calibration

Maintenance considerations that influence flow meter selection are described in terms of:

- Typical maintenance concerns by flow meter type
- Meter failure concerns

5.13.6.1 Typical Maintenance Concerns

Typical maintenance concerns by flow meter type are listed in Table 5.9.

Table 5.9: Maintenance concerns

Flow Meter	*Flow Element*	*Maintenance Concerns*
Differential pressure	Orifice plate Pitot Venturi	Simple, no moving parts Susceptible to wear in dirty services except vertically Orifice edge sharpness affects accuracy
Turbine	Rotor	Moving parts can wear
Vortex	Bluff body	No moving parts; bluff body can corrode
Positive-displacement	Oval gear Sliding vane Nutating disk	Many moving parts subject to wear Prefilter for dirty service
Magnetic field (magmeter)	ac field dc field	Low-maintenance element, although electrode may foul.
Ultrasonic		Very low maintenance, nonintrusive
Mass	Coriolis thermal mass	Very low maintenance, nonintrusive (Coriolis). No moving parts, corrosive fluid may affect element (thermal mass).

5.13.6.2 *Meter Failure Concerns*

Flow meters will, at some time in their life cycle, need repair. With that in mind, the engineer should review the following failure concerns:

- Reparability of flow meter
- Spare parts availability
- Whether the failure would be catastrophic or not
- What consequences will result if the meter fails

5.13.7 Compatibility with Existing Process Instrumentation

Compatibility with existing process instrumentation is described in terms of relationship to metering system, general transmission practices, and signal levels to receiving devices.

5.13.7.1 *Relationship to Metering System*

Flow meter selection is just one aspect in designing a liquid metering system. It should be noted that it is common to use meters in parallel. For greater accuracy, the same orifice primary can be connected to two differential pressure transmitters. A typical dual-range system can have transmitters sized to a 10:1 pressure ratio that, when square-rooted, works out to a 3:1 flow ratio. Whether the meter is in parallel or not, the engineer reviews the following list of design criteria. Along with selecting the correct meter and meter size, the engineer considers the following:

- The minimum and maximum flow rates
- What system pressure drops occur
- The minimum backpressure for the meter run
- The length of meter run
- What isolation, block, or bleed valves are needed
- What flow control and back pressure valves are necessary
- Temperature and pressure indicators
- Readout devices.

The intent of the previous discussion is to illustrate that metering system design is more than just selecting the correct flow meter. While metering system design is beyond the scope of this topic, the selection and installation of the above devices has a major influence on the flow meter's accuracy. It can become a very complex process to design a liquid metering system, because the design involves more than just selecting the correct flow meter.

5.13.7.2 *General Transmission Practices*

Receiving instruments (e.g. transmitters, transducers, switches, etc.) should be located to provide convenient access for their operation, maintenance, and removal. Hydrocarbons or other process fluids should not be piped to any instruments located in a control room. Standard industry practice is to convert the flow measurement to an electrical or pneumatic signal and transmit the signal to remote receiving instruments.

5.13.7.3 Signal Levels to Receiving Devices

Control systems and/or computers that interface to flow measurement systems/meters must interface with four common types of input and output signals:

- **Analog input/output signals:** Input signals are traditionally the 4–20 mA dc signal representation of a process variable. Analog inputs provide the portion of data that represents the temperature, pressure, and flow rate data. Analog output signals provide the variable signals for recorders, display, or control functions.
- **Computer communication protocols:** Flow measurement computers use common protocols such as RS232C and RS422. The measurement system's speed and compatibility with an existing system's protocol are common selection considerations.
- **Contact closures:** Discrete digital inputs can come from valves, pressure switches, or push buttons. Digital outputs from the computer system can control devices, transmit totalization data, and initiate alarm annunciators. The most common interface voltage is 24 V dc.
- **Frequency signals:** Flow meters can generate pulses that represent an amount of product. The receiving device counts the number of pulses generated during the flow's duration. The main concern here is that the receiving device and flow meter are compatible in the minimum and maximum frequencies. The receiving device is also evaluated for the capability to sense a pulsed waveform's positive and negative thresholds.

5.13.8 Custody Transfer Concerns

Custody transfer concerns are described in terms of reasons for metering hydrocarbons, classifications of custody transfer measurements, metering approaches, and meter provers required.

5.13.8.1 Reasons for Metering Hydrocarbons

In typical oil processing plants, liquid hydrocarbons are metered at each custody transfer point and often at points where custody does not change. Several reasons for the metering are:

- Corporate accounting requires data
- Billing is dependent upon accurate measurements
- Losses are detectable
- Business decisions are based on the measurement data
- Assist negotiations, if necessary
- Provide auditable, historical records

5.13.8.2 Classification of Custody Transfer Measurements

For a custody transfer measurement of a liquid hydrocarbon, a contract requires a volumetric measurement at standard conditions of temperature and pressure. The techniques to do this are broadly categorized as "static" and "dynamic." Static measurements are accomplished through automatic tank gauging. Another example of a static measurement is the measurement of a marine cargo tank. Approximately 30% of custody transfer occurs this way in processing industries. Dynamic measurements are accomplished through liquid metering methods.

5.13.8.3 Metering Approaches

Two types of meters are traditionally used in most industries for custody transfer of liquid hydrocarbons—the turbine meter and positive-displacement meter. Several custody transfer concerns can be mentioned in terms of the following:

- **Turbine meter custody transfer considerations**: These are best seen by reviewing how a turbine calculates flowrate. A turbine meter measures flowrate based on the calculation:

$$Q = V \times A \tag{5.30}$$

  where, Q = volumetric flowrate, V = measured flow velocity, A = constant flow area. Thus, anything that affects A or V has a direct bearing on Q, the volumetric flow rate. The custody transfer concerns are summarized as:
  - **Over-registering:** The meter over registers when the constant flow area is reduced. The reduction in flow area causes the flow velocity to increase. Either the flow area is reduced through coating buildups or debris caught on the final conditioning element. A coating buildup of 0.001 inch on a 4-inch turbine meter internal parts can have a 0.5% effect on its registration. Coating effects are proportional to the square of the meter size. Thus, a 0.001-inch coating causes a 2% shift on a 2-inch meter. Turbine meters are used to measure high paraffin content products have a tendency to buildup coatings.
  - **Under-registering:** The meter under-registers if the flow area, A, increases. The increased flow area decreases the flow velocity. Under registering occurs when swirling occurs near the leading edge of a turbine rotor. Flow conditioners installed according to API standards prevents this occurrence.
- **Positive-displacement meter custody transfer considerations:** Unlike turbine meters, positive displacement meters transfer fixed volumes of liquids. The flowing stream is sent into measuring chambers; the meter totalizes the fixed volumes transferred through the measuring chambers. A typical approach is to use displacement meters for custody transfer operations. Several reasons for this are the following:
  - Historically, the positive displacement meter has been successful
  - Electrical power not required
  - Smaller than turbine meters (less space required)
  - Can be temperature compensated
  - Crude oil provides good lubrication to the PD meter

A positive displacement meter's custody transfer performance is a function of slippage and wear. Slippage represents the amount of product that passes the seal in the measuring chamber of a positive-displacement meter. Slippage is dependent on the clearances in the measuring chamber remaining constant. However, if the viscosity or flow rate changes, the amount of slippage changes.

5.13.8.4 *Meter Provers Required*

Any flow meter's indication of a volume represents an unknown volume unless the volume can be compared to a known volume. The known volumes are called "meter provers". For a meter to be considered accurate, the meter must be proved at the same conditions of flowrate, temperature, pressure, and product viscosity.

5.13.9 Economic Considerations

Economic considerations are described in terms of cost of ownership and pumping costs.

5.13.9.1 *Cost of Ownership*

Cost of ownership can easily exceed the initial purchase price of the meter. Cost of ownership includes the following factors:

- **Meter cost:** The initial purchase price of a meter is the most obvious cost. Generally, meter costs increase as greater accuracy is required. Cost should include primary and secondary devices and auxiliary equipment.
- **Accuracy:** The cost of accuracy (or inaccuracy) is best seen in custody transfer operations, where the cost of unaccounted for products can be quantified.
- **Repeatability:** If a device became inaccurate because of wear or process damage, its repeatability may still be acceptable for continued process use.
- **Installation:** Cost including labor and materials.
- Mean time between failure (MTBF)
- **Number of mechanical parts:** As the number of moving and exposed parts increases, so does the probability of repair.
- Process downtimes caused by failure or scheduled maintenance and calibration.
- **Cost to repair:** Some flow meters may require specialized personnel skills or equipment.
- **Implementation costs:** If the device can interface and share date with other instrumentation, the costs are obviously lower.
- **Disposal costs:** A device exposed to toxic chemicals may contain hazardous chemicals.

5.13.9.2 *Pumping Costs*

Pumping costs account for the energy costs in overcoming the pressure losses through a flow meter. Calculations are available for determining the operating cost of a flow meter. For a simple orifice plate, these costs can reach thousands of rupees per year.

5.13.10 Technical Direction

Technical directions in flow instrumentation improvements are occurring in the following areas: improvement in overall design, increasing integration of microprocessor technology, improvements in vortex and mass based meter designs, introduction of multivariable transmitters, and evolution of fieldbus standard.

5.13.10.1 Improvement in Overall Design

Flow meter manufacturers have improved the meter's design in order to facilitate flow meter cleaning and disposal. Product redesigns eliminate or minimize the number of crevices or openings where process fluids accumulate.

5.13.10.2 Increasing Integration of Microprocessor Technology

Increasing integration of microprocessor technology has led to flow meters that have increased performance functionality and communication capabilities. The improvements in performance are seen in better accuracies and improved effect specifications. A temperature effect specification, for example, is improved in mass flow meters because of ambient measurements that compensate for the thermal expansion coefficients in the flow meter's materials of construction. Increased functionality includes the flow meter's ability to access additional process variables. The additional process variables can include process density, process temperature, and gravimetric flow rates. Use of microprocessor-based differential pressure transmitters in flow applications can significantly improve performance without the need to replace the orifice plates (or other primary element). In pre-existing applications that have a conventional transmitter, there is usually no need to shut down the process or make new process tap connections.

The microprocessor-based instruments can be expected to develop into a spectrum of performance levels. On the low end of the spectrum, flow meters with remote communication capabilities would be used in hard to reach locations. On the high end of the spectrum, flow meters that offer higher accuracies and functionality will find use in applications such as custody transfer. As microprocessor-based flow meters evolve, and the meter is related performance improvements become commonplace, product differentiators will be the meter's added software capabilities. The capabilities are hard to predict, but could include data collection, predictive maintenance, embedded control, or other software functions.

5.13.10.3 Improvements in Vortex and Mass-based Meter Designs

Although the orifice plate and differential pressure transmitter are the most commonly applied flow meter, advances in flow meter designs have created new interest in other flow meters, such as vortex and mass based flow meters. Vortex meters have been successfully used in sulfur and crude oil operations that traditionally are measured with orifice plates. Vortex meters prices have been decreasing and are slightly higher than an orifice plate. The reliability for a vortex meter is better than that of an orifice plate, which wears because of corrosive/erosive flows. Vortex meters also offer higher turndown ratios. Mass-based flow meters are finding use in applications that require higher accuracies, measurements in terms of mass instead of volume, or nonintrusive measurements. A Coriolis flow meter, for example, can measure low flow rates. The rangeability for a Coriolis flow meter is greater than that of an orifice plates.

5.13.10.4 Introduction of Multivariable Transmitters

In measuring flow, temperature is required to compensate for changes in density. Correct placement of a temperature probe (process temperature not body temperature) is required whether measuring with a multivariable technique or the old-fashioned way. A multivariable transmitter is essentially four transmitters in one package. A multivariable transmitter (Figure 5.43) measures differential pressure, absolute pressure, and process temperature. The multivariable transmitter also calculates the compensated flow. Traditionally, three separate transmitters and flow calculation were required for this measurement. The multivariable transmitter incorporates microprocessor-based technology, which provides the advantages of better readability and tighter integration. Additionally, the multivariable transmitter reduces installation costs, spares inventories, and commissioning times. The transmitter has the flexibility to be used in applications such as custody transfer, energy and material balances, and advanced control and optimization.

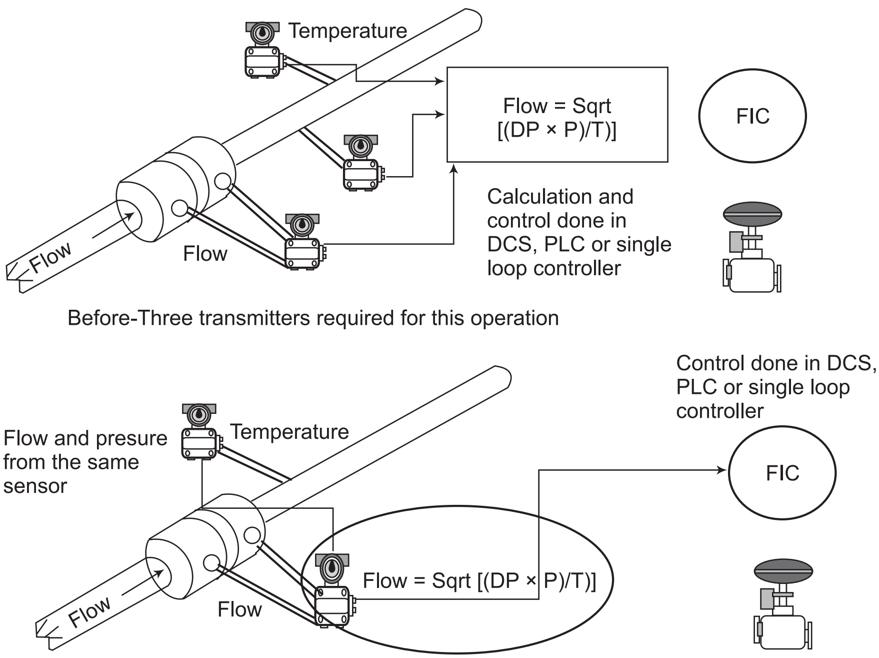

Figure 5.43: Multivariable transmitter

5.13.10.5 Evolution of Fieldbus Standard

Improved communications are accomplished with proprietary digital communications protocols and/or a standardized fieldbus. The improved communications provide tighter control, better reporting, and data collection. The development of a fieldbus standard has the potential for the following:

- Reduced wiring costs
- Interoperability among field devices
- Field devices that send messages to the control system or other field devices
- Reduced need for controller I/O hardware

- Reduction of maintenance costs
- More precise control
- Migration of control to field devices
- Reduced need for conventional “non-smart” flow meters.

Checkpoint

✦✦ 1. Explain how meter body ratings and pipe flanges needs to be matched?

✦ 2. What are the characteristics of material of construction of meters?

✦✦✦ 3. What happen to instruments if sulfides are present in the flowing fluid?

✦✦ 4. What are the approaches to get the proper flow profile for measuring flow?

✦✦✦ 5. What are the major concerns of integration of flow meters with pulses and receiving devices?

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5.14 CALIBRATION PROCEDURES FOR FLOW METERS

LO 11

Illustrate the calibration procedures for flow meters

Calibration is typically performed in a laboratory setting at several different flow rates, and uses conditions such as changing densities, pressure, and temperatures. When calibration is performed, the meter’s inherent calibration factors are determined. Proving differs from calibration in that it is done in the field, typically under a single set of conditions. During the meter proving process, a meter correction factor is determined which is multiplied by the reading from the meter to offset its indication. The calibration can be defined as the comparison of a measuring instrument with specified tolerance but an undetermined accuracy, to a measurement standard with known accuracy. The use of noncalibrated instruments creates potentially incorrect measurement and erroneous conclusions and decisions. Calibration provides assurance and confidence in measurement that the instrument has an accuracy required to maintain product or process-specified ranges. Calibration can be a simple dimensional check to detect measurement variables. Before starting calibration, a decision must be made for the following:

- Which variables should be measured?
- What accuracy must be maintained?

The calibrated device must show sufficient range and be capable of transferring to the desired level of accuracy. Some element of error exists in all measurements no matter how carefully they are conducted. The magnitude of error can never be easily determined by experiments; the possible value of the error can be calculated.

This section introduces the following flow measurement topics: methods of calibrations, provers, and weight and volume methods.

5.14.1 Method of Calibrations

In general, the flow measurement devices are calibrated by three methods: wet calibration uses the actual fluid flow; dry calibration using flow simulation by means of an electronic or mechanical signal; and measurement check of physical dimensions and use of empirical tables relating flow rate to these dimensions.

5.14.1.1 Wet Calibration

Wet calibration uses actual fluid flow. Generally, it provides high accuracy for a flow meter and is used when accuracy is a prime concern. Precision flow meters are usually wet calibrated at the time of manufacture. Depending upon the size of the meters, calibration can be performed at the user site, manufacturer's facility, or laboratory. Wet calibration for flow meters is usually performed with water, air, or hydrocarbon fuels.

5.14.1.2 Dry Calibration

Dry calibration is performed on a flow meter without the presence of a fluid medium. In a wet calibration system, flowing fluid produces the input signal. In a dry calibration system, the input signal is input as a frequency, millivoltage, or differential pressure. Dry calibration measurement is much more uncertain than wet calibration and overall accuracy of the flow device is inferred because the flow transducer is bypassed. The input signal for a dry calibration must be provided by a measurement standard. The value of the output signal requires use of other measurement standards. Follow the manufacturer's guideline and procedures for dry calibration.

5.14.2 Provers

The proving operation verifies the meter's performance and assures the meter users that the metering system is operating properly. The necessity of meter proving depends on how accurate the measurement must be for the product being handled. Larger volume and higher value products are the most important reasons for using a meter prover. Oil industry measurement of crude oil and refined products is an example of where the proving system should be used. The proving system is considered part of the cost of the meter stations and is permanently installed at the facilities. When the product has a lesser value, portable proving systems are used. The following discussion describes reasons and methods of meter proving.

5.14.2.1 Reasons for Meter Proving

Meter proving is generally conducted in oil processing industries for one of these three reasons:

- **Custody transfer:** Proving ensures that product inventory accounting is of the highest accuracy. Two types of custody transfer, namely, legal custody which falls under weights and measures requirements, and contract custody which is a contractual agreement between buyer and seller are possible. Proving must be performed under actual operating conditions. A field reference device is used to prove the meter.
- **Quality audit (ISO 9000):** Proving ensures that the product quality is consistent. When a meter is used to control the addition of various fluid components to make

a final product, the meter performance must be repeatable to ensure that there is no degradation of the final product.

- **Environmental audit:** Proving ensures material balances during the manufacturing process and transfers to the pipelines are correct. The main intent is to verify that what went in and what came out was accounted for, so there is no loss of product during the process. It also ensures that there is no violation of environmental regulations. As a part of environmental regulations, it is important to show that the plan is working properly and accurately. Maintain proper records to show that meter verification is being conducted on a regularly scheduled basis. In general, proving in house is seldom done. Metering is assumed correct unless the process goes out of control or breaks down. The proving procedure can be very expensive and time consuming. The ability of these tests to prove a flow meter's accuracy varies from the very best calibration to a test that has nothing to do with flow accuracy. The ratio of the meter factor is true volume to the indicated or meter volume.

Meter Factor = True Volume/ Indicated or Meter Volume

5.14.2.2 Methods of Meter Proving

Pipe provers are one of the most common types of provers in industry today. Their popularity is due their accuracy over a wide variety of flow ranges and fluids. Pipe provers allow proving to occur under actual operating conditions. The process does not have to be shut down when proving a meter. Two types of pipe provers are the unidirectional prover and the bidirectional prover. Several methods are used for a proving application; typical approaches include using unidirectional provers, bidirectional provers, small volume provers, and master meter method.

Unidirectional Provers The unidirectional prover displaces a known volume by means of a displacer (piston or sphere) traveling in only one direction inside the prover. The displacer's travel is detected by detector switches within the prover. Unidirectional provers are often used in pipeline operations because they can operate at higher displacer velocities. Because the prover allows flow in only one direction, the prover can simulate normal pipeline operations. Figure 5.44 represents a typical unidirectional prover.

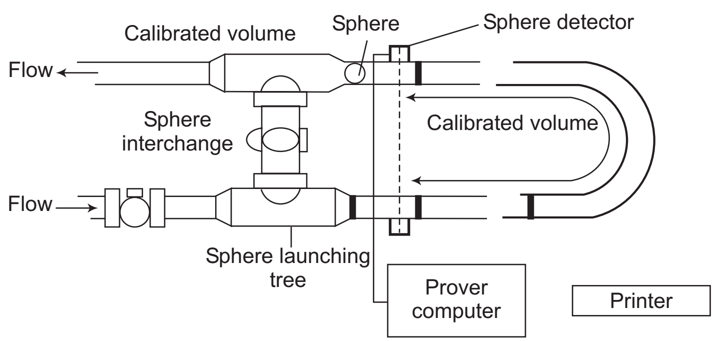

Figure 5.44: Typical unidirectional prover

Unidirectional provers always have the fluid flowing in the same direction through the prover. If the calibrated volume is used only in one direction, there is a potential for the sphere detector switches to develop an error. With bidirectional proving and half-trips in both directions, the detector switches have a chance at cancelling that error. Bidirectional provers are more accurate and more widely used. Usually provers are themselves calibrated by third parties.

Bidirectional Provers The bidirectional prover requires a displacer to travel in both directions to complete one prover run. Provers can be U-shaped, folded, or straight pipe depending upon the space requirements or space availability. Fluid is passed through an operating meter into the prover. After stabilizing pressure and temperature, the displacer is put into the system. It will slow down flow in the system for a time until the displacer picks up speed. A pre run distance is allowed for the fluid to stabilize before moving into the prover. Normally, a switch is used to indicate the entry of the displacer into the calibration section. The pulses are generated to measure the amount of fluid flowing through the same. Figure 5.45 represents a typical bidirectional prover.

In these provers, the fluid is allowed to enter the prover until sufficient amount of fluid is passed and sufficient number of pulses are generated by the meter under test. After some pre defined time and amount of fluid is passed, the exit switch will become on indicating calibrated volume and pulses achieved.

Pulses generated by the operating meter are sent to the billing meter's counter. This procedure is repeated several times while recording the stabilized fluid pressure and temperature. Calculations convert the pressure and temperature for the meter and the meter prover at the same condition. The ratio of the prover volume to meter volume is the meter factor for this flow rate.

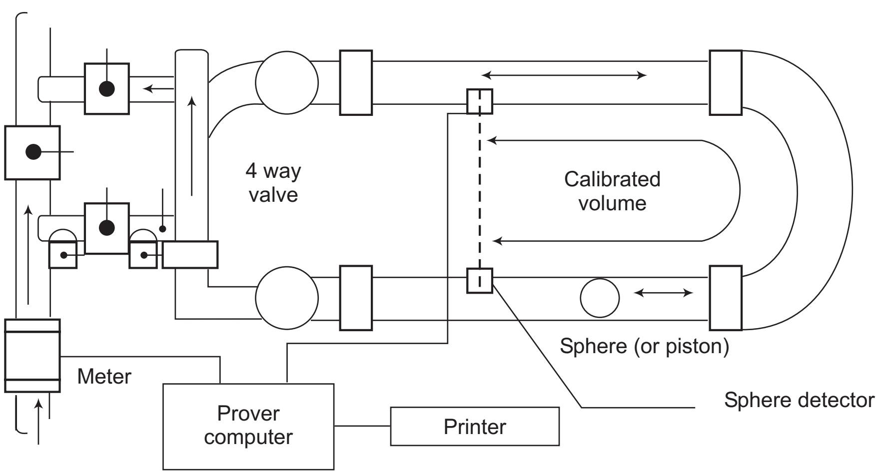

Figure 5.45: Typical bidirectional prover

Small Volume Provers Small volume provers are becoming more widely used over conventional pipe provers because they can accommodate a wide range of flow rates, products, and pressures. Small volume provers are so named because they are compact in size and have less volume than conventional unidirectional and bidirectional pipe provers have. The small volume provers use advanced detector switches and pulsed interpolation techniques to measure a known volume. Because of the smaller volumes required, the time to obtain a meter factor is significantly decreased.

Master Meter Method Master meter method is used when a pipe prover is unavailable. The master meter method uses a known reliable meter configured in series with the meter to be proved. The meter measurements are then compared.

5.14.3 Weight and Volume Methods

For weight and volume related applications, the following three methods of calibration are in common practice—static calibration, dynamic calibration, and hybrid dynamic start-stop, static reading system.

5.14.3.1 Static Calibration

In a static calibration method, the liquid is passed through the meter with a defined start, running and stop time. Once the flow is passed through, the totalized volume as seen from the meter is compared to the total weight or volume of the collected fluid. The compared values are adjusted as calibration is performed. The static calibration system operates best with flow meters that have low sensitivity to low flow rates. The static calibration system does not give maximum results with high performance digital output meters such as a vortex meter.

5.14.3.2 Dynamic Calibration

In a dynamic calibration system, the flow through the pipe is kept at a constant rate, with a note of reading at the beginning of the test and initial volume of the liquid. These two readings are taken at the beginning and at the end of the test and the results are compared between the meter and volume collected. The success of using the dynamic calibration methods depends on the response time of the meter for the flow rates.

5.14.3.3 Hybrid Dynamic Start-Stop, Static Reading System

The hybrid dynamic start and stop, static reading system is more accurate than the other two methods of liquid calibration. In this system, the desired flow rate is diverted from the line to a standard volume system. Once the test is completed, the flow is diverted back to its original path. The digital control signals are used to make the switch on and off the path of the flow. The weight or volume is read after a configured time and compared with the totalized flow meters reading. In this start and stop system, the diverter valve switches the flow in and out of the standard. The diversion time is less than actual collection time, and the flow pattern through the diverter valve is independent of the flow rate. The error can be reduced to less than 0.1 % of the reading. The hybrid dynamic start and stop system is accurate, but relatively few are used because of its cost.

5.14.3.4 Volumetric Tank Proving Example

Volumetric tank proving uses a start-stop method that simulates conditions of vessel loading. The volumetric tank prover is most often used to prove product-loading rack meters because a start-stop method is used in actual loading.

There are numerous sensor technologies for flow instrumentation. The type of the sensor used for an application is very specific to the type of the process fluid, process conditions of the fluid such as temperature, pressure and pressure drop, installation and maintenance aspects, etc., differential pressure flow meter, magnetic flow meter, vortex-shedding flow meter and turbine flow meter are mainly used flow meters. Each has its own principle to measure the flow. For example differential pressure flow meter is based on the principle that flow rate is proportional to the square root of the differential pressure across the restriction. An orifice plate or Venturi is installed in line with the process flow to restrict the liquid flow.

There are several methodologies for flow meter calibration. In certain scenarios, it is difficult to hold the process and remove the flow meter for calibration. Hence, field-mounted or inline master meters have been developed. The general methodology adopted is to calibrate only the electronics for signal processing using a test instrument to simulate the sensor. However, other methods (such as weighing the flow meter output collected over a specified time) can be used to check the accuracy of flow meter depending on the application and system configuration. It must be understood that no single method works for all flow meters and tests must be performed regularly in accordance with specific manufacturer's instructions.

5.14.4 Experimental Setup for Bench Calibration

5.14.4.1 Differential Pressure Transmitter Calibration

The application of differential pressure transmitter for measurement of flow has a square root relation with the pressure drop. It means as the flow increases, the drop increases and vice versa. This differential pressure is primarily produced by the restrictions placed in the pipe in the path of the fluid flow. The difference in pressure at the upstream and downstream of the obstruction becomes differential pressure.

5.14.4.2 Differential Pressure Transmitter Connections

In the calibration process, first the pressure calibrator needs to be connected to the transmitter as per the guidelines provided by the calibrator supplier. The supply pressure to the calibrator needs to be connected and should be in the range as guided by the manufacturer and also as per the needs of the transmitter range.

The high pressure port of the transmitter is to be connected to the calibrator and low pressure side of the port is vented to atmosphere. The atmospheric pressure at the low pressure port becomes the reference for the differential pressure measurement. In this setup, the transmitter needs to be connected electrically in a loop power connection as shown in the figure with an milliammeter in series to the loop. The description as mentioned above is illustrated in the Figure 5.46.

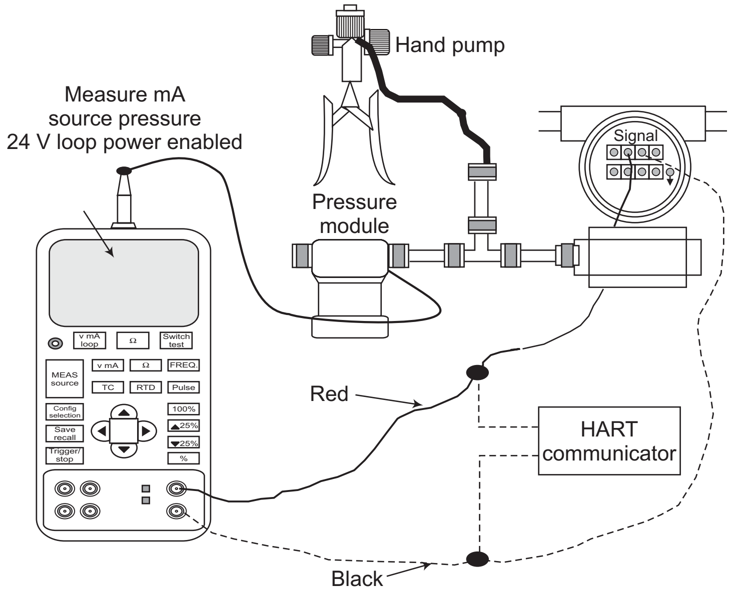

Figure 5.46: Experimental setup for flow transmitter calibration

5.14.4.3 Differential Pressure Transmitter Five-Point Check

Based on the needs, generally the five-point check calibrations are performed. In this method, an input of 10%, 30%, 50%, 70%, and 90% of span are used as input points. The measured value is recorded and adjustments and calibrations are performed. The first thing to observe is the hysteresis. Hysteresis is the instruments' output that becomes different for the same input. The hysteresis also depends on whether input is in increasing or decreasing mode. The check and calibrations are performed and recorded in a predefined data sheet.

5.14.4.4 Adjusting for Error Correction

While adjusting the errors, first the zero input is applied and corrected for the output. After the completion of the zero, the span is adjusted. Zero input can be treated as properly adjusted only if the output is 10% is produced for 10% input. The span will be adjusted after applying 90% of the input and expect a 90% of the output. The typical calibration procedure of a flow transmitter is represented in the form of a flow chart in the Figure 5.47.

5.14.4.5 Calibration Procedure

1. Connect the handheld communicator to verify the device parameters such as tag number, PV, LRV and URV.
2. Isolate the instrument and the process. If the process is hazardous, then the safety instructions from the manufacturing maintenance practices shall be followed.
3. Remove the pressure and drain the liquid in the impulse lines using the isolation valves and manifolds, etc.

4. Connect the pressure transmitter high side of the port to the pressure calibrator using the manifold.
5. The low side of the transmitter shall be left unconnected and exposed to the atmosphere.
6. Connect the milliammeter in series with the current loop for measuring the current output from the transmitter.
7. Generate and apply a pressure as per the instruments LRV (Normally 0 mm H_2O). Apply pressure as per data sheet LRV (normally 0 mm H_2O).
8. Check the output from the transmitter and verify that it should be 4 mA, if not a zero adjustment needs to be performed using the handheld communicator.
9. Generate and apply a pressure as per the instruments URV.
10. Check the output from the transmitter and verify that it should be 20 mA, if not, then a span adjustment needs to be performed using the hand held communicator.
11. Perform the same operation for different levels in the values such as 10%, 30%, 50%, 70%, 90%, 70%, 50%, 30% and 10% of range which are increasing and decreasing order.

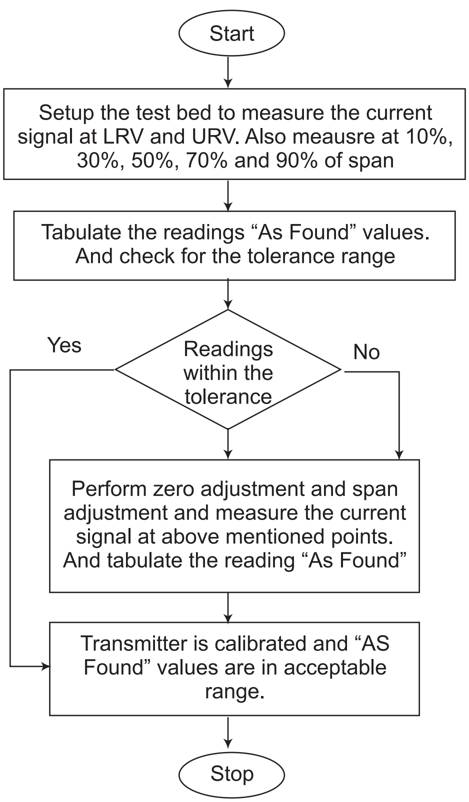

Figure 5.47 Flowchart for flow transmitter calibration

Checkpoint

✦✦ 1. Define the calibration of measuring instruments?

✦✦ 2. What is dry calibration?

✦ 3. What is wet calibration?

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Summary

LO 1: Describe the purpose of flow measurement, terminology, symbols, categories and units of measure

- In general oil-processing plants require material flows through successive operations, flow measurement is central to oil processing equipment design and operation.
- Flow meter is defined as a device that measures the rate of flow or quantity of a moving fluid in an open or closed conduit. It usually consists of a primary device and a secondary device. Flow is generally measured inferentially by measuring velocity through a known area.
- A primary device is defined as the device mounted internally or externally to the fluid conduit that produces a signal with a defined relationship to the fluid flow in accordance with known physical laws relating the interaction of the fluid to the presence of the primary device.
- A secondary device is defined as device that responds to the signal from the primary device and converts it to a display or to an output signal that can be translated relative to flow rate or quantity.
- Meter run or meter tube is defined as upstream and downstream length of pipe containing the orifice flanges and orifice plate or orifice plate with or without quick change fittings. No other pipe connections should be made within the normal meter tube dimensions except for pressure taps and thermowell. A meter tube is an important part of a flow meter installation. The meter run must create an acceptable flow pattern (velocity profile) for the fluid when it reaches the primary device ex. orifice plate. Distortions occurring in the flow pattern result in pressure drop errors.
- Flow rate can also be used to determine the distance a substance moves over a period of time.
- Volume flow rate represents the volume of fluid that passes a measurement point over a period of time.
- Mass flow rate represents the amount of mass that passes a specific point over a period of time.
- The compressibility factor represents the ratio of the actual volume of gas at a given temperature and pressure to the volume of a gas calculated by the ideal gas law.
- Totalization represents the process of counting the amount of fluid that has passed through a flow meter. The purpose of totalization is to have periodic (daily or monthly) readings of the material usage or production.

- Rate meters measure the process fluid's velocity. Velocity is expressed in terms of distance per time, such as m/s or ft/s. Because a pipe is cross sectional area is known, the velocity is then used to calculate the flow rate.
- A differential pressure flow meter infers the flow rate from the differential pressure across a restriction in a line. The flow rate in this case is inferred from the measured differential pressure and accepted correlations to rate. A velocity measurement, as in the case of a turbine meter, uses the velocity of the fluid times the area through which the fluid is flowing to determine the flow rate.
- Quantity meters continuously divide the flowing material into predetermined volume segments. Quantity meters count and keep track of the number of these volume segments. An example of a quantity meter is a positive displacement meter.
- In the extractive energy approach, flow meters take energy from the fluid flow. These flow meters, because they are intrusive, often introduce pressure losses into the fluid flow. An orifice plate is an example of an extractive type device
- In the additive energy approach, flow meters introduce some form of energy into the fluid flow. These flow meters, because they are nonintrusive, do not produce pressure losses in the fluid flow. The energy-electromagnetic, acoustic, or mechanical is required for the flow meter to operate. A magnetic flow meter is an example of an additive type device.
- Flow is considered laminar when the Reynolds number is below 2,000. Turbulent flow occurs when the Reynolds number is above 4,000.
- An example of an incompressible fluid is water. In theory, water does change density in its temperature excursion from ice (solid) to steam (vapor or gas), but ever so slightly.

LO 2: Explain the restriction flow meters with primary devices and differential pressure transmitters

- The oldest known method of metering flow is by using the orifice plate.
- An orifice plate is constructed as a thin, concentric, flat metal plate. The plate has an opening or "orifice." An orifice plate is installed perpendicular to the fluid flow between the two flanges of a pipe.
- As the fluid passes through the orifice, the restriction causes an increase in fluid velocity and a decrease in pressure. The potential energy (static pressure) is converted into kinetic energy (velocity). As the fluid leaves the orifice, fluid velocity decreases and pressure increases as kinetic energy is converted back into potential energy (static pressure). Orifice plates always experience some energy loss, i.e. a permanent pressure loss caused by the friction in the plate.
- The beta ratio is also called a diameter ratio. The beta ratio defined as the calculated orifice bore's diameter to the internal pipe's diameter.
- The section downstream of an orifice bore shows an increase in velocity and decrease in a pressure at a point called a "vena contracta point".
- The differential pressure flow meters output a nonlinear signal that corresponds to the square of the flow rate. A change in flow at a low rate produces a very small signal change. A change in a large flow rate produces a much larger signal change.
- For those systems that are used to meter hot fluids such as steam, it may be necessary to keep the sensing lines filled with water or another liquid to isolate the high process temperature from the transmitter to protect the sensor and electronics.

LO 3: Elaborate the applications of variable area flow meters

- Rotameters are limited to vertical installations. Rotameter installation includes a small needle valve that regulates the flow. The bottom portion of the tube is connected to the pipe inlet where the fluid enters and the upper portion of the tube is connected to the pipe outlet where the fluid leaves after metering the flow.

LO 4: Analyze the applications of magnetic flow meters

- In magnetic flow measurement, the conductor is the flowing electrically conductive liquid. A cross section of liquid generally has no specific velocity. However, calculations show that the voltage generated between two opposite points on the inner pipe wall is largely independent of the velocity profile.
- A magnetic flow meters always comprises a nonferromagnetic pipe (magnetically nonconductive) with a lining material, one or two coils with a magnetic core, and two measuring electrodes.

LO 5: Demonstrate the applications of turbine flow meters

- Turbine flow meter bodies have straightening vanes at the inlet and outlet to stabilize the fluid flow in the rotor area. Experts recommend a minimum of 10 pipe diameters of straight pipe upstream and 5 diameters downstream from the flow meter installation to ensure accurate measurement.
- Pressure drop is also considered when selecting a turbine flow meter. A high pressure drop could damage the blade of rotor. High velocity can damage the bearings.
- Swirl is the most sensitive external influence on a turbine meter, and swirl can exist for up to 100 pipe diameters. Thus flow straighteners are also installed to minimize swirl.

LO 6: Explain the applications of oscillatory flow meters

- Vortex swirls are shed continuously, always180 degrees out of phase with each other. The velocity of the material flowing past the bluff body or shedder bar determines the frequency of the shedding process. Each vortex swirl is of the same volume, regardless of the flowing medium.
- The vortex meter works well on relatively clean liquids, gas, and steam, which do not contain a significant amount of solids.
- Accuracy and rangeability are the main advantages of the vortex meter. The rangeability of the typical vortex meter is 20:1 and sometimes even higher. Ranges of 45:1 are possible, depending on the viscosity of the liquid or the density of the gas.

LO 7: Analyze the applications of Coriolis flow meters

- When fluid is flowing, inertial (Coriolis) forces cause a phase shift between inlet and outlet sections. Two sensors measure the phase difference, which is directly proportional to mass flow.
- Coriolis flow meters are applicable to single-phase liquid metering installations which are not susceptible to gas entrainment problems. Coriolis flow meters eliminate many of the problems commonly encountered in mass flow measurements. The output of the meter is directly proportional to mass flow rate. Therefore, there is no need to measure the critical parameters of pressure, velocity, temperature, viscosity, or density.
- The Coriolis meter has a very high turndown ratio.

LO 8: Elaborate the applications of ultrasonic flow meters

- For the Doppler principle to work in a flow meter, it is mandatory that the flowing stream contain sonically reflective materials, such as solid particles or entrained air bubbles. Without these reflectors, the Doppler system does not operate. In contrast, the transit-time ultrasonic flow meter does not depend on the presence of reflectors.
- In transit time ultrasonic meters, Since the fluid is flowing at a certain velocity (to be measured), sound travels faster in the direction of flow and slower against the direction of flow. By measuring the difference in arrival time of pulses traveling downstream and pulses traveling upstream, this T serves as a measure of fluid velocity.

- In dual-path ultrasonic flow meter, two pairs of transducers are installed in the piping. The upstream and downstream propagation times between each pair of transducers are integrated in a microprocessor-based electronics package to determine the flow rate.

LO 9: Demonstrate the applications of positive-displacement flow meters, flow indicators and totalizers

- Utilities and their consumers are among the largest users of PD flow meters, with millions of units in use for distributing and dispensing water, gas, gasoline, and other commodities.
- Positive displacement meters precisely separate a flowing stream into discrete volume, count them, and then return the discrete volume to the flowing stream.
- The energy required to drive the meter's mechanical components is generated from the flow stream.
- A PD meter has output hardware can convert each unit of volume displacement into an electrical pulse. There is only one moving part in the measuring chamber, the disk.
- The process of totalization means to totalize or to determine the total amount of fluid flow passing through a flow meter.

LO 10: Summarize the flow-measurement device selection criteria

- The meter's materials of construction must not react with the process media. Fluids such as oxygen can present explosive hazards if they chemically react with certain materials.
- Sulfide stress cracking refers to the fracturing of metal in response to pressure and a corrosive fluid. If sulfides, such as H_2S, are present in a fluid, then carbon and low alloy steels are susceptible to sulfide stress cracking.
- Flow meters can generate pulses that represent an amount of product. The receiving device counts the number of pulses generated during the flow's duration. The main concern here is that the receiving device and flow meter are compatible in the minimum and maximum frequencies. The receiving device is also evaluated for the capability to sense a pulsed waveform's positive and negative thresholds.
- Any flow meter's indication of a volume represents an unknown volume unless the volume can be compared to a known volume. The known volumes are called "meter provers".
- A multivariable transmitter measures differential pressure, absolute pressure, and process temperature. The multivariable transmitter also calculates the compensated flow. Traditionally, three separate transmitters and flow calculation were required for this measurement.

LO 11: Illustrate the calibration procedures for flow meters

- The calibration can be defined as the comparison of a measuring instrument with specified tolerance but an undetermined accuracy, to a measurement standard with known accuracy.
- Dry calibration uses flow simulation by means of an electronic or mechanical signal.
- Wet calibration uses actual fluid flow. Generally it provides high accuracy for a flow meter and is used when accuracy is a prime concern.
- Master meter method is used when a pipe prover is unavailable. The master meter method uses a known reliable meter configured in series with the meter to be proved. The meter measurements are then compared.

Questions

I. Objective-type questions

✦✦ **1.** The maximum flow rate at specified accuracy provided by a device is 20 gpm, and the minimum is 4 gpm. The turndown ratio is:

a. 1:4 b. 1:5
c. 5:1 d. 20:1

✦✦✦ **2.** A fluid with a high Reynolds number indicates that the flow is:

a. Laminar b. Erratic
c. Turbulent d. Transitional

✦ **3.** Which of the following velocity measurement methods does not require an obstruction in the flow path?

a. Vortex shedding flow meter b. Magnetic flow meter
c. Orifice flow meter d. Turbine meter

✦✦ **4.** Which of the following actions is associated with a vortex shedding flow meter?

a. Coils outside the pipe generate a pulsed DC magnetic field.
b. A bluff body/shedder bar is placed in the pipe.
c. Sound waves are sent through the following stream.
d. A multi-bladed rotor is supported by bearings in the pipe.

✦✦ **5.** Which of the following is true of rotating paddle wheel measurement?

a. Measurement is based on a shift in resonant frequency.
b. It has a very high MTBF number.
c. It is less accurate and more expensive than a continuous level measurement.
d. A buildup of material creates a stall and triggers a micro switch.

✦✦ **6.** For flow measurement of steam applications, transmitter must be installed below the process line.

a. True b. False

✦✦✦ **7.** Turbine flow meter can be used for measuring flow of slurry type of liquids.

a. True b. False

✦✦✦ **8.** Vortex flow meters are suggested for high viscous fluids.

a. True b. False

✦✦ **9.** Which flow meter is not affected by fluid properties and provides very high accuracy?

a. Orifice flow meter b. Coriolis flow meter
c. Turbine flow meter d. Magnetic flow meter

✦✦ **10.** How the differential pressure is related to the flow?

a. Inverse b. Square
c. Direct d. None

✦ **11.** What is the relation between flow and differential pressure created across the flow element like orifice?

a. Square b. Square root
c. Logarithmic d. Exponential

✦ **12.** Which of the following is not a flow measurement element?

a. Venturi b. Rota meter
c. Bourdon d. Flow nozzle

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II. Short-answer questions

✦✦✦ **1.** What is totalization and illustrate its purpose?

✦✦✦ **2.** What are the types of the custody transfer in flow measurement?

✦ **3.** Define a rate meter?

✦ **4.** Provide an example for the extractive type flow measurement element.

✦ **5.** Provide an example for the additive type flow measurement element.

✦✦ **6.** What is hydrodynamics?

✦✦ **7.** Explain smart instrumentation.

✦✦ **8.** What is the main advantage of magnetic flow meter?

✦ **9.** What are the factors to which oscillatory flow meters are sensitive?

✦✦ **10.** Explain the principle of operation of dual path ultrasonic flow meters?

✦ **11.** How a turbine meter is powered?

✦✦ **12.** What is proving in flow measurement?

III. Unsolved problems

✦✦ **1.** An incompressible fluid is flowing in a 300 mm pipe under a pressure head of 2 kg/cm^2. Calculate the fluid velocity and volumetric flow rate.

✦✦✦ **2.** Consider 1 kg/cm^2 = 10 meters water head. A differential pressure transmitter is used to measure the flow Q across a pipe in conjunction with an orifice. Determine the flow rate when D_p = 25 Pa and C = 0.0004 m^3/s per Pa.

✦ 3. The pressure of a process increases from 1 bar to 3 bar. For the purposes of flow measurement, by what percentage has the pressure increased?

✦ 4. A turbine flow meter coupled to an electric voltage generator produces 4 mV for each litre/s flowing. Calculate the output when 1 V is produced.

IV. Critical-thinking questions

✦ 1. Define viscosity and its relation to the flow measurement.

✦ 2. Give an example for velocity measurement applied for flow?

✦✦ 3. Define laminar and turbulent flow.

✦✦✦ 4. Provide an example of incompressible fluid.

✦✦ 5. Define kinematic viscosity.

✦ 6. Explain the rational for rotameters being limited to vertical installations.

✦✦ 7. What are the advantages of Coriolis flow meter?

✦ 8. What is radial type sensor configuration with ultrasonic metering?

✦ 9. How many moving parts are available in positive displacement meters?

✦✦ 10. What are the advantages of multivariable transmitter over traditional transmitters?

✦✦ 11. When is master meter method used?

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Control Valves

6

Control valves are one of the most used type of final control element. Control valves are installed in the process to manipulate the process as needed by the process operators or the control systems. Control valves are designed to operate using the pneumatic, hydraulic and electrical power based on the type and application in the process.

Control valves constitute the subsystems such as valve body, actuator, positioners, signal converters, etc. Each of these subsystems were discussed along with their types and application of different types to different conditions. Control valves have typical failure modes such as cavitations, noise, etc., which can be associated with improper designs. This chapter deals with different types of control valves and calculation of the size of the valves for different applications.

The characteristics of the valves and their suitability to applications and design conditions are discussed. The chapter also discusses the increasingly important consideration of control valves such as capacity and performance. A review of actuator styles, distinctions, and selection follows the different types of valve designs. Finally, the chapter covers digital valve controllers, positioners and other valve and actuator accessories.

Keywords:
Valves, stem, globe valve, actuators, butterfly valve, positioner, rangeability, process connection, cavitation's noise, I/P converters, pneumatic supply, hydraulic

LEARNING OBJECTIVES

After reading this chapter, you will be able to:

1. Describe and classify control valves
2. Analyze the parameters to evaluate the performance of control valves
3. Outline control valves' capabilities and capacities
4. Describe control valve actuators
5. Explain valve controllers and accessories
6. Illustrate the calibration procedures of control valves

"Action is the real measure of intelligence"
Napoleon Hill

6.1 INTRODUCTION

LO 1
Describe and classify control valves

A valve is a device for adjusting, or manipulating the flow rate of liquid or gas in a pipeline. It contains a flow passage, or port, with varied flow area. The valve stem transmits some external motion to the port, changing its port area. The external motion produced manually or from an actuator positioner through pneumatically, electrically or hydraulically in response to an external positioning signal together forms an automatic control valve or a control valve. The control valve, or final control element, is the last device in a control loop. It takes a signal from the process instruments and acts directly to control the process fluid. Control valves maintain process variables such as pressure, flow, temperature, or level at their desired value, despite changes in process dynamics and load.

The control valves respond to maintain a steady load on the process irrespective of the dynamics. Control valves are designed to accommodate the needs and characteristics of the process fluid, they control. Likewise, the control valve must react to the protocol and needs of the controlling devices in the process control system. The evolution of control valves is in response to the combined forces of the processes they handle and the systems that control them. Evidence of these factors exists in the design of valve bodies, actuators, valve controllers, and interface accessories.

6.1.1 General Categories of Control Valves

Control valve refers to any power-operated valve, whether used for throttling or on/off control. Different types of valves are listed in Table 6.1 (including sliding-stem valves and rotary valves). Typical sliding stem valves are straight-pattern valves (also known as globe valves) and angle-pattern valves. Rotary valves include ball and butterfly valves. Other varieties such as motorized gate valves, louvers, pinch valves, plug valves, and self-operated regulators are not considered here. These major types—sliding-stem and rotary—are further divided into ten subcategories according to relative performance and cost. Despite of the variations found within each category; such as cage guiding and stem guiding, all valves within a given subcategory can be considered in the early stages of the valve selection process. Selecting a valve involves narrowing the selection to one of these subcategories and then comparing specific valves in that group. Designations NPS and DN are used in Table 6.1 and throughout this section. NPS is an abbreviation for normal pipe size and is usually represented with a number which is size of the pipe in inches. Similarly, DN is an abbreviation for nominal diameter and is represented with a number which is the size of the pipe in millimeters.

Table 6.1: Characteristics of different types of control valves

Valve Style	*Main Characteristics*	*Available Ranges*	*Typical Body Materials*	*Typical End Connections*	*Maximum Pressure*	*Flow Capacity*	*Relative Shutoff Capability*	*Available Control Characteristics*	*Pressure Drop*
Sliding-stem	Heavy duty, versatility	NPS: 1/2–20, DN: 15–500	Cast iron, carbon alloy, stainless steel	Flanged, welded, screwed	Class 2500, PN 420	Moderate	Excellent	Equal percentage, linear, quick opening	High
Bar-stock	Compact	NPS: 1/2–4, DN: 15–100	Stainless steel, nickel alloy	Flangeless, screwed	Class 600, PN 100	Low	Excellent	Equal percentage, linear	Moderate
Economy sliding-stem	Light Duty, Inexpensive	NPS: 1–24, DN: 15–100	Bronze, cast iron, carbon steel	Screwed, Flanged	Class300, PN 50	Low	Good	Equal percentage, linear	Moderate
Through bore ball	On/off Service	NPS: 1–24, DN: 25–600	Carbon steel, stainless steel	Flangeless	Class900, PN 150	High	Excellent	Equal percentage	Moderate
Partial Ball	Catheterized for throttling	NPS: 1–24, DN: 25–600	Carbon steel, stainless steel	Flangeless, Flanged	Class 600, PN 100	High	Excellent	Equal percentage	Moderate
Eccentric Plug	Erosion resistance, versatility	NPS: 1–12, DN: 25–300	Carbon steel, stainless steel carbon steel, stainless steel	Flangeless, Flanged	CLASS 600, PN 100	Moderate	Excellent	Linear	High
Swing-through Butterfly	No seal	NPS: 2–36, DN: 50–900	Cast iron, carbon steel, stainless steel	Flangeless, lugged, welded	Class 2500, PN 420	Moderate	Poor	Equal percentage	Moderate
Lined-butterfly	Elastomer or PTEF lined	NPS: 2–24, DN: 50–600	Cast Iron, Carbon steel, stainless steel	Flangeless, Lugged	Class 150, PN 20	High	Good	Equal percentage	Low
High-performance Butterfly	Offset disk, flexible seals	NPS: 2–72, DN: 50–1800	Carbon steel, stainless steel	Flangeless, Lugged	Class 600, PN 100	High	Excellent	Linear	Moderate
Special	Custom to applications	NPS: 2–24, DN: 50–600	Carbon, alloy, stainless steel	Flanged, welded	Class 4500, PN 760	High	Excellent	Custom	High to very high

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Checkpoint

✦ 1. What is a control valve?
✦✦ 2. Define DN and NPS.
✦✦✦ 3. What is dead band?

6.2 PARAMETERS TO EVALUATE THE PERFORMANCE OF CONTROL VALVES

LO 2
Analyze the parameters to evaluate the performance of control valves

Global competition in the process industry is creating an increasing pressure on companies to provide the highest quality products and the maximum plant throughputs with fewer resources. While meeting these demands, companies also must meet ever changing customer needs. When the quality of a product conforms to a set of specifications, the manufacturing company makes profit. Any deviation from the standards, results in lost profit, due to reprocessing costs, excessive material use, or wasted product. Better process control allows in reducing process variability and optimizes the process. This ensures that products production comes right in the first time. If the process variability is high, one of the many contributors could be a control valve. Many studies and experiences indicate that control valve is a major contributor for control loop disturbances and hence leading to the variability in the control loop. The reasons for this behavior are many and hence the manufacturers of the valves perform the testing on dynamic conditions. The evaluation of the control valve in a control loop with dynamic process conditions is the right measure to know the performance and process variability. That is why selecting the control valve based on the process conditions is the first step towards designing a good control loop. For best performance, valves must be developed or optimized as a unit. Following are the important design considerations—dead band, actuator-positioner design, valve response time, and valve type and sizing.

6.2.1 Dead Band

Dead band is the range through which an input can be varied without initiating an observable response. For example, in a diaphragm, actuated control valve dead band is the amount with

Note: ✦ Level 1 & Level 2 category
✦✦ Level 3 & Level 4 category
✦✦✦ Level 5 & Level 6 category

which the diaphragm pressure can be changed without causing the valve stem to move. Studies suggest that dead band is one of the major contributors to excess process variability. The control valve assemblies can be a primary source of dead band in an instrumentation loop. It is usually expressed as a percentage of diaphragm pressure spans. Backlash and striction behavior is caused by mechanical tolerances and friction in the control valve-positioner-actuator-linkage system. Friction and backlash, and dead zones in relays are some forms and reasons for the dead band. Most process control applications using advanced systems send signals which are very small (sometimes less than 1 percent). A well designed valve is expected to respond to these small changes to keep a tight control on the process. If the dead band is more, the valve may not respond to these signals which in turn creates disturbance to the process and hence to the process variability.

6.2.2 Actuator-Positioner Design

Actuator is one subsystem in the control valve assembly and is meant to convert the control signal to the force that acts on the valve, connected to the process. The same can be extended to other forms of the final control elements such as motors, cylinder and solenoid valves. The actuator and positioner systems are one of the potential source of dead band in control system. The same is also responsible to use more or less energy based on the type and their design. Properly selected assemblies can improve the static and dynamic responses of the control valve assemblies. A good positioner for process variability reduction should contain a high-gain device. Typical two-stage positioners use pneumatic relays at the power amplifier stage. Relays are preferred over spool valves for this purpose because relays can provide a high-power gain that gives excellent dynamic performance with minimal steady state air consumption. With microprocessor devices becoming more popular, positioner designs are being overhauled. These microprocessor-based positioners seamlessly provide dynamic performance that equals any of the best conventional two-stage pneumatic positioners. To ensure that the performance of the positioners does not degrade over the time, valve monitoring and diagnostic capabilities are provided. For any given valve assembly, the high performance positioners having both high static and dynamic gain provides the best overall process variability performance.

6.2.3 Valve Response Time

The modern control systems can control difficult process with less variability only if the final control element such as valve can reach its desired position quickly, and responds to smallest changes in the control signals (less than one percent).

The process variability is improved when the control valve assembly identifies and quickly responds to the small changes. This is a function of the volume of air that is required to produce any desired pressure on the diaphragm of a valve actuator. To a lesser extent, speed of response depends on the friction between the valve stem, packing the bushings in the valve (rotary) body and actuator, and the seal to rotary element.

6.2.4 Valve Type and Sizing

Choosing the correct valve size is as equally important as choosing appropriate control valve materials and pressure temperature ratings. Oversized valves limit the efforts of reducing process variability. The valve oversize is a consequence of improper design. The pipes may be designed larger than required considering some future plans and safety factors and some larger rotary manual ball valves etc. The oversized control valves operate at lower levels of positions due to less flow (from valve size point of view). These valves at lower positions produce a large flow change, with small change in position. The situation becomes worse, if there is a dead band associated with the valve. The large flow of liquid in sudden jerks disturbs the process and other loops in the process. This disturbance leads to process variability. While selecting a valve, consider the valve style, valve size, and inherent characteristics that provide the broadest possible control range for an application. The economic results of an operating plant are directly impacted by the performance factors. The performance factors can be response time, dead time and gain in process load. These parameters are measured in open-loop and closed-loop conditions. Control valve assemblies play a vital role in loop/unit/plant performance. Earlier, the control valves were selected based on the static parameters such as material of construction, flow capacity, leakage and open-loop lab performance data. The parameters are not treated as not enough to specify and select valve, unless the dynamic characteristics are specified. This is due to the fact that a single subsystem in its isolation cannot be specified to achieve the loop performance. As discussed earlier, the bench type tests and open-loop tests are not adequate to specify the valve compared to the test done in loaded type tests with actual hardware and process conditions.

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Checkpoint

✦✦ 1. Which is the major source of process variability?

✦ 2. What is actuator?

✦✦ 3. What are the advantages of microprocessor-based positioners?

6.3 CONTROL VALVES' CAPABILITIES AND CAPACITIES

LO 3

Outline control valves' capabilities and capacities

Flow characteristics, rangeability, pressure drop capabilities, end connection style, shutoff and capacity are very important to consider when you select a valve. Valve manufacturers publish these characteristics as specifications in sales literature or data sheets.

6.3.1 Valve Type and Characterization

For process optimization, the installed flow characteristics of the entire process and gain are more important. The best process performance can be achieved through an appropriate trim selection, instead of adjusting the positioners, cams and other methods. The trims are manufactured with various characteristics to get a specific behavior. The most usually available types are linear, equal-percentage and quick-opening types. The linear type trim allows a flow rate which is proportional to the stem position, while the equal percentage generates a flow which is nonlinear, low at low flow at lower side of stem positions and higher at higher side of the stem positions. The quick opening provides higher flow at lower side of the stem positions. The linear trim types, exhibit the characteristics, if there is a constant drop across the valve. An equal percent trims can counter the drop created in the pipe for changes in the flow. Refer to Figure 6.1 for the characteristics of a control valve.

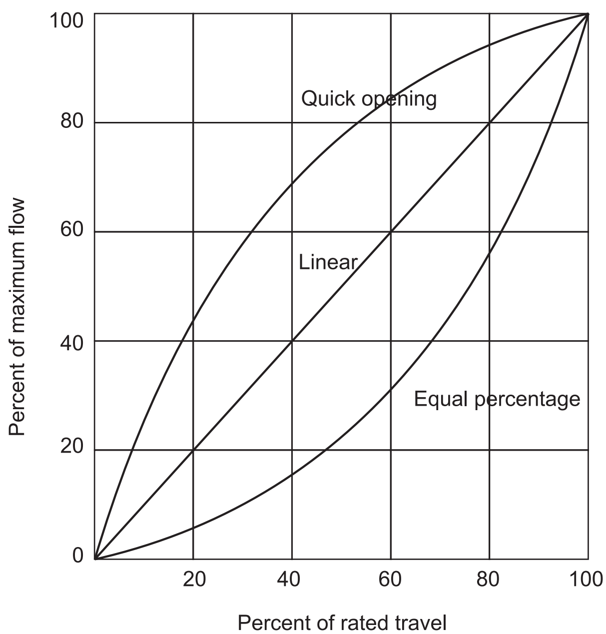


Figure 6.1: Characteristics of control valves

The C_v for linear and equal percentage control valve trims is given by the following formulae:

$$\left.\begin{array}{ll} C_v = xC_{vm} & \text{Linear trim} \\ C_v = C_{ym} \times R(x-1) & \text{Equal percentage trim} \end{array}\right\} \quad (6.1)$$

where, C_v = Flow coefficient of control valve at stem position x, C_{vm} = Flow coefficient of control valve while wide open (x = 100%), x = Stem position, from 0 to 1 (0% to 100%) inclusive, R = Rangeability coefficient of equal percentage trim

Installed flow characteristic, is obtained when the pressure drop ΔP across the valve varies as dictated by flow and other related conditions in the system, where the valve is installed. Most control valves used in the process industry have one of the three flow characteristics: linear, quick-opening, or equal percentage.

Linear describes the straight line on a rectangular plot of flow versus percentage of rated valve stem travel. A linear valve gives approximately equal increments of flow per increment of valve stem travel at a constant pressure drop.

Equal Percentage describes the equal increments of rated travel will ideally give equal percentage changes of the existing flow.

Quick-opening describes maximum flow achieved with minimum travel. A quick-opening valve has an approximately straight-line characteristic near its seat (from 0 to about 60% flow at 30% travel). Beyond this point, flow increases too rapidly with valve opening for the quick-opening characteristic to be useful in a flow-proportioning application.

Reshaping the valve trim, results in different valve characterizations. For instance, you can achieve the common linear, quick-opening and equal-percentage characteristic by modifying the plug profiles of a single-ported, stem-guided globe valve. Refer to Figure 6.2 for different types of the seats for each of these valve types.

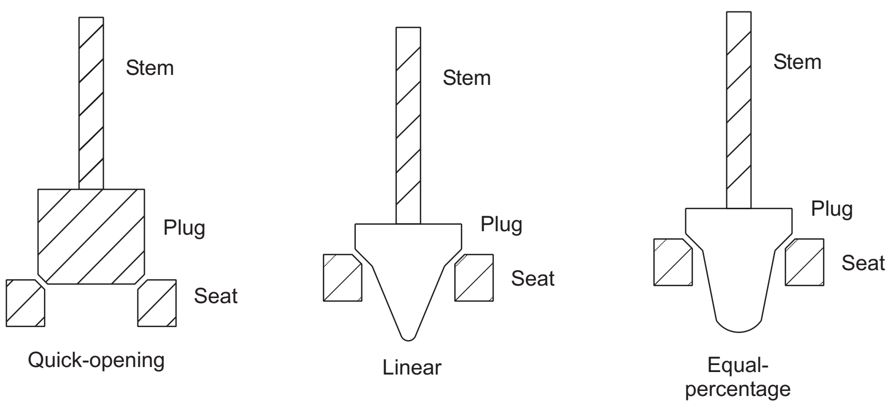


Figure 6.2: Valve seats for each type of characteristics

6.3.2 Control Valve Performance Considerations

6.3.2.1 Rangeability

The ratio of maximum to minimum flow rate in a control valve can be defined as Rangeability, a characteristic of a control valve. Higher rangeability is needed if there is an anticipated large change in the flow and also in case the valve is designed for working in startup, normal and maximum flow conditions. For a wide rangeability, partial ball valves, rotary valves are preferred compared to the normal sliding stem varieties.

6.3.2.2 *Pressure Drop*

The valve's toleration of maximum pressure drop at shutoff, when fully or partially open, is an important selection criterion. Generally, Sliding-stem valves are considered as superior in both regards due to their rugged and well-supported design of their moving parts. Unlike most sliding-stem valves, various rotary valves are restricted to pressure drops, well below the body pressure rating. This is especially true, under flowing conditions as the dynamic stresses imposed on the disk or ball segment by high-velocity flow.

6.3.2.3 *Noise and Cavitation*

Noise and cavitation are undesirable behaviors in a valve and they occur in conditions where there is high pressure drop and flow rate. This can be managed through the special modifications in the valve. Cavitation is the noisy and potentially damaging implosion of bubbles formed when the pressure of a liquid shortly dips below its vapor pressure through a constriction at high velocity. In controlling gases and vapors, noise results from the turbulence associated with high-velocity streams. When cavitation or noise found to be a problem, its severity must be predicted from the valve's specifications according to well-known techniques, and valves with better specifications must be sought, if necessary. Cavitation-control and noise-control trims for various degrees of severity are widely available in regular sliding-stem valves—at a progressive penalty in terms of cost and flow capacity. Rotary valves have more limited noise and cavitation-control options and are also much more susceptible to cavitation and noise at a given pressure drop.

6.3.2.4 *End Connections*

The valve end connections must also be considered during valve selection. The question to be answered is whether the desired connection style is available in the valve style being considered. In some situations, end connections can quickly limit the selection or dramatically affect the price. For instance, if a piping specification calls for welded connections only, the choice might be limited to sliding-stem valves. The few weld-end butterfly and ball valves that are available are rather expensive.

6.3.2.5 *Shutoff Capability*

A valve's shutoff capability, which ordinarily is rated in terms of classes specified in ANSI/FCI 70-2 [4] or IEC 534–4, must also be considered during valve selection. In real time service, shutoff leakage depends on various factors that include temperature, the condition of the sealing surfaces, pressure drop, and stem valves (very importantly for sliding). Stem valves force load on the seat. Shutoff ratings are generally stated based on standard test conditions. The actual service conditions will be different from standard conditions. However, it is difficult to predict the leakage at service conditions and hence the standard conditions are used for comparison among different types of valves.

Tight shutoff is particularly important in high-pressure valves because leakage can cause seat damage, leading to ultimate destruction of the trim. Special precautions in seat materials, seat preparation, and seat load are necessary to ensure success. Valve users tend to over specify shutoff requirements, incurring unnecessary cost. Actually, very few throttling valves really need to perform double duty as tight block valves. Since tight shutoff valves generally cost more initially and to maintain serious consideration is warranted.

6.3.2.6 Flow Capacity

While selecting a valve, its size and capacity can be an overriding constraint. For large lines, sliding-stem valves are very expensive when compared to the rotary types. However, for small flows, an ideal rotary valve might not be available. If the same valve is desired to handle a significantly larger flow at a future time, a sliding-stem valve with replaceable, restricted trim might be indicated. In general, rotaries capacity is bigger than sliding-stem valves. As a result, where the pressure drop is rather small, rotaries are used in the applications. However, in high-pressure drop applications (letdown or pressure regulation), rotaries are not suitable.

The valve selection considerations can be roughly simplified as follows:

- For both economic and technical reasons, the following valves are recommended. For lower ranges: sliding-stem valves; for intermediate capacities: ball valves; and for very largest sizes: high-performance butterfly valves.
- For the very least demanding services in which price is the dominant consideration, one might consider economy sliding-stem valves for the small-size applications and butterfly valves for the largest.
- For sizes of NPS 0.5–3 or DN 15–80, general-purpose sliding-stem valves provide exceptional value. For a minimal price premium over rotary products, they offer unparalleled performance, flexibility and service life. The premium for these devices over rotary products is warranted. For severe service applications, the most frequently used and often the only available product is the sliding-stem valve.
- Applications ranging from NPS 4 to NPS 6 or DN 100 to DN 150 are best served by such transitional valve styles as the eccentric plug valve or the ball valve. These products have excellent performance and lower cost. They also offer higher capacity levels than globe designs.
- In valve sizes such as NPS8 or DN200, the maximum pressure ratings are high while maintaining the pressure drop to lower levels. This gives rise to the possibility of using high-performance butterfly valves for most situations. These valves are economical, offer tight shutoff and provide good control capability. They provide cost and capacity benefits well beyond those of globe and ball valves.
- There will be situations where the general commercially available valves do not meet the process demands. In such circumstances, the special valve design and manufacturing is performed which are meant to handle high noise, high pressure, cavitation, temperature, etc.

Different types of valves are appropriate for use in different size ranges because they provide the most cost-effective solution in each given instance. If you stick with the same type of valve over a wide size range then you sacrifice either performance at the low-end or economy at the high-end or both. After going through all the other criteria for a given application, engineers who specify valves often find that they can use several types of valves. Selection of a valve depends on the price versus capability along with individual and organizational experience and preferences. At the same time, it is not possible to have a single valve or type of valve that meets all the needs of the process conditions in a process control application.

6.3.3 Valve Sizing

Earlier it was common to select valve size strictly as a function of pipe size. Soon it became apparent that this practice contributed to very poor control and resulting process problems. The wide range of flow, pressure and fluid conditions required a more indepth selection methodology. Selecting the correct valve size for a given application requires knowledge of the flow and process conditions the valve would actually undergo in service and information on valve function and style. Sizing valves is based on a combination of theory and empirical data. The results are predictable, accurate, and consistent.

Early efforts in the development of valve sizing were centered on liquid flow. Daniel Bernoulli was one of the early experimenters who applied theory to liquid flow. Subsequent experimental modifications to this theory produced a useful liquid-flow equation. This equation rapidly became accepted for sizing valves on liquid service and manufacturers of valves began testing and publishing C_v data in their catalogs.

Good results obtained from the C_v equation were used to predict the flow of gas. The results however, were inaccurate, leading to modifications of the equation over time with consequent improvement of results. There was no common formulation until the Instrument Society of America (ISA) (now called as International Society for Automation) put forth its standardized guidelines.

$$Q = C_v\sqrt{\frac{P_1 - P_2}{G}} \tag{6.2}$$

where, Q = flow rate; C_v = valve sizing coefficient, determined by testing; P_1 = upstream pressure; P_2 = downstream pressure; G = liquid specific gravity

In order to assure uniformity and accuracy, the procedures for measuring flow parameters and for valve sizing are addressed by ISA standards. Measurement of C_v and related flow parameters are covered extensively in ANSI/ISA S75.02, 1981. The basic test system and hardware installation are outlined so that coefficients can be tested to an accuracy of ±5%. Water is pumped into the pipe with the control valve installed with specific flow rate, inlet pressure, pressure drop and temperature. For a specific stem position, the inlet pressure and pressure drop along with flow rate are recorded. The result provides the required knowledge to calculate necessary sizing parameters. Numerous tests must be performed to arrive at the values published by the valve manufacturer for use in sizing. As the results are not predictable, it is important that these factors are based on analysis but not estimates.

6.3.3.1 Basic Sizing Procedure

To ensure uniformity and consistency, a standard that delineates the equations and correction factors to be used for a given application (ANSI/ISA S75.01-1985) is used to size valves for liquid flow:

$$C_v = \frac{Q}{\sqrt{\frac{P_1 - P_2}{G}}} \tag{6.3}$$

The simplest case of liquid-flow application involves the basic equation developed earlier. These factors, when incorporated, change the form of the equation to the following:

$$C_v = \frac{Q}{NF_P F_R \sqrt{\frac{P_1 - P_2}{G}}} \tag{6.4}$$

where, N = numerical coefficient for unit conversion, F_P, F_R = correction factors

Rearranging the equation so that all of the fluid and process-related variables are on the right-hand side, the expression for the valve C_v required for the particular application is based on a given flow rate and pressure drop, a required C_v value can be calculated. This C_v can then be compared to C_v values for a particular valve size and valve design. Generally, the required C_v must be between 70% and 90% of the selected valve's C_v capability. Allowance for minimum and maximum flow pressure conditions should also be considered.

Once a valve is selected and C_v is known, the pressure drop for a given flow rate or the flow rate for a given pressure drop is calculated by substituting and solving for the appropriate quantities in the equation. Refer to Figure 6.3 for the flow with reference to the pressure drop.

This basic liquid equation covers conditions governed by the test assumptions. Unfortunately many applications fall outside the bounds of these standards and therefore outside of the basic liquid-flow equation. Instead of developing a special flow equation for all possible deviations, it is better to account for different behavior using a simple correction factor.

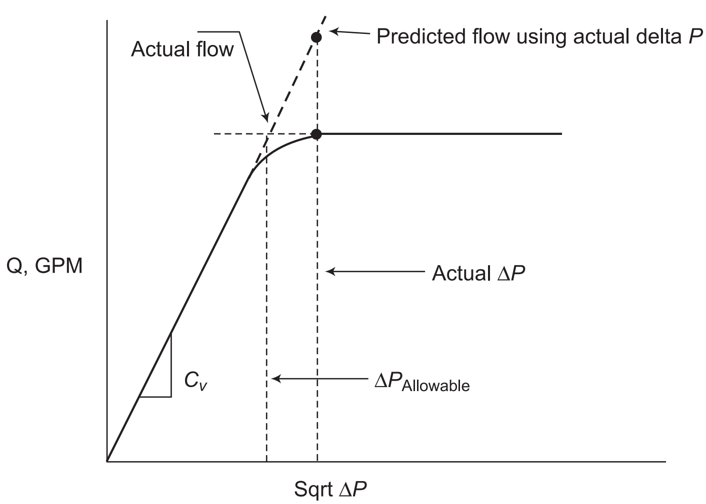


Figure 6.3: Flow characteristics with pressure drop

6.3.3.2 *Gas and Steam Sizing*

Air, gas, and steam valve sizing are just as important as considerations for liquid sizing. The only additional steps involve correction for the physical properties of the particular gas and pressure ratio factors that determine the degree of compression and predict choked flow. The general form of the sizing equation for the fluids is provided in Equation 6.4. If the factors mentioned above are considered, then the sizing equation is as follows:

$$C_v = \frac{Q}{NF_P P_1 Y \sqrt{\dfrac{X}{GT_1 Z}}} \tag{6.5}$$

where, Y = expansion factor, $X = \dfrac{P_1}{P_2}$, T_1 = temperature

For additional knowledge on valve sizing, consult the referenced ISA publications or the manufacturer's literature. Computer sizing programs are available to alleviate the need to solve complex equations manually and provide exceptional accuracy.

6.3.3.3 *Choked Flow*

A plot of the basic equation implies that flow can be increased continually by increasing the pressure differential across the valve. However, relationship given by this equation is valid only for a limited range.

Sizing equations suggest that as the pressure drop is increased, flow increases proportionally—forever. In reality, this relationship holds only for certain conditions. As the pressure drop is increased, choked flow caused by the formation of vapor bubbles in the flow stream imposes a limit on liquid flow. A similar limitation on flow of gases is realized when velocity at the valve vena contracta reaches sonic velocity. These choked-flow conditions must be considered in valve sizing.

If the pressure drop across the valve is increased, the flow rate increases. After sometime the flow rate does not increase as expected inspite of increasing pressure difference. The situation reaches a point where there is no additional flow rate increase for any additional increase in pressure difference. This condition is referred as chocked flow. This phenomenon occurs on both liquids and gases. It is necessary to account for the occurrence of choked flow during the sizing process to ensure against under-sizing a valve.

6.3.3.4 *Viscous Flow*

The type of flow such as laminar or turbulent plays a role in the selection and design of the control valve. In the case of laminar flow, the fluid particles move horizontally and parallel. In the case of turbulent flow, the flow of the fluid is random, in all the directions, with different velocities at different directions. However, the net flow remains the same which is sum of flow in all the directions. The correction factor F_r is a function of Reynolds number which describes the extent of the turbulent flow.

6.3.3.5 *Piping Considerations*

Valve installation on a pipeline will be different from the standard test conditions even though the recommendations from the suppliers are followed such as straight lines in the upstream and downstream. This is due to additional elbows, reducers and tee junctions installed in the pipes and the additional pressure drop in the line due to all these components. In order to compensate the effects of such additional components in the pipe, a correction factor F_p is considered.

6.3.4 Control Valves, Terminology and Types

It is essential to know the terms associated with actuators and valves before we get into further details. Fundamental comprehension is that actuator is controlled by the system (control system) and valve is in turn driven by that (Figure 6.4). Keeping the above idea in mind a simple final control element composition would look as described in Figure 6.5. Different terms are described as follows:

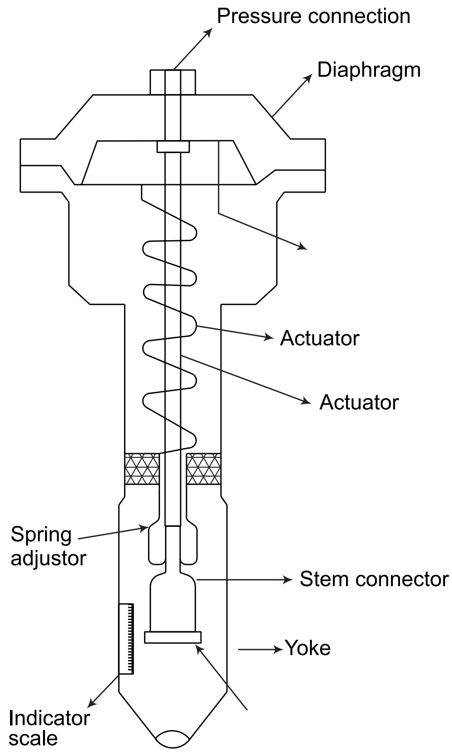
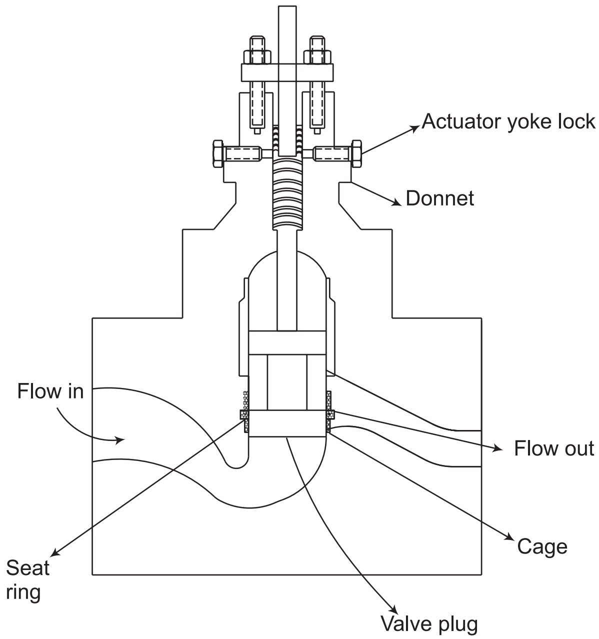


Figure 6.4: Actuator in a control valve

- **Actuator spring:** An actuator spring is installed inside the casing and creates a counter balance to the direction of the diaphragm pressure.
- **Actuator/valve stem:** The stem in the actuator connects the actuator and valve, and is used as transmission line for the force generated from the actuator to the valve.
- **Bonnet:** Bonnet is the casing in which the valve is packed and all the internal parts of the valve are arranged. Bonnet is also the part of the housing which is used for opening the valve to access the internal components. It also provides the mechanism for connecting the actuator to the valve body. Usually the bonnets are bolted, threaded or welded with pressure seals to the body.
- **Cage:** A cage is a part that is housed inside the valve and surrounds the trim. The cage along with the trim defines the characteristics of the valve and flow. In addition, the cage provides a seating surface to the trim and provides stability, guidance and facilitates assembly of other parts of the trim. These are the reasons for which the walls of the cage are sensitive parts and can change the flow characteristics if damaged.
- **Diaphragm:** A flexible, pressure responsive element that transmits force to the diaphragm plate and actuator stem is known as a diaphragm.

Figure 6.5 **Different parts of control valves**



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- **Diaphragm case:** The diaphragm case is meant for enclosing the diaphragm with top and bottom sections. The casing is designed to create the pressure chambers to act on the diaphragm from both directions.
- **Plug/valve plug:** A term frequently used to refer to the closure member. Closure member is nothing but the moving part in a valve which fundamentally decides the rate of fluid flow.
- **Seat:** The seat in the valve is the place where the trim closes the flow path using a surface and establishes the shutoff to the valve.
- **Seat ring:** A seat ring in the valve provides the surface for plug and is part of orifice created for flow control.
- **Spring adjustor:** A fitting that is usually threaded on the actuator stem or into the yoke, to adjust the spring compression. This compression is what decides the movement of the actuator.
- **Stem connector:** The device that connects the actuator stem to the valve stem.
- **Travel/indicator:** The travel is the movement of the stem or the closing member from a fully open to the fully closed position. The indicator will be provided to know the position of the closing member such as percent of opening or degree of rotation.
- **Yoke:** Yoke is the structure that rigidly connects the actuator power unit to the valve.
- **Actuator yoke lock:** Actuator yoke lock is the area where the actuator is joined with the valve stem.
- **Trim:** A trim is the subsystem in the valve that includes plug, seat ring, cage, stem and stem pin, etc. The trim is the component that modulates the liquid for a controlled flow. Based on the popular applications valve selection is done as shown in Table 6.2 to 6.4:

Table 6.2: Liquid level systems

Control Valve Pressure Drop	*Best Inherent Characteristics*
Constant ΔP	Linear
Decreasing ΔP with increasing load, ΔP at maximum load > 20% of minimal load ΔP	Linear
Decreasing ΔP with increasing load, ΔP at maximum load < 20% of minimal load ΔP	Equal-percentage
Increasing ΔP with increasing load, ΔP at maximum load < 200% of minimal load ΔP	Linear
Increasing ΔP with increasing load, ΔP at maximum load > 200% of minimum load ΔP	Quick-opening

Table 6.3: Pressure control systems	
Application	*Best Inherent Characteristics*
Liquid process	Equal-percentage
Gas process, small volume, less than 10 ft of pipe, between control valve and load valve	Equal-percentage
Gas process, large volume (process has receiver, distribution system, or transmission line exceeding 100 ft of nominal pipe volume), decreasing ΔP with increasing load, ΔP at maximum load > 20% of minimum load ΔP	Linear
Gas process, large volume (process has receiver, distribution system, or transmission line exceeding 100 ft of nominal pipe volume), decreasing ΔP with increasing load, ΔP at maximum load > 20% of minimum load ΔP	Equal-percentage

Table 6.4: Flow control processes			
Flow Measurement Signal to Controller	*Location of Control Valve in Relation to Measuring Element*	*Best Inherent Characteristics*	
		Wide range of set point	Small range of flow but large ΔP change at valve with increasing load
Proportional to flow	In series	Linear	Equal-percentage
	In bypass	Linear	Equal-percentage
Proportional to flow squared	In series	Linear	Equal-percentage
	In bypass	Equal-percentage	Equal-percentage

6.3.4.1 Sliding-stem Valves

The most versatile of the control valves are the sliding-stem valves. Mostly these are referred as globe valves the reason being they are often designed in the shape of globe. Based on the internal structure (ports) they are divided into multiple categories; however, the most popular and widely used ones are straight-pattern, angle-pattern, and three-way valves. They can be purchased in sizes ranging from NPS 0.5 to NPS 20 or from DN 15 to DN 500. These patterns are based on the ports, which are nothing but the openings available for the fluid to flow outside or inside, and classification is done depending on their number and the way they are located.

A straight-pattern valve has the structure as shown in Figure 6.6. The stem moves vertically in a linear motion and offers a linear flow in accordance to the motion while maintaining necessary resistance to the flow.

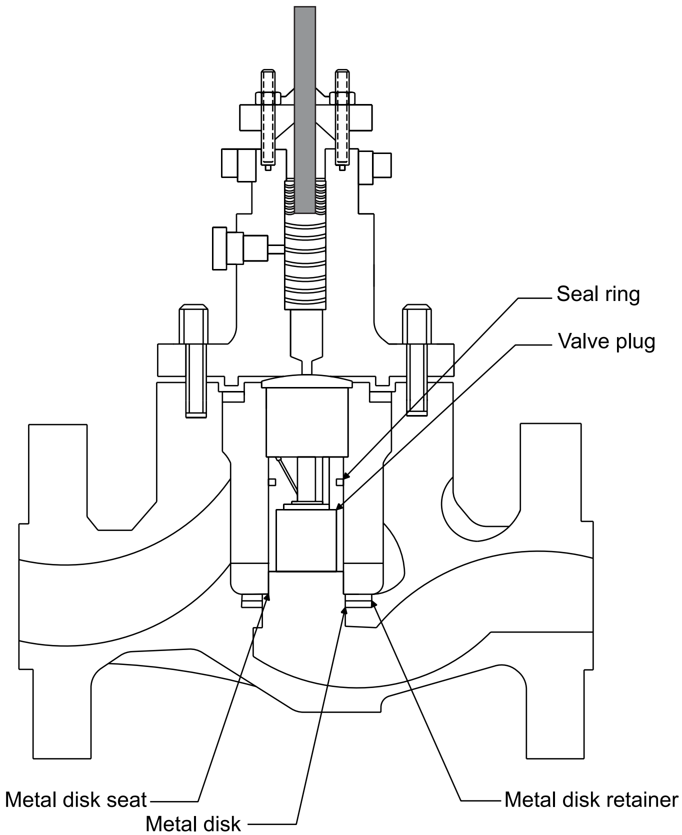

Figure 6.6: Standard straight-pattern, sliding-stem valves

Sliding-stem valves are available in a broad range of sizes, materials and end connections. The balanced plug shown reduces unbalance force and allows the use of smaller actuators. A soft seat provides tight shutoff. Valves such as this are the first choice for applications smaller than NPS 3 or DN 80.

Angle-pattern valve normally has input and output ports at specific angles and the popular one being right angles. In situations where the valve needs to be installed near a bend or tee joint, an angle-pattern valves is preferred. These valves offers many advantages such as reduced flow resistance compared to other valves and reduced pipe joints.

Reduced trim, angle-pattern, sliding-stem valve is shown in Figure 6.7 and it shows the capability for trim reduction in a sliding-stem valve. The valve also features an outlet liner for resistance to erosion. The unbalanced plug provides tight shutoff but requires a larger actuator than balanced designs. Normally, the above valves can be:

- Single-port valves with single port and plug
- Double-port valves with two ports and single plug
- Two-way valves with two flow connections, single inlet and single outlet

- Three-way valve bodies with three flow connections, two of inlets combine or mix flows), or one inlet and two outlets (for diverging or diverting flows) can be inlets with one outlet (for converging flow) also known as deformable flow passage whose diagram is given in Figure 6.8.

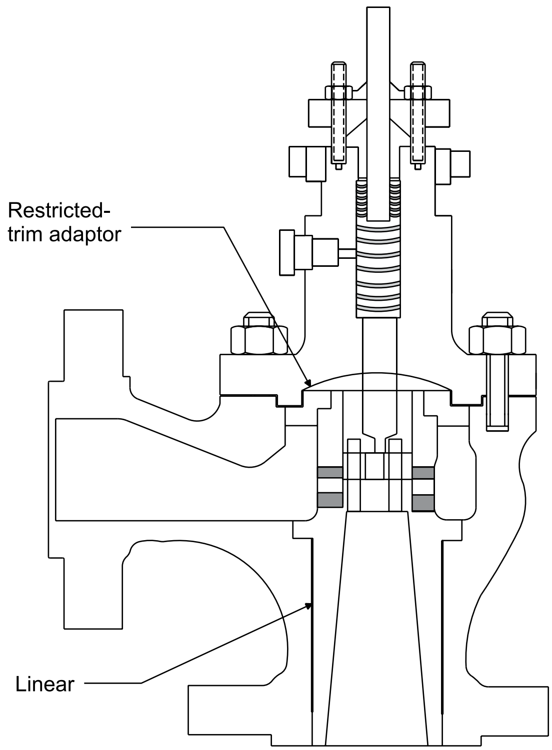

Figure 6.7: Reduced trim, angle-pattern valves

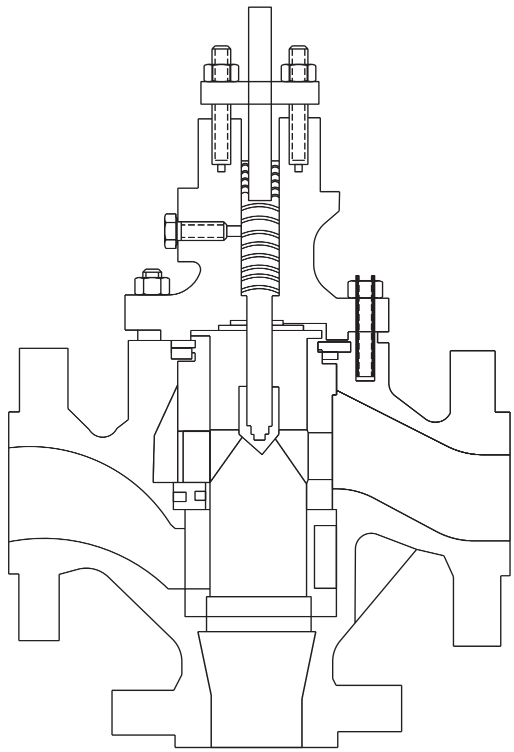

Figure 6.8: Three-way valves

Valves using this principle have a flow passage made wholly or in part of an elastomer. The actuator is arranged to squeeze the elastomer so that the flow passage becomes constricted.

Three-way valves have three end connections to allow for converging (flow mixing) or diverging (flow splitting) operations. It is available in two variations—diaphragm valve and the pinch valve. The diaphragm valve uses a linear actuator to squeeze the diaphragm onto a hard seat formed in the valve body. In the pinch valve, the fluid flows through a hose, which is pinched with a suitable linear actuator. One major disadvantage of these valves is that the elastomer deteriorates above 100°C and its strength limits operating pressure to 500 kPa or less. More choices of materials, end connections, and control characteristics are available for sliding-stem valves than for any other product family. Sliding-stem valves are available in cage-guided, port-guided, and stem-guided designs with flanged, screwed, or welding ends.

A cage-guided one is the one in which a cage-guided trim provides valve plug guiding, seat ring retention and flow characterization. The important point to note here is that there is a cage in which the valve plug always sits and its motion is guided throughout. The arrangement does not allow the leakage of the inlet fluid in high pressure to outlet in low pressure. Outlet pressure acts on both sides of the plug and removes the static unbalancing force acting on it there by reducing the thrust required on the valve. This arrangement can have actuators with lower sizes compared to the traditional single-port valves.

6.3.4.2 Cage-guided Valve

Cage-guided valves are similar to plug-in seat valves differing by having a cage member around a flat-bottomed plug. This cage member has shaped flow passages and as the plug rises, this passage or window opens to allow flow to be established and controlled. They may be balanced or unbalanced in design. In an unbalanced valve, the ΔP across the valve acts upon the full unbalanced area of the seat ring. A balanced valve uses a piston seal ring, which enables the downstream pressure to act on both sides of the valve plug, thereby nullifying most of the static unbalanced force. Interchangeability of trim permits choice of several flow characteristics or of noise attenuation or anti cavitation components.

Port-guided valve plugs are usually selected in applications with low pressure, on/off type. The ports guided from both sides makes the operations reliable and stable in harsh operating conditions. Port-guided valves do not reside in a cage they are only guided by the ports, as seen in Figure 6.9. There is no structure resembling a cage and all the way ports are the ones that directly reflect the valve plug position thereby determining the flow characteristics.

High-pressure globe valves are typically available in sizes NPS 1–20 (or DN 25–500) and classes 900, 1500, and 2500 (or PN 150, PN 260, and PN 420). These valves provide throttling control of high-pressure stream and other fluids. Refer to Figure 6.10 for an illustration on the valve. An anti-noise or anti-cavitation trim is often used to handle problems caused by high-pressure drops.

Economical cast iron as well as carbon steel, stainless steel and other high-performance body materials are available. Pressure ratings up to and above class 2500 or PN 420 are available. Their precise throttling capabilities, overall performance, and general sturdiness make sliding-stem valves a good bargain despite their slight cost premium. The buyer gets a rugged, dependable valve intended for long, trouble-free service. Sliding-stem valves are built ruggedly to handle conditions such as piping stress, vibration, and temperature changes. In sizes NPS 3 or DN 80, incremental costs over rotary valves are low in comparison to the increments in benefits received. For many extreme applications, sliding-stem valves are the only suitable choice. This includes valves for high pressure and temperature, anti-noise valves and anti-cavitation valves. Because of process demands, these products require the rugged construction design of sliding-stem products.

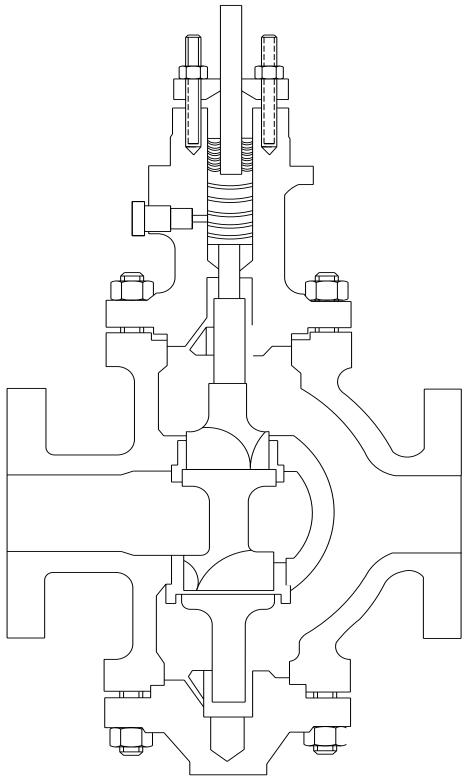

Figure 6.9: Port-guided globe valves

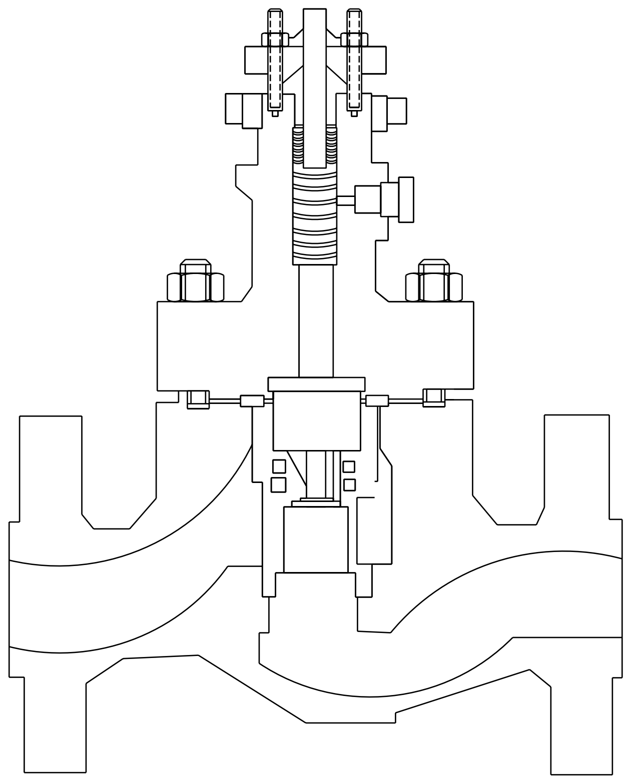

Figure 6.10: High-pressure globe valves

6.3.4.3 Ball Valves

The ball valve is a typical valve where the ball or plug can be rotated within the body through a quarter of a turn. The plug has a passage through it. There are three variations of the ball valve. In the first, the plug is a ball with a line sized circular flow passage, offering minimal flow restriction when fully open. The second is a ball with a V-shaped passage, enabling smooth control at low and high flows. The third is the cock which uses a conical shaped plug. While cocks are traditionally popular in the gas industry, they are seldom used as automatic control valves because the plug tends to jam in the body. Valves employing a rotatable plug achieve tight shutoff.

There are two subcategories of ball valves. The through-bore or full-ball type valve shown in Figure 6.11 is often used for high-pressure drop, throttling and on/off applications in sizes to NPS 24 or DN 600. Full-port designs exhibit high flow capacity and low susceptibility to wear by erosive streams. However, sluggish flow throttling response in the first 20% of ball travel makes full-bore ball valves unsuitable for throttling applications. Newer designs in full-ball, reduced-bore valves provide better response.

Pressure ratings up to class 900 or PN 150 are available, as are a variety of end connections and body materials. Another popular kind of ball valve is the partial-ball style (Figure 6.12). This subcategory is very much like the reduced-bore group except that the edge of the ball segment has a contoured notch shape for better throttling control and higher rangeability. Partial-ball valves intended primarily for modulating service and not merely for on/off control are generally higher in overall control performance than full-ball products. They are engineered to eliminate lost motion that is detrimental to performance. The use of flexible or movable metallic and fluoroplastic sealing elements allows tight shutoff and wide temperature and fluid applicability. Their straight-through flow design achieves high capacity. Sizes range through NPS 24 or DN 600. Pressure ratings go to class 600 or PN 100. Price is normally lower than that of globe valves. The valve shown can be used for pressure drops to 2220 psi (152 bars). Class 600 and 900 or PN 100 and 150 bodies are available; sizes range to NPS 24 or DN 600.

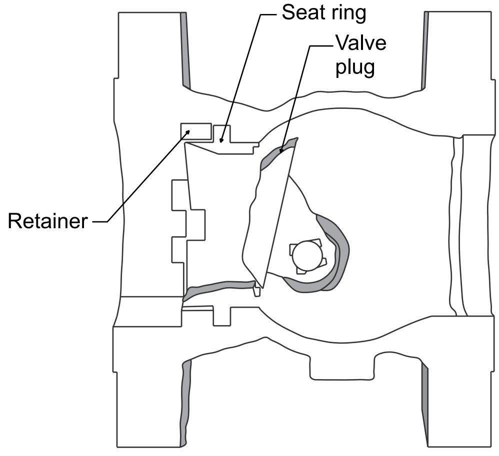

Figure 6.11: Ball valve

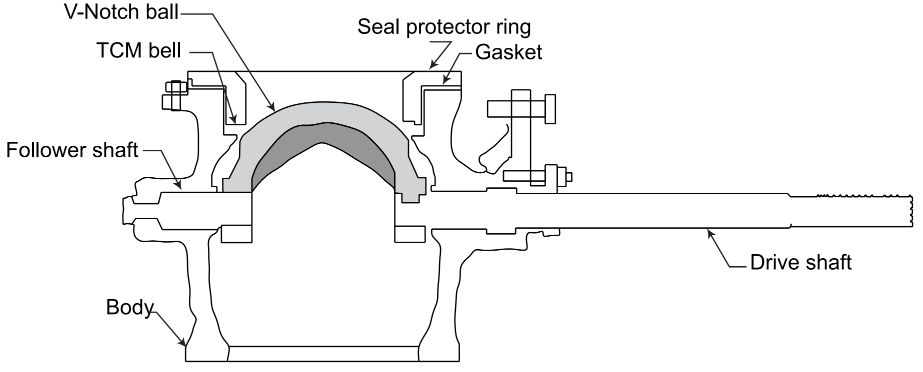

Figure 6.12: Partial ball valve

Applications to class 600 or PN 100 can be handled by this segmented or partial-ball valve. The flangeless body incorporates many features to improve throttling performance and rangeability. Tight shutoff is achieved by either metal or composition seals.

6.3.4.4 Eccentric-plug Valves

Eccentric-plug valves combine many features of sliding-stem and rotary products and use rotary actuators. This design has the shaft centerline different from the body centerline so that the spherical surface of the closure member only contacts the seal near the closed position. As the shaft rotates towards the open position, there is no contact between the closure member and the seal. All eccentric designs must have rotation in only one quadrant.

These valves are available for different types of service. The valve is used for a variety of fluids in both industrial process and utility applications. The valve shown in Figure 6.13 features oversized shafts and rigid seat design for severe service and erosion resistance. Both designs have excellent throttling capability and combine many of the good aspects of rotary and sliding-stem valves. Sizes are available through NPS 8 or DN 200 in ratings to class 600 or PN 100. Flanged and flangeless constructions are usually available.

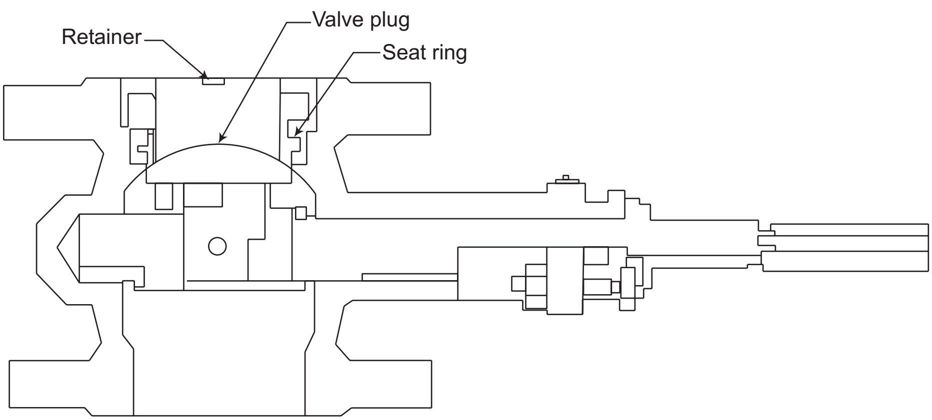

Figure 6.13: Rotary eccentric-plug valve

6.3.4.5 Butterfly Valve

The butterfly valve's vane is so shaped that it closes off the flow passage when it is positioned normal to it. The vane can be rotated with a quarter-turn actuator. Butterfly valves are divided into three subcategories: swing-through, lined and high-performance out of which swing-through design is the most rudimentary one. More like a stovepipe damper but considerably more sophisticated, this kind of valve has no seals—the disk swings close to but clear of the body's inner wall. Such a valve is used for throttling applications that do not require shutoff tighter than +1% of full flow. Sizes range from NPS 2 to NPS 96 or DN 50 to DN 400. Body materials are cast iron, carbon steel, or stainless steel. Mounting is flangeless, lugged, or welded. Body pressure ratings up to class 2500 or PN 420 are common and wide temperature ranges are also available.

While a very broad range of designs is available in these products, they are limited by lack of tight shutoff. Need for no or low leakage requires the lined and high-performance butterfly valves. Lined butterfly valves feature an elastomer or polytetrafluoroethylene (PTFE) lining that contacts the disk to provide tight shutoff. Because this seal depends on interference between disk and liner, these designs are more limited in pressure drop. Temperature ranges are also restricted considerably because of the use of elastomeric materials. A benefit, however, is that because of the liner, the process fluid never touches the metallic body. Thus, these products can be used in many corrosive situations. Elastomer-lined butterfly valves are generally the lowest-priced products available as control valves in medium to large sizes. Heavy shafts and disks characterize high-performance butterfly valves, full pressure rated bodies and sophisticated seals that provide tight shutoff. These valves provide an excellent combination of performance features, lightweight and very reasonable pricing. Eccentric shaft mounting allows the disk to swing clear of the seal to minimize wear and torque. The offset disks used allow uninterrupted sealing and a seal ring that can be replaced without removing the disk. High-performance butterfly valves come in sizes from NPS 2 to NPS 72 or DN 50 to DN 1800 with flangeless or lugged connections. Bodies are carbon-steel or stainless steel and pressure ratings are up to class 600 or PN 100. With their very tight shutoff and heavy-duty construction, these valves are suitable for many process applications. Advanced metal-to-metal seals provide tight shutoff in applications that are too hot for elastomer-lined valves to handle.

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Checkpoint

✦✦ 1. Name two important characterizations of control valves.

✦✦✦ 2. Define linear flow characteristic of the valve.

✦✦ 3. Define equal percentage in control valve.

✦✦ 4. Define rangeability.

✦ 5. What is cavitation?

✦ 6. Which types of valves have more cavitation?

✦✦ 7. Why shutoff capability is an important valve characteristic?

✦ 8. What happens to flow if the pressure drop is increased?

6.4 CONTROL VALVES ACTUATORS

LO 4

Describe control valve actuators

Actuators are the distinguishing elements between valves and control valves. The actuator designs were modified and improvised due to multiple process conditions and ease of operations and maintenance. They were also improvised in terms of the designs, power sources, diagnostic capabilities, etc. As like any other instrumentation system, selection of the right actuator needs knowledge of the process, types of valves and actuators. The actuators ability to perform during static and dynamic conditions of the process will determine the functionality of a control valve. That was the reason why selection and sizing of the actuator is critical.

The types of actuators and their sizes available in the market provide a great selection option in terms of cost and functionality, which is why it of course becomes tough to select. The selection is easier with process knowledge, fundamental needs of the process, etc.

The selection process shall start with the information on the following needs:

- Power source availability
- Failure mode requirements
- Torque or thrust requirements (actuator capability)
- Control functions
- Economics
- Actuator designs and sizing

These factors are important because they quickly narrow the selection process.

6.4.1 Power Source Availability

The first and foremost is the power source to operate the actuator. There are various types of actuators that operate on power sources such as compressed air, electrical power, hydraulic fluid or pipeline pressure, etc. The selection depends on which one is available, and sometimes regulations, safety and also cost. The majority of actuators sold today use compressed air for operation. They operate at supply pressures from as low as 15 psig (1.0 bar) to a maximum of about 150 psig (10.4 bars).

In general most of the industrial operations will have compressed air and electrical sources. Availability of the power source may not be an issue, but ease of the operations with these sources and operating cost of these sources becomes an attribute in the selection criteria. One must also consider reliability and maintenance requirements of the power system and their effect on subsequent valve operation. Consideration should be given to providing backup operating power to critical plant loops.

6.4.2 Failure Mode Requirements

The power sources will be designed to be reliable considering all the failure modes. Redundant operations, multiple sources and redundant lines are general design considerations. After all such design considerations, many loops will demand a specific valve action if the power source fails. This failure action is decided to protect the equipment or personal in the event of a power source failure to the valve. The actuators are designed to store energy, either using springs or volume tanks or hydraulic accumulators in the event of failure. During a failure mode, the actuator takes a predefined position as defined and resumes to normal after the failure event is recovered. The actuator designs provide options to choose the action of the valve as fail open, fail close, hold to last value, etc. These features became fundamental such that they are available at the base price with no additional cost. Usually, spring and diaphragm-based actuators are fail close, fail open by the basic physics. The electrical actuators can provide holding to the last position.

6.4.3 Torque or Thrust Requirements (Actuator Capability)

Actuators have to create the thrust or torque required to move the stem to the desired position. The torque or thrust is required to counter the force in the pipeline. Many times the thrust needs of the application are critical for selecting the type of actuator and the type of power source. In case of a need to control a valve with large pipeline with high pressure an electric or electrohydraulic actuator is required. The pneumatic solutions do create such thrust with the currently available technologies. Similarly, electrohydraulic actuators applied in process with low thrust requirements is a bad choice. Again, the type of actuator and the type of valves considering the frictional forces and fluid forces operating on the valve becomes a criteria for selection.

6.4.4 Control Functions

The control functions required in an actuator should be known before selection. Knowledge of such functions helps to select the actuators with optimum functions and cost. Some of these functions include signal (pneumatic, electrical, analog, etc.), ranges of such signals, vibration levels, ambient temperature, granularity of control expected, etc. Again the type of signal can be further divided if the type of control is on/off type, two position control or throttling type analog control. The simple on/off type can be achieved using switches for each type of signals. This is simplest form of automatic control with less cost.

The analog type throttling control requires more sophistication and is driven for performance due to the nature of control. In this case, the actuator receives a signal from a controller. Based on the signal, the actuator has to move the stem to a position by exerting force accurately with a good response time. This is required to ensure better control by the valve during static and dynamic loading in the process. The signal types required for actuators can be provided by suitable converters; however, for higher size actuators a signal without a conversion of a better choice. This can provide a valve with low hysteresis and minimum dead band.

Stroking speed, vibration, and temperature resistance must also be considered if critical to the application. Stroking speed is generally not critical; however, flexibility to adjust it is desirable. With liquid service, fast stroking speeds can be detrimental because of the possibility of water hammer.

Vibration or mounting position can cause problems as the actuator weight combined with the weight of the valve might require bracing. If extremes of temperature or humidity are to be experienced by the control valve, this information is essential to the selection process. Sometimes the actuators can be made of elastomeric or electronic components which might get degraded if there is high humidity or high temperature.

6.4.5 Economics

Evaluation of the actuators should not be limited to the purchase cost, but should also include cost of installation, cost of maintenance, cost of spare parts, etc. A simple actuator such as a spring and diaphragm actuator has few moving parts, is easy to service, and normally causes fewer problems. Initial cost of such an actuator is low and maintenance technicians are quite conversant with these. Generally, an actuator designed for a type of valve is suitable for the application and eliminates the mismatch of the performance and also if the actuator and valves are purchased as a package, the cost will reduce due to less spare parts and easy maintenance, etc. Similarly if there are parts that are interchangeable with multiple valve/actuators, then the spare part inventory can be minimized.

Savings of installation and maintenance costs are available from packages that combine the valve, actuator, and accessories in a modular unit. The components are designed to work together, external piping is reduced and complicated exposed linkages are eliminated.

6.4.6 Actuator Designs and Sizing

There are many types of actuators for rotary and sliding-stem valves. There are five major types of actuators commercially available—spring and diaphragm, high-pressure spring and diaphragm, pneumatic piston, electric motor, and electrohydraulic.

Every actuator has its own strengths, weaknesses and different applications. Actuator designs are mostly available for either sliding-stem or rotary valve bodies as these are most prevalent in the industry. The only difference amongst them is in terms of linkage or motion translators.

6.4.6.1 Spring and Diaphragm Actuators

Push Down to Close Construction/Air to Close A globe-style valve has a connection between the actuator and the seat ring in which the closure member is located. The stem extended to the valve chamber moves the seat ring to closer and restricts the flow path. The same is applicable in a rotary shaft valves where in the stem moves the ball or disk towards the closure.

Push Down to Open Construction/Air to Open A globe-style valve has a connection between the actuator and the seat ring in which the closure member is located. The stem extended to the valve chamber moves the seat ring to open and allow the flow path. The same is applicable in a rotary shaft valves where in the stem moves the ball or disk towards the opening (reverse acting).

Rotary valve designs are similar to the sliding-stem designs with additional linkages, gears to convert a linear movement to a rotary movement.

Sliding-stem actuators are rigidly fixed to valve stems by threaded-and-clamped connections. Sliding-stem actuators are very simple in design. Because they do not have any linkage points and their connections are rigid, they exhibit no lost motion and excellent inherent control characteristics.

As rotary and sliding-stem actuators are similar in concept and characteristics, they cannot be further differentiated in this section.

Spring and diaphragm actuators offer an excellent choice for most control valves. They are inexpensive and simple, and they have an ever-present, reliable spring fail action. Following are two styles: on the left, air-operating pressure opens the valve and the spring closes it (air to open; spring closes); on the right, air to close and spring opens. The spring and diaphragm actuators provides mechanism for an accurate throttling control.

Diaphragm Actuators The spring and diaphragm type actuators are the most widely used variety in the process control valves. The reason for their widespread adaptation is their simplicity, low cost and better reliability. These actuators act on the pneumatic signals received from the control system and these signals will be typically in the range of 3–15 psi. Due to these features, these actuators are most suitable for throttling service as they can act on the valve based on the signal received from the control systems directly.

The spring and diaphragm designs offer flexibility to adjust the spring tension or a range of springs for a wide variety of applications. Due to less moving parts, these actuators are treated as reliable since there is no contributing parts that fail often. Even in the case of failure, maintenance of the same is simple. The designs are also made safe for the maintenance engineers during repairs with less compression while having the same force.

The widely accepted advantage of these actuators is their inherent characteristics during failure. As discussed earlier, these valves can reach a position in the event of supply failures. Once pressure is acted on the actuator, the diaphragm moves the valve. The movement of the valve compresses the spring. The energy stored in the spring moves the valve back, if there is no pressure acting on the diaphragm. The same mechanism is applicable in the event of failure of power source to the valve. The process conditions will define the type of action required for each type of valve and they can either fail to open or fail to close.

The disadvantage with these actuators is the limited thrust they can create. The thrust created by the diaphragm is shared by the spring and the stem. This will limit the application of these actuators where there is moderate force. For large applications, building such a diaphragm and spring is not economical for the benefits that we get and also compared to the other alternatives. This limitation is mitigated, however, by the fact that most valves are small and have low force requirements.

6.4.6.2 High-Pressure Spring and Diaphragm Actuators

High-pressure spring and diaphragm actuators share many of the advantages of standard spring and diaphragm actuators and offer additional advantages. The use of higher supply pressure allows the actuator to be smaller and lighter than typical diaphragm actuators. The smaller size makes modular construction easier to provide. Modularity makes maintenance easier and allows complete integration of instruments and accessories. High-pressure spring and diaphragm actuator are featuring integral control and accessories and modular construction. The spring and diaphragm are contained in the power module assembly. Tubing, linkage, and mounting brackets are either eliminated or enclosed.

6.4.6.3 Pneumatic Piston Actuator

Piston actuators are the second most popular control-valve actuators. These are small in size, but can generate torque more than spring and diaphragm types. These actuators operate with pressure between 50 psi to 150 psi (3.5–10.4 bar). Although piston actuators can be equipped with spring returns, this construction has limits similar to those of the spring and diaphragm style (Figure 6.14).

Generally, piston actuators are provided with double acting positioners if they are used for regulatory control where throttling of the valve is a primary need. In these cases, the piston is loaded and unloaded in opposite sides of the actuators. The pressure differential so created makes the piston move the actuator towards the lower side and get settled once the pressure on both sides is equal. These actuators are preferred if the thrust required for the application cannot be met by the spring and diaphragm type actuators. Even though these actuators require higher supply pressure, the stiffness, smaller size and more thrust on the valve makes them the choice of selection.

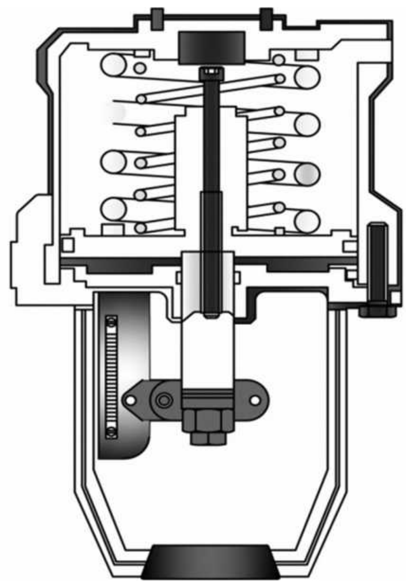

Figure 6.14: Piston actuator

Spring fail action is available in this spring-based piston actuator. Process pressure acting on the valve plug can aid fail action, or the actuator can be configured so that the spring alone closes or opens the valve on failure of operating pressure. Piston actuator controls a rotary valve. The valve linkage and clamped connector eliminate lost motion and provide throttling accuracy. For on/off service and some throttling applications, requirements for accuracy and minimum lost motion are not necessary, and a simple design such as this can save money.

It is an excellent choice when a compact high-power unit is required. It can also be used in applications where there are high ambient temperatures.

As discussed earlier, the major disadvantages are high supply pressure needs, lack of inherent failure modes. There are some designs such as spring return piston actuators available which again operate on the same spring and diaphragm mechanism. These actuators load the piston chamber to move the actuator while compressing the spring. The spring moves the piston back once the supply pressure is removed. These mechanisms need high output springs for overcoming the fluid forces in the valve. Alternative designs have small springs and use the fluid force to act in fail action. In normal situation, it acts like a double acting piston and during failure the spring initiates the force and is supplemented by the force at the plug created by the fluid.

The only failure-mode alternative to springs is pressurized air volume tank pneumatic trip system to move the piston actuator to its fail position. Although these systems are quite reliable, they add to overall system complexity, maintenance difficulty, and cost. Therefore, for any failure-mode requirement prime consideration should be given to spring-return actuators if they are feasible.

During the selection of the piston actuator, the hysteresis and dead band needs to be considered. The hysteresis and dead band should be minimum to operate the valve for throttling applications. If there are more linking points, there will be large dead band and similarly if there are more sliding parts, there will be more hysteresis. The cost of a diaphragm actuator is less compared to a similar piston actuator, where in the diaphragm type can use instrument output air and also operates with a fail action. These two points strongly favor the diaphragm type whereas pistons ability to create more thrust has its favors based on its application.

6.4.6.4 Electric Motor Actuators

The electric actuators are selected in many applications where there is a need for wide range of torque output, or special needs for thrust or stiffness or no other suitable power source is available. Electric actuators are economical, compared to pneumatic ones, for applications in small size ranges only. Larger units operate slowly, weigh considerably more than pneumatic equivalents, and are more costly. Precision throttling versions of electric motor actuators are quite limited in availability. In case of using the electric motors for throttling control, where the precision movement in a more frequent manner is needed, a suitable duty cycle should be selected. However, the electric motor actuators provide higher output for similar other sizes and are stiff to resist the valve forces acting on the seat. These actuators are also selected in high pressure valves for regulatory control.

6.4.6.5 Electrohydraulic Actuators

Electrohydraulic actuators are electric actuators in which motors pump oil at high pressure to a piston, which in turn creates the output force. The electrohydraulic actuator is an excellent choice for throttling because of its high stiffness, compatibility with analog signals, excellent frequency response, and positioning accuracy. Most electrohydraulic actuators are capable of very high outputs, but they are limited by high initial cost, complexity, and difficult maintenance. Failure-mode action on electrohydraulic actuators can be accomplished by the use of springs or hydraulic accumulators and shutdown systems.

6.4.6.6 Actuator Sizing

An important consideration in the selection of actuators is their sizing needs. The process is generally towards matching it with the needs of the valve and its size. The general factors considered are the valve forces acting in its critical positions (travel) and the output of the actuator. In general the total forces acting on the valve depend on the type of valve and the designs specific to manufacturer. However, the forces such as static fluid force, dynamic forces, friction, seat loading, etc., are considered as forces.

6.4.7 Actuator Selection Factors

As discussed earlier, the fundamental selection criteria for selecting an actuator is the type of the control signal, its mode of operation, available power source, thrust, etc. Table 6.5 helps the engineer to make an informed decision on actuator selection.

Table 6.5: Actuator selection criteria	
Advantages	*Disadvantages*
Spring and diaphragm actuator	
Lowest cost	Limited output capability
Ability to throttle without positioner	Large size and weight
Simplicity	
Inherent failure-mode action	
Low supply-pressure requirement	
Adjustability to varying conditions	
Ease of maintenance	
High-pressure spring and diaphragm actuator	
Compact, light weight	Requires high supply pressure
No spring adjustment needed	psig (2.8 bars) or higher
Costly cast components not needed	Positioner required for throttling
Inherent fall-safe action	
No dynamic stem seals or traditional stem connector block needed	
Design can include integral accessories	
Pneumatic piston actuator	
High force or torque capability	Fall-safe requires accessories or addition of a spring
Compact, light weight	Positioner required for throttling
Adaptable to high ambient temperatures	Higher cost
Fast stroking speed	High supply-pressure requirement
Relatively high actuator stiffness	
Electric motor actuator	
Compact	High cost
Very high stiffness	Lack of fail-safe action
High output capability	Limited duty cycle
Supply pressure piping not required	Slow stroking speed
Electro hydraulic actuator	
High output capability	High cost
High actuator stiffness	Complexity and maintenance difficulty
Excellent throttling ability	Fail-safe action only with accessories
Fast stroking speed	

In addition to the above, ease of maintenance, life cycle cost and safety are additional parameters to be critically evaluated.

The spring-and-diaphragm actuator is the most popular, versatile, and economical type and is recommended to be tried first. If the limitations of available diaphragm actuators eliminate them, pistons or electric actuators may be considered, bearing in mind the capabilities and limitations of each.

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Checkpoint

✦✦ **1.** How actuators are powered?

✦✦✦ **2.** What is the significance of failure mode in actuators?

✦ **3.** If the valve requires high thrust, then what is the option for the power source (electric or electro hydraulic)?

✦✦ **4.** From where the signal for the throttling actuator is received?

6.5 VALVE CONTROLLERS AND ACCESSORIES

LO 5

Explain valve controllers and accessories

The study of control valves is incomplete without a look at devices that augment the valve function and interface it to control systems. Included in this category are devices such as digital valve controllers and traditional valve positioners, electropneumatic transducers, limit switches, and manual actuator overrides. These devices assure controllability, provide information about valve operation, and allow for operation or shutdown in emergencies.

6.5.1 Valve Positioners and Controllers

The position of a control valve actuator is accurately positioned in response to a control signal thereby improving the control. The positioner takes the input signal (4–20 ma or 3–15 psi) and gives the output power in the form of pneumatic pressure to the actuator. The feedback mechanism between the valve stem and positioner is formed by the linkage and proper signal and position can be established as needed by the controller.

Positioners are required to linearize the stem position with the control signal and thereby improve the performance of the control valves. Sometimes, the process dynamics eliminate use of positioners. The use of positioners degrades on very fast loops as the response of the positioner is unable to keep up with the system.

Positioners operate with an electronic input signal and pneumatic output or with a pneumatic input and output signal. A few of the electronic versions of positioners accept an analog input signal, and while others accept a digital input signal.

6.5.2 Digital Positioners

Digital valve positioners are of three types:

- **Analog signals:** An output signal (4–20 mA) from the controller is provided to the positioner. The loop powered signal is used for the positioner electronics as well as a control signal.
- **HART communications:** Similar to the above, with a HART (highway addressable remote transducer) signals are superimposed on control signals. These signals can provide additional diagnostics information in the same wires used for control signal and loop power purposes.
- **Fieldbus:** It receives digital signals and positions the valve by using digital electronic circuitry coupled to mechanical components. In these positioners, the analog communication is completely removed and the data/signal is transmitted in both directions by digital means. These methods of communication provide more diagnostics, better reliability and reduced cost of installation.

There is a general trend toward greater use of digital valve controllers on control valves for the following reasons:

- Reduced cost of loop commissioning that includes installation and calibration.
- Using diagnostics maintain loop performance levels.
- By reducing the process variability, process control is improved.
- Offsets the decreasing mechanical skill base of instrument technicians.

The following features of digital valve controllers create most value addition to the users:

- **Automatic configuration and calibration:** The ability to configure the system by automatic means and ability to calibrate the system easily reduces the cost of engineering and cost of maintenance.
- **Valve diagnostics:** The valve diagnostics is important information for troubleshooting the issues in the field. The digital valve positioners can provide the diagnostics information to the DCS, or to the special software tools or handheld communicators. This information can be used to assess the health and further action can be taken very easily.

6.5.3 Electropneumatic Transducers

Electropneumatic transducers are devices that convert an electronic input into a proportional pneumatic output signal. Electropneumatic transducers are used in electronic control loops to help operate pneumatic control valves.

Most transducers convert a standard 4–20 mA signal to a 3–15 psig (0.2–1.0 bar) pneumatic output. Devices are also available that can respond to digital signals and nonstandard analog inputs. The transducer function is sometimes included with the valve positioner. If the transducer is included, the device is known as an electropneumatic positioner, where the input is an electronic signal and the output is position.

6.5.4 Volume Booster

The volume booster is normally used in control-valve actuators to increase the stroking speed. These pneumatic devices have a separate supply pressure and deliver a higher-volume output signal to move actuators rapidly to their desired positions. Special booster designs are also available for use with positioners. These devices incorporate a dead-band feature to adjust their response and eliminate instabilities. This booster, therefore, permits high actuator stroking speeds without degrading the steady-state accuracy provided by positioners in the loop.

6.5.5 Trip Valves

The trip valves are pressure sensing in nature and are required if a special valve action is required in case of problems in the supply pressure. These valves sense the supply pressure getting reduced or no supply pressure and cause the actuator to force the valve to specific position such as open, close or last position. The valve operation is regained back once the supply pressure is resumed. Pneumatic volume tanks provide the auxiliary power to actuator action in case of trip valve operation.

6.5.6 Limit Switches

Electrical position switches are often incorporated on control valves to provide the operation of alarms, signal lights, relays, or solenoid valves when the control-valve position reaches a predetermined point. These switches can be either integrated, fully adjustable units with multiple switches or stand-alone switches and trip equipment. Keep harsh environmental conditions in consideration while selecting limit switches to assure functionality over time.

6.5.7 Solenoid Valves

Small, solenoid-operated electric valves are often used in a variety of on-off or switching applications with control valves. They provide equipment override, failure-mode interlock of two valves, or switching from one instrument line to another. A typical application involves a normally open solenoid valve, which allows positioner output to pass directly to the actuator. On loss of electric power, the solenoid valve closes the port to the valve positioner and bleed pressure from the diaphragm case to the control valve, allowing it to achieve its fail position.

6.5.8 Position Transmitters

Electronic position transmitters are available that send either analog or digital electronic output signals to control-room devices. The instrument senses the position of the valve and provides a discrete or proportional output signal. Electrical position switches are often included in these transmitters.

6.5.9 Manual Hand Wheels

A variety of actuator accessories are available which allow for manual override in the event of signal failure or lack of signal previous to start-up. Nearly all actuator styles have available either gear-style or screw-style manual override wheels. In many cases, in addition to providing override capability, these hand wheels can be used as adjustable position or travel stops.

In this concept animation, the final control element, which is the critical element of the closed loop is presented. The control valves includes, valve, actuators and positioners. The principle of operation and dynamic movements in the event of a signal are presented.

For process-related video, scan the QR code
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Checkpoint

✦✦✦ **1.** What is the need for positioners in control valves?

✦✦ **2.** What are the different types of inputs received by the positioners?

✦ **3.** What is the purpose of the electropneumatic transducer in control valve systems?

✦✦✦ **4.** What is the purpose of the volume boosters in control valve systems?

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6.6 CALIBRATION PROCEDURES OF CONTROL VALVES

LO 6
Illustrate the calibration procedures of control valves

6.6.1 Pressure to Current Transmitter (PIT)

The following is a sample setup to be used while performing the calibration of the control valve systems.

6.6.6.1 Calibrating Pressure

The following steps explain calibrating a pressure to current transmitter using standard calibrator.

1. Connect the calibrator to the instrument under test as shown in Figure 6.15.
2. Press button appropriate for current (upper display). If required, press appropriate button again to activate loop power.
3. If necessary, press source mode button.
4. Zero the pressure module.
5. Perform checks at 0% and 100% of span and tabulate the readings "As Found" values.

6. Adjust the transmitter as necessary to minimize the deviation of As Found value and *actual value*.
7. Repeat step 6 and tabulate the reading "As Left" values. If error % is within the range. Then the calibration is performed successfully. If not repeat steps 6 and 7 until error % is within the specified range.

6.6.2 Current to Pressure Transmitter (IPT)

6.6.2.1 Calibration Procedure

There are two options as shown in Figure 6.15—current to pressure calibration setup for monitoring the output of the IPT. The input current can be measured by connecting a multimeter (current mode) in series with the input terminals as shown by M1. The same can be done by connecting test pins across the multimeter with less than 10Ω impedance (+*T* and –*T*) as indicated by M2. The list of equipment is shown in the Table 6.6 and the general flowchart for the calibration procedure is shown in Figures 6.16 and 6.17. The steps are as follows:

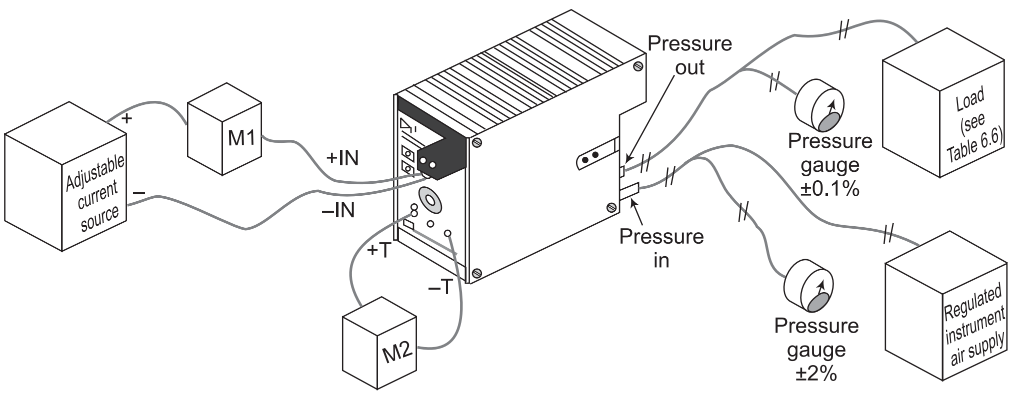

Figure 6.15: Current to pressure calibration setup

1. For zero correction, connect the current source to the input terminals. Set the input current to be 4 mA.
2. Connect the pressure gauge to measure the input supply pressure. Connect the filtered clean air supply to the port allocated. Please make sure that the pneumatic connections are made with no leakages.
3. Measure the pressure in the gauge and it should be 3 psi for the unit connected with the input of 4 mA.
4. The deviations from the above readings needs to be recorded and adjusted by the potentiometers or using the digital communication commands based on the type of the instrument.
5. The deviation in the output pressure (e.g. 15 psig for a 3—15 psig unit) is corrected by the span potentiometer or digital commands from the communicators based on the

type of instruments. Note that sometimes the adjustments are not performed if the deviations are not more than certain threshold.

6. Repeat steps 1 through 5 (as applicable) until no further adjustments are required.

Table 6.6: List of equipment for calibration

Equipment	*Characteristics*	*Purposes*
Adjustable current	0–50 mA output	Simulate input signal
Source dc milliammeter	Accuracy to ±0.05%	Measure input signal
Instrument air supply	Filtered	Air supply
Air supply pressure gauge	Accurate to ±2%	Measure air supply pressure
output pressure gauge	Accurate to ±0.1 %	Measure output pressure
Phone tip probes	Must have 2 mm diameters tips, etc.	Easy access to input signal (optional)
Pneumatic test coupler	For IPT with optional test jacks	Easy monitoring of output pressure (optional)
Load	Volume of 7.5 in^3	Provide standard load for testing

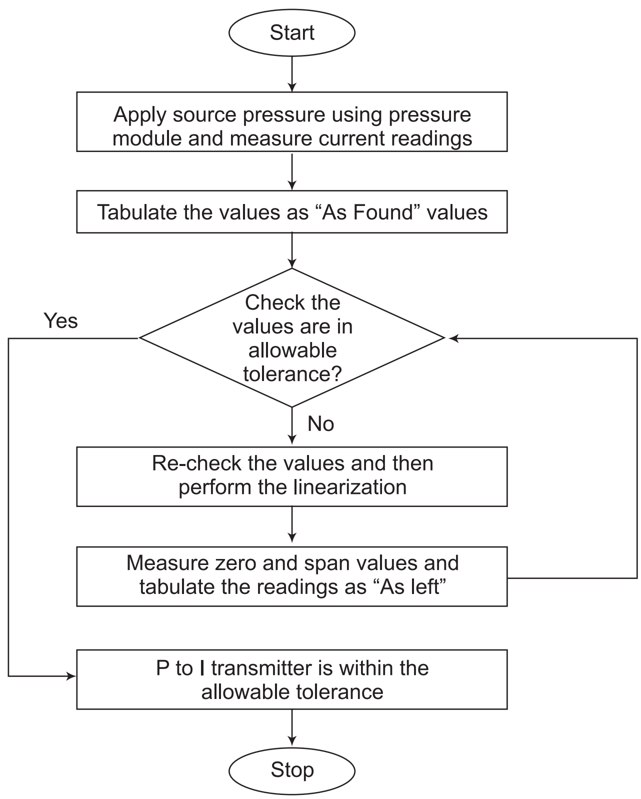

Figure 6.16: Flowchart for the calibration of PI converter

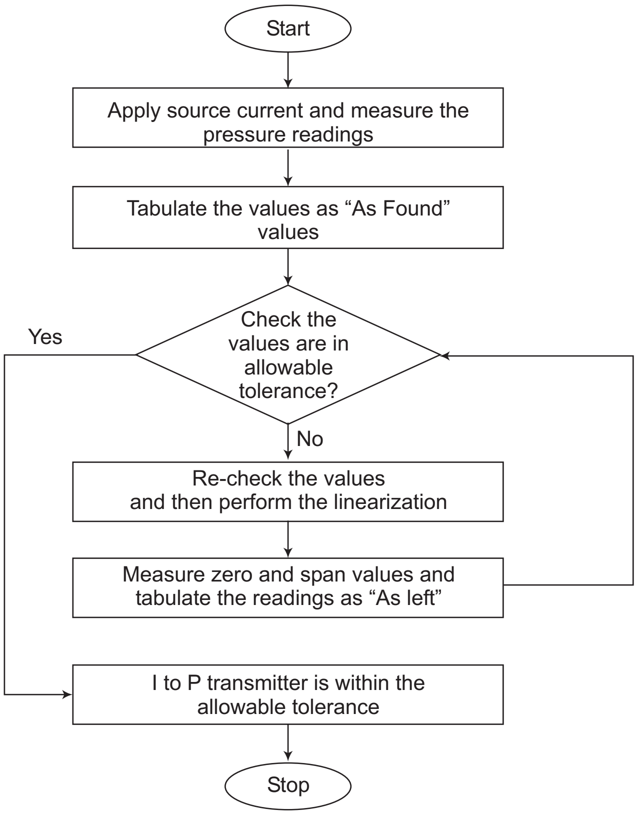

Figure 6.17: Flowchart for the calibration of IP converter

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Checkpoint

✦ 1. List the equipment needed to calibrate a control valve positioner?

✦✦ 2. How the valve characteristics are calibrated in a laboratory environment?

Summary

LO 1: Describe and classify control valves

- The combination of valve and actuator is called an automatic control valve or simply a control valve.
- The control valve, or final control element, is the last device in a control loop. It takes signal from the process instruments and acts directly to control the process fluid.
- Control valves maintain process variables such as pressure, flow, temperature, or level at their desired value, despite changes in process dynamics and load.

LO 2: Analyze the parameters to evaluate the performance of control valves

- Dead band is the range through which an input can be varied without initiating an observable response.
- Control valve assemblies can be a primary source of dead band in an instrumentation loop. It is usually expressed as a percentage of diaphragm pressure spans.
- An actuator is the final part of control element that converts the control signal into action of the final control device. Cylinders, motors, and solenoids are some of the examples.
- The microprocessor-based positioners have performance equivalent to the conventional two-stage pneumatic positioners. They also provide diagnostic capabilities and valve monitoring that ensures initial good performance does not deteriorate with use.
- If a control valve assembly can quickly respond to these small changes, process variability is improved. This is a function of the volume of air that is required to produce any desired pressure on the diaphragm of a valve actuator.
- For a given increase of valve travel, an oversized valve usually produces a disproportionate flow change. This phenomenon in turn produces friction and exaggerates the process variability associated with dead band.
- Control valve assemblies play an important role in loop/unit/plant performance.

LO 3: Outline control valves' capabilities and capacities

- Installed flow characteristic is the flow characteristic that is obtained when pressure drop ΔP across the valve varies as dictated by flow and related conditions in the system in which the valve is installed.
- Linear describes an inherent flow characteristic that can be represented ideally by a straight line on a rectangular plot of flow versus percentage of rated valve stem travel. A linear valve gives approximately equal increments of flow per increment of valve stem travel at a constant pressure drop. Equal-percentage describes an inherent flow characteristic that for equal increments of rated travel will ideally give equal-percentage changes of the existing flow.
- Quick-opening describes an inherent flow characteristic in which there is maximum flow with minimum travel.
- Rangeability, an important flow characteristic is the ratio of maximum and minimum controllable flow rates.
- Sliding-stem valves are generally superior in both regards because of the rugged, well-supported design of their moving parts.
- Cavitation is the noisy and potentially damaging implosion of bubbles formed when the pressure of a liquid momentarily dips below its vapor pressure through a constriction at high velocity.

- Rotary valves have more limited noise and cavitation-control options and are also much more susceptible to cavitation and noise at a given pressure drop.
- Tight shutoff is particularly important in high-pressure valves because leakage can cause seat damage, leading to ultimate destruction of the trim.
- Sizing equations suggest that as the pressure drop is increased, flow increases proportionally—forever. In reality, this relationship holds only for certain conditions. As the pressure drop is increased, choked flow caused by the formation of vapor bubbles in the flow stream imposes a limit on liquid flow. A similar limitation on flow of gases is realized when velocity at the valve vena contracta reaches sonic velocity.
- As the pressure differential is increased, a point is reached where the realized flow increase is less than expected. This phenomenon continues until no additional flow increase occurs in spite of increasing the pressure differential. This condition of limited maximum flow is known as choked flow.

LO 4: Describe control valve actuators

- Large valves requiring high thrust might be limited to only electric or electrohydraulic actuators because of a lack of pneumatic actuators with sufficient torque capability. Conversely, electrohydraulic actuators would be poor choice for valves with very low thrust requirements.
- Throttling actuators have considerably higher demands put on them for both compatibility and performance. A throttling actuator obtains input from an electronic or pneumatic control process instrument. This causes the actuator to move to the final control valve in response to the instrument signal in an accurate and timely manner which in turn ensures effective control.
- Spring fail action is available in this spring-biased piston actuator. Process pressure acting on the valve plug can aid fail action, or the actuator can be configured so that the spring alone closes or opens the valve on failure of operating pressure.
- The cost of a diaphragm actuator is generally less than that of a comparable-quality piston actuator. Part of this cost savings is in the ability to use instrument output air directly, thereby eliminating the need for a positioner. The inherent provision for fail action in the diaphragm actuator is also a consideration.
- The electric actuator provides highest output available within a given package size. In addition, electric actuators are stiff and resistant to valve forces. Thus, electric actuators become the best choice for throttling control of large high-pressure valves.

LO 5: Explain valve controllers and accessories

- Positioners operate with an electronic input and pneumatic output or with both input and output pneumatic signals. Some of the electronic versions accept an analog input signal, and others accept a digital input signal.
- Most transducers convert a standard 4- to 20-mA (milliampere) signal to a 3- to 15-psig (0.2–1.0 bar) pneumatic output. Devices are also available that can respond to digital signals and nonstandard analog inputs.
- These pneumatic devices have a separate supply pressure and deliver a higher-volume output signal to move actuators rapidly to their desired positions.

Questions

I. Objective-type questions

✦✦ **1.** In a simple complete measurement and control loop, the current output from the controller is sent to what element on the control side?

(a) I/P current coil (b) Transmitter
(c) 250 ohm transistor (d) Flapper and nozzle or pilot valves

✦✦✦ **2.** The purpose of the plug within the control valve is to:

(a) Send a signal to the control valve to maintain the setpoint
(b) Allow the valve to rotate without any linear motion
(c) Create a flow area that modifies the flow rate
(d) Measure the upstream pressure of the property

✦✦ **3.** What is the most important thing to know in troubleshooting a valve problem?

(a) Composition of the valve (b) Fail-safe mode of the valve
(c) Velocity of the valve (d) Temperatures the valve is exposed to

✦✦ **4.** Which of the following valve actuators has the lowest cost and low friction and dead band?

(a) Pneumatic (b) Electric
(c) Solenoid (d) Hydraulic

✦✦✦ **5.** Which of the following works well when a great deal of force and a small actuator are needed?

(a) Pneumatic actuation (b) Electrical actuation
(c) Hydraulic actuation (d) Manual actuation

✦✦ **6.** Cavitation occurs in liquid flow when:

(a) Mixtures of fluid and vapor cause erosion of the valve and pipe surfaces
(b) Fluid pressure drops below the liquid's vapor pressure and the vapor pressure is above the outlet pressure
(c) Gas and vapor flow become sonic and the flow rate drops
(d) Fluid pressure drops below the liquid's vapor pressure and the vapor pressure is below the outlet pressure

✦ **7.** What is the difference between a linear valve and a rotary valve?

(a) Linear valve has an integral bonnet; a rotary valve has a separable bonnet
(b) Linear valve is flangeless; a rotary valve is usually threaded
(c) Linear valve is suited to low pressure applications; a rotary valve can handle high-pressure applications
(d) A linear valve has a low recovery; a rotary valve has a high recovery.

✦✦ **8.** A pneumatic positioner is used to:

(a) Increase fast venting capability
(b) Overcome packing friction

(c) Diagnose itself and the valve actuator system.
(d) Eliminate use of piston actuators

✦✦✦ **9.** In selecting the appropriate control valve, the initial consideration is:
(a) Calculating the valve sizing coefficient
(b) Determining the pressure rating of the valve
(c) Identifying the point of highest fluid velocity and lowest pressure
(d) Determining the degree of pressure recovery downstream

✦✦ **10.** In a post-guided valve application, the valve:
(a) Is positioned in the active flow stream
(b) Uses a shaft to connect the closure member to the actuator
(c) Is well suited for slurries and fluids with entrained solids
(d) Has a cylindrical plug with a seat ring

✦✦ **11.** Cavitation is typically not caused by which of the following?
(a) Internal recirculation (b) Air temperature
(c) Flow turbulence (d) Vaporization

✦✦ **12.** Which type of control valve is most appropriate for handling a low pressure drop in a pipe over 2 inch in diameter?
(a) Ball
(b) Linear motion globe/angle type with simple plug
(c) Linear motion globe/angle type with cage
(d) Butterfly

✦✦✦ **13.** Which of the following is final control element in process control?
(a) Thermocouple (b) Control valve
(c) Controller (d) Temperature transmitter

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II. Short-answer questions

✦ **1.** Valve response is a function of volume of air to__________.

✦✦ **2.** Which type of valve plugs are used for on/off or low pressure throttling service?

✦✦✦ **3.** What are the advantages of electric actuators?

✦✦ **4.** What is the purpose of trip valves in control valves?

✦✦✦ **5.** What is the purpose of the limit switches in control valves systems?

III. Unsolved problems

✦✦ **1.** A control valve has to be selected to measure the water flow with a range of 0–2500 gallons per minute at 60°F. the specific gravity of water at 60°F is 1. If the maximum allowed pressure drop across valve is 0.25 psi. Calculate the C_v (valve capacity) of the control valve.

✦ **2.** In an equal-percentage valve with maximum flow capacity as 10,000 GPM and valve rangeability of 50, when the valve is at 49% open position, calculate the flow rate of the liquid.

✦✦✦ **3.** An instrumentation engineer needs a quarter turn shutoff valve to flow approximately 12 GMP (Q) of fluid with an inlet pressure (P1) of 3000 psig and outlet pressure (P2) of 2900 psig. The fluid is clean water at room temperature. Calculate the C_v (flow coefficient) of the control valve required for this application.

✦✦✦ **4.** An instrumentation engineer needs a high performance check valve for an ammonia system. His required flow rate is 2.25 GPM (Q). He selects a control valve with $C_v = 0.32$. If specific gravity of ammonia is 0.662, calculate the pressure drop across the valve.

IV. Critical-thinking questions

✦✦ **1.** What are the consequences of an oversized valve selection?

✦✦✦ **2.** What is a chocked flow?

✦✦ **3.** What is a globe valve?

✦✦ **4.** How the problems arising in high pressure valves with high pressure drop are handled?

✦✦ **5.** What are the different categories of butterfly valves?

✦ **6.** Why cost of the diaphragm actuators are less compared to others.

✦✦ **7.** What is the significance of calibration of I/P converter?

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Process Control

7

Process control refers to a form of automatic process control in which the information from both sensing elements and actuating devices can have any value between minimum and maximum limits. This is in contrast to discrete control where the information normally is in one of the two states such as on/off, open/closed, run/stop, etc.

In addition to a controlled process, each control loop consists of a sensing device that measures the value of a controlled variable; a controller that contains the control logic along with provisions for human interface; and an actuating device that manipulates the rate of addition or removal of mass or energy or some other property that can affect the controlled variables. In emerging technology, the control logic may be located at either the sensing or the actuating device. There are also applications for continuous control in discrete industries like a temperature controller on an annealing furnace, or motion control in robotics. The central device in a control loop, the controller, may be built as a standalone device or may exist as shared components in a digital system, like a distributed control system (DCS) or programmable logic controller (PLC). Process control systems, and the related functions of measurements and alarms, are represented using special symbol on "piping and instrument diagrams" (P&IDs). A P&ID shows the outline of the process units and connecting piping as well as a standard symbolic representation of the instrumentation and control (I&C) systems.

Keywords:
Accuracy, control, PID, feedforward, feedback, ratio, split range, model predictive control, loop tuning, inferential control, control loop, process

LEARNING OBJECTIVES

After reading this chapter, you will be able to:

1. Describe process control, symbols and hardware components of a control loop
2. Outline the characteristics of industrial process
3. Analyze the role of PID controller in process control
4. Illustrate the applications of cascade/feedforward controller in process control
5. Explain the applications of inferential control
6. Illustrate the applications of split-range control
7. Describe the control of MIMO processes in process control applications

"If a measurement matters at all, it is because it must have some conceivable effect on decisions and behavior. If we can't identify a decision that could be affected by a proposed measurement and how it could change those decisions, then the measurement simply has no value"

Napoleon Hill

7.1 PROCESS CONTROL SYMBOLS AND HARDWARE COMPONENTS OF A CONTROL LOOP

LO 1

Describe process control, symbols and hardware components of a control loop

To develop effective control solutions, it is essential for a process control engineer to understand the underlying process. It is important to understand the interconnections of the process, rank order priorities for the objectives of the process, various constraints, and major disturbances affecting the process. Control solutions design must effectively solve the real process problems and function properly with regards to the entire plant. Often, simple and effective process control solutions stem from a good understanding of the process and fundamental characteristics of various control options.

Let us consider a level controller (LC) for the overhead accumulator of a distillation column that provides feed to a reactor (Figure 7.1). The quality of the primary product of the overall process is affected by sharp changes in feed rate that upset the reactor. Therefore, it is important to provide only slow and gradual feed flow rate changes to the reactor. It is also important to detune the level controller to the point where the feed rate to the reactor changes very slowly and the level deviates from set point. The operation of the reactor is more important than maintaining the level in the accumulator, leading to a compromise on the performance of the level control to improve the performance of the reactor. Accumulator/distillation column need to be defined as shown in Figure 7.1.

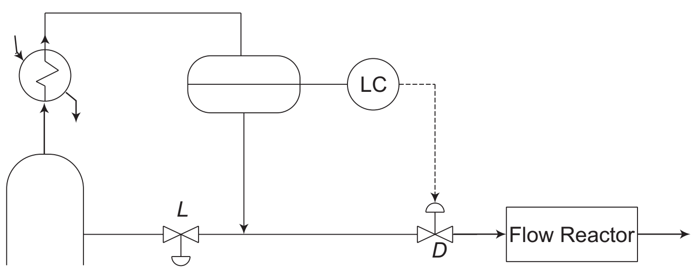

Figure 7.1: Example of control loop tuning criterion

On the contrary, to control the level of the reaction mixture in a continuous-flow stirred tank reactor (CSTR) (Figure 7.2), the level in the reactor directly determines the total production rate and distribution of products produced in the CSTR. Consequently, it is important to maintain tight level control to maintain a constant production rate and thereby reduce the upsets to be handled by the downstream processing equipment.

One can infer the following two important results—the overall process objective and how a control loop fits into the process have a dominant effect on the development of the ideal control solution. There are process-specific differences in application within a general type of control loop (e.g. level control loops).

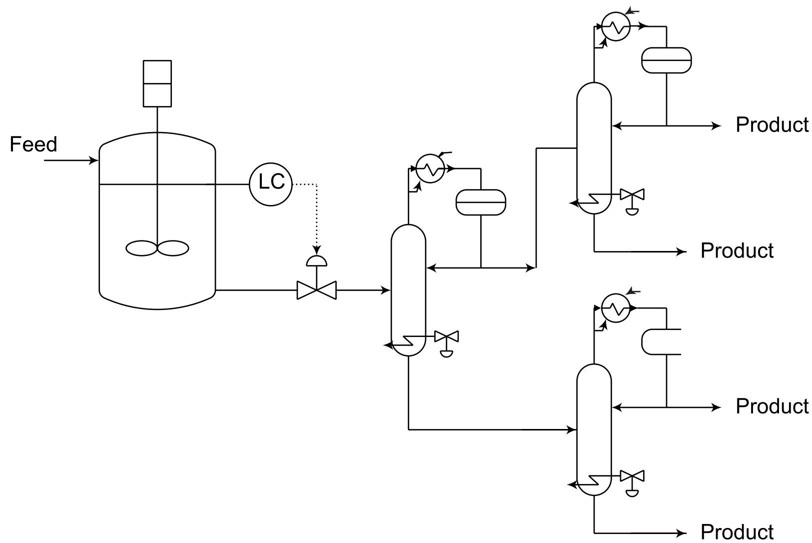

Figure 7.2: Continuous-flow stirred tank reactor

7.1.1 Responsibilities of a Process Control Engineer

The following are the typical responsibilities of a process control engineer:

- Tuning controllers
- Troubleshooting malfunctioning control loops
- Developing designs for control loops
- Documenting process control changes

It is important to make a prudent selection of tuning parameter values to ensure a reliable performance by the control loop. The control engineer is responsible for determining the source of poor performance of the control loops arising out of poor design, equipment failure, process problems, or improper tuning and makes appropriate corrections. Control engineers are responsible for designing controllers for a system every time new processes are constructed or when existing processes are modified. It is common industry practice to seek the approval of any significant changes to a process, including changes to the process controls, by a safety review committee before they are implemented. The process control engineer is expected to complete a process change data sheet that details the changes, addresses their effect on the rest of the process, and analyzes the effect of the proposed changes when dangerous conditions develop in the plant before making any control changes.

7.1.2 Process and Control Diagrams

The documentation procedure for process control changes encompasses the creation of a range of process and control diagrams, from block diagrams of the process to P&IDs.

7.1.2.1 Block Diagrams

The block diagram depicts the main processing steps in the process. A series of rectangular blocks, representing a unit operation or a process area are used in the block diagram. The block diagram differentiates between new and existing equipment and may present the major flows between units. These diagrams provide an overview of the process and its control loops. A process block diagram is usually represented in a single sheet.

7.1.2.2 Process Flow Sheets

A flow sheet is a more elaborate version of the block diagram. A symbol that reflects the actual shape of the equipment is used to pictorially represent each unit. The process flow sheet illustrates all the major pieces of equipment, and indicates all the principal lines and flows. Major control instruments represent the mode of operation, but the bulk of instrumentation used for startup, shutdown, and minor control is usually omitted. The flow sheet also illustrates known tank capacities and identifies all major motors. An entire process is normally represented by a flow sheet spanning many drawings, with well-defined inter-connections between the drawings.

7.1.2.3 Piping (or Process) and Instrumentation Diagrams

Piping and instrumentation diagrams are process design drawings that are of great use to all the disciplines involved with the process. P&IDs illustrate all major and minor pieces of equipment in the process including motors, agitators, and so on. Each unit is uniquely identified by an equipment number, a short description, and some capacity details. P&IDs also illustrate every pipeline connecting the units together or connecting the main utility headers to the units, including bypasses around control valves, tank drain line overflows, and so on.

Flow data is copied from flow sheets to the P&IDs. Process engineers, along with the piping engineers are responsible for calculating additional flows for lines that were not initially on the flow sheets. Lines branching from other lines are indicated in their correct relative order to indicate the correct placing and sizing of pipe reducers and fittings, and changes in line diameters. Every pipe is assigned a line identifier to indicate the line diameter, its material of construction, the commodity or fluid it transports, and information about if it is insulated or heat traced. Each pipe is also assigned a unique line number.

The process engineers define the lines required in the process. The piping designers, responsible for running the lines in the new or the existing plant buildings choose line branching points and show them the P&IDs. There are times when the process engineers are required to redo their balances to define the correct flow throughout different sections of a line after its routing has been established.

P&IDs indicate every single control loop and every manual valve in the process design. The process mechanical engineers and instrumentation specialists work together on this task. Instrumentation on P&IDs is normally represented in one of two ways, depending on company policy. Normally, the P&ID illustrates every loop in its entirety, including the measurement element, the transmitter, the pneumatic/electric signal converter, the control function and location of controller, the control valve or control element, and the actuator and air feed line to the actuator. This loop representation adds a lot of detail to a P&ID and calls for the process to be shown on numerous drawings to improve clarity of presentation. Engineers sometimes choose a simpler method for indicating a control loop that consists of only the control element connected to a symbol that identifies the control loop function, with a line connected to the measured stream.

In both cases, separate loop schematic diagrams are created for each individual loop. In addition to these details, these diagrams also identify more details about the wiring and cabling of the signals to assist in running and testing of each loop in the field. Figure 7.3 illustrate a simple P&ID diagram for the stripping section of a distillation column. Figure 7.4 lists the definition of the symbols used in Figure 7.3.

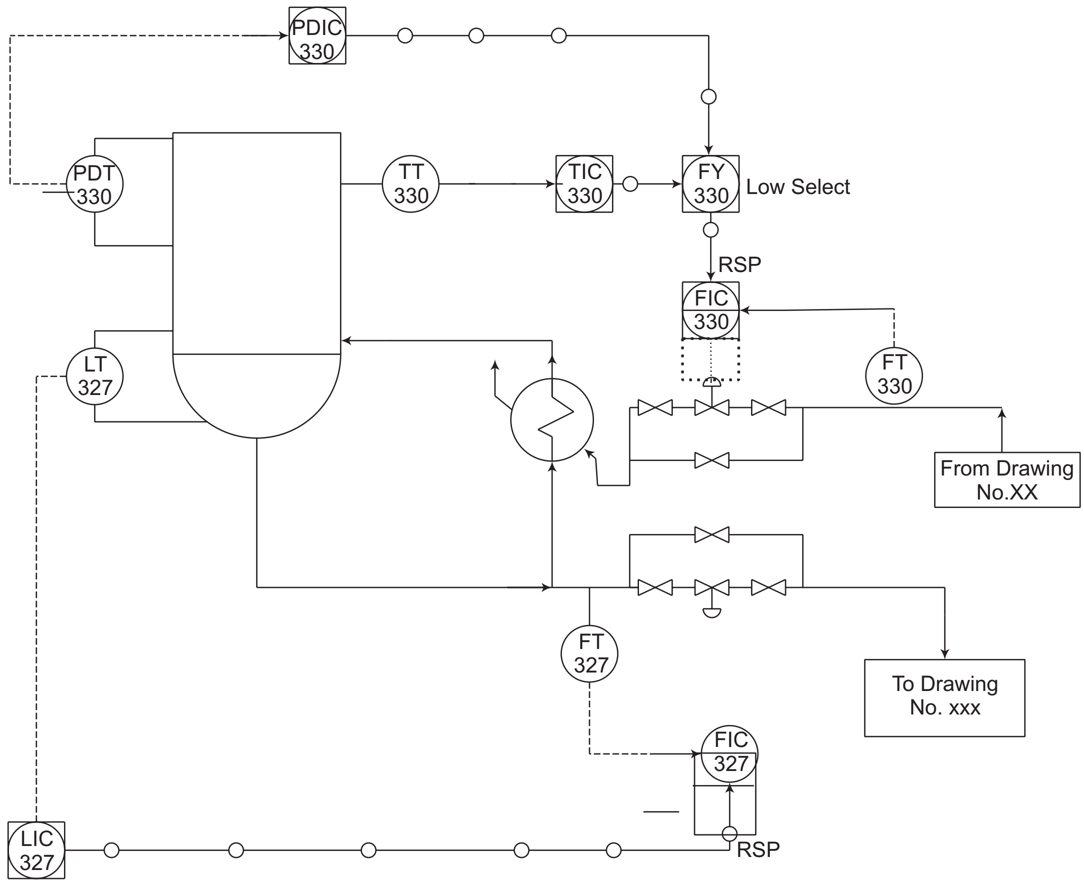

Figure 7.3: Simplified P&ID of the section of a column

7.1.3 Text Documents

Process control changes are normally documented in two types of text documents. These are:

- **Instrument list**: The instrument list is prepared simultaneously with the loop diagrams. It lists every loop in the plant, assigns it a unique loop number, and describes its function, components, vendors, characteristics, and sizes.

- **Process operating manuals**: The team of process, mechanical, electrical, and instrumentation engineers summarize the steps to be followed to start the process and the plant, to run it at normal operating conditions, and to shut it down both normally and under emergency conditions in a series of operating manuals.

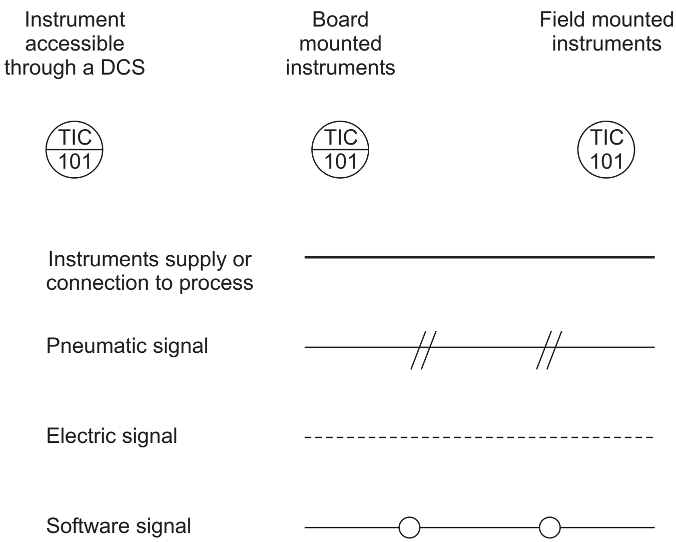

Figure 7.4: Symbols used in the P&ID

7.1.4 Operator Acceptance

Much as it may seem like a social obligation, operator acceptance is an important aspect for the process control engineer's success. Operator acceptance depends on the engineer's ability to develop process control solutions that work effectively in an industrial setting in addition to developing a rapport with the operators and win their respect. Regardless of how well your controller functions on the process are, an offended operator is capable of ensuring that the controller does not stay on line.

Operators can actually be a valuable source of operating experience. Operators often provide information on what happens and under what conditions. Their advice and input can be valuable whenever you start a control project. It is essential for the control engineer to choose the appropriate controller type for the process in question and tune it efficiently to ensure proper implementation of controllers for an industrial setting.

The use of bumpless transfer and anti-windup is also recommended in addition to validity checks and filtering to sensor readings thereby, ensuring a reliable and good control performance by controllers. The best controllers meet their control objectives, stay in service unless there is a sensor or actuator failure, and respond "gracefully" in the event of an actuator or sensor failure.

7.1.5 Control Loop Hardware

Figure 7.5 represents the schematic of a feedback control loop for a temperature controller on a continuous stirred tank thermal mixer. It is to be observed that this feedback control loop consists of a controller, a final control element, a process, and a sensor. The schematic diagram of the hardware system encompassing such a feedback loop of temperature control and the signals transmitted between different hardware components are illustrated in Figure 7.6. It is interesting to note that the sensor system shown in Figure 7.5 correspond to the thermocouple, thermowell, and transmitter shown in Figure 7.6 while the actuator system shown in Figure 7.5 correspond to the control valve, I/P converter, and instrument air system shown in Figure 7.6. The controller shown in Figure 7.5 is made up of the A/D and D/A converters, the DCS, and the operator console in Figure 7.6.

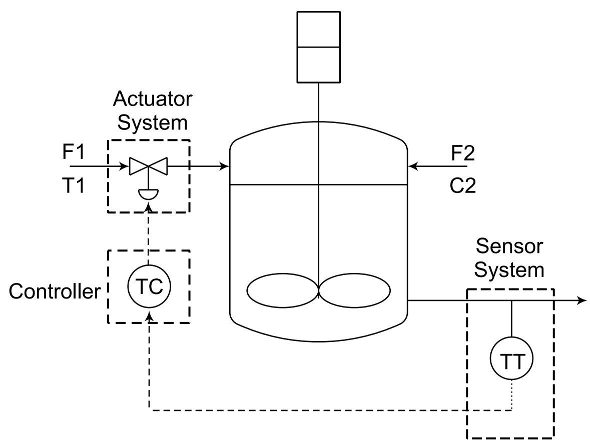

Figure 7.5: Schematic of a feedback controller on a CST thermal mixing tank

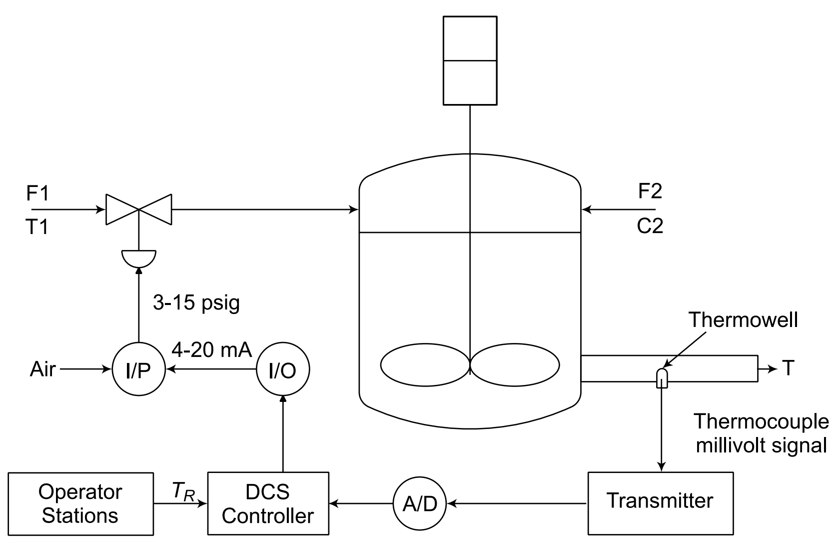

Figure 7.6: Schematic of the hardware for a feedback controller for the mixer

The temperature inside the mixing tank is measured using a thermocouple. The thermocouple is placed in thermal contact with the process fluid leaving the mixing tank by a thermowell in the product line. The thermocouple generates a millvolt signal proportional to the temperature inside the thermowell. The millivolt signal generated by the thermocouple is converted into a 4–20 mA analog electrical signal by a calibrated temperature transmitter. When the thermowell is properly designed and located, the value of the analog signal corresponds closely to the temperature in the mixing tank. The sensor system for this process consists of a thermocouple, thermowell, and temperature transmitter.

An analog-to-digital (A/D) converter is used to convert the 4–20 mA analog signal from the temperature transmitter to a digital reading. The A/D converter provides a digital output of the temperature that is used in the control calculations. The operator console enables the operator or control engineer to observe the performance of the control loop and calibrate the control loop set point and controller tuning parameters for this loop. The control algorithm of the distributed control system (DCS), i.e., the control computer uses the value of the temperature set point and the digital value of the measured mixer temperature. A digital-to-analog (D/A) converter is used to convert the digital signal output from the controller to a 4–20 mA analog signal. The 4–20 mA analog signal from the D/A converter passes to the current to pneumatic (I/P) converter. The I/P converter uses the instrument air to change it to pneumatic (3–15 psig) that is applied to the control valve which in turn corresponds to the value of the analog signal. Any change in control valve's instrument air pressure cause changes in its stem position, resulting in changes in the flow rate to the process. These flow changes in turn cause changes in the temperature of the mixer, which is measured by the sensor thus completing the feedback control loop. Usually, the DCS, A/D converters, D/A, converters, and the operator consoles are located in a centralized control room while the remaining equipment are located in the field near the process equipment. The final control element consists of the "I/P converter", the instrument air system, and the control valve. Explanation for various elements is given as follows.

7.1.5.1 Final Control Element

The final control element comprises of the control valve, I/P converter, and the instrument air system. The signal from the control system like DCS is fed to the I/P converter of the control valve, which in turn sends the pneumatic signal to the actuator thereby forcing the valve to reach a certain movement/position as desired by the operator or the control system. Refer to Chapter 6 for more information on final control elements.

7.1.5.2 Sensor Systems

A sensor system consists of a sensor, a transmitter, and the associated signal processing treatment. Flow, pressure, temperature, level, and composition sensors are most commonly used sensors in the chemical processing industry. Most sensors in the chemical processing industry actually measure a quantity that is directly related to the desired measurement. For example, a thermocouple generates a millivolt signal that is directly related to the temperature experienced by the thermocouple. In general, sensors provide either a continuous or a discrete measurement. Flow, pressure, temperature, and level sensors produce continuous measurements, while many analyzers provide discrete measurement. Analyzers sample the process stream periodically to generate a composition analysis. Consequently, such an analyzer provides an analysis measurement only once during each cycle time of the analyzer. On the other hand, a temperature sensor continuously produces its millivolt signal. Hence, a new measurement from the temperature sensor is available whenever the millivolt signal is measured.

The performance of a sensor is characterized by span, accuracy, and repeatability. Span is the difference between the largest measurement value made by the sensor/transmitter and the lowest measurement value. Zero is the lowest reading measured from the sensor/transmitter. It refers to the sensor reading which corresponds to a transmitter output of 4 mA. Accuracy is the difference between the value of the measured variable and its true value. Since the true value is never known, the accuracy is projected to be the difference between the sensor value and an accepted standard. Repeatability is related to the difference between the sensor's readings while the process conditions remain constant, indicative of the noise on the sensor reading.

Flow Sensors The most common type of a flow indicator is a flow sensor. It is based on differential pressure measurement across an orifice and may be called a differential pressure orifice meter. Differential pressure orifice meters are less expensive than other options, but typically require more maintenance as a result of plugging of the pressure taps. Magnetic flow meters and vortex shedding flow meters require less maintenance because they do not use pressure taps but their capital costs are considerably larger than differential pressure orifice meters. Refer to Chapter 5 for more information on flow sensors.

Pressure Sensors Process measurements are achieved through devices that employ mechanical elements. A differential pressure cell uses a balance bar that is deflected based on the pressure differential between two compartments that are in contact with opposite sides of the balance bar. The balance bar is maintained at a specific position using a precision forcing motor. The measurement of the pressure is directly related to the force used by the forcing motor to balance the bar. Refer to Chapter 3 for more information on pressure sensors.

Temperature Sensors The temperature of a process fluid is measured using thermocouples (TCs) and resistance temperature devices (RTDs) by inserting either the thermocouple or the RTD into a thermowell in thermal contact with the process fluid. Thermocouples are more rugged and less expensive than RTDs, but RTDs have a repeatability of ±0.1°C, while thermocouples have a repeatability of ±1.0°C. The use of RTDs is recommended when an accurate temperature measurement is required. Example, when a distillation tray temperature is controlled to approximate composition control for one of the products. Refer to Chapter 2 for more information on temperature sensors.

Level Sensors The most common type of level sensors measure the hydrostatic head in a vessel using differential pressure. This approach typically works well, as long as the difference between the density of the light and heavy phases is large. Since the level sensor is based on pressure measurement, it usually has relatively fast measurement dynamics. Refer to Chapter 4 for more information on level sensors.

Composition Analyzers The gas chromatograph (GC) is the most common composition analyzer used in the process industries. It is extensively employed for measuring the composition of light hydrocarbon streams. GCs pass a vaporized sample of the stream to be analyzed through a small-diameter tube. The tube contains a packed bed of various materials that exhibit different tendencies to absorb each of the components in the sample. Consequently, the sample passes out the end of the packed bed, and separates into its individual components, which when detected produce the analysis measurement.

7.1.5.3 Process Control Performance

The performance of a control loop depends on the dynamic response and dead band or repeatability of the final control element or sensor. Evolution of control and the dynamic response details are discussed in the next section. In addition, a device's operating range is indicated by it's upper and lower limits or upper and lower range values. Table 7.1 lists the expected range of performance for commonly encountered final control elements and sensors.

Table 7.1: Summary of control-relevant aspects of actuators and sensors

	Time constant (s)	*Valve dead band or sensor repeatability*	*Turndown ratio, rangeability / range*
Control valve	3–15	10–25%	9:1
Control valve with valve positioner	0.5–2	0.1–0.5%	9:1
Flow control loop with valve positioner	0.5–2	0.1–0.5%	9:1
TC with thermowell	6–20	±1.0°C	–200°C to 1300°C
RTD with thermowell	6–20	±0.1°C	–200°C to 800°C
Magnetic flow meter	< 1	±0.1%	20:1
Vortex shedding meter	< 0.1	±0.2%	15:1
Orifice flow meter	< 0.2	±0.3 to ±1%	3:1
Orifice meter with smart transmitter	< 0.2	±0.3 to ±1%	10:1
Differential pressure level indicator	< 1	±1%	9:1
Pressure sensor	< 0.2	±0.1%	9:1

7.1.6 Evolution of Computers in Control

As discussed in Chapter 1, 1920s saw the introduction of pneumatic PID controllers, which came into widespread use by the mid1930s. Pneumatic controllers apply control action using bellows, baffles and nozzles along with a supply of air pressure and are in limited use today. The early versions of pneumatic controllers were installed in the field near the sensors and control valves. Transmitter-type pneumatic controllers replaced the field-mounted pneumatic controllers in the late 1930s owing to the increasing size and complexity of the processes being controlled. For the transmitter-type pneumatic controllers, the sensor readings and the control action were converted into pneumatic signals (i.e. 3–15 psig) that were conveyed by metal tubing.

The late 1950s ushered in the commercially available electronic controllers (i.e. electronic analog controllers). These devices used capacitors, resistors, and transistor-based amplifiers to implement control action. Electronic analog controllers eliminated the need for long runs of metal tubing by the use of electronic transmitters. Use of electronic devices resulted in faster-responding controllers and greatly reduced the installation costs. By 1970s, the sales of electronic controllers took over the sales of pneumatic controllers in the control program interface (CPI).

The year 1959 saw the installation of the first supervisory computer control system in a refinery. The greatest disadvantage of a centralized control system was that in case of the slightest failure, the entire control system failed and suffered shutdown approach was that if the control computer failed, the entire control system was shut down. Thus, in order to overcome this problem, distributed control systems (DCSs) were developed and introduced during 1970s. DCSs are based on using a number of local control units (LCUs), having their own microprocessors and interconnected by shared communication lines, namely data highway. The LCU network is connected to a data acquisition system, operator/engineer consoles and a general-purpose computer.

Programmable logic controllers (refer to Chapter 9) have primarily been used in the process industries for controlling batch processes, sequencing process startup and shutdown operations. PLCs have been traditionally based on ladder logic which enables the user to specify a series of discrete operations. For example, "start the flow to the reactor until the level reaches a specified value, next start steam flow to the heat exchanger until the reactor temperature reaches a specified level, next start catalyst flow to the reactor," and so on.

7.1.7 Characterizing Dynamic Behavior

The operational behavior of a process can be predicted using steady-state models if all its inputs are known and fixed in time. On changing an input, the dynamic characteristics of a process determine the path it is likely to take when it moves from its current condition to a new steady-state condition.

Process dynamic behavior may be classified into self-regulating and non self-regulating processes. When an input to a self-regulating process at steady state is changed, the process moves to a new steady-state condition. When an input to a non self-regulating process at steady state is changed, the process moves away from the steady state but does not reach a new steady state. For a non self-regulating process, the input must be adjusted to correct for the original change, otherwise it continues to move until it reaches a limit to the process. For example, most level control systems overflow or become empty under these conditions.

Almost all dynamic characteristics of complex industrial processes can be described by relating them to characteristics associated with the dynamic behavior of ideal systems. For example, a system's response can be described by stating the time constant of the response, even though the process is not precisely a first-order process. In addition, the aggressiveness with which a controller's tuning is applied to a process can be described by the decay ratio of the response, even though the closed-loop process is clearly not a second-order system. Consequently, it is important to understand the terminology associated with the dynamic behavior of ideal systems.

7.1.7.1 First-order System

Following an input change, a first-order dynamic response exponentially approaches its new steady state. The characteristic response of a first-order process to a step input change of magnitude "A" is illustrated in Figure 7.7.

A first-order process is a self-regulating process. The other characteristic of a first-order process is the steady-state gain of the process, K_p. The gain indicates the change in the output of the process for a unit-input change.

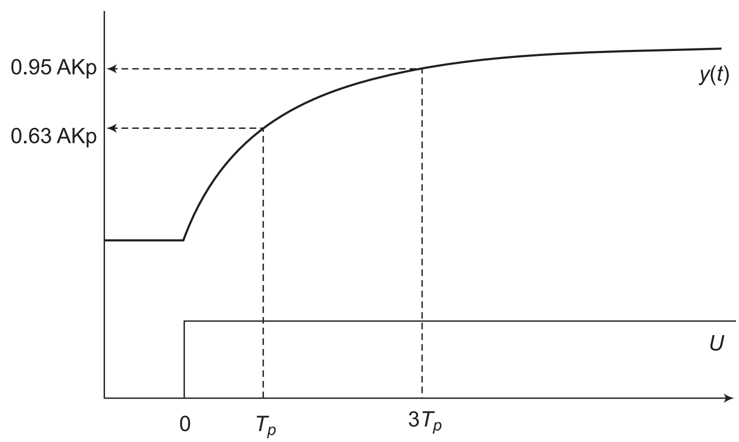

Figure 7.7: Dynamic response of first-order process to step input change

Note

It takes three time constants' ($3T_p$) worth of time for the process to achieve 95% of its ultimate change.

7.1.7.2 Second-order Process

The dynamic response of a second-order process also known as "over-damped response" involves an asymptotic approach to a new steady-state condition or an oscillatory approach. The asymptotic approach is shown in Figure 7.8, where "z" is the damping factor.

Note

Most second-order processes are self-regulating.

The dynamic response of an oscillatory second-order response is shown in Figure 7.9. Many characteristics of a second-order response are shown in this Figure 7.9. For example, the rise time, T_{raise} is the time required for the response to first cross its ultimate settling value. The percentage overshoot is given by 100 B/D. The decay ratio is C/B.

The period of oscillations is shown as T, and the response time T_{rt}, is the time taken for the oscillations to damp out to less than ±5% of the steady-state change in the output variable.

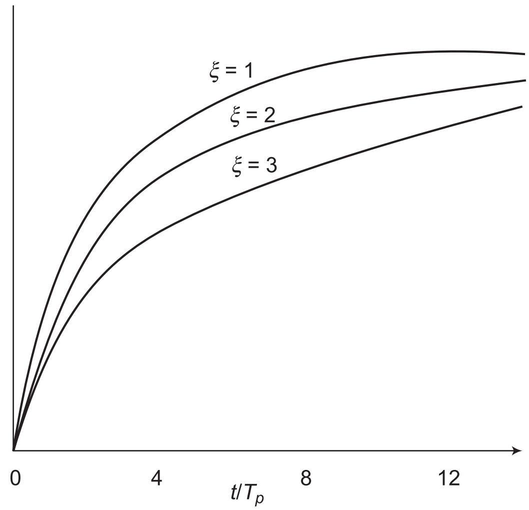

Figure 7.8: Dynamic response of second-order processes to a step input change

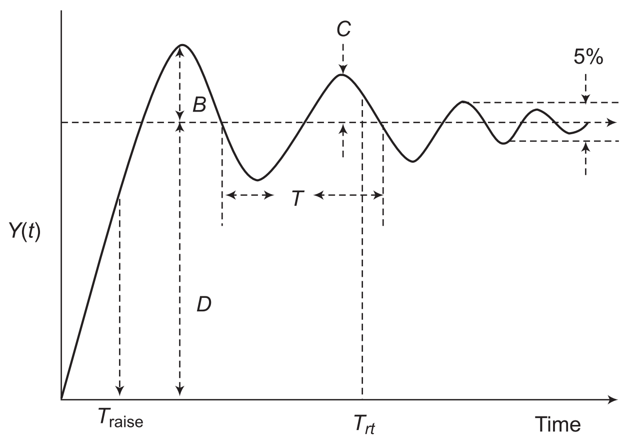

Figure 7.9: Key characteristics of an under damped second-order response

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Checkpoint

✦✦ 1. What is the common source of poor control loop performance?

✦✦ 2. What is the role of block diagram in process design?

✦✦ 3. What is the purpose of process flow sheet?

✦ 4. What is the full form of P&ID?

✦✦ 5. What does a P&ID represents from an instrumentation point of view?

✦✦ 6. What is instrument list?

✦✦✦ 7. What is bumpless transfer?

✦✦✦ 8. What is the role of I/P controller in closed loop control?

7.2 CHARACTERISTICS OF INDUSTRIAL PROCESS

LO 2

Outline the characteristics of industrial process

7.2.1 Integrating Processes

The most common type of process integration involves the level in a tank for which the outflow and inflow are set independent of the level. Figure 7.10 illustrates the dynamic response of a level for a tank in which the inflow is fixed and the outflow undergoes a step increase.

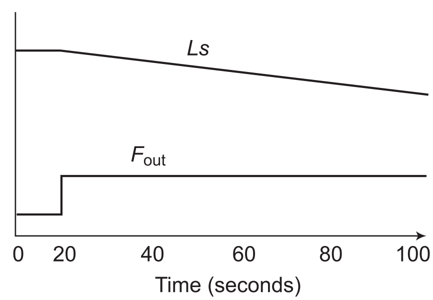

Figure 7.10: Dynamic response of tank level

A self-regulating process typically means, if the variables in the process are set constant then the output settles at a steady state.

The best example is an air-conditioning system in which the cooling gas inflow and disturbances are kept at constant rate and delivered temperature as an output remains constant. It is very easy to attain control in a regulatory process. However, the trickiest is the nonregulatory process where the behavior is very dynamic and cannot be controlled easily. Pressure can also act as an integrating variable where flow rates to and out of a process are set independent of pressure. Integrating processes are non self-regulating processes.

Note: ✦ Level 1 & Level 2 category
✦✦ Level 3 & Level 4 category
✦✦✦ Level 5 & Level 6 category

7.2.2 Inverse-acting Processes

When opposing factors act within a process then (one that is faster in response but has less steady-state gain than the other has) an inverse-acting process may occur.

Consider a mercury-in-glass thermometer that is initially at ambient temperature and is submerged in hot water. The glass can be viewed as a container for the mercury and the temperature is measured by measuring the height of the mercury column. When the thermometer is immersed in hot water, the temperature around the glass increases at a faster rate than the temperature of mercury. On applying heat, the internal diameter of the glass container increases slightly causing the height of the mercury column to decrease slightly. When the height of the mercury column decreases, the temperature of the mercury rises, causing the overall height of the mercury column to increase sharply. The change in measured temperature in response to the expansion of glass is the low-gain, small time-constant effect. The expansion of mercury column in response to an increase in temperature is the high-gain, slower-responding process.

Together, these result in inverse action. Figure 7.11 shows the response of an inverse-acting process to a step input change.

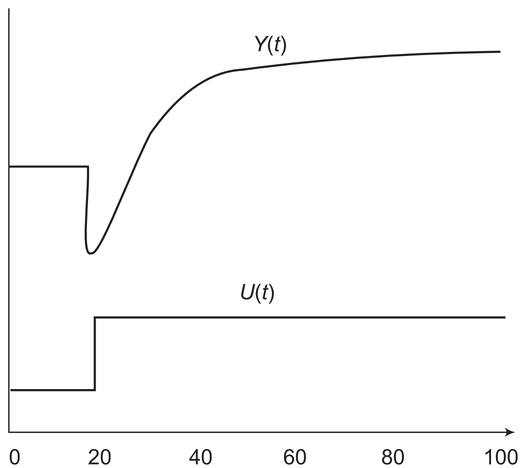

Figure 7.11: Dynamic response of an inverse-acting process

7.2.3 High-order Processes

Staged separation devices like distillation and adsorption columns, can be represented as a series of first-order processes, that is, as a high-order process. Figure 7.12 shows the response to a step input for an n^{th} order process for various values of n (i.e. $n = 3, 5, 15$, etc.).

The response becomes more sluggish with the increase in n, that is, the slope of the response becomes smaller. For larger values of n, a period of time passes before a significant change in the output variable can be observed and this period of time (the effective dead time) increases with increasing "n".

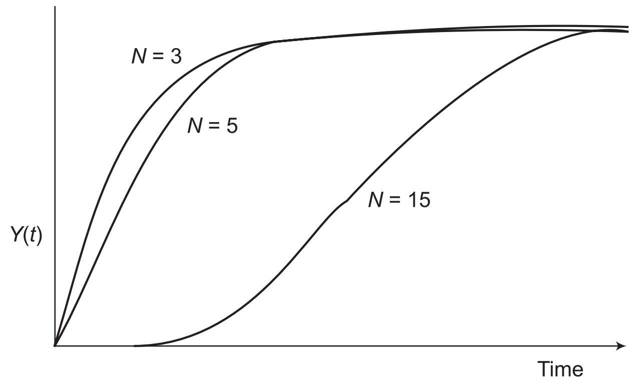

Figure 7.12: Dynamic response of several high-order systems

7.2.4 First-order Plus Dead Time Model (FOPDT Model)

FOPDT models are a convenient means of representing a high-order process. FOPDT models are often used to model industrial processes. Figure 7.13 shows a comparison between an FOPDT model and a fifth-order process for a step input change.

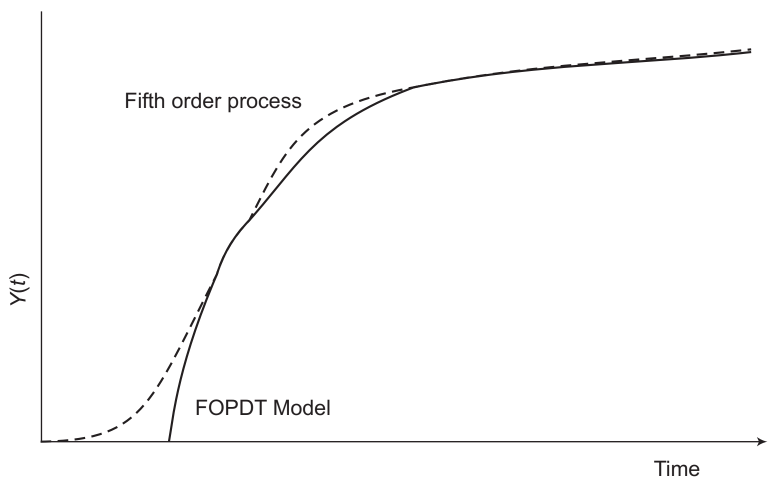

Figure 7.13: Comparison of dynamic response of an FOPDT model and a fifth-order process

There is initially a slight mismatch between the FOPDT model and the high-order process model but overall the FOPDT model approximates over damped process behavior well. The FOPDT model is therefore considered one of the best-idealized models for representing industrial processes.

A step test can be conveniently used to develop a FOPDT model (Figure 7.14):

- Identify the resulting change in y (i.e. Δy) and the step change in the input, Δu.
- From the step response, identify the time required for one-third of the total change in y to occur, $T_{1/3}$.

- Identify the time required for two-thirds of the total change in y to occur, $T_{2/3}$.
- Then, use the following estimates for the gain K_p; the time constant T_p; and the process dead time θ_p: $T_{1/3}$ and $T_{2/3}$ assume that time is equal to zero when the step change in u is implemented.

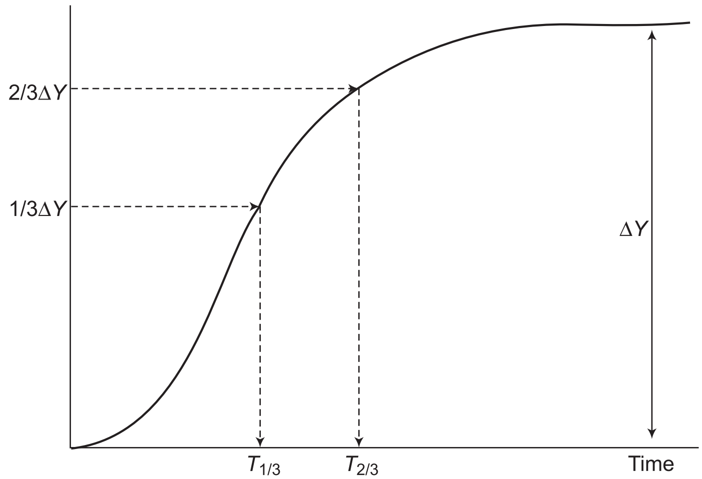

Figure 7.14: Schematic graphical representation of the determination of $T_{1/3}$ and $T_{2/3}$

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Checkpoint

✦✦ 1. What is a self-regulating process?

✦✦✦ 2. What is the response for step change in input for higher-order process?

7.3 ROLE OF PID CONTROLLER IN PROCESS CONTROL

LO 3

Analyze the role of PID controller in process control

7.3.1 PID Controller

Control action that is directly proportional to the error from set point is determined by the fundamental characteristics of proportional, integral and derivative action. Proportional action as the name indicates drives the output in proportion to input. Hence, there exists a directly proportional relationship between output and input. For example, OP = x × IP indicates that output is made x times than input. Since this is used for closed-loop control, the closed-loop response is faster than the open-loop response. The proportional control always results in offset, that is, a sustained error from set point as a result of which output cannot equal set point in proportion only control. To compensate the abovementioned offset, integral action is employed.

Integral action is directly proportional to the integral of the error from set point. The error within which the output has settled down without reaching set point, integral action leads to all the steady-state correction for disturbances. Integral action eliminates offset but increases the oscillatory character of the response.

Derivative action is directly proportional to the time rate of change of the control variable. Derivative action tends to reduce the oscillatory nature of feedback control. However, derivative action as it mentions acts only when there is an oscillatory behavior because if there is no oscillation then derivative on a constant becomes "zero" since derivative of a constant is zero. Derivative control mode is used for responses that need to be proportionate to the rate at which the process is changing.

Derivative is an inverse operation of integration and deals with the expression of a variable's rate-of-change with respect to another variable. With derivative, the system calculates the ratio of a variable's change per unit of time. Integration is fundamentally a multiplicative operation (products) whereas differentiation always involves division (ratios). Thus, a controller with derivative (or rate) action looks at how fast the process variable changes per unit of time and takes action proportional to the rate of change. A derivative (rate) action represents the "cautious" side of the controller.

If the process variable starts to change at a high rate of speed, the job of derivative action is to move the control valve in such a direction as to counteract this rapid change thereby moderating the speed at which the process variable changes. Doing so, the controller would be made "cautious" of the rapid changes in process variable. If the process variable is headed towards the set point value at a rapid rate, the derivative term of the equation will diminish the output signal thus slowing tempering the control response and slowing the process variable's approach toward set point.

Two major issues of concern with the close-loop operation with PID controllers are the integral windup and the requirement of providing bumpless transfer. These two issues are elaborated next.

7.3.1.1 Integral/Reset Windup

A significant problem with integral action is that when the error signal is large for a significant period of time that can occur every time when there is large change in set point.

If there is a sudden large change in set point, the error will be large and the integrator output in a PID control will build up with time. As a result, the controller output may exceed the saturation limit of the actuator. Unless prevented, this windup, may cause continuous oscillation of the process that is not desirable.

To put it in other words, if the error is "x" over time "t" then it can be represented as follows, $\int_0^t x$, and when an integral action is performed it will result in the compensation of $x^2/2$ with upper limits as "t" and "0", this value may be pushing the valve to act more than 100% of the given range. Hence, larger the error for a sustained period, greater is the compensation needed and the compensation may be beyond what actuator can afford. Hence, precautions recommended for anti-windup are:

- Closing the I-action only when the error is small (say 5% to 10% of the range)
- Limiting the output of the I-action block.

7.3.1.2 *Bumpless Transfer*

When a controller is switched from manual mode to auto mode, it is desired that the input of the process should not change suddenly. However, there is always a possibility that the decision of the manual mode of control and the auto mode of control be different. In addition, there may be a sudden change in the output of the controller causing a sudden jerk in the process operation. Special precautions are taken for bumpless transfer from manual to auto mode.

This can be achieved by forcing the integral output at the instant of transfer to balance the proportional and derivative outputs against the previous manual output, i.e.,

Integral output = {(previous manual) – (proportional + derivative) output}.

Similarly, for automatic to manual transfer, initially the manual output is set equal to the controller output and the difference is gradually reduced by incrementing or decrementing the manual output to the final value of the manual signal thus affecting a changeover.

Another way to transfer from auto to manual mode in a bumpless manner is to make the set point equal to the present value of the process variable and then slowly change the set point to its desired value.

The above features can be easily be implemented if a digital computer is used as a controller. This provision eliminates the chance of the process receiving sudden jolt during transfer.

7.3.2 Types of PID Controller

The standard PID controller has gone through several modifications to improve its performance. For example, if the derivative action is calculated based on the error from set point, it results in a spike in the derivative action when a set point change is implemented. Calculating the derivative on the measurement of the controlled variable eliminates this problem (derivative kick). In addition, tuning the PID controller to handle disturbances can severely upset the process for set point changes in the case of certain processes. Calculating the proportional action from the measurement of the controlled variable instead of the error from set point eliminates this problem (proportional kick). There are three commonly used forms for a PID controller:

- Calculating the proportional, integral and derivative action based on the error from set point.
- Calculating the proportional and integral action according to the error from set point while calculating the derivative from the measured value of the controlled variable.
- Calculating the integral action in accordance with the error from set point while the derivative and the proportional action are determined based on the measured value of the controlled variable instead of the error from set point.

7.3.3 Direct-acting and Reverse-acting Controllers

In some cases, the controller output is expected to increase with the increase in the error from set point, while in some other cases the controller output must decrease. For example, consider a steam-heated heat exchanger that is used to heat a process stream. For an air-to-open actuator on the steam line, the steam flow increases with the increase in control signal. This causes an increase in the outlet temperature of the process fluid. In this case, the controller output must increase when the outlet temperature of the process fluid decreases. This is an example of a reverse- acting controller.

$$u_{i+1} = u_i + \Delta u \tag{7.1}$$

where, u_{i+1} = Output at i+1, Δu = Change in output, u_i = Output at i

Conversely, if an air-to-close actuator is used on the steam control valve, the controller output must decrease when the outlet temperature of the process fluid decreases. This is an example of a direct-acting controller.

$$u_{i+1} = u_i - \Delta u \tag{7.2}$$

This example of a steam-heated heat exchanger has a positive gain since, as the steam flow is increased, the controlled variable increases. If a process has a negative process gain (e.g., a heat exchanger that cools a process fluid using cooling water), then a reverse-acting controller must be used when the actuator is air-to-open, and a direct-acting controller should be selected for an air-to-close actuator. The typical guideline for selecting is listed in Table 7.2.

Table 7.2: Guidelines for selecting direct and reverse-acting PID controllers

Process gain	Air-to-open valve actuator	Air-to-close valve actuator
Positive	Reverse-acting PID	Direct-acting PID
Negative	Direct-acting PID	Reverse-acting PID

When a control loop is set up using one of the control monitors on a DCS, a direct or reverse-acting controller must typically be selected on the form. For analog controllers, the proper form of the controller, direct acting or reverse acting, is selected using a switch located on the back of the controller.

7.3.4 PID Design

It is important to consider the dynamics of the combined system of actuator, process and sensor when choosing between P-only, PI, or PID controllers. A rough statistics indicates more than 90% of the control loops use PI controllers and the remaining two share the rest of 10%. Following are some of the guidelines that can be used to choose the type of control to be used based on the dynamic of the process and objectives of the control:

7.3.4.1 P-only Control

P-only control is used in applications that are slow and is acceptable to have a degree of offset. Here the slow process means the processes that respond very slowly for a change in the manipulated value. For example, consider the temperature of a large tank and by changing the heat input, it takes more time to raise the temperature based on the type of the tank and type of the heat input. Similar is the case of large tanks where the level is measured and controlled with small pumps. In general, for the slow process, if the operator does not want an offset, then a traditional PI or P-only control with a small amount of integral constant is added.

7.3.4.2 PI Control

PI controllers, as discussed earlier, are most widely used. The controllers are used for the control of the processes which are not sluggish and needs no offset. The typical applications are flow control, level control, pressure control and composition control, etc.

7.3.4.3 PID Control

The PID control is applied in sluggish processes. The typical industrial sluggish processes are temperature and composition control, etc. If we apply a PI control to a sluggish process, there will be oscillations due to the lag in the process. In order to reduce the oscillations, the derivative action/constant is added to the control that acts counter to the oscillations and thereby allowing more of the proportional action on the response. This helps in improving the control performance and hence process becomes more stable. The key point here is to know if the process is sluggish enough and is in need of a PID controller. Assume that a FOPDT model has been fit to an open-loop step test. If the resulting dead time, θ_n and time constant τ_p, are such that:

$$\frac{\theta_n}{\tau_p} \leq \frac{1}{2} \tag{7.3}$$

then the process is not sufficiently sluggish to warrant a PID controller. If,

$$\frac{\theta_n}{\tau_p} \geq \frac{1}{2} \tag{7.4}$$

then the process is sufficiently sluggish that a PID controller should offer significant benefits over a PI controller. If,

$$\frac{1}{2} \leq \frac{\theta_n}{\tau_p} \leq 1 \tag{7.5}$$

then either PI or PID control could be preferred. If FOPDT models are not available, then a PI controller that suffers from excessive oscillations or sluggish response indicates that a PID controller may provide improved control performance. In addition, significant noise levels in the controlled variable can render the derivative action ineffective because the derivative is sensitive to noise. If sufficient filtering is used in measuring the controlled variable, the lag added by the filter could negate any benefit produced by the derivative action.

7.3.5 Analysis of Typical Control Loops

The five control loops commonly encountered in the chemical process industries are flow control loop, level control loop, pressure control loop, temperature control loop and composition control loop. Let us understand the relevant control characteristics of each loop from the point of view of an actuator, process, and sensor and address the problem of selecting a P-only, PI, or PID controller for each case.

7.3.5.1 Flow Controllers

The dynamics of the process and sensor are quite fast compared with the dynamics of the control valve. Since overall procedure is fast and calls for accurate control to set point, a PI controller is the proper choice for most flow control applications.

7.3.5.2 Level Controllers

The dynamics of the sensor are quite fast and the dynamics of the actuator are faster than the dynamics of the process (i.e. percentage level changes for changes in flow leaving the tank). Since level systems integrate processes, the rate of change of the level depends upon the change in flow rate and the cross-sectional area of the vessel. For a system in open-loop condition, a 5% level change occurs in one minute for a 10% change in the feed-rate to the tank. Therefore, process dynamics typically control the response of the actuator/process/sensor system.

In general for the process of level filling is not a slow one, a P-only control is enough if the offset is acceptable. In case if offset is not acceptable in applications such as reactor level control, a PI control is used.

7.3.5.3 Pressure Controllers

The pressure sensors have the highest response times where the valves remain slow compared to other elements in the process loop. The changes in the pressure and associated control expected from the pressure control is high and in such situations a P-only control is enough if the offset is acceptable. However if the offset is not acceptable a PI control is recommended.

7.3.5.4 Temperature Controllers

The temperature has both a fast responding and slow responding loop for control in any process applications. In case of a gas fired heater, the changes in the actuator are faster than the changes in the process. It takes some time for an increase in flow rate of the gas to increase the temperature of the heater. In addition to this delay, there will be a lag in the sensor response time, which in the case of an RTD will be anywhere between 6 s and 20 s depending on the type of the installation and type of the element such as RTD or thermocouple. The process liquid enters the heater in the tubes and gets heat exchanged through these tubes with the high temperature combustion gas. In this case as well there is a lag associated with the temperature of the metal tubes and flowing fluid. These transportation delays and dead times also increase with the reduction in the feed rate of the liquid. Consequently, the process can be sluggish, particularly for low feed rate operations. Since the heater is likely to behave as a sluggish process, a PID controller would usually be the controller mode of choice in this example. Derivative action becomes ineffective in the presence of excessive sensor noise. A PI controller is preferable for a less sluggish process. The guidelines provided in the previous section must be used to determine if the process is sufficiently sluggish to warrant using PID control.

7.3.5.5 *Composition Controllers*

A composition controller may be used for the overhead product of a distillation column that uses the reflux flow rate as the manipulated variable. In this case, the changes in the actuator from the flow controller are fast, where the sensor inputs are slow. The analyzers in this case are generally slow and take up to 10 minutes for each sample. In such cases, a change in impurity level for a change in set point of the reflux flow is very slow. If the process and analyzer delay make the actuator/process/sensor system sluggish, then a PID controller may be preferred. Once again, the guidelines presented in the previous section should be used to determine if the process is sluggish enough to warrant using PID control.

7.3.6 Controller Tuning

7.3.6.1 *PID Tuning*

It is recommended to consider the following tuning objectives as guidance for the tuning process.

- Minimize deviations from set point.
- Attain good set point tracking performance.
- Avoid excessive variation of the manipulated variable levels.
- The controlled process should remain stable for major disturbance upsets.
- Offset elimination may or may not be important.

It is not possible to simultaneously satisfy each of these objectives. Tuning is a characterization of the controller to meet some of the above objectives while compromising something else. For example a tuning can be performed to have minimum deviation from set point for a normal upset versus remain stable for major process upset.

This means if the tuning is performed on a controller with considerations for normal process upsets, the controller can potentially become unstable during major process upset. Same way if the controller is tuned for potential major upsets, then the control becomes slow and does not respond to small upsets in the process.

7.3.6.2 *Qualitative Analysis of Controller Tuning*

As the aggressiveness of a *P*-only controller is increased (i.e. the controller gain, K_c, is increased), an open loop over-damped process (Figure 7.15a) becomes critically damped (Figure 7.15b), oscillatory (Figure 7.15c), and ringing (Figure 7.15d). It then exhibits sustained oscillations (Figure 7.15e) and finally unstable oscillations (Figure 7.15f).

Figure 7.16(a) shows the effect of the controller gain on the closed-loop dynamic response of a PI controller. Figure 7.16(b) shows the response to a set point change for a controller that was tuned for quarter amplitude damping (QAD), that is, a decay ratio of 0.25. Figure 7.16(a) shows the response to a set point change with a lower value of K_c but with the same reset time as used for the controller in Figure 7.16(b). The response is over-damped when the controller gain is reduced. Figure 7.16(c) shows the response to a set point change with a larger value of K_c but with the same reset time as used for the controller in Figure 7.16(b).

Note

Increase in controller gain leads the controlled variable to ring.

Figure 7.16(a) shows the effect of the reset time on the closed-loop dynamic response of a PI-controller while Figure 7.16(b) shows the response to a set point change for a controller that was tuned for QAD, that is, a decay ratio of 0.25.

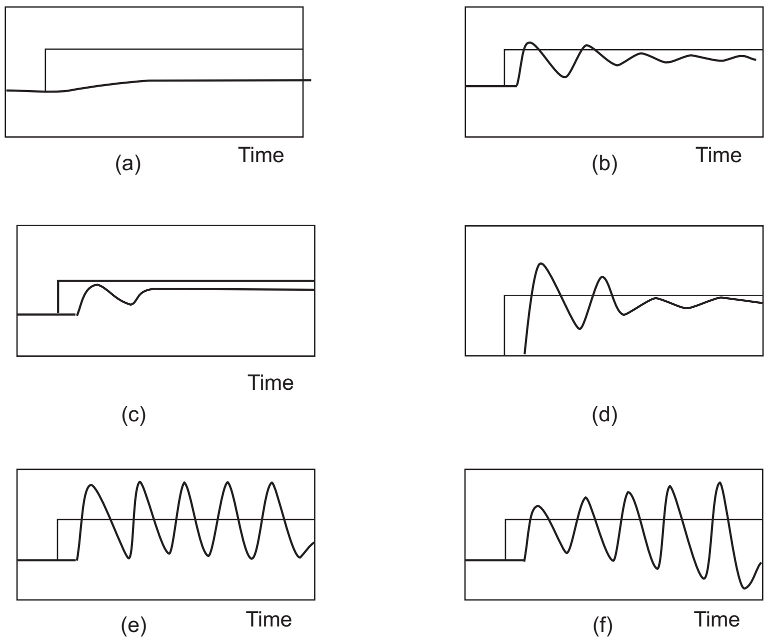

Figure 7.15 (a to f): Different dynamic modes for a *P*-only controller applied to an over-damped process

Figure 7.16(a) illustrates the response to a set point change with a larger value of t_I (the reset time) but with the same controller gain as used for the controller in Figure 7.16(b). Note that increasing the reset time gradually removes the offset. Figure 7.16(c) illustrates the response to a set point change with a smaller value of the reset time but with the controller gain as used for the controller in Figure 7.16(b).

When the reset time is decreased, the controlled variable value begins to oscillate. The process response to high proportional action or high gain (Figure 7.16b) and oscillations from high integral value look similar (Figure 7.16c). This is why it is difficult to locate the problem once the oscillations starts if proportional action or integral action needs adjustments.

The process response of manipulated variable on controlled variables for a QAD-tuned controller is shown in Figure 7.17. In this case the controller output will lag behind the controlled variable. For the same controller if the tuning parameter such as gain or proportional action is increased by 25%, and other settings twice, the process responds with the oscillations due to the increase in gain, whereas the lag between the two is reduced, which means the excessive gain can reduce the lag between controlled variable and output of the controller as shown in Figure 7.18. Similarly, if the gain and integral constant is reduced, as shown in Figure 7.19, the lag increases significantly. It means an excessive integral action increases the lag in the process. This is one of the way to know if the oscillations are due to excessive gain or due to excessive integral action.

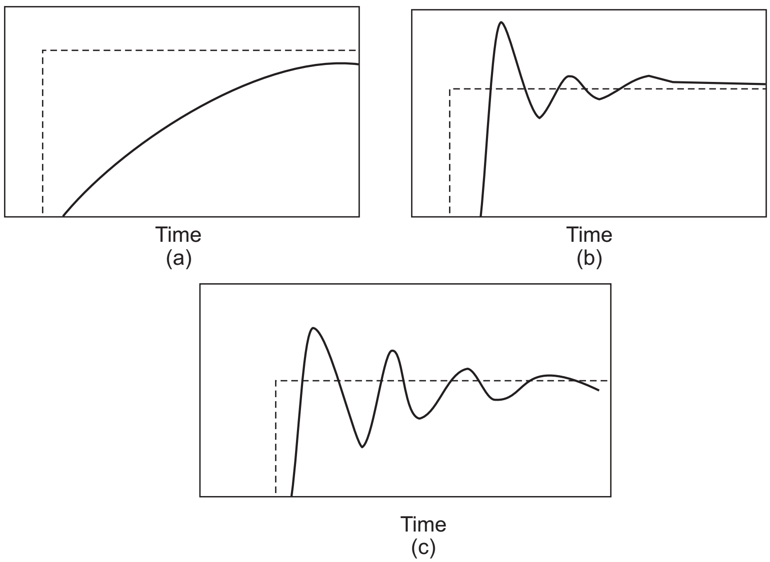

Figure 7.16 (a to c): Effect of controller gain on dynamic response for a PI controller. Controller reset time on dynamic response for a PI controller

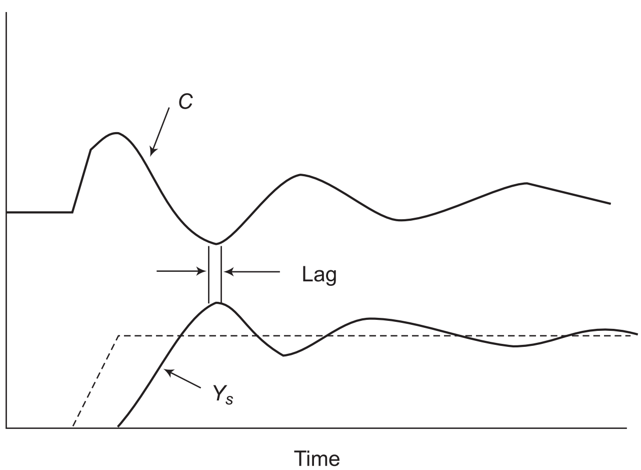

Figure 7.17: Lag between control variable and controller o/p for a QAD-tuned PI controller

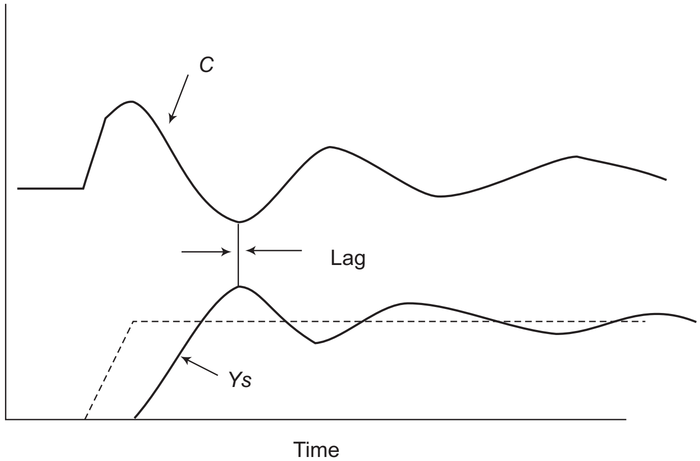

Figure 7.18: Lag between controlled variable and controller o/p for PI controller with extreme proportional action

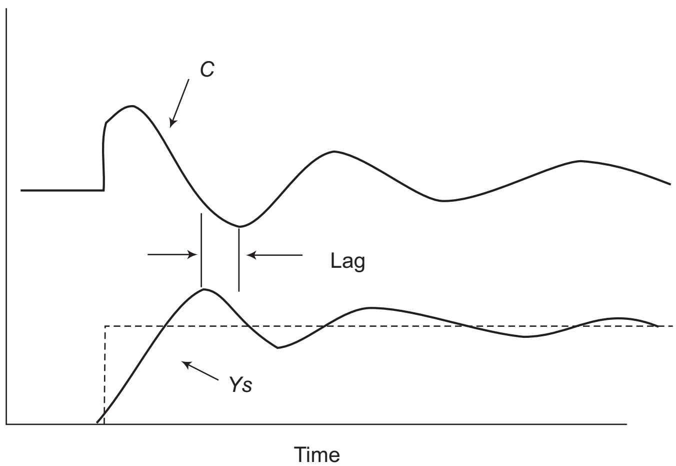

Figure 7.19: Lag between controlled variable and controller o/p for PI controller with extreme integral action

7.3.6.3 Control Interval

The digital application of feedback control occurs at discrete points in time. DCSs use sequential microprocessors that perform control calculations for a large number of control loops. Generally the process control regulatory control loops will be executed for 200 ms to 1 second and supervisory control systems operates at 10–30 s. The time interval in which the controller executes the control on the loop is called control interval (Δt).

In an industrial set up, digital formulas are applied at discrete control levels for a PID control is applied on DCSs by using digital formulas that are applied at discrete control intervals.

As a general rule, the control interval should be selected such that:

$$\Delta t < 0.05\,[\tau_p + \theta_p] \tag{7.6}$$

This will ensure that a control performance of "continuous control" is obtained.

7.3.6.4 Controller Tuning Procedure

For tuning PID control loops, the following procedure is recommended:

- **Select the tuning criterion for the control loop:** Based on how the control loops affect the overall process objectives, tuning criteria is selected. Sometimes, the criteria involve a compromise between reliability and performance.
- **Apply filtering to the sensor reading**: The filtering applied to the process signals in the transmitter can reduce the noise in the measurement and hence reduce the variations in the control. The negative side of such a filtering is introduction of the lag in the process measurement which again can have a potential impact on the process. The engineer should enforce sufficient care while using the filter values such that the noise is reduced with little effect from the lag.
- **Determine the speed of response of the closed loop:** The closed-loop response time of the system distinguishes between fast and slow-responding control loops. In a fast-responding control loop process, set point changes occur within a reasonable time (e.g. less than 10 minutes). If not, it is a slow-responding control loop.
    - Apply field training for fast-responding control loops.
    - **Apply the auto tune variation (ATV)** tuning for slow-responding control loops.
    - The typical ranges of values for different types of controllers based on the application are listed in Table 7.3.

Table 7.3: Typical range of tuning parameters for control loops in the CPI

Loop type	*PB*	*I*	*D*
Flow controller	100–500%	0.2–2.0	0
Gas pressure controller	1–15%	5–100	0
Liquid pressure controller	100–500%	0.2–2.0	0
Level controller	5–50%	5–60	0
Temperature controller	10–50%	40–4000	30–2000*
Composition controller	100–1000%	100–5000	30–4000*

*D should always be smaller than I.

7.3.6.5 Controller Reliability

A controller's ability to remain in service for typical levels of disturbances defines controller reliability. For example, if an unstable controller begins making excessively large changes in the manipulated variable without bringing the process under control, the operators put the controller into manual operation to stabilize the process. Control to the set point is sacrificed for some time until the process stabilizes and the process can be returned to its normal operating mode. A large disturbance entering the process can destabilize a control loop tuned for stable operation. Consider the FOPDT representation of a process. If a disturbance introduced into the process causes the process gain to increase, the process time constant to decrease, and/or the process dead time to increase (i.e. nonlinear behavior), a control loop that was tuned for QAD performance begins to ring or possibly make it unstable. Conversely, a disturbance that enters the process causing the process gain to decrease, the process time constant to increase, and/or the process dead time to decrease, a control loop that was tuned for QAD performance can result in over-damped performance. Controller reliability is determined by the nonlinearity of the process and the type and magnitude of the disturbance.

Process instability caused by a disturbance is directly proportional to the controller tuning. On the other hand, the control performance suffers excessively in the case of a conservatively tuned controller. Therefore, tuning often results in compromise between performance and reliability.

7.3.6.6 Selecting the Tuning Criteria

Selecting the tuning criterion is the foremost thing that a control engineer must do when tuning a control loop. Tuning criterion is often defined by the decay ratio. A 0.16 decay ratio is considered to be a very aggressive tuning criterion. A decay ratio of 1/10 or 0.1 is considered less aggressive, and critically damped tuning is even more conservative. The tuning criterion for a control loop determines the aggressiveness of the feedback controller.

Note

Optimal decay ratio is considered to be 0.25 decay ratio.

When choosing the proper tuning criterion, the most important factor that must be considered is how the control loop affects the overall objectives of the process. For example, in a case in which, an aggressively tuned level controller undermines the overall process objectives, a case in which an aggressively tuned level controller is preferred because of the overall process objectives.

The tuning criterion is opted based on a compromise between the loop performance and stability of the control. It means either the loop can be aggressive for small disturbances with minimum variability or more variability with less aggression on the control. Process nonlinearity and disturbances determine a controller's reliability. Controller reliability is likely to be a problem in case of a highly nonlinear process subject to large disturbances. Such cases call for a more conservative tuning criterion (e.g. a critically damped response). Conversely, in the case of relatively linear process with mild disturbances, a more aggressive tuning criterion should be advised (e.g. a 0.16 decay ratio). It is important to know the process in terms of its nonlinearity and the degree of impact during process upset while selecting the tuning criteria.

7.3.6.7 Filtering the Controlled-variable Value

Electrical interference, mechanical vibration, or changes in the process (e.g. variations resulting from turbulent flow) introduce some degree of noise to all process measurements. Noise is a high-frequency variation in the process measurement that is not associated with the true changes in the process. Therefore, a controller responding to the noise in a measurement makes high-frequency changes to the manipulated variable which causes short-term process variations in the controlled variable. The variability of the controlled variable about its set point is influenced by noise, but the average value of the controlled variable does not change. Consequently, a controller that uses measured controlled-variable values with significant noise levels passes the noise into the process through the manipulated variable in the absence of preventive steps. In fact, depending on the process gain and time constant, the controller amplifies the noise level. When derivative action is used, the feedback system is more likely to amplify the noise on the measurement of the controlled variable. Filtering process measurements is an effective way to reduce the effects of measurement noise.

As mentioned, filtering the measurement signal reduces the effects of high-frequency noise on a process measurement. Filtering can be considered as taking a running average of the measurement readings of the last "n" samples. In this way, the high-frequency variations resulting from noise can be "averaged" out. A digital version of a linear first-order filter can be represented by the following equation:

$$y_f(t) = (1 - f)y_f(t - \Delta t) + fy_s(t) \tag{7.7}$$

where, f is the filter factor ($0 < f < 1$), $y_s(t)$ is the current process measurement value, $y_f(t - \Delta t)$ is the calculated filter value at the previous time, and $y_f(t)$ is the current value of the filtered measurement.

Consider the case for which $f = 0.05$, the filter for this case can be viewed as an average of the current sensor reading (y_s) and the previous sensor readings. As $f = 0.05$, 5% of the new filtered value comes from the current measurement and 95% comes from the previous readings.

Filtering can add additional lag to a control loop. It is a good impression to decrease the filter factor before it reaches the point where it adversely affects the performance of the control loop. The impact of the filtering on the control loop performance can be evaluated by comparing the time constant of the actuator, process, and sensor with the filter time constant. The time constant for the lag associated with a digital first-order filter is given by:

$$\tau_t = \Delta t\left[\frac{1}{f} - 1\right] \tag{7.8}$$

In many control systems such as DCSs, process measurements from the transmitters are updated six times per second (i.e. 0.2 s). For a filter time constant of two, the filter factor is something like to 0.04. Therefore, most sensors use high frequency updating by a DCS call for a relatively extensive sensor filtering.

The amount of noise determines the amount of sensor filtering required. For example, it is expected that the reading from a thermocouple requires more filtering than a reading from an RTD that has an order-of-magnitude smaller repeatability. The advanced process measurement transmitters remove the noise in the measurement much more effectively than their predecessors. In such devices for a flow, level and pressure applications, a filter time constant of 2–3 s is used which does not have any impact on the loop performance. Composition analyzer readings from GCs are updated so infrequently that filtering is usually not used for them. In contrast, filtering can be used effectively if composition measurements are available at a sufficiently high frequency.

In certain cases, it is necessary to filter a noisy sensor, as they are a challenge. Typical example of a noisy process transmitters are pressure transmitters close to a 90° elbow, an obstruction type flow meter such as orifice or venture installed immediately downstream of a control valve, etc. Such of these installations necessitates the filtering constant in the measurement to remove the noise and add some lag in the control to avoid loss of performance.

7.3.6.8 Tuning Fast-control Loops

The simplest and quickest tuning method available for PI controllers is field tuning for fast-response loops such as flow control and pressure control loops. Such tuning is a result of fine tuning the parameters. In addition, some level and temperature loops also act as fast-responding control loops. Trial-and-error tuning is effective since these processes respond rapidly. Sometimes, the engineers feel tuning the fast responding loops in field is easier than identifying the FOPDT parameters from a tuning method and then adjusting these parameters again to meet the process conditions. The generally followed procedure for the loop tuning in the field is as follows:

1. Select the tuning criterion for the control loop.
2. Filter the process measurement.
3. Turn off the derivative action and the integral action.
4. Make an initial estimate of the controller gain (K_c)
5. $K_c = 0.5\ K_p$, estimate K_p from process knowledge
6. Increase K_c in small increments, using set point changes, until the response meets the tuning criterion.
7. Decrease K_c by 10%.
8. Make an initial estimate for $t_I = 5t_p$. Estimate t_p from process knowledge.
9. Decrease t_I using set point changes until offset is eliminated and the tuning criterion is met.
10. Check to ensure that adequate levels of proportional and integral action are being used.

7.3.6.9 Tuning Slow-control Loops

Field tuning can be a lengthy procedure that leads to less satisfactory results for slow-response loops (e.g. certain temperature and composition-control loops). It is recommended to use step test results to generate FOPDT models, and variety of techniques can be used to calculate tuning parameters. The problem with this method is that it takes too long time to get an open loop response time from process for a step input or step change. In addition, the measured results may go wrong due to the known and unknown disturbances on the process. After all the tests, there is no way to know if the resultant constants are optimized for a balance between stability versus performance. These uncertainties along with model mismatch or inappropriate tuning criteria, significant adjustments are necessary in the field. The ultimate gain and period needs to be calculated using ATV method, which is already discussed earlier. This test can be performed without significantly disturbing the process. Once the tuning parameters are calculated, the controllers are tuned to meet the loop performance.

Figure 7.20 is a graphical representation of the ATV method. Select "h" (the relay height used or the change in the manipulated variable to be applied) such that it is small enough to process that is not unnecessarily upset, yet large enough to enable the accurate measurement of the resulting amplitude.

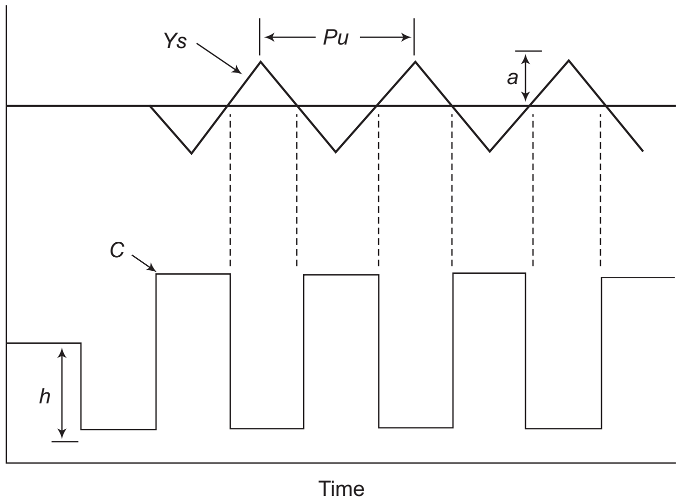

Figure 7.20: Graphical representation of an ATV test

The process must be in steady state or near steady-state conditions, c_0 and y_0, to initiate an ATV test. The output is set to $c_0 + h$ (or $c_0 - h$) until y deviates more from y_0. During this time, the output is set to $c_0 - h$ (or $c_0 + h$), which turns the process back towards y_0. Each time y crosses y_0, the controller output is switched from $c_0 + h$ to $c_0 - h$ or from vice-versa. This process is also referred to as a relay feedback experiment. It takes three to four cycles to establish a standing wave. The advantage with this test is that the variables of "a" and the ultimate period, P_u, can be measured directly. The ultimate gain, K_u, is calculated by:

$$V_u - \frac{4h}{\pi a} \tag{7.9}$$

You can use the K_u and P_u in one of several tuning schemes. Ziegler- Nichols (ZN) method is one of the tuning method and widely used. The ZN values for a PI controller are as follows:

$$\left.\begin{aligned} K_c^{ZN} &= 0.45 K_u \\ \tau_f^{ZN} &= \frac{P_u}{1.2} \end{aligned}\right\} \tag{7.10}$$

The ZN values are moderately aggressive and can create oscillations in nonlinear processes. This is due to small value of t_I (i.e. large integral action).

Another tuning approach called the Tyreus and Luyben (TL) settings were developed for processes that behaves like an integrator plus dead time system:

$$\left.\begin{aligned} K_c^{TL} &= 0.31K_u \\ \tau_f^{TL} &= \frac{P_u}{0.45} \end{aligned}\right\} \tag{7.11}$$

The TL settings are less aggressive, with considerably less integral action than the ZN settings. Sluggish processes well represented as integrator plus dead time for a good portion of its step test (e.g. a sluggish distillation column) are recommended to adopt TL settings. After the ZN or TL settings are calculated, they may need to be tuned on line, particularly if the ZN settings are to meet the desired dynamic performance (e.g. 1/6 decay ratio or critically damped). As an example, the ZN settings would be tuned on line as follows:

$$K_c = \frac{K_c^{ZN}}{F_T} \tag{7.12}$$

By adjusting F_T on line, K_c decreases with an increase in F_T while t_I increases by the same proportion (detuning). To meet the performance requirements of an application, the tuning factor F_T is adjusted. Therefore, online tuning has been reduced to a one-dimensional search for the proper level of controller aggressiveness for a PI controller. F_T is increased for an aggressive controller and F_T is decreased for a sluggish controller.

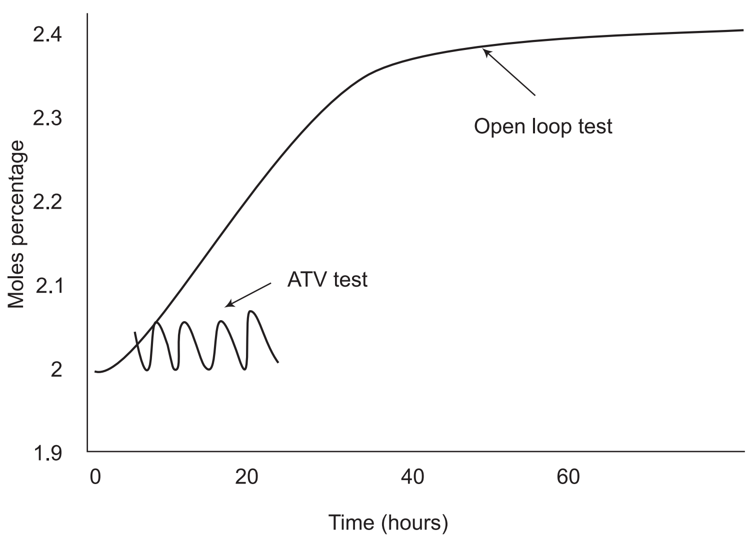

Figure 7.21: Comparison of ATV test and open-loop test for slow-responding processes

Figure 7.21 shows an ATV test and an open-loop step test on the same time scale for a very slow-responding control loop.

The four cycles of the ATV test take only about 10% of the time of an open-loop test. The ATV method provides a "snapshot" of the process without unduly upsetting the system while identifying the ultimate controller gain and ultimate period of a slow-responding loop is a relatively fast process. In addition, the online tuning procedure provides a systematic method for selecting the proper degree of controller aggressiveness. Therefore, the ATV test with online tuning represents an industrially relevant way to attain high-quality controller tuning for loops that have large response times.

7.3.7 PID Tuning Procedures

The PID tuning of slow responsive process is less procedural compared to tuning the PI controller. The online tuning procedures are not proper for a PID controller. Adjusting only the derivative constant to the PID does not create a well-tuned PID. The recommended procedure for tuning PID controllers is as follows:

- Use identification with online tuning to tune a PI controller.
- Use balanced proportional and integral action.
- Reduce t_I to generate sinusoidal oscillations at new set point.
- Enter derivative constant and tune t_D for minimum response time.
- Firstly set t_D equal to $P_u/8$ where P_u is measured from the ATV test discussed earlier.
- Increase K_c and t_D by the same way until the required response is received.
- Verify the output to ensure that the sufficient integral action is being used.

Checkpoint

✦ **1.** What is proportional action?

✦ **2.** What is integral action?

✦✦ **3.** Which entity is reduced by integral action?

✦✦ **4.** What is increased by integral action?

✦✦ **5.** What is reduced by derivative action?

✦ **6.** For the responses which need to be proportionate to the rate at which process is changing, which mode is applied?

✦✦ **7.** Integration is always multiplicative and derivative involves division. Explain.

✦✦✦ **8.** What is anti-reset windup?

✦✦✦ **9.** What is bumpless transfer?

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7.4 APPLICATION OF CASCADE/ FEEDFORWARD CONTROL IN PROCESS CONTROL

LO 4
Illustrate the applications of cascade/feedforward controller in process control

Over a period of time, advanced PID techniques have been developed to overcome the limitations of PID control with respect to disturbance rejection, measurement dead time, process nonlinearity, and process constraints.

7.4.1 Cascade Control

Cascade control is used to effectively reject specific disturbances. Cascade control uses two control loops that are connected together. The primary or master controller determines the set point for the secondary or slave controller. The secondary controller responds to disturbances more quickly than the primary controller, thereby rendering the secondary controller more efficiency than the primary controller in rejecting certain disturbances. Therefore, the secondary control loop must be at least three times faster than the primary loop for a cascade controller to be effective. In addition, secondary loop normally controls the final control element, since it is faster, a better control can be attained. The cascade arrangement's effectiveness with respect to improving the rejection of disturbances depends on how well the secondary control loop rejects a specific disturbance.

Figure 7.22(a) illustrates a schematic diagram of a steam-heated exchanger that does not have a cascade control. An increase in the steam supply pressure causes an increase in steam pressure in the heat exchanger, which increases the temperature of the process steam leaving the heat exchanger. With an increase in the outlet temperature, the controller sends the output to decrease the stem position of the control valve in steam pipe. Any excessive heat from the steam would have been transferred to the process fluid in the heat exchanger by the time the controller initiates corrective action.

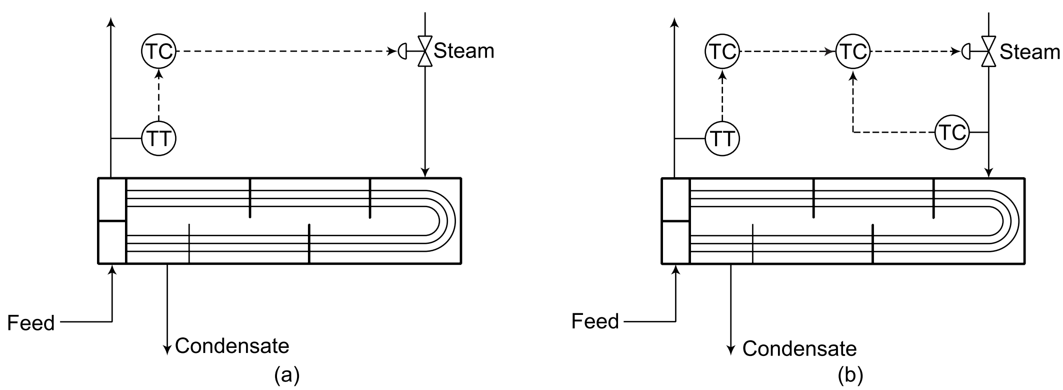

Figure 7.22: Temperature controllers applied to a steam-heated exchanger (a) without cascade control and (b) with cascade control

Figure 7.22(b) is the schematic representation of a heat exchanger with steam input. The control system is configured to be a cascade control. The pressure control loop is the inner loop or secondary loop and temperature is the outer or primary loop of the cascade control. In this case, the temperature controller output becomes the set point signal for pressure controller. If there is no cascade, this output from temperature control will act on steam valve directly. Since it is cascaded, the temperature controller acts on pressure loop and hence the steam pressure valve is acted to increase the pressure. In this case, the pressure controller can act fast by closing the valve to maintain the desired pressure of steam in the heat exchanger. The inlet pressure disturbances are controlled by the pressure valve before it impacts the temperature of the process (primary loop). In this case, since the pressure loop can act faster than the temperature, any disturbances in the process will be limited to the pressure loop and does not propagate to temperature loop.

7.4.2 Feedforward Controller

Feedforward control is applicable to process control loops that are significantly affected by online measurable disturbances. A feedback controller reacts to deviations from set point caused by the disturbance until the process is returned to set point. Hence, feedback control is more reactive in nature where control action is taken after a disturbance. However, contrary to feedback is feed forward control because it predicts the error before it is introduced to process and corrects it. In this control, the proportional and derivatives constants are kept zero at the steady state. The integral constant in the PID drives the compensation for the process upsets. The feedforward controller can generate a signal based on the upset to compensate the effect of upset. In other words, the feedforward control generates an output signal that otherwise might have been generated by the feedback controller after the effect or upset. That means if used together, the feedforward can provide necessary integral action to the controller that the feedback controller does not need to provide any integral action to compensate the measured disturbance.

An example of a feedback controller applied to control the level of a boiler drum (Figure 7.23(a). The feedback controller measures level with the set point and changes the flow rate of the feed water to the drum. Therefore, the drum level changes in response to changes in the demand for steam. In case of large swings in steam demand, a large gain is needed to enable the feedback controller to maintain the level near its set point. The process is more susceptible to oscillatory behavior in the level and feed water flow rate to the drum for large controller gains. Also, high-gain controllers are sensitive to noisy measurements of the controlled variable.

The schematic of a feedforward controller applied to control level in a steam drum is illustrated in Figure 7.23(b). In summary, the drum level remains constant if the flow rate of the makeup feed water is equal to the steam usage. However, feedforward controller is all that is needed for this application may be a misleading conclusion. In this case, the consumption of the steam and rate of flow of feed water may not be perfectly accurate. In such situations even a small error in the measurement of feed water flow rate can lead to both filling the drum with water which is passed into the steam lines and damaging the equipment down. The other extreme is the drum being empty and the boiler tubes getting damaged due to lack of water.

This concludes that neither feedback nor feedforward alone can solve problem on its own and resulting to have a combination of these controllers for an effective control.

Figure 7.23(c) shows a combined feedforward and feedback controller for controlling level in the steam drum. The feedback controller only compensates for measurement errors and unmeasured disturbances, making it a relatively low-gain controller.

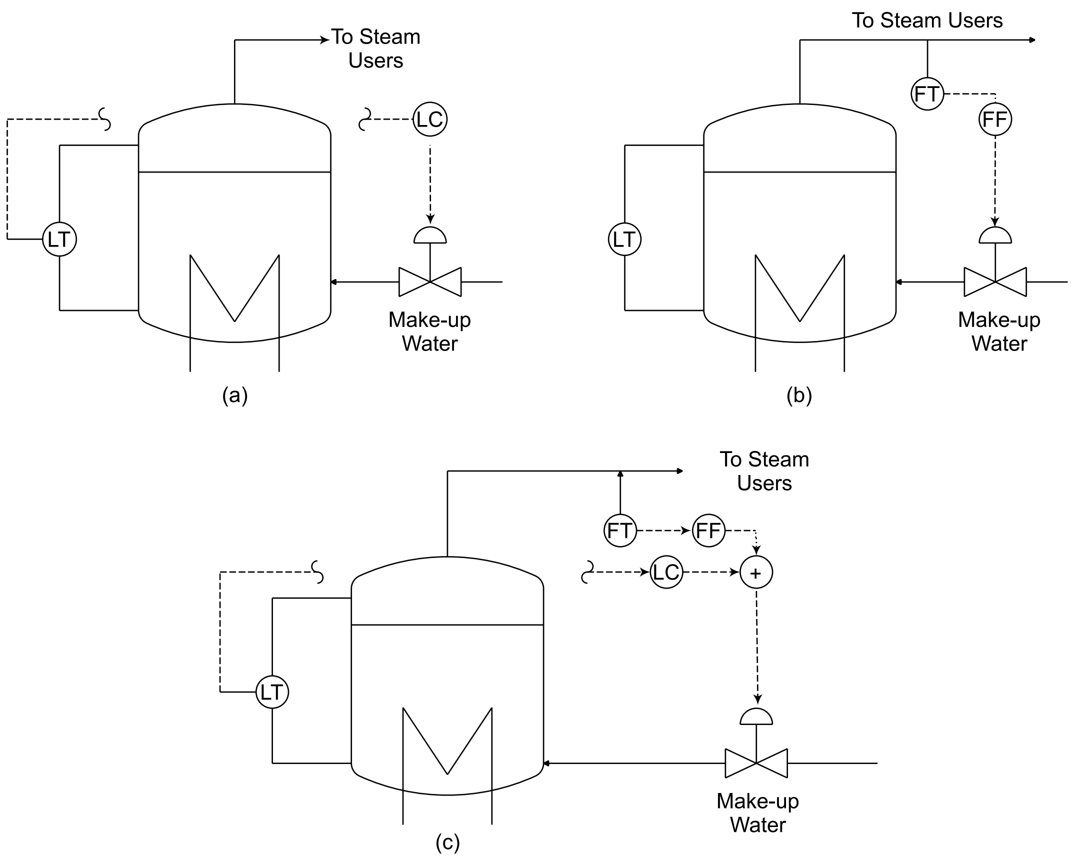

Figure 7.23: Steam boiler level control; (a) Feedback control; (b) Feedforward control; (c) Combined feedforward and feedback control

Note

Most of the required control action is provided by the feedforward controller, by responding to the measured steam usage.

7.4.2.1 Generalized Feedforward Controller

A general formulation of a feedforward controller can be derived as:

$$G_{ff}(s) = \frac{-G_d(s)}{G_p(s)} \tag{7.13}$$

where, $G_{ff}(s)$ is the transfer function for the feed-forward controller, $G_d(s)$ is the transfer function for the effect of the measured disturbance on the controlled variable, $G_p(s)$ is the transfer function for the effect of the manipulated variable on the controlled variable.

If $G_d(s)$ and $G_p(s)$ are described using FOPDT models, the feedforward controller would be represented as a lead-lag element plus dead time with a gain, a lead, a lag, and a dead time. Note that the gain of the feedforward controller is the negative of the ratio of the disturbance gain and the process gain, the lead is the process time constant, the lag is the disturbance time constant, and the dead time is the dead time for the disturbance minus the process dead time.

7.4.2.2 Tuning a Feedforward Controller

The steps for tuning a feedforward controller are as follows:

1. Estimate the lead-lag plus dead time parameters based on process knowledge.
2. Under open-loop conditions, adjust K_{ff} while maintaining the rest of the tuning parameters at their initial levels so as to minimize the steady-state deviation from set point. Figure 7.24(a) shows the dynamic response of a feedforward controller for a step change in the disturbance after K_{ff} has been adjusted to eliminate offset.
3. Adjust q_{ff} after analyzing the dynamic mismatch. The direction of the deviation causes dynamic mismatch indicating whether the feedforward correction is applied too soon or too late. The feedforward control performance after q_{ff} is tuned is illustrated in Figure 7.24(b).
4. Finally, adjust either t_{ld} or t_{lg} until you attain approximately equal areas above and below the set point. The result after t_{ld} and t_{lg} are adjusted is illustrated in Figure 7.24(c).

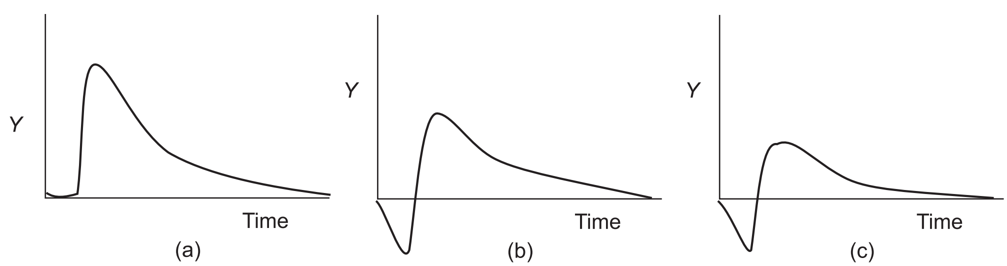

Figure 7.24 (a to c): Tuning feedforward controller

7.4.2.3 Combined Feedforward and Feedback Control

The advantages and disadvantages of feedforward and feedback control are summarized in Table 7.4. Feedforward and feedback control complement each other, such that each overcomes the disadvantages of the other so that together they are superior to either method alone. A feedback-only controller efficiently absorbs disturbances in processes such that, the advantage provided by feedforward control for fast-responding processes is insignificant. In case of process with more dead time or slow response, a feedback only control is not enough. The controller starts acting on the system after the error is seen, but by the time the corrective action has the effect on the process, the process is already upset. If there is a feedforward controller added to the same process with more dead time, it reduces the deviation from the controlled variable from set point leading to smaller disturbances to the process. Therefore, feedforward provides a better feedback control performance when the performance compensates for a major disturbance to the process. Typically, feedforward control is useful when:

- Feedback control by itself is not satisfactory, i.e. for a process having substantial dead time or for a process having significant dead time.
- The major disturbance to a process is measured on line.

For a nonlinear process, feedforward control provides only partial compensation as it provides a linear correction. Nevertheless, when feedforward control is properly implemented, it can be very effective. Since feedforward control reduces the amount of feedback correction required. When tuning a feedforward controller for a nonlinear process, ensure that the feedforward controller is tuned in consideration of both increases and decreases in the disturbance level. For example, tuning the feedforward controller for a certain size increase in the disturbance may work advantageously for that scenario, but that tuning may actually contribute to poorer performance during a different size disturbance decrease. Note that the changes in the manipulated variable calculated by the feedforward and feedback controllers are simply added.

From the above discussion, there are clear advantages and disadvantages of each type of control and application of the same to specific process conditions play a critical role. Refer to the Table 7.4 for the detailed comparison.

Table 7.4: Comparison of feedback and feedforward control

Feedback control	
Advantages	*Disadvantages*
Disturbance measurement not required.	Takes action only after the disturbance has affected the process.
Can effectively reject disturbances for a fast-responding process.	Susceptible to disturbances if the process is slow or in the presence of significant dead time.
Simple to implement.	Can make the closed-loop system unstable because of nonlinearity.

(*Contd.*)

Feedforward Control	
Advantages	*Disadvantages*
Compensates for disturbances before they affect the process.	Requires the measurement of the disturbance.
Can improve the reliability of the feedback controller by reducing the deviation from set point.	Does not compensate for unmeasured disturbances.
Offers noticeable advantages for slow processes or processes that have significant dead time.	Since it is a linear-based correction, its performance deteriorates with nonlinearity.

7.4.2.4 Ratio Control

Ratio control is another way of feedforward control where two loads are measured and the ratio is maintained at constant rate. In general, this will be with respect to different flow rates, where the flow rate ratio is maintained at a constant rate, commonly one of the streams is not controllable and referred as wild stream.

In distillation columns (Figure 7.25) and wastewater neutralization (Figure 7.26), processes scale directly with the feed rate to the process. For a given product quality and tray efficiency in a distillation column, the liquid and vapor flow is directly proportional to the feed rate. The illustration of the distillation column using a ratio controller for the bottom product quality is shown in Figure 7.25. This is a direct application of the ratio control with an exception for an additional dynamic compensation for feed rate in to the distillation column.

For an increase in column feed rate, if the steam flow to the reboiler is increased immediately, the corrective action would initially be an over correction. This is because it takes some time for the bottoms product composition to respond when a feed rate change occurs. The dynamic compensation (DC) element ensures the correct timing for the compensation for feed rate changes. The dynamic element for the example in this figure could simply be a lag element, for example, a digital filter.

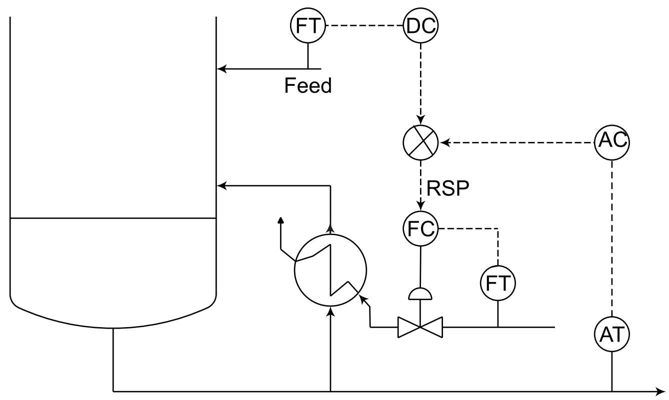

Figure 7.25: Schematic diagram of ratio control for feed rate changes in a distillation column

In a wastewater neutralization process, the quality of the reagent to maintain pH of the effluent is proportional to the flow rate of the feed water. Figure 7.26 explains the adoption of ratio control to the effluent pH for a wastewater neutralization process in a mixing tank. The ratio controller can handle the feed water flow changes while maintaining the pH as constant. The feedback controller is usually capable of handling small changes in the chemical makeup of the wastewater, which adjusts the reagent-to-wastewater ratio to maintain the specified effluent pH.

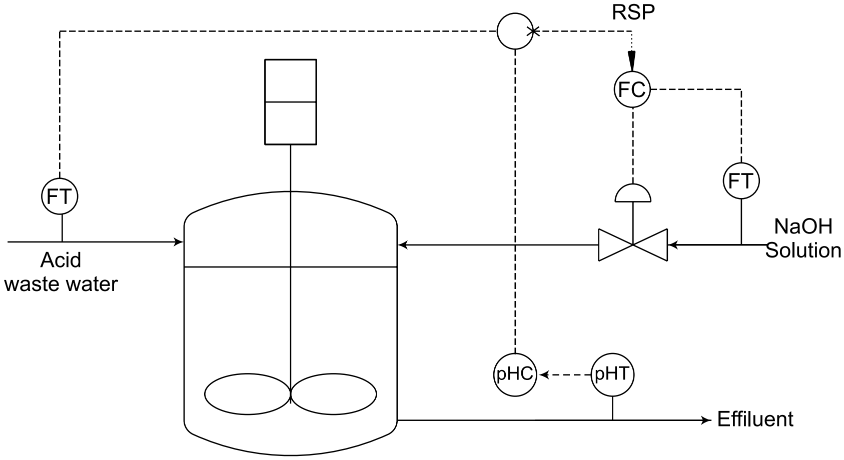

Figure 7.26: Schematic of ratio control applied for pH control of an acid neutralization process

This application does not require dynamic compensation due to the process pH response to feed rate changes. The feed rate changes and their response to NaOH flow rate changes have similar dynamic behavior.

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Checkpoint

✦✦ **1.** What are the limitations of a PID Controller?

✦✦✦ **2.** Name the controllers that form the cascade control.

✦✦✦ **3.** Which controller in the cascade form responds fast for disturbances?

7.5 APPLICATIONS OF INFERENTIAL CONTROL

LO 5
Explain the applications of inferential control

7.5.1 Inferential Control

Generally the widespread assumption is that sensor measures the process variable by direct means. The above is true, but there are various methods in which the measurement is made for some other variable and the actual measurement is inferred. For example, the thermocouple, an RTD actually, is a measure of resistance wherein the change in temperature causes a change in resistance. The change in resistance is measured and is correlated for temperature. Likewise, the level in a tank can be inferred from the pressure difference between the top and the bottom of a vessel, and a flow rate can be estimated from the pressure drop across an orifice plate. Parameters like pressures, temperatures, and flow rates that can be readily measured can be effectively used to infer difficult to measure quantities, such as molecular weight, compositions, and extent of reaction. In all these cases, the inferred value is treated as actual process measurement and is used in the controller to generate the output. Following are some of the needs in the industry where the inferential measurement is needed as controlled variable:

- Inferential measurements are the industrial chosen method for counteracting large measurement delays for controlled variables.
- Inferential measurements can greatly reduce the measurement dead time because they use measurements (e.g. temperatures, pressures, and flows) that have relatively low levels of measurement dead time.
- The installation and maintenance cost of an online analyzer can be expensive. Whereas, the installation and maintenance cost of an inferential measurement is less expensive as they are based on pressure, temperature, and flow measurements.

If an online analyzer is unavailable for any parameter, an inferential measurement may be the only alternative for feedback control. It is important for the inferential measurement to correlate strongly with the controlled variable value for an inferential control to be effective, and this correlation must be relatively insensitive to unmeasured disturbances.

7.5.1.1 Inferential Temperature Control for Distillation

In distillation columns, the tray temperatures at different levels can be used to infer the quality and compositions of the liquid inside. Some experts can tell the quality by measuring the temperature alone at different heights. Therefore, inferential control is widely used for distillation product composition control. Figure 7.27 shows the arrangement for inferential temperature control of the bottom product composition for a column in which the temperature on tray 10 correlates strongly with the bottom product composition. The tray temperature controller is cascaded to a flow controller.

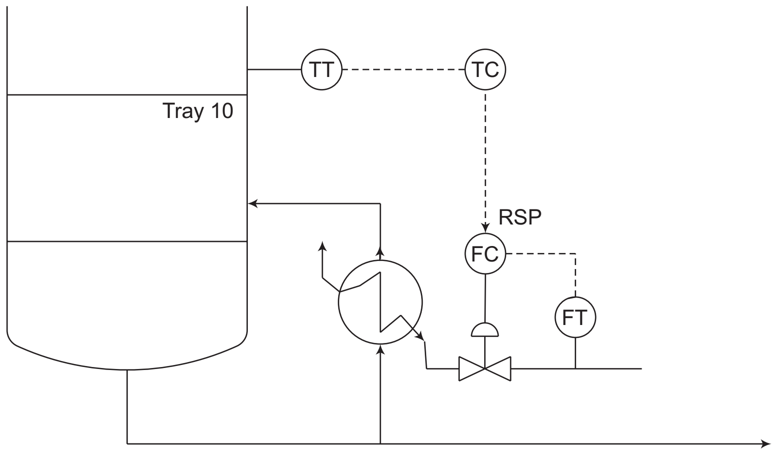

Figure 7.27: Schematic for inferential control of the bottom product composition control of a distillation column

In multicomponent columns, the correct tray temperature for a specified product composition changes as the feed composition to the column changes. In these situations, a composition controller can be cascaded to the tray temperature controller. Alternatively, the composition controller can be administered by an operator by adjusting the set point for the tray temperature controller as laboratory analysis results on the product become known. Other examples of applying inferential measurements to overcome measurement delay for industrial processes include inferential control of reactor conversion based on temperature measurements, inferential molecular weight control of a polymer, and inferential control of NOx emissions from an electric utility boiler. The inferential NO_x analyzer uses an artificial neural network that uses a large number of process measurements, such as coal feed rate, excess air, coal composition, etc., to predict the NO_x content of the flue gas.

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Checkpoint

✦✦ 1. What is inferential measurement?

✦✦✦ 2. List two examples of inferential control.

7.6 ILLUSTRATE THE APPLICATIONS OF SPLIT-RANGE CONTROL

LO 6
Illustrate the applications of split-range control

7.6.1 Split-range Control

This control is used when a single output variable is to be produced from several manipulated variables. This control ensures that a proper coordination among various manipulated variables is present.

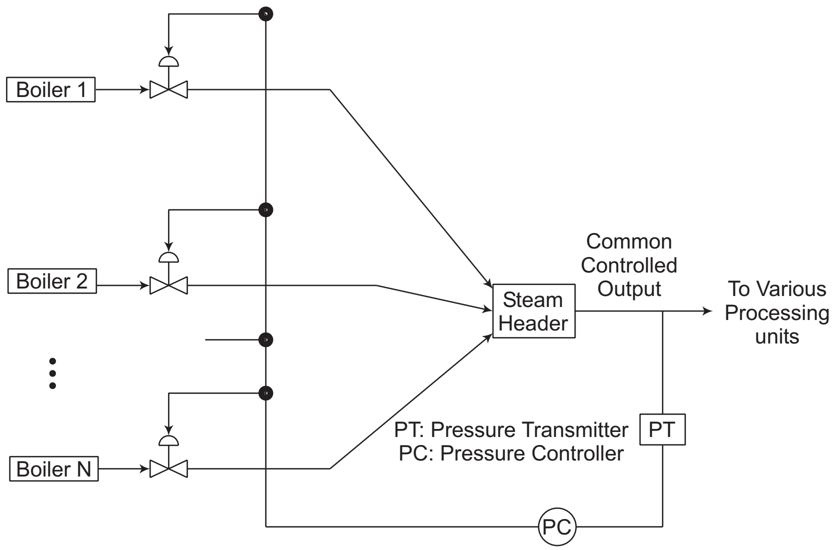

Figure 7.28: Split-range control

Figure 7.28 is one of the most common example of a typical split-range control scheme. In this process, the steam discharges from various boilers merge at a steam header. The combined steam pressure at the header should be maintained constant using a pressure control loop. For controlling simultaneously the steam flow rates from the boilers in parallel, the command from the pressure controller is used. This confirms that a single output variable (steam header pressure) results from manipulating numerous variables (discharge from different boilers).

7.6.2 Override Control

The strategy of this control involves a selection between two or more controller output signals, while a single controller exerts control over a process at any given time. All other "de-selected" controllers are thus overridden by the selected controller. An industrial example of override control is seen in a water pumping system as shown in Figure 7.29. Here, a variable-speed electric motor drives a water pump and draws water from the well and provide constant water pressure to the customers.

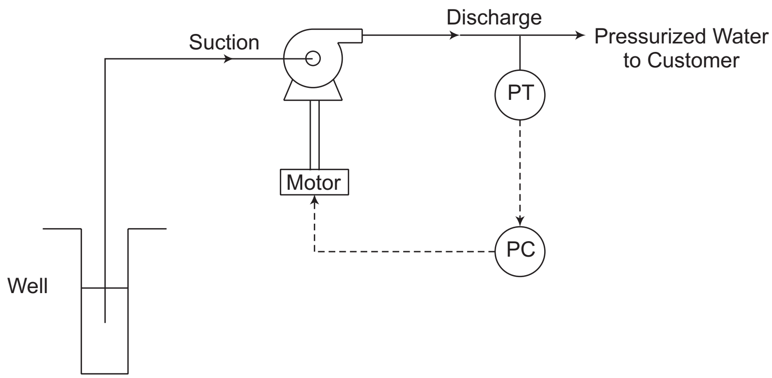

Figure 7.29: Override control

Most of the applications of override control are seen with variable speed motors and drives as the final control element than the traditional control valves. In the low-flow conditions, by reducing pump speed a lot of energy can be saved, over a period of time. Hence, using Override control is advantageous compared to the constant-speed pump and control valve, which results in wastage of energy.

One of the challenges with this system is the pump running "dry". This challenge is encountered during the summer months, when the water levels in a well are low and the demand for the water from the customer is high.

Running the pump "dry" for a long period will result in damaging the pump. This may render the pump unusable, right at the time when the customer needs it most. One of the solutions to this problem is installing a level switch in the well. The switch senses the water level and shuts off the electric motor that is driving the pump when the water level gets too low as shown in Figure 7.30.

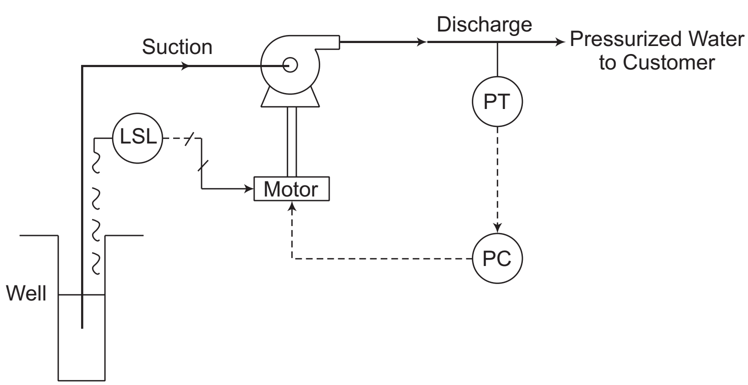

Figure 7.30: Override control with switch protection

This mode of control is seen as an override strategy due to the fact that a switch can override a controller output to start a motor. It is a primitive solution to the problem of protecting the motor and pump from damage, with an inconvenience of lack of fluid or water to the customers.

One way to address this issue would be to allow the pump reduce the water output when water levels are low. In this mode of control, the drive/pump mechanism keeps driving the pump with minimum amount of pressure maintained and at the same time reducing the demand on the well along with maintaining water needs, while protecting the system from damage. This is a soft override control achieved through control systems such as DCS.

In order to implement such a strategy in a control system, the level switch with discrete output will be replaced with level transmitter with continuous signals and a level controller receives these signals and use a function block or combination of blocks that selects the lowest valued output between pressure and level controllers. The overall schematic of such an operation is shown in Figure 7.31. The level controller's set point will be set at some low level above the acceptable limit for continuous pump operation.

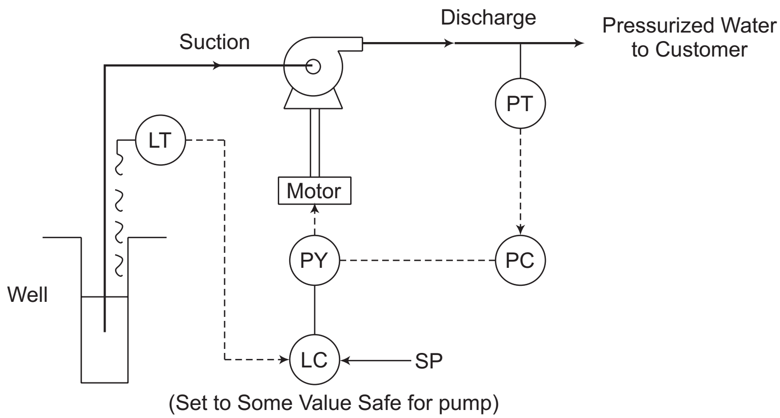

Figure 7.31: Override control with soft control

In this control strategy once the level reaches the set point, the output of the controller reduces which in turn drives the pump for reducing the speed, in spite of needing more pressure as per the pressure controller which sends output for higher speed. In this situation, the level control signal overrides the pressure control signal to protect the motor/pump for their longevity. The second level protection provided is also considered where the level switch installed in the lower side of the tank shuts off the pump. This type of hard shutdown by additional means like switches is considered in case of any failures on the main control operation which could be a wrong tuning or improper set point or hardware failure, etc. These two layers of protection, one is a soft means by the controllers and other by the hard means through a switch is a common practice for all the critical controls. The soft control tends to be moderate in action and tries to throttle, where the hard control will aggressively shutoff. In order to make both the ways to work, the set point of the level in soft control is set less than the alarm limit (LAL) for trip in hard control as shown in Figure 7.32.

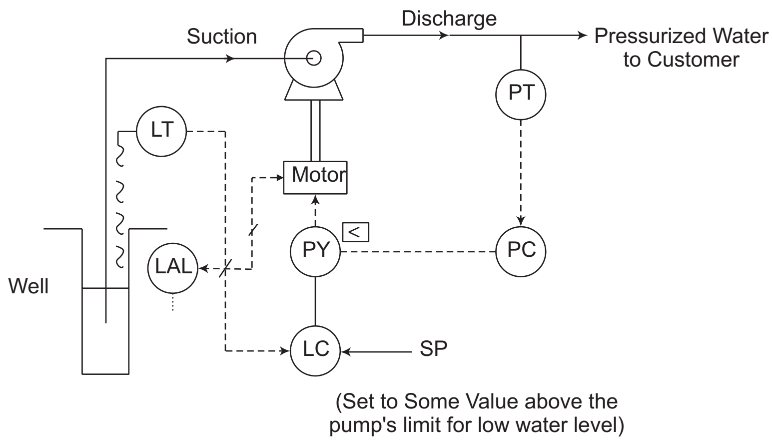

Figure 7.32: Override control with control strategy and switch

7.6.3 Scheduled Tuning

Nonlinear process behavior injects instability to a controller in certain situations and renders it extremely sluggish in others. For example, a process gain increase by over 100% could cause the controller to become unstable. A 50% or more decrease in process gain can render the process sluggish. A PID controller tuned with high gain can reduce the oscillations, but introduces delay in performance. The magnitude of the disturbances in combination with the inherent process nonlinearity determines the degree of observed process nonlinearity. Certain measurements, for many processes, directly indicate whether the process parameters have increased or decreased and by how much. Therefore, an effective way to compensate for process nonlinearity is by scheduling the controller tuning based on process measurements. The feed rate and the controlled variable are examples of key process measurements. These are used, typically, to schedule the controller tuning.

A good example of a process that can substantially benefit from scheduling the controller tuning is steam-heated heat exchanger. With a variation in the feed rate of the process stream, there is a significant change in the gain and effective dead time of the process. The process dead time is inversely proportional to the feed rate. Without the use of scheduling, the temperature controller on a steam-heated heat exchanger tuned for a large feed rate becomes unstable when the feed rate is reduced by a factor of two. The temperature controller performs reliably for a wide range of feed rates when controller tuning for different feed rates is scheduled.

7.6.4 Constraint Control

Process control systems operate with constraints from the process. The process always tends to move towards better yield and naturally tends to reach the limits. It becomes necessary to apply different control loops from those previously used once the higher and lower limits of the process variable in reached. It is important to install safeguards while implementing an industrial controller effectively, while operating safely, economically and environmental friendly using the control strategies such as override control, etc.

For example let us discuss the case of a furnace fired heater as shown in Figure 7.33. During its normal operations, the fuel rate needs to be varied to control the desired temperature of the fluid at the outlet. The temperature of the furnace tube increases with an increase in the feed rate of the process fluid. At some point, the upper limit on furnace tube temperature (an operational constraint) is encountered.

It is important to adjust the fuel flow rate to the furnace to keep the furnace tube temperature from exceeding its upper limit. If the tube temperature constraint is exceeded, the furnace tubes are damaged, significantly reducing their useful life. As shown in Figure 7.33 the temperature controller output for both process fluid and furnace tubes are measured and controlled. In such situations, the fuel rate to the furnace is controlled from both these parameters with a function block called low select (LS). Based on the dynamic situation of the control, the low select will feed the appropriate control output for the fuel feed valve. The temperature of the process fluid can be controlled at the set point when the feed rate of the process is suitably low. Thus, the output of the process fluid temperature controller can be selected as it is lower than the output of the tube temperature controller. Similarly, the output of the tube temperature controller can be selected when the tube temperature reaches its upper limit. Therefore, there are two separate loops that use fuel flow rate as a manipulated variable. The LS controller switches between them as the flow rate of the process fluid changes.

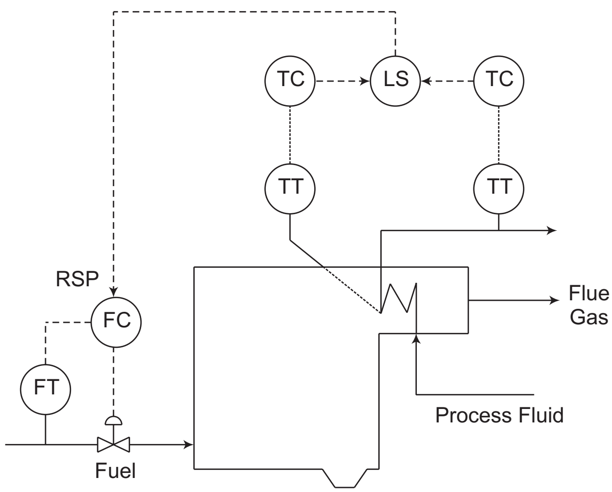

Figure 7.33: Schematic of a furnace fired heater with low select firing controls

Figure 7.34 is another example of a distillation column which can reach the upper limits with a reboiler in circulation. If the set point to the steam flow rate is more than set point then the override control can take over and feed the column feed flow as a manipulated variable to maintain the quality at the bottom of the vessel. Once the column federate is adjusted to the rate required, the control on the steam line for reboiler is no more saturated (fully open) while maintaining the quality. This is an example of the override selection of a secondary manipulated variable when the primary manipulated variable reaches a limit (becomes saturated).

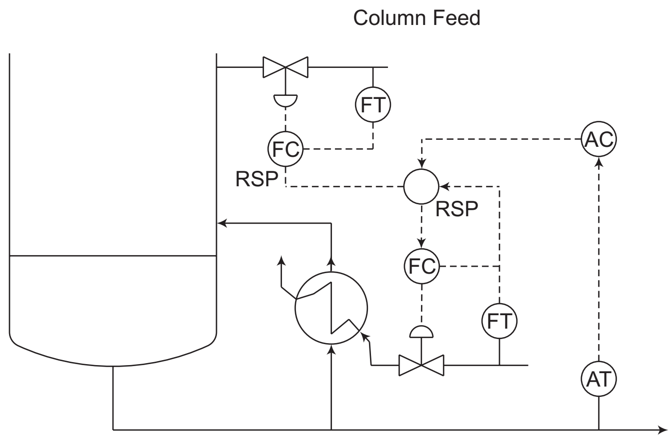

Figure 7.34: Schematic of the stripping section of a distillation column with low select controls applied to prevent flooding of the column

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Checkpoint

✦✦ **1.** What is split range control?

✦✦✦ **2.** What is override control?

7.7 CONTROL OF MIMO PROCESSES IN PROCESS CONTROL APPLICATIONS

LO 7

Describe the control of MIMO processes in process control applications

MIMO processes have multiple inputs and multiple outputs and therefore the name MIMO. The manipulated variables and controlled variables selected in these processes have a dominant effect on the control performance.

7.7.1 Selecting Control Configuration

The process of pairing the manipulated and controlled variables consists of selecting a control configuration. The selection of control configuration is crucial for PID controllers, where each controlled variable must be paired with a manipulated variable and control performance depends on control configuration. An inferior control configuration can result in poor control performance even though the individual PID controllers may be functioning properly and are properly tuned. It is essential to identify the manipulated variables and the controlled variables for multivariable controllers also, which do not have to pair manipulated and controlled variables due to the MIMO nature of multivariable controllers. Many times, this is equivalent to selecting the control configuration.

The closed-loop performance of a decentralized control configuration is affected by the following three factors:

- The coupling or interaction between SISO control loops
- The dynamic response of a controlled variable to a change in its manipulated variables
- The sensitivity of disturbances.

The coupling between two SISO control loops is schematically illustrated in Figure 7.35. A change in c_1 that the controller for control loop 1 requires, to return y_1 to its set point affects the value of y_2, which in turn initiates the controller for the control loop 2 to take corrective action. These changes in c_2 also affect y_1. Therefore, when the controller on control loop 1 takes corrective action to return y_1 to set point, it can cause an upset in y_1 as a result of coupling. Coupling can be analyzed from a steady-state point of view using an RGA analysis. However, since dynamic factors also affect coupling, a dynamic RGA analysis may be required. Control engineers do not normally have the detailed dynamic models of a process that are needed to develop an accurate dynamic RGA analysis of multivariable process.

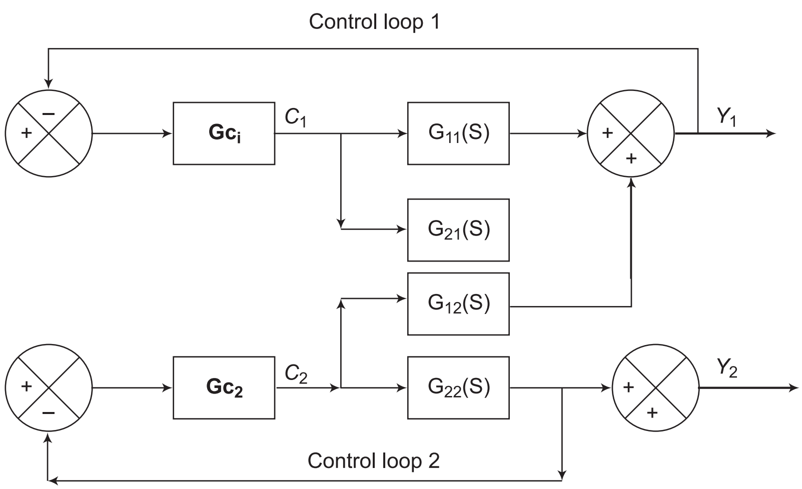

Figure 7.35: Schematic of a two-input/two-output process with single-loop controllers showing coupling between the control loops

Choosing manipulated variables such that they have a relatively large and immediate effect on the controlled variables with which they are paired is one way to avoid dynamic coupling. Therefore, select a configuration such that each of the manipulated variables has a fast and consistent dynamic effect on its controlled variable. It is recommended to avoid pairings that result in a sluggish response or inverse action.

Finally, each control configuration has its own sensitivity to disturbances. A control configuration with less sensitivity to a disturbance requires less feedback correction during regulatory control than another configuration that is more sensitive to the disturbance. Therefore, the sensitivity of a control configuration to the key disturbances is a major consideration when selecting configuration.

The selection of the proper control configuration must take into account coupling, dynamic response, and sensitivity to disturbances. In cases such as selecting control configuration for distillation columns, there may be no clear choice. One configuration may be the best with regard to coupling but the worst with regard to sensitivity to disturbances. Another may be best for disturbance sensitivity and the worst for coupling. In the absence of operating experience and clear configuration choice, it may be necessary to make control comparisons using dynamic simulators to identify the best control configuration.

7.7.2 Tuning Diagonal PID Controllers

The tuning procedures discussed earlier for the single PID controllers can also be used as a subset for decentralized control of MIMO. At first an ATV test is performed for each loop in such a way that while one is tested, the other is maintained in open-loop condition. The second step is to know if any of the loop responds faster than the other. Compare the values of the ultimate periods, P_u, obtained in the ATV tests to achieve this. If the smallest value of P_u is five times or more small than the next largest Pu, implemented that loop first by itself before tuning the other loops. It can be tuned as a single PID loop.

The ATV test is again executed on other loops the tuned loop is in closed-loop condition. After this, the rest of the remaining loops are fine-tuned with the procedure explained. For example, if it is necessary to tune a PI controller on a 2 × 2 MIMO process. The results from the ATV test are used for calculating the gain and reset time using techniques such as Zeigler-Nichols methods, etc. After this the single tuning factor F_T is used for both control loops.

First control loop

$$K_c = \frac{K_c^{ZN}}{F_T} \tag{7.14}$$

$$\tau_f = \tau_f^{ZN} \times F_T \tag{7.15}$$

Second control loop

$$K_c = \frac{K_c^{ZN}}{F_T} \tag{7.16}$$

$$\tau_f = \tau_f^{ZN} \times F_T \tag{7.17}$$

F_T is adjusted until the proper dynamic response is obtained. For example, set point changes in y_1 and/or y_2 can be used to select the proper value of F_T. Alternatively, adjust the value of F_T to provide reliable performance of the controllers based on the day-to-day operating performance of the controller. If the closed-loop response is sluggish while tuning, decrease the value of F_T. Likewise, if the controller exhibits periods of ringing, increase the value of F_T.

Fine-tune the controller settings after adjusting F_T to tune the set of decentralized P_I controllers. For example, if one observes that one of the control loops is slow to settle at set point, test an increase in integral action for that loop. If a loop exhibits ringing, test the derivative action to determine if it would improve the feedback control performance of that loop. In the latter case, tune derivative action as described previously.

7.7.3 Model Predictive Control

The most widely used form of multivariable control is the model predictive control (MPC). There are more than five thousand industrial MPC applications worldwide, and the number is rapidly growing. Dynamic matrix control (DMC) is the most popular form of MPC and is based on having a step-response model for each input-output pair of the process. A step-response model is a series of terms that represent the deviation response of the process to a unit step input change. That is, each coefficient in a step-response model indicates the change from steady state for a different point in time after the unit input has been applied to the process. In this way, the step-response coefficients are arranged in order, with the first coefficient indicating the response after one control interval and the last coefficient representing a point in time after which the process has had time to reach its new steady state.

The dynamic matrix is derived from the step-response models using the principal of superposition. Therefore, the dynamic matrix is composed of the coefficients of the step-response model and can be multiplied by a series of input changes to directly calculate the future changes in the value of a controlled variable. When MPC determines control action, it also calculates the future behavior of the process. Even though it calculates a number of manipulated variable moves into the future, only the first move is implemented. In the next control cycle, another set of future moves is calculated, and, once again, only the first move is implemented. Because of this methodology, MPC is known as a moving horizon controller.

The DMC control law is based on minimizing the error from set point but if applied directly it can be too aggressive. Therefore, tuning parameters, called as move suppression factors are used to augment the DMC control law and to reduce its aggressiveness. The DMC controller adjusts the one move suppression factor for each manipulated variable to control the process. Move suppression factors are the primary tuning factors for a DMC controller. Also, select the relative priorities, also called the equal concern errors of the controlled variables. In addition, choose the model horizon (i.e. the length of time that the model is assumed to reach steady state) and the control horizon (i.e. the period of time over which the future control moves are calculated). Once the input-output models are determined, use the standard guidelines for choosing appropriate values for the model and control horizons.

The widespread industrial use of DMC and MPC, in general, is the result of their ability to operate processes more profitably. The industry use of DMC would have been drastically lower if DMC provided only reduced variability operation. DMC improves the profitability of processes because it can operate processes for more highly valued products at higher production rates. This is mostly achieved by processing the largest feed rate to the process by maintaining the operation against the most advantageous set of constraints, that is, constraint control.

A linear program (LP) assesses the economics of the process and constraints and specifies to the DMC controller the constraints against which it should control the process. An LP determines the optimum values of the decision variables for a linear economic objective function, subject to a set of linear constraints. In the case of an LP, the optimum is located at a vertex because the number of active constraints is equal to the degrees of freedom in the LP, i.e. the intersection of "n" constraints where "n" is the number of decision variables. The LP determines the most favorable set of constraints for control action. In this way, as the operation of the process or the cost of the feeds and value of the products change, LP ensures that the process maintains the most profitable operation. Because the process gains used by the LP are identical to the steady-state gains for the step-response models used by the DMC controller, the LP and DMC controller work together in a consistent fashion. The prerequisite for a successful MPC application is the appropriate application of the MPC to the process.

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Checkpoint

✦ 1. What is MIMO?

✦✦✦ 2. List three factors on which the decentralized control configuration depends.

✦✦ 3. How coupling can be analyzed from steady state point of view.

✦✦✦ 4. What is MPC?

Summary

LO 1: Define process control, symbols and hardware components of a control loop

- The control engineer is responsible for determining the source of poor performance of the control loops arising out of poor design, equipment failure, process problems, or improper tuning and makes appropriate corrections.
- A series of rectangular blocks, representing a unit operation or a process area are used in the block diagram. The block diagram differentiates between new and existing equipment and may present the major flows between units.
- The process flow sheet illustrates all the major pieces of equipment, and indicates all the principal lines and flows.
- P&ID illustrates every loop in its entirety, including the measurement element, the transmitter, the pneumatic/electric signal converter, the control function and location of controller, the control valve or control element, and the actuator and air feed line to the actuator.
- Instrument lists every loop in the plant, assigns it a unique loop number, and describes its function, its components, its vendors, its characteristics, and its sizes.
- The use of bumpless transfer and anti-windup is also recommended in addition to validity checks and filtering to sensor readings. Thereby ensuring a reliable and good control performance by controllers. The best controllers meet their control objectives, stay in service unless there is a sensor or actuator failure, and respond "gracefully" in the event of an actuator or sensor failure.

- The performance of a sensor is characterized by span, accuracy, and repeatability. Span is the difference between the largest measurement value made by the sensor/transmitter and the lowest measurement value. Zero is the lowest reading measured from the sensor/transmitter. It refers to the sensor reading which corresponds to a transmitter output of 4 mA. Accuracy is the difference between the value of the measured variable and its true value. Since the true value is never known, the accuracy is projected to be the difference between the sensor value and an accepted standard.

LO 2: Outline the characteristics of industrial process

- A self-regulating process typically means, if the variables in the process are set constant then the output settles at a steady state.
- When opposing factors act within a process then (one that is faster in response but has less steady-state gain than the other) an inverse acting process may occur.

LO 3: Analyze the role of PID controller in process control

- Proportional action as the name indicates drives the output in proportion to input. Hence, there exists a directly proportional relationship between output and input.
- Integral action is directly proportional to the integral of the error from set point. The error within which the output has settled down without reaching set point. Integral action leads to all the steady-state correction for disturbances. Integral action eliminates offset but increases the oscillatory character of the response.
- Integration is fundamentally a multiplicative operation (products) while differentiation always involves division (ratios).
- If there is a sudden large change in set point, the error will be large and the integrator output in a PID control will build up with time. As a result, the controller output may exceed the saturation limit of the actuator. Unless prevented, this windup, may cause continuous oscillation of the process that is not desirable.
- When a controller is switched from manual mode to auto-mode, it is desired that the input of the process should not change suddenly. However, there is always a possibility that the decision of the manual mode of control and the auto mode of control be different. Also, there may be a sudden change in the output of the controller causing a sudden jerk in the process operation.
- The dynamics of the process and sensor are quite fast compared with the dynamics of the control valve. Since overall procedure is fast and calls for accurate control to set point, a PI controller is the proper choice for most flow control applications.
- The P-only controller is recommended if offset elimination is not important and a PI controller can be used when offset elimination is important.
- If the controller is tuned for normal disturbances, the closed-loop system may become unstable when a major disturbance enters the process. On the other hand, if the controller is tuned for the largest possible disturbance, control performance is likely to be excessively sluggish for normal disturbance levels.
- The time between control applications samples is the control interval (Δt).
- Controller reliability is likely to be a problem in case of a highly nonlinear process subject to large disturbances. Such cases call for a more conservative tuning criterion (e.g. a critically damped response).
- Filtering process measurements is an effective way to reduce the effects of measurement noise.

LO 4: Illustrate the applications of cascade/feedforward controller in process control

- The secondary control loop must be at least three times faster than the primary loop for a cascade controller to be effective.

- A feedback controller reacts to deviations from set point caused by the disturbance until the process is returned to set point. Hence, feedback control is more reactive in nature where control action is taken after a disturbance. However, contrary to feedback is feed forward control because it predicts the error before it is introduced to process and corrects it.
- A feedback-only controller efficiently absorbs disturbances in processes such that, the advantage provided by feed-forward control for fast-responding processes is insignificant.
- Ratio control is another way of feedforward control where two loads are measured and the ratio is maintained at constant rate, In general this will be with respect to different flow rates, where the flow rate ratio is maintained at constant rate, commonly one of the streams is not controllable and referred as wild stream.

LO 5: Explain the applications of inferential control

- It is important for the inferential measurement to correlate strongly with the controlled variable value for an inferential control to be effective, and this correlation must be relatively insensitive to unmeasured disturbances.
- The inferential NOx analyzer uses an artificial neural network that uses a large number of process measurements, such as coal feed rate, excess air, coal composition, etc., to predict the NOx content of the flue gas.

LO 6: Illustrate the applications of split-range control

- A selection between two or more controller output signals wherein a single controller exerts control over the process at any given time forms the basis of the override control strategy. All the remaining nonselected controllers are thus overridden by the selected controller.
- An effective way to compensate for process nonlinearity is by scheduling the controller tuning based on process measurements. The feed rate and the controlled variable are two examples of key process measurements that are typically used to schedule the controller tuning.
- Constraints are a natural part of industrial process control. As processes are pushed to produce as much product as possible, process limits are inevitably encountered. It becomes necessary to apply different control loops from those previously used when an upper or lower limit on a manipulated variable is encountered, or when an upper or lower value of a controlled or output variable from the process is reached. It is important to install safeguards while implementing an industrial controller effectively, to prevent the process from violating safety, environmental, or economic constraints. These constraints can be met using over-ride or select controls.

LO 7: Describe the control of MIMO processes in process control applications

- MIMO processes have multiple inputs and multiple outputs and therefore the name MIMO. The manipulated variables and controlled variables selected in these processes have a dominant effect on the control performance.
- The selection of the proper control configuration must take into account coupling, dynamic response, and sensitivity to disturbances.
- Dynamic matrix control (DMC) is the most popular form of MPC and is based on having a step-response model for each input-output pair of the process. A step-response model is a series of terms that represent the deviation response of the process to a unit step input change.

Questions

I. Objective-type questions

✦✦ **1.** In developing an instrument loop diagram, square symbols are used to represent:
(a) Communication links (b) Field instruments
(c) Control stations (d) Junction boxes

✦✦✦ **2.** The function of PID parameters are best described as:
(a) Optimizing a control loop
(b) Ensuring that specified components are properly installed
(c) Placing the system in a safe condition during process upsets
(d) Ensuring that specified components are properly calibrated

✦✦ **3.** Which of the following statements is true regarding controller tuning from open loop tests?
(a) The data is valid at multiple operating points
(b) The normal process operations may be interrupted for testing
(c) The process can be approximated with a first order plus dead time model
(d) Measurement noise may obscure the results of the test

✦✦✦ **4.** Which of the following is true of the newest generation of adaptive controllers?
(a) The degree of performance and robustness is preset
(b) They have the same performance as traditional PIDs
(c) The controller must wait for an excitation and adaptation when the controller enters a region
(d) The algorithm uses model switching to adapt most quickly

✦✦✦ **5.** Which of the following statements about process disturbances is true?
(a) Feedback controllers will maintain the average value of the controlled variable at set point if disturbances are not severe
(b) Reducing the variability of disturbances can be done by the feedback controller
(c) Severe disturbances will create minimal feedback in the control loop because the controller minimizes output changes
(d) Reducing the margin of safety will increase the number of process disturbances

✦✦✦ **6.** Which of the following is characteristic of the operation of an MPC?
(a) An MPC goes unstable with an increase in process dead time
(b) MPC performs best in a process where the dead time is smaller than the time constraint
(c) MPC is more sensitive to a decrease in dead time than to an increase
(d) An increase in the process dead time of 50% can cause damped oscillations

✦✦ **7.** In cascade control, the primary loop controller:
(a) Establishes the set-point for the secondary loop controller
(b) Eliminates the need for a feedback control loop

(c) Corrects and confines disturbances in the secondary loop controller
(d) Must be significantly faster than the secondary loop controller

✦✦ **8.** A piping and instrument diagram does not include which of the following?
(a) Instrumentation devices
(b) Communication between instrumentation devices
(c) Accessibility of devices to the operator
(d) Failure thresholds

✦✦✦ **9.** The primary purpose of process modeling is to:
(a) Correct errors in the process as they occur.
(b) Determine how well a controlled variable can be predicted.
(c) Determine the complexity of the system.
(d) Provide controlled variables from process outputs.

✦✦✦ **10.** At a plant that uses transistor-based single-loop controllers, when switching from a proportional-integral (PI) to a proportional-integral-derivative (PID) type controller and retuning the device in one instance, which of the following is true?
(a) The change requires changing controllers, but tuning the devices differently can be accomplished without new purchases.
(b) The change, including retuning the device, requires changing controllers or at least the circuit board.
(c) Transistorized controllers use a type of microprocessor that can be reprogrammed because they are a type of counter instead of a type of valve.
(d) The change is accomplished by tuning the device differently without any new purchases.

✦✦✦ **11.** Which of the following statements about controller tuning is accurate for most applications?
(a) Response to set point change that provides a quarter-amplitude decay reaction curve is preferred.
(b) The penalty for aggressive tuning is that a disturbance will require a greater time to return to set point.
(c) The controller tuner must decide the acceptable criteria for loop performance after the actual tuning.
(d) Controller tuning techniques require a formal testing of the process.

✦✦ **12.** A configuration option that permits the user to make the derivative mode sensitive only to changes in the controlled variable, not to the set point, is called:
(a) Proportional band variable (b) Proportional controller offset
(c) Derivative-on-measurement (d) Reset action

✦✦✦ **13.** Which of the following statements is not true of feedforward control?
(a) Feedforward control is used in a similar fashion to integral control
(b) Feedforward control is intended to compensate for external disturbances to a control loop
(c) Feedforward control modifies the output of the feedback controller when feedback and feedforward control are used together
(d) Feedforward control synchronizes the effects of a disturbance and the control action of the proportional integral derivative

✦✦ **14.** Which of the following statements is true regarding controller tuning from closed loop tests?
(a) The magnitude of the oscillation required can be easily predicted.
(b) Moderate disturbances during the testing can be tolerated.
(c) The technique is based on the assumption that a first order plus dead time (FOPDT) process model approximates the real process.
(d) Multiple tests are usually not required, minimizing interruption to normal operations.

✦ **15.** Trial-and-error tuning is best accomplished by:
(a) Using an open loop test to define tuning parameters
(b) Minimizing the effects of the decay ratio
(c) Adjusting the relationship between the integral time and the period of oscillation
(d) Examining the as-found data set related to the process

✦✦ **16.** The simplest technique for addressing the nonlinearity problem is:
(a) Closed-loop tuning
(b) Scheduled tuning
(c) Trial-and-error tuning
(d) Self-tuning

✦✦ **17.** In a direct-acting controller, an increase in the controlled variable will cause the output to:
(a) Do nothing (b) Decrease
(c) Fail (d) Increase

✦✦ **18.** P&ID symbols depict which of the following types of information?
(a) Detailed functionality
(b) Measurement range of the device
(c) Maintenance requirements
(d) Process location of a device

✦✦ **19.** Which of the following are valid forms of PID algorithm?
(a) Proportional and integral modes on measurement, derivative on error
(b) Proportional, integral, and derivative modes on measurement
(c) Proportional and derivative modes on error, integral on measurement
(d) Proportional, integral, and derivative modes on error

✦✦ **20.** Bumpless transfer is an issue in which of the following?
(a) Manual-automatic switching
(b) Direct and reverse acting
(c) Interactive PID algorithm
(d) Time-proportioning control

✦✦ **21.** Components in a feedback loop usually have some form of signal communication because
(a) The components may be physically separated.
(b) Wireless communication cannot replace electrical signal transmission.

(c) The controller may be a stand-alone device in a digital system.
(d) A backup to a manual system must employ shared digital signals.

✦ **22.** What is process lag?
(a) Time for the process control loop to make necessary adjustments to the final control elements
(b) Time elapsed in the process variable returning to set point value.
(c) Time consumed between the instant the error is detected and the corrective action is taken
(d) None of the above

✦ **23.** Which of the following best defines the dead time?
(a) Is the time interval between a change in the input signal to a process control system and the response to the signal
(b) Is the time when the deviation or error is detected
(c) Is the finite time for an error to become zero
(d) Is the time when the error is corrected

✦✦ **24.** What is proportional band (PB) in PID control?
(a) PB = 100/Gain (b) PB = Gain/100
(c) PB = 100 * Gain (d) PB = 100 + Gain

✦✦ **25.** What is feedback control?
(a) Output is fed back to the system to calculate the error.
(b) Set point is fed back to the system to calculate the error
(c) Process value is fed back to the system to calculate the error
(d) All of the above

✦✦ **26.** Which of the following is not a continuous controller mode?
(a) Proportional control mode
(b) Integral control mode
(c) Derivative control mode
(d) Two- position mode

✦✦✦ **27.** Which of the following is an example of an open-loop system:
(a) Respiratory system of an animal
(b) Household refrigerator
(c) Execution of a program by a computer
(d) Stabilization of air pressure entering into a mask

✦✦✦ **28.** In control loop the error is:
(a) Measured value – set point
(b) Set point + measure value
(c) Measured value + set point
(d) Set point – measured value

✦✦ **29.** Zeigler-Nicholas is a method for:
(a) Deriving process tuning constants
(b) Detecting flow parameters
(c) Detecting the oscillations in the process
(d) None of the above

✦✦ **30.** PID controller is:
(a) Proportional inductive derivative
(b) Proportional integral derivative
(c) Proportional inductive directional
(d) Proportional indicative directive

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II. Short-answer questions

✦✦ **1.** How is the sensor performance characterized in process control?

✦✦ **2.** What is span?

✦ **3.** What is accuracy?

✦✦✦ **4.** What are steady state models?

✦✦✦ **5.** What is a first-order process?

✦ **6.** What is the rise time in second-order process?

✦✦✦ **7.** What is damping factor in process response curve?

✦✦ **8.** List three commonly used PID controllers?

✦✦✦ **9.** Which is a preferred control mode for flow control loops? And why?

✦✦✦ **10.** Which is a preferred control mode for pressure control loops? And why?

✦✦ **11.** What is the optimal decay ratio for proper loop tuning?

✦✦ **12.** What is an effective way to reduce the effects of measurement noise?

✦✦ **13.** What is ratio control?

✦✦ **14.** List three advantages of inferential control.

✦✦ **15.** What is scheduled tuning?

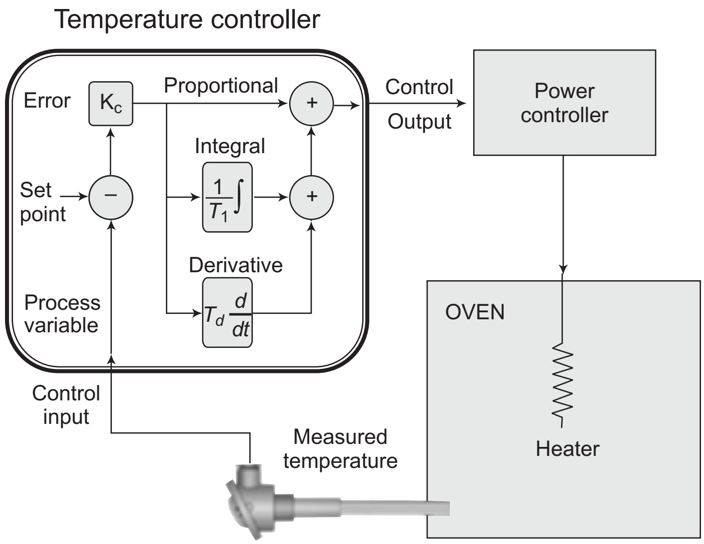
✦✦✦ **16.** What is constraint control?

III. Unsolved problems

✦✦✦ **1.** If a p-only controller has sensitivity of 0.25 mA/°C and the output range is 4–20mA with the range of CV (controller variable) is 100–235°C; find the proportional band of the controller.

✦✦✦ **2.** For a loop whose phase cross over frequency w_0=2.536 Rad/s and ultimate gain is 72 find out the optimum settings for PID action using Ziegler/Nichols method.

✦✦ **3.** When a PID controller is used to control a first order temperature process, calculate the order of the overall process (neglecting the order of the power controller).



✦✦ **4.** A direct acting controller has a proportional band of 50% subjected to a sustained error. The set point is 50% and the measurement 55%. After 4 minutes the total output signal from the controller has increased by 30%. What is the reset rate setting in RPM and MPR?

✦✦ **5.** A disturbance causes a process to change by 5%. What will be the change in controller output if the PB is 100%, 50%, and 200%?

✦ **6.** Consider a first order process-temperature oven with time constant of 10 seconds. When the set point is increased from 100°C to 200°C. How much time it would take for the oven to reach 199°C?

✦✦ **7.** Consider an open, first order process-temperature controlled oven with time constant of 10 s. When the set point is increased from 100 degree Celsius to 200 degree Celsius. How much time it would take for the oven to reach 200 degree Celsius? What can be inferred from the result?

✦✦ **8.** In a first order temperature process which is controlled using an open loop controller, the set point is increased from 100°C to 200°C. The time constant of the process is measured to be 10 s. Calculate the process temperature after 10 s of changing the set point.

✦✦✦ **9.** A PID controller is tuned to have following tuning parameters: Gain = 1, Integral (Reset) action is switched off, Derivative gain: 10%s. At a stable condition, the output of the PID controller is around 20%. When the set point of the process is changed from 50% to 55%, calculate the output of the PID controller and draw the output response.

IV. Critical-thinking questions

✦✦ **1.** Define the decay ratio?

✦ **2.** When does inverse acting process occur?

✦✦ **3.** What is FOPDT model?

✦ **4.** What is a direct acting controller?

✦✦ **5.** If the controller is tuned for normal disturbances, what happens if the major disturbances occur to the process?

✦✦ **6.** What is quarter amplitude damping?

✦✦ **7.** What is control interval?

✦✦ **8.** Explain why control loop tuning is a compromise between performance and reliability?

✦ **9.** For nonlinear process with large disturbances, what are the tuning options preferred?

✦✦ **10.** What is the effect of filtering on closed loop performance?

✦✦ **11.** What is feedback control loop?

✦✦✦ **12.** How feedforward is contrary to feedback control?

✦✦ **13.** How the measurement of NOx helps control different parameters in flue gas?

✦✦ **14.** What is the most popular form of MPC?

✦✦ **15.** How dynamic matrix is derived from the step response models?

✦✦ **16.** Which is called moving horizon controller?

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Data Acquisition Systems

8

LEARNING OBJECTIVES

After reading this chapter, you will be able to:

1. Describe data acquisition system with basic architecture
2. Analyze various elements/ subsystems of a data acquisition system

Data acquisition system (DAS) is a type of automation system that is used for collection of data from the process. These systems replace the use cases in which humans log the data for record keeping purposes in a scheduled manner. The functional components of a DAS/DAQ system and their functionality are discussed in this section. By the end of the chapter, the student gains knowledge on the DAS/DAQ systems and their use in the industrial process control applications.

The DAQ systems are matured along with the technology and are available in various configurations where multiple communication options can be adopted. In this context, the telemetry is discussed even though it is used in various architectures.

The data loggers which is another important application of the data are discussed in terms of the features and their applications.

Keywords:
Data acquisition system, scan times, transducers, sensors, signal conditioning, field wiring, filtering

"One line alone has no meaning; a second one is needed to give it expression"
Eugene Delacroix

8.1 DATA ACQUISITION SYSTEMS WITH BASIC ARCHITECTURE

LO 1
Describe data acquisition system with basic architecture

Data acquisition is something like collecting the data and in the context on industrial control systems, it is about collecting the data related to the process variables, physical things, etc. The physical variables in the field are measured from one form to another by means of transducers. Transducers convert the physical phenomenon to an electrical phenomenon. As discussed earlier, the data acquisition systems collect these electrical analog signals, convert them to digital format for further processing, storage, analysis, reporting or for real time view to the humans. Typically, commercially available computers with suitable software and add on hardware modules carry out the job expected from a data acquisition system. Data acquisition system (DAS or DAQ) acts as an interface between the real world of analog physical parameters, and the world of digital computation and control.

DAQ systems range from the very simple manual systems to highly advanced computer controlled ones with a network of computers or network of acquisition hardware connected over general purpose bus networks. Imagine the early days of industrial revolution and if the temperature of an oven needs to be recorded. The operator needs to enter the readings in a log book with the time and date information. The manual logging of the information fails due to various reasons in addition to the additional cost of labor. The manual entry is subjected to mistakes such as wrong reading, reading taken at an improper interval, missing records and at the end consolidating the readings for any analysis. The problems increase if a large number of readings are required due to the timing and volume concern. Using computers to perform the data acquisition can help in overcoming this problem. Over the years, digital computers and other microprocessor-based devices have replaced analog recording and display technologies. Computerized systems are used in various industries to achieve greater productivity. Digital systems are widely used because complex circuits are accurate, low cost, and relatively simple to implement. While computers have a positive impact on data acquisition, they speak only in a binary language. However, manufacturing processes and natural phenomenon vary over time in a process control, not discontinuously changing from ON to OFF state. To record or manipulate these analog (continuous) measurements such as pressure, temperature, flow rate, and position by a computer, the recordings must be translated into digital representations.

In majority of applications, the DAQ system is designed to acquire data, and to include control functions. However it is important to specify the vendor for the needs of control from the data acquisition systems. In such cases, the DAQ will be provided with hardware that can execute control functions and also can provide output signal hardware to drive actuators or relays or LEDs, etc. These control devices can control the system or process to which they are interfaced.

8.1.1 Basic Data Acquisition System

A general-purpose data acquisition system typically consists of analog to digital (A/D) converters, and digital inputs and outputs. Figure 8.1 illustrates the outline of a system with major subsystems included. Some cases, instead of a point-to-point connection, a multiplexer is used before the analog-to-digital converter (ADC), such that multiple transducers are connected and every transducer will get time to send information to the system using the ADC.

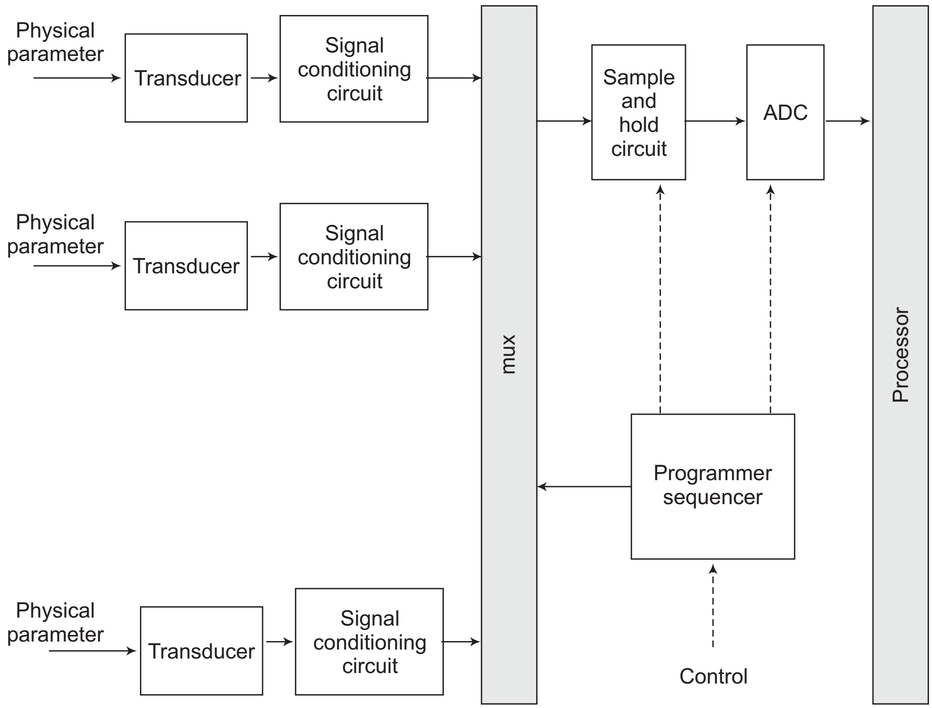

Figure 8.1: Block diagram of basic data acquisition system

The physical inputs to these systems are general industrial process variables such as temperature, pressure, level, flow, etc., which are continuous in nature, meaning they change with time. The physical parameter is first converted into an electrical signal by means of transducer; once the parameter is converted to electrical form; electronic circuits do all further processing. Transducer outputs may be microvolt or millivolt level signals, which are then amplified and filtered for unwanted electrical interference noise using signal-conditioning circuits.

The analog signal is sent to an analog multiplexer which connects the signal to a sample and hold circuit. In this format, the sample and hold circuit acquires and holds the signal in current or voltage format. This sample and hold circuits are used as buffers or small time memory while the multiplexer goes on to connect the other channels and acquiring the signals. The signals form the sample and hold circuit are sent to the ADC for digital conversion. The ADCs continue to take the value form sample and hold, and convert to digital format on a sequence basis. The converted digital signal with the time stamp are received either by the processing input cards or by the computer itself with a suitable application software. Since there are multiple sequence of activities, the timing and sequencing has to be controlled and a supervisory hardware modules or computer itself does the activity.

It is not easy to explain a system which can be applied to all the available systems. Most commonly used components in DAQ are described with some exceptions. Some configurations can have multiplexing at low signal side and some at high-level signal side. If they are used for low-level signal side, then there might be need for some amplification of the signals. In such cases, an amplifier may be needed in each channel. Again the amplifier can also be positioned after the multiplexer so that one is enough for the entire input system. Some other variations exists, where the transducer does the amplification, analog to digital conversion. It can be either in transducer or somewhere near to the transducer. These signals are then transmitted over a serial bus to the acquisition system. In such systems the digital data is made parallel and sent in the form of a bus with less number of cables for long distance. The same is covered back to individual form at the receiving end.

Figure 8.2 gives the basic concept of a DAQ system. A data acquisition system is a collection of software and hardware that connects to the physical world. The diagram below indicates the functional mapping and their interrelation and interaction with various other subsystems. The following figure illustrates the functional diagram of a typical data acquisition system.

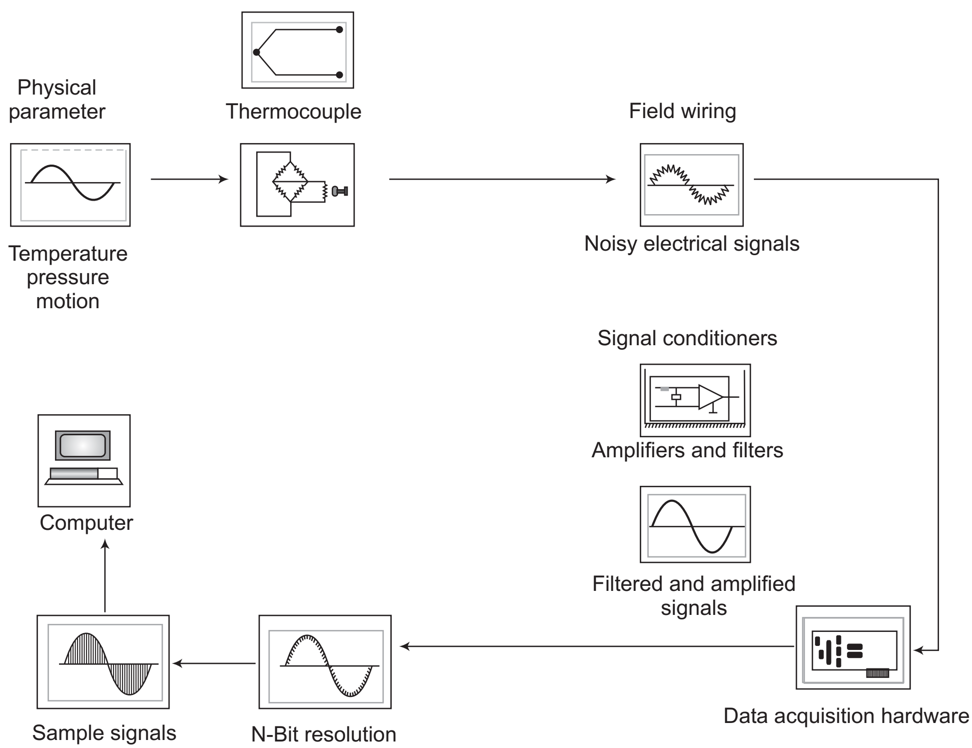

Figure 8.2: Functional diagram of the data acquisition system

8.1.2 Data Loggers

The other most widely used way of logging the data is by means of a data logger or a recorder (both paper and paper less). The data loggers are standalone devices with a built in input, digital conversion and signal processing. The device can store the information or data inside for certain amount of time and has got a display in the front of the device to show the data in graphical, tabular format. The data loggers have the capability to move the data from the device to PC or to external storage equipment for offline analysis and storage of the data for extended periods of time. The loggers and recorders can also be connected in a network wherein one input can be shown in some other logger over the network. The logger industry has also matured from a single channel to multiple channels, from a single input type to multiple input types. These are also certified and capable to be installed in harsh industrial environment and also in the areas certified as hazardous.

Checkpoint

✦✦ 1. How is data acquisition abbreviated?

✦✦✦ 2. How have the DAQ systems replaced analog and/or manual recording of the process variables?

✦ 3. What is the input to the data acquisition system?

✦✦ 4. What is the role of a multiplexer in data acquisition system?

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8.2 VARIOUS ELEMENTS/SUBSYSTEMS OF A DATA ACQUISITION SYSTEM

LO 2

Analyze various elements/subsystems of a data acquisition system

The following are the basic subsystems of a DAQ—sensors and transmitters, cables and wiring, signal conditioning and processing, application software, data acquisition hardware, and personal computer used for hosting the system. Each element of the DAQ system is important for accurate measurement and collection of data from the process or physical parameter.

8.2.1 Sensors and Transmitters

The sensor and transmitter for each of the process variable are the means of converting a physical variable to an electrical variable or signal. The type of signal will be selected based on the type

Note: ✦ Level 1 & Level 2 category
✦✦ Level 3 & Level 4 category
✦✦✦ Level 5 & Level 6 category

of data acquisition hardware and its type of input signals. The transmitters technologies as discussed in early chapters can convert any physical variable in industrial process to analog, hybrid or digital forms of output signals. For example a temperature element such as RTD or thermocouple can convert the temperature to an analog signal. Similarly, a strain gauge or piezoresistor can convert a pressure, force into a electrical signal. Likewise there are various other types that can convert linear, angular velocity, displacement into a suitable signal for processing by the microprocessor or computer-based systems. In all these cases, the electrical signal is proportional to the physical variable with a defined relationship.

8.2.2 Cables and Wiring

Cables and wiring, also called as field wiring is the physical connection established between the field sensors to the DAS hardware installed in a central room or remote place. If the means of communication is by digital signals, then a serial communication cable is used which is also called as communication cabling. If the transmitters or sensors are directly connected in one-to-one mode, then individual wiring needs to be arranged. Often this cabling and wiring is costly, time consuming, labor intensive and prone to mistakes. The cables are also susceptible to the effect of external noise. A separate earth and adequate shielding are essential for reducing the noise in the field.

8.2.3 Signal Conditioning

The electrical signals from the transmitters can be either analog or digital. For the sake of transporting the signal over large distance if a pure analog signal is used, then it requires a suitable hardware at the data acquisition side for ADC. In addition, for proper and accurate functioning, many transmitters require some form of excitation or bridge completion. The signal conditioning circuits performs the following tasks—filtering, amplification, isolation, and excitation.

8.2.3.1 Filtering

The signals form the sensor such as thermocouples and strain gauges will be at low level and very small. It is difficult to receive these signals coupled with the noise in it. If the noise is of greater magnitude than the required signal, the noise must be filtered out. Care must be taken to use appropriate filters, such as low pass filters, designed to remove noise which can sometimes lead to inaccurate data.

8.2.3.2 Amplification

Amplification is used to improve the accuracy of data because real world signals are often very small in magnitude. The received signal needs to be amplified for matching it with the hardware and also for increasing the resolution and sensitivity of the measurement. The amplifier in the signal source or in the transmitter will improve the signal-to-noise ratio of the measurement by increasing the signal level before getting impacted by environmental noise.

8.2.3.3 *Isolation*

Signal conditioned hardware are used to provide the isolation for transient high voltage. The signals, cabling and wires from the transmitters to the DAQ hardware becomes a source of these transients which has the potential to damage the rest of circuitry. The transients can be because of electrostatic discharge or some electrical signal failures, etc.

8.2.3.4 *Excitation*

Signal conditioning in a data acquisition system is also used to power the circuitry to measure the process parameters—for example, in the case of a bridge circuit in a piezoresistor-based pressure sensors or an RTD, etc. The most common applications that need the excitation from external signals are strain gauges, thermistors, RTDs, etc.

8.2.4 Hardware Elements of DAS

DAQ hardware is what usually interfaces between the analog signal and a PC. DAQ hardware can be defined as the component of DAQ system, which performs input processing and conversion to digital format. The DAQ hardware use ADC to process the analog signals received from the field. The output from the ADCs is used for display, analysis and storage purposes.

DAQ hardware is available in numerous forms from multiple manufacturers. The most commonly utilized item of the DAQ hardware is plug-in expansion bus boards, which plugs directly into the computer's expansion bus. The other devices that can also be included to the same system will be data loggers, controllers, analyzers, etc. All the above systems can be connected to the PC with special application software and together they can be used to configure, monitor and analyze the information over a serial communication interface such as RS232/RS485. In a similar way, there are needs to include the special equipment from the research labs. These types of instruments are standalone, remote from the hardware and gets integrated by using the communication interface such as IEEE 488, etc.

The speed of data acqusition is a performance criteria for the user and it typically depends on the type of PC, processing capability, memory, type of disk, capacity of disk, speed at which the peripherals operates, and the types of data transfer, etc.

All PCs for example are capable of programmed I/O and interrupt driven data transfers. Direct memory access is used to transfer data directly into computer's memory, and increases the system throughput and leaves the processor free for doing other tasks. The other dependency on the PC is the type of operating system used such as DOS, Linux or Windows as each of them has a special way of handling multitasking and multiple threads. However, the role of internals of the operating systems on the data acquisition application software is not deterministic, for example, interrupt latencies introduced by the multitasking nature of Windows leads to problems when interrupt driven data transfers are used; also managing memory can provide difficulties in the use of direct memory access. Therefore, it is important to consider the operating system where high-speed data transfers are required. The role of the capabilities of the personal computer is critical if the data acquisition system is used for processing real time data. Sometimes it may require a 64-bit processor with very high frequency with accompanying coprocessors, etc., if a large number of inputs at high frequency needs to be processed. On the other side, for processing a low frequency of signals which are also small in nature can be managed with a low end PC DAQ system. In many ways, the type of PC is a balance between the cost of PC versus current and anticipated future needs of the users.

8.2.5 Software Elements of DAS

DAQ software is needed for the DAQ hardware to work with a PC, because it is the software running on the computer that transforms the system for complete data acquisition for analysis, storage, and display.

In general, software applications are used in multiple ways in the usage of DAS in context of add on system hardware:

- Applications used to program the registers and memory locations of DAS hardware, sometimes these are called configuration tools.
- The drivers that are hosted in the PC which acts as a bridge between the data acquisition hardware and application software for different purposes.
- The commercial off-the-shelf software applications are used to communicate with the data acquisition hardware for collecting and presenting the data. Generally, the application software provided with the hardware is enough for the task in hand, but sometimes in order to gain a standardization and customization across many data acquisition hardware platforms, a commercially available third party, and open protocol-based application softwares are preferred. These packages provide tools required to analyze the data and display the data in a format as required by the user based on the type of the variable/instrument.

8.2.6 Multichannel DAS

Most of the discussions in the earlier topics cover the multichannels in DAS. In simple words, multiple input signals are multiplexed at the signal end and only ADC is carried at the data acquisition hardware end. Finally, the raw signal which is filtered, amplified and multiplexed is converted to the digital form. This signal is used for the storage and archival of the data (Figure 8.3).

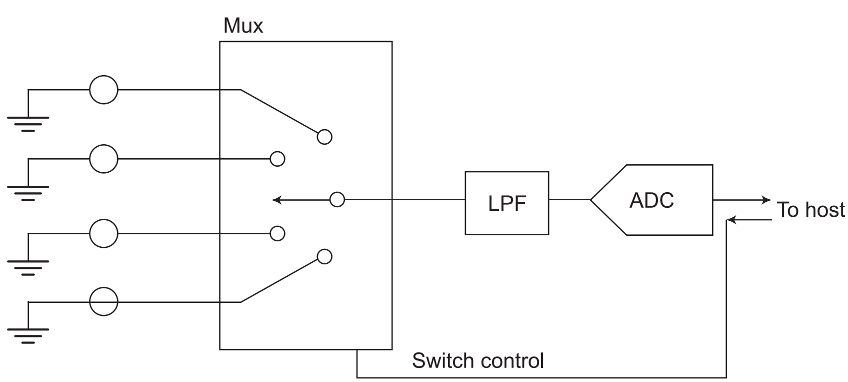

Figure 8.3: Multichannel data acquisition systems

8.3 GENERAL TELEMETRY SYSTEMS

LO 2

Telemetry refers to the method of measuring process variables or physical phenomenon or monitoring the status of the devices or equipment from a remote place using tele technologies. The basic representation of a telemetry system is shown in Figure 8.4. The block or group of blocks that represent a sending end is the source of the information and a block or group of blocks where the information is used is the receiving end or sink of the system. The function of each of these blocks is described as follows:

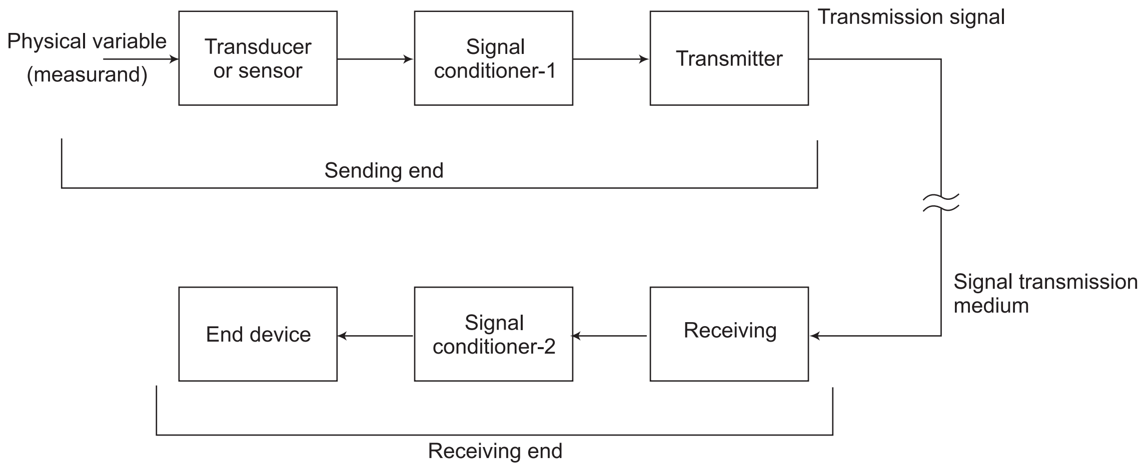

Figure 8.4: Schematic of a basic telemetry system

- **Transducer or sensor:** The transducer or sensor is the primary means of measuring, sensing a physical variable and converting them to other physical variables or an electrical variable such as current or voltage. Basically this is the parameter that needs to be transported to a remote place, to the consumer of the data using telemechanisms.
- **Signal conditioner 1:** The signal conditioner at the sending end or the sourcing side is the interface between the sensor/transducer to the signal transmitters. The interfacing is required either due to the type of the signal (analog or digital), parameter type (voltage or current), magnitude and frequency of the signal (voltage levels), etc. These are required to match the next subsystem to accept the signals and transport them in a transparent manner without losing the integrity of the signal from the source.
- **Transmitter:** The signal transmitters are the subsystems used for transferring the signal from the signal conditioner to the carrier signals. The transmitter is the interface for the information from the signal conditioner to the suitable carrier types which carries the signal information and overhead required to transmit the information to the carrier at the receiving end or the sinking end.
- **Signal transmission medium:** The transmission medium is the most generic term used for various methods and technologies used for signal communication in a variety

of the telemetry systems. It can be a medium of communication such as wire, wireless, fibre, etc. or it could be a link such as wireless, satellite, cellular, etc. By all means this signal transmission medium is the critical technology that has changed over a period of time as the communication technologies evolved. The speed of communication, the cost of data transfer, cost of the equipment, maturity of the technology, etc., are some of the deciding factors while choosing the medium.

- **Receiver:** It is the counterpart to the transmitter in the receiving end or sinking end. The receiver is meant for receiving the signal from the transmission medium, extract the information from other overheads (decapsulate), and perform an amplification, demodulation, demultiplexing and digital to analog (D/A) conversion, etc.
- **Signal conditioner 2:** The signal conditioner 2 at receiving end is similar to the signal conditioner 1 on the transmitting side, wherein it converts the received information to a form suitable to drive the output device or a form suitable for display of the information or storage.
- **End device:** End device is the receiving device or the sink of the information. There are various reasons for having a telemetry system and end device will indicate and meet the purpose. The end device may be used for an analog indication, digital display, or it may be meant for storage, data processing. Not so often, but sometimes it is used for closed loop control especially in the control and safety of applications such as remote offshore oil platforms.

8.3.1 Telemetry Classification Based on Modulation Method

The wired transmission of the telemetry can be either using dc voltage or dc current. As discussed earlier, in either case, the signal transmission medium is a pair of copper cables. The discussion provides more such information.

8.3.1.1 Direct Voltage Telemetry System

Principle Transmission signal for direct voltage telemetry system is a dc voltage (straight voltage) signal. The signal is transmitted through a copper wire line, which is designed for a voltage of about 80 V.

Sending-end Scheme The transducer (sensor) changes the measurand (input physical variable) to an electrical entity, which could be an electrical parameter or an electrical signal. This output is passed through appropriate electronic circuits (signal conditioner unit) to produce a voltage signal in the range 0–1 V to 0–10 V. Naturally the voltage is linearly equal to the value of the measurand. The voltage signal is appropriately increased to a value Vdc1 and to the copper wire link.

Receiving-end Scheme The last device placed at the receiving end is a permanent-magnet moving-coil (PMMC) voltmeter. A PMMC voltmeter offers two advantages of being highly sensitivity and able to scale linearity. The meter calculates the voltage at the receiving end of the line, Vdc2. Its scale is calibrated in terms of measurand (M), to help the user read the value of M directly (Figure 8.5).

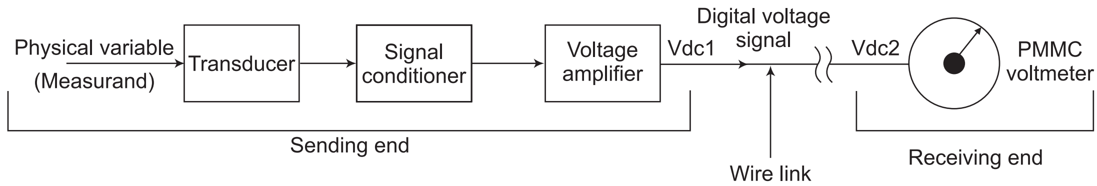

Figure 8.5: Direct voltage telemetry system

8.3.1.2 Direct Current Telemetry System

Principle Transmission signal for direct current telemetry system is a dc signal and the transmission material is a copper wire line. The most preferred current signal is in the range 4–20 mA, but occasionally other ranges like 0–20 mA or 0–10 mA are also preferred in industry.

Sending-end Scheme As shown in Figure 8.6, this telemetry scheme is similar to the direct voltage telemetry scheme explained in Section 8.3.1.1. The only difference in the sending-end scheme is that the direct current telemetry system uses a voltage to current converter while the direct voltage telemetry system employs a voltage amplifier.

Receiving-end Scheme As it has to find the value of the line current at the receiving end, Idc2, which is in milliampere range, the end device is a PMMC milliammeter. For user to read the value of M directly, the scale must be calibrated in terms of the measurand (M).

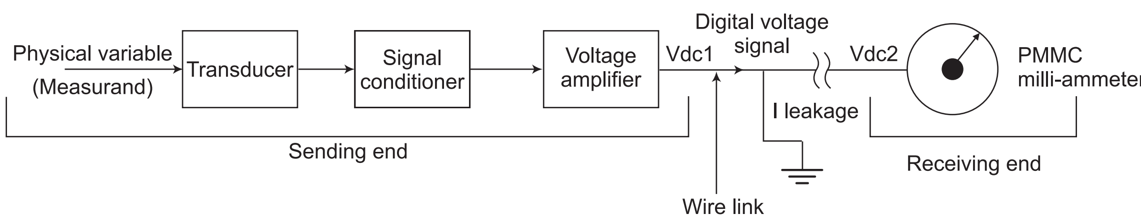

Figure 8.6: Direct current telemetry system

8.3.2 Classification of Telemetry Systems on the Basis of Signal Transmission Medium

If the telemetry is classified based on the transmission medium of the signals, then it can be represented as—wired telemetry systems, wireless telemetry systems (short and long range), and fiber optic telemetry systems.

8.3.2.1 Wired Telemetry System

A representative wired telemetry system is illustrated in Figure 8.7. The basic specifications of such a system are given as follows:

- The wired telemetry uses a pair of copper cables for signal transmission.
- The transmitter in this case consists of a modulator and an amplifier before sending the signal to the medium. In case of copper wires meant for single channel, there will be no need for a multiplexer, otherwise it may be needed.

- Similar to the transmitter, the counterpart on the other side of the transmission medium called the receiver has a demodulation method and ability to extract the data from the signal with the matching amplifier circuits.

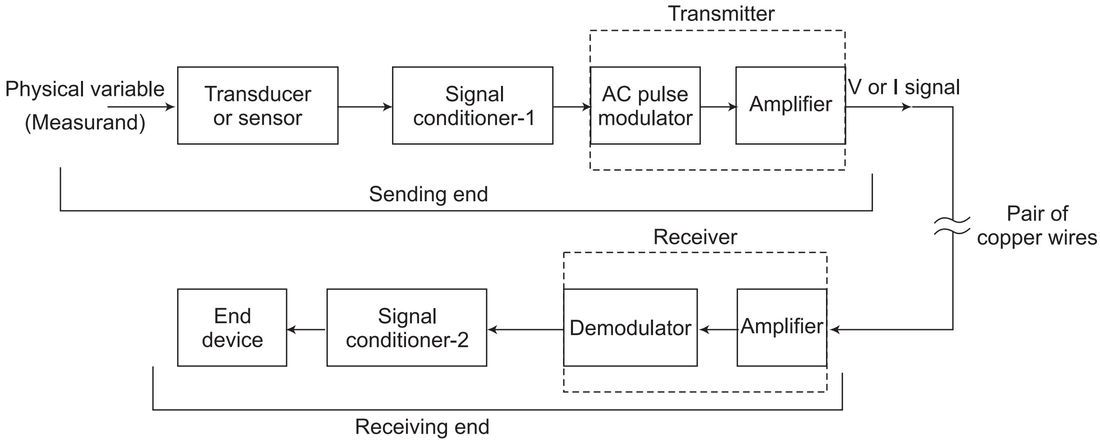

Figure 8.7: Wire link or wire telemetry

8.3.2.2 *Wireless Telemetry System*

A representative wireless telemetry system for both short and long range is illustrated in Figure 8.8. The basic specifications of such a system are given as follows:

- In this case, the medium of signal transmission is a radio link. The radio link constitutes an antenna in source side and sink side and the space between them is the medium. The radio signals are broadcasted or send over in this medium.
- Like earlier, the transmitter in the sending side or source side consists of an RF modulator (different types based on cost, speed, etc.) coupled with an amplifier.
- Similar to the wired, the receiver side constitutes a demodulator and an amplifier again based on the cost, performance and matching requirements of the source.

Short Range Radio Telemetry System The description provided in the previous section is applicable and same for the short range radio communications. In this schematic, the transmitter is supplied with the power required to send the signals from few meters to few hundreds of meters. The cost of the selection of the radio frequency is based on cost and local conditions and regulations from government agencies etc.

Satellite Radio Telemetry System The block diagram representation of a telemetry system that uses a satellite for the communications is illustrated in Figure 8.9. The system has the following basic specifications:

- The transmission channel is through the space above earth surface where in the satellite orbiting the earth connects the transmitters and receiver side of the telemetry.
- In these type of communications, since the radio frequency used is more than 3.3 GHz, it is also is called as microwave.

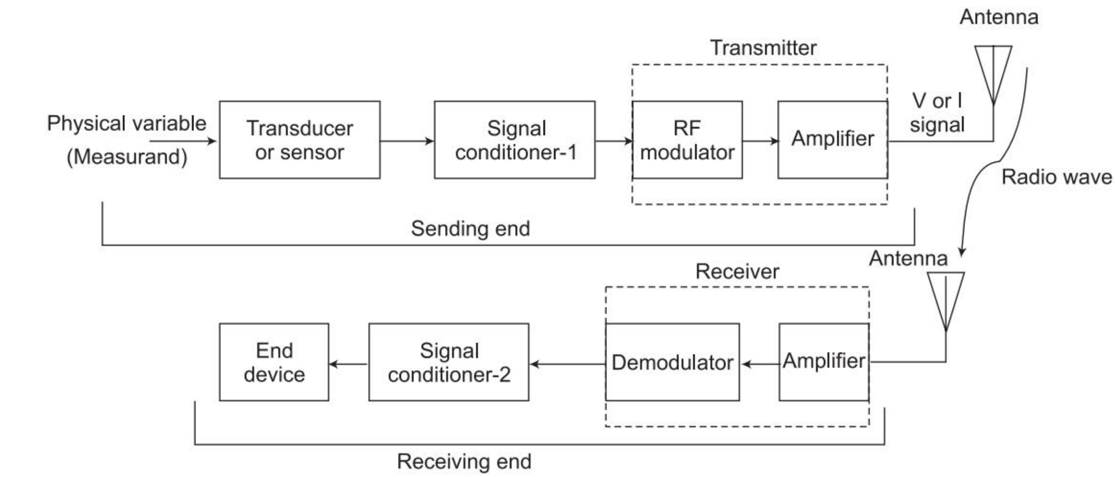

Figure 8.8: Wireless telemetry system

- The transmitter side of the telemetry has a modulator and amplifier with suitable technologies for analog and digital communication. It also is provided with a suitable converter to match the frequencies of the signals and frequencies of the carriers and suitable mixers as required for long distance communications.

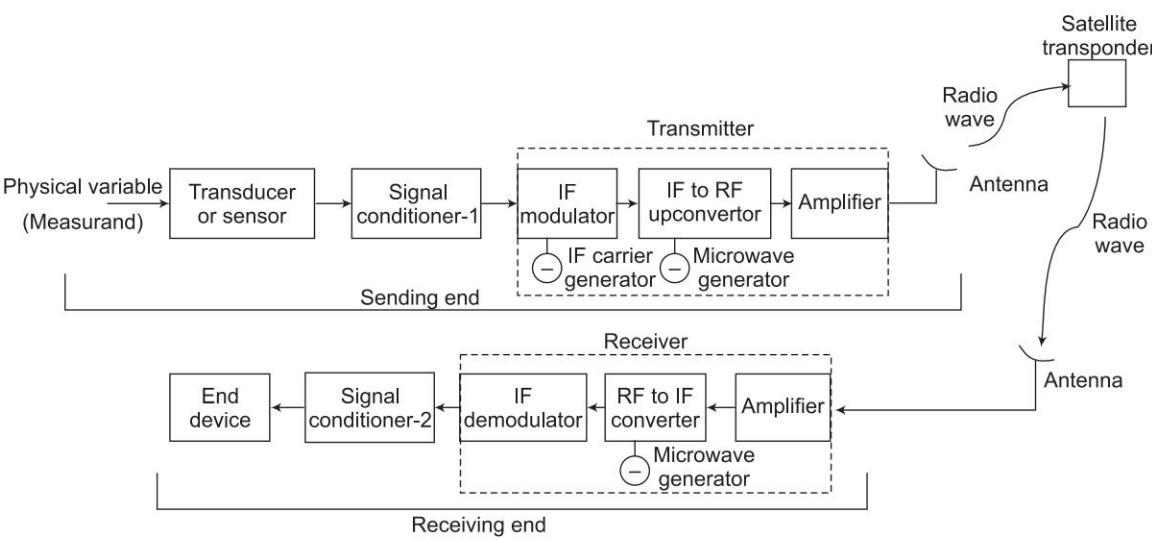

Figure 8.9: Satellite radio telemetry system

- Similarly the receiver side is equipped with interpretors of these signals, mixed signals and extraction of the actual signals, filters and amplifiers, etc. These receivers are the primary link between the satellite equipment and frequencies to the signal conditioners.

8.3.2.3 *Fiber Optic Telemetry System*

The block diagram representation of a telemetry system that uses fiber optics for the communications is illustrated in Figure 8.10. The system has the following features as basic specifications:

- The transmission channel or medium of channel is a fiber optic cable with the signal being an intense optical beam in infrared region. In this case, the fiber acts as a guide and signal is transmitted on total internal reflections principle.
- The source side or sending side consists of a modulator that sends the digital values of the measurement and converts them to series of pulses. The series of pulses are converted to a sequence of light emitting devices. This way, the current is converted to binary optical pulses which are sent to the transmission medium.
- Similar to the above, the receiver constitutes the devices and equipment to receive the optical pulses and convert them to electrical signals for sinking devices such as analog displays, or storage devices. If the sinking device is an analog device, then there may be a need for DAC and if the end-sinking device is a digital device, which is the case in most of the times, then DAC is not needed.

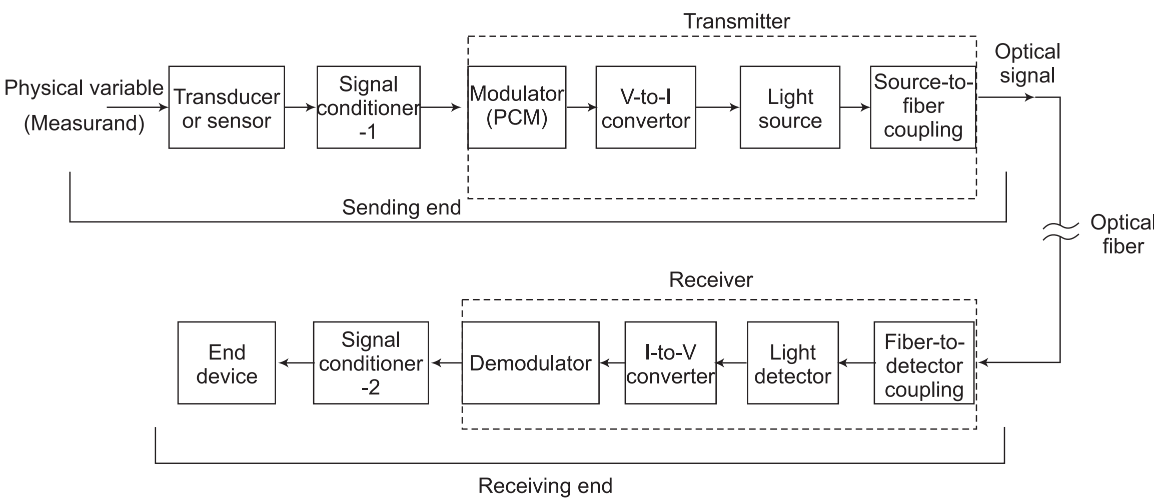

Figure 8.10: Fiber optic telemetry system

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Checkpoint

✦✦ **1.** List at least four basic elements of a data acquisition system.

✦✦ **2.** What is the role of transducers and sensors in data acquisition systems?

✦✦ **3.** What is field wiring and its susceptibility?

✦✦ **4.** What are the four tasks performed by the signal conditioner?

✦✦✦ **5.** What are the different attributes of the personal computer that can have an impact on the performance of DAQ?

Summary

LO 1: Describe data acquisition system with basic architecture

- Use of computers to perform the data acquisition helps in overcoming the problems related to manual errors and tedious data processing and costly data storage. Over the years, digital computers and other microprocessor-based devices have replaced analog recording and display technologies.
- The input to the system is a physical analog parameter such as temperature, pressure, flow, acceleration, and position, which continuously varies with time.
- The processed analog signals are connected to a multiplexers which are programmed to receive the input in a defined time periods. Use of multiplexers helps to design the systems in a cost effective manner by sharing the resources for multiple input signals.

LO 2: Analyze various elements/subsystems of a data acquisition system

- Sensors and transducers provide an interface between real world and DAS by converting physical phenomena into electrical signals that the signal conditioning and/or data acquisition hardware can accept.
- Field wiring represents the physical connection from the transducers and sensors to the signal conditioning circuit and/or data acquisition hardware.
- The speed at which the computer continuously acquires data depends on the kind of application under consideration, microprocessor speed, hard disk access time, disk capacity and types of data transfer available.

Questions

I. Objective-type questions

✦✦✦ **1.** Identify two elements of signal conditioning in a data acquisition system.
(a) Filtering (b) Aliasing
(c) Amplification (d) Processing

✦✦ **2.** The role of transmitters is to convert a physical variable to:
(a) Another physical variable (b) Electrical variable
(c) Pneumatic variable (d) B&C

✦✦ **3.** DAQ is abbreviated as:
(a) Data acquisition system (b) Digital acquisition system
(c) Dynamic acquisition system (d) None of the above

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II. Short-answer questions

✦✦ **1.** What is the functional definition of a DAS?

✦✦ **2.** List the different components of the signal conditioning in data aquisition system.

✦✦ **3.** What is filtering in DAS?

✦ **4.** List the software components of a DAS.

✦✦✦ **5.** What are the three different types of telemetry systems used in DAQ?

✦✦ **6.** What do you understand by the term multichannel data aquisition systems?

III. Critical-thinking questions

✦✦✦ **1.** What is the difference between a DAQ and PLC?

✦✦ **2.** Why are various telemetry systems used in DAQ?

✦✦✦ **3.** What is the role of fiber optics in the DAQ?

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Programmable Logic Controllers

9

Programmable logic controllers (PLCs) are used in all the manufacturing and process industries to enhance the quality and productivity while providing flexibility. In this chapter, PLCs, their basic architecture, operation, and types of different subsystems are discussed.

PLCs are configured with different architectures and topologies and hence various options are discussed. PLCs are differentiated from the relay panels in terms of their flexibility in the form of programming languages. Different programming languages used for the PLCs such as ladder logic, function blocks, sequential function charts and Function blocks are discussed in detail.

Additionally various types of input, output and communication modules are discussed which enables to students to understand the concept of PLC in real application scenarios.

Some sample applications are discussed to create a practical understanding on the usage. The chapter also covers different types of IO modules and the advantages of using PLCs over other controllers for the special needs. Once you complete the chapter, your fundamental understanding on the PLC will improve.

Keywords:
PLC, DCS, scan time, ladder logic, function block, sequential function charts, instruction list, I/O modules, bus, Modbus

LEARNING OBJECTIVES

After reading this chapter, you will be able to:

1. Describe programmable logic controllers and their evolution
2. Explain the architecture and functionality of PLCs
3. Analyze different programming languages and operations of PLCs

"He that invents a machine augments the power of man and the well-being of mankind."
Henry Ward Beecher

9.1 PROGRAMMABLE LOGIC CONTROLLERS AND THEIR EVOLUTION

LO 1
Describe programmable logic controllers and their evolution

9.1.1 Introduction to PLCs

Programmable logic controllers are the most widely used controllers for logic and sequence applications in manufacturing and industrial process applications. These are the solid state devices made of silicon like any computer or microcontrollers. PLCs use the integrated circuits and application specific integrated circuits for driving the outputs instead of using electromechanical devices for implementing control logic. The control logic constitutes sequencing, counting timing, logics, delays, decision making, and communication with other equipment. PLCs are also capable of storing the data for a limited amount of time and can transfer it to the application software. They are also known for their speed of execution of the logic and flexibility for the programs to be changed by an instrumentation engineer. Figure 9.1 depicts an abstract view of the PLC. The concept is much similar to a microprocessor which uses a program/instructions stored in a memory and executed sequentially. However, the complexity is much higher to improve the reliability, speed and ease of operation and flexibility to change.

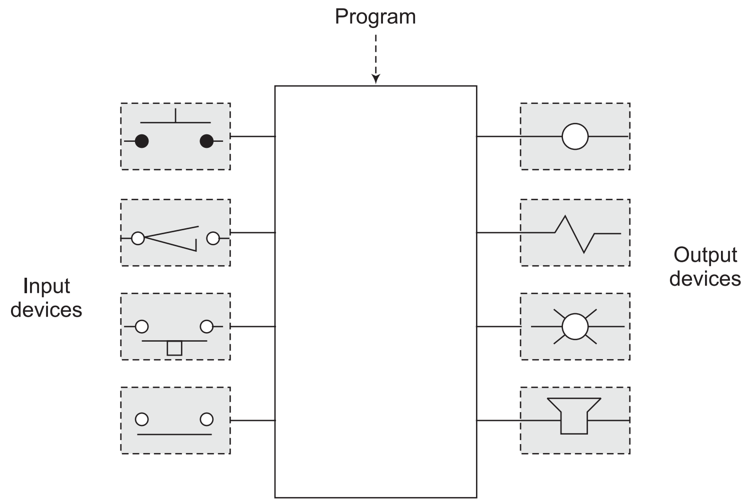
PLCs are designed for engineers to operate with perhaps a limited knowledge of computers and computing languages. The term "logic" is used as programming is primarily concerned with implementing logic and switching operations. The PLCs are connected with input devices, such as switches, sensors, etc., and the output devices such as valves, solenoid valves, motor starters, etc. The engineer enters a program that is stored in the memory of the PLC. The inputs are monitored on a continuous basis based on its scan time and the program is executed and logic drives the output as needed.

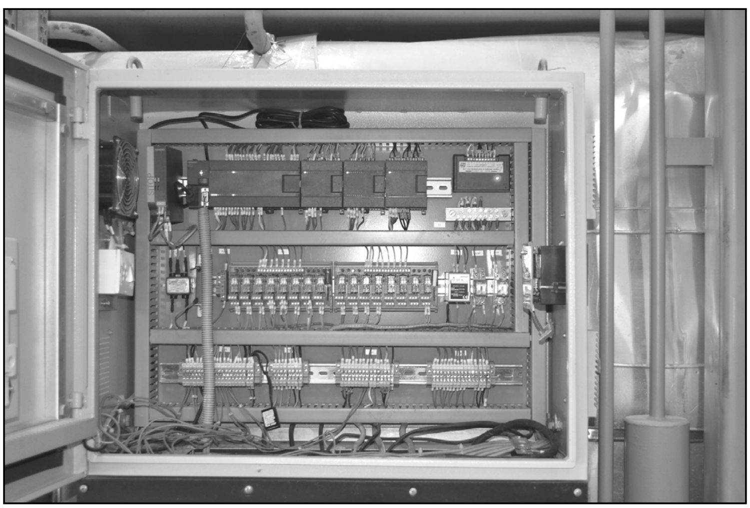
Since its first availability in the market in late sixties, PLCs gained widespread adoption from all the segments in the industry. The maturity in the electronics, mechanical engineering and manufacturing engineering, PLCs are scalable from a small unit with integrated I/O for 20 signals to a large system with multiple racks of subsystems, with I/Os, processors, communication systems, etc. PLCs in the present world are also capable of handling digital or analog inputs/outputs. PLCs have a great advantage of enabling the same basic controller to be used with a wide range of control systems. Rewiring is not required to modify a control system as it can be achieved by an operator with a different set of instructions. The result is flexible and cost effective. PLCs are similar to computers with the difference being— computers are optimized for calculation and display tasks whereas PLCs are optimized for control tasks and the industrial environment.

PLCs are a special purpose industrial microprocessor-based real-time computing systems which perform the following functions in the context of industrial operations:

- Monitors input/sensors
- Executes logic, sequencing, timing, counting functions for control/diagnostics
- Drives actuators/indicators
- Communicates with other computers

Figure 9.1 Programmable logic controller





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9.1.2 Evolution of PLCs

Prior to the advent of microprocessors, industrial logic and sequence control were performed using elaborate control panels containing electromechanical or solid-state relays, contactors and switches, indicator lamps, mechanical or electronic timers and counters, etc. All these panels were hardwired by complex and elaborate wiring. In fact, for many applications such control panels are used even today. However, the development of microprocessors in the early 1980s quickly led to the development of PLCs which had significant advantages over conventional control panels, some of which are listed as follows:

- Programming the PLC is easier than wiring physical components; the only wiring required is that of connecting the I/O terminals.
- The PLC can be reprogrammed using user-friendly programming devices.
- PLCs occupy much less space.
- Installation and maintenance of PLCs is easier with greater reliability owing to present day solid-state technology.
- The PLC can be connected to a distributed plant automation system that can be supervised and monitored.
- Beyond a certain size and complexity of the process, a PLC-based system compares favorably with control panels.
- Ability of PLCs to accept digital data in serial, parallel and network modes implies a drastic reduction in plant sensor and actuator wirings as single cable runs to remote terminal I/O units. Wiring only needs to be made locally from that point.

An example of this would be PLC connection to RTU through Modbus. In this case, a PLC has a specialized card for reading Modbus serial interface data along with other cards capable of handling digital/analog inputs. This card will have connection of one end to PLC and other end to RTU, and on the RTU entire input sensor wiring is terminated. Hence, there may be multiple input sensors but none of them will reach the PLC directly. Hence, a single cable from RTU to PLC substitutes multiple wires running from field instruments to PLC.

- Special diagnostic and maintenance modes for quick troubleshooting and servicing without disrupting plant operations.
- Reliable components make these likely to operate for years before failure.
- Computational abilities allow more sophisticated control.

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Checkpoint

✦✦ 1. Define a PLC.

✦✦✦ 2. What does that mean "logic" in PLC?

✦✦✦ 3. List the four basic functions of a PLC in industrial operations.

Note: ✦ Level 1 & Level 2 category
✦✦ Level 3 & Level 4 category
✦✦✦ Level 5 & Level 6 category

9.2 ARCHITECTURE AND FUNCTIONALITY OF PLCs

LO 2
Explain the architecture and functionality of PLCs

9.2.1 PLC System Overview

Vendors supply PLC systems in many hardware configurations to cater to a variety of customer requirements and affordability. However, some common components are present in each of those PLCs. The functional subsystems in any PLCs are a processor unit, a power supply unit, communication interface, input and output modules, and software and hardware for programming the unit. Figure 9.2 shows the basic arrangement of a PLC.

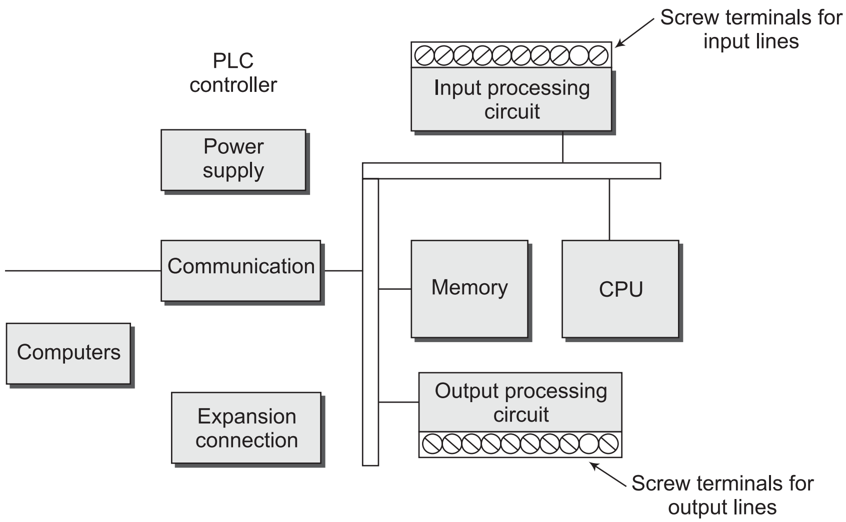

Figure 9.2: PLC system

9.2.1.1 Processor

The processor unit in a PLC constitutes a microprocessor or central processing unit. The unit is a participant in a bus network and is provided with necessary interfaces to communicate with the outside systems. The processor unit is also provided with diagnostic indicators on the front panel. The processor unit monitors the input signals (indirectly through the I/O modules) and executes the instructions in a sequence as defined in the program and generates the control actions again as defined in the program. The programs are stored in the memory of the unit along with the run time values and buffers required for the execution.

9.2.1.2 Power Supply

The power supply unit takes the stable supply from the mains and converts it to a low voltage dc as required for different circuits in the rest of the modules. The same power supply unit is also used to provide power to the field instruments such as analog transmitters and digital relays, etc. Common voltage levels required by the PLCs are 5 V dc, 24 V dc, and 220 V ac. This module can either be built into the PLC processor or can be present as an external circuit. It is extremely important to understand the power supply that comes along with the PLC as it is helpful in choosing the right PLC for the supply available in industry.

9.2.1.3 Memory

The memory unit is used for storing the program and also for storing the data from the input and output devices. This data is used by the processor while executing the programs. The memory is partitioned for fixed and variable storage. The variable storage cannot be changed during the PLC execution. Some PLCs do not have a separate module for the memory where it will be integrated in the circuit of the processor module.

9.2.1.4 Input and Output Modules

The input and output modules are the subsystems where the external devices are connected to the PLC. These modules are the interfaces from/to the field instruments to the processor of the PLC. The inputs are received from sensors such as temperature and flow sensors while the output is provided to the motor starter coils, solenoid valves, etc. The I/O modules can again be categorized as input modules and output modules. The input modules can further be classified into analog, digital, and special types such as RTD, pulse, etc. The output modules are further classified as analog, digital, and simple contact type, relay output, etc. (Figure 9.1).

9.2.1.5 Programming Device

The PLC needs a program to be configured and loaded to the processor. The programs can be developed in the device and sometimes a laptop using familiar and easy to use program languages and can be connected to the PLC. The tools or programming devices are also used to monitor the run time status of the process values and also to write/modify the values, and troubleshoot the program in the PLC. The programming device or tool is not necessarily connected always and it can be disconnected during the normal operation of the PLC. Sometimes the tool or display device is connected to monitor the values on a continuous basis while the program is running.

9.2.1.6 Expansion Units

The base unit of the PLC has limited or none of the I/O modules attached. Based on the needs and configuration of the system, I/O modules are increased by adding additional units or racks. Sometimes these racks are referred as expansion units. Each of these expansion unit can accommodate input or output modules. Some configurations can allow the gateway modules in the expansion unit. The general gateways are something like digital communication protocols. Modules for the input and output signals are plugged into expansion units. The latter are connected to the processor via interface modules. Expansion units can be connected as per the following two configurations:

Centralized Configuration In centralized configuration, the expansion units are located in the same cabinet as the controller or in an adjacent cabinet in the centralized configuration. Several expansion units can be connected to the controller. The length of the cable from the central controller to the most distant expansion unit is often limited based on data transfer speeds.

Distributed Configuration In the distributed configuration, the expansion units are located at a distance up to 1,000 m from the central controller. In this configuration, up to 16 expansion units can be connected to one central controller, and four additional expansion units can be connected in the centralized configuration to each distributed expansion unit and to the central controller.

9.2.1.7 Communication

The communication interface aids in receiving and transmitting the data on communication networks from/to other remote PLCs. The communication interface is responsible for device verification, data acquisition, synchronization between user applications and connection management. The PLCs must be linked to each other and to the computer by a communication network as shown in Figure 9.3. Twisted pair, coaxial and fiber optic cables are used as a communication networks depending on the size of the information to be sent through the network.

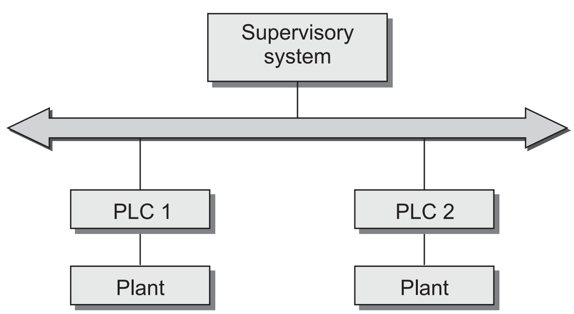

Figure 9.3: Basic communications model

9.2.2 Internal Architecture of PLC

The basic internal architecture of a PLC is represented in Figure 9.4. As discussed earlier, just a recap that a PLC has a central processing unit, memory modules, and input and output modules. The CPU is responsible to control and process the signals, and execution of the program. The frequency of the CPU is generally the most contemporary in terms of the speed and featues in the semiconductor industry. The frequency of the CPU is the factor which determines the speed of the PLC which means the scan rates of the PLC such as timing and synchronization.

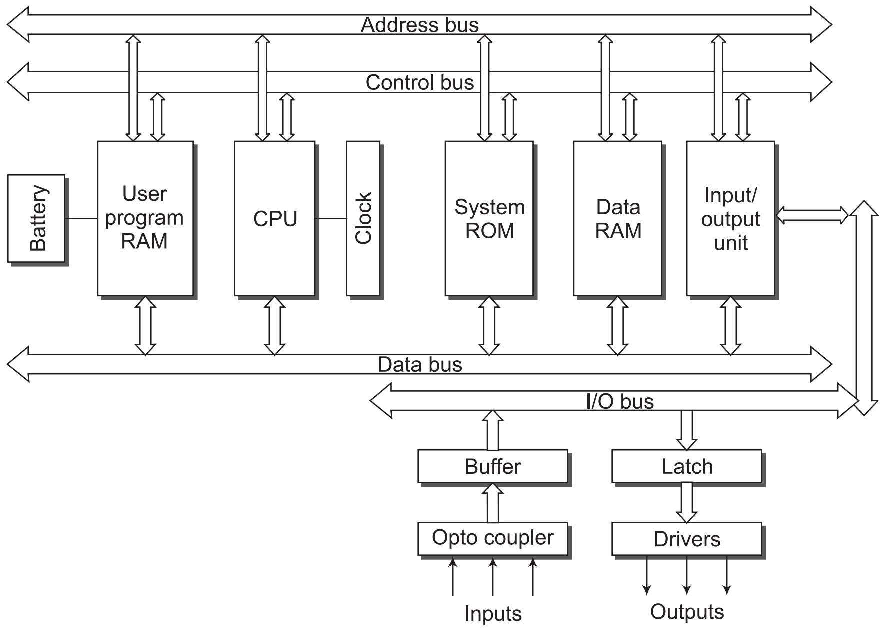

Figure 9.4: Internal architecture of PLC

9.2.3 Central Processing Unit

The internal architecture of a CPU is similar to the architecture of any microprocessor and has the following components as a minimum:

- **Arithmetic and logic unit:** Arithmetic and logic unit (ALU) is a logical system for data processing and executing the arithmetic operations such as addition, subtraction or logical operations such as "AND", "NAND", etc. The internal memory and registers are used for executing the data processing.
- **Control unit**: Control unit is a logical entity in the CPU used for controlling the timing and synchronization of the operations such as read, write, movement of the data, etc.

9.2.3.1 Buses

Buses are the physical communication means for the signals within the PLC. In general, the information within different parts of the CPU are in the form of digital information stored in binary format. The binary form constitutes a group of bits which are either 1 or 0 such as "on" or "off" states. The group of these bits is called "word". Within a processor, the bus constitutes parallel lines to transmit the data. The CPU has four buses in the architecture which are as follows:

Address Bus The address bus is used for locating the storage of each word in the memory. Each location in the memory has an address and the address is used by the processor during operations on the data such as read, write, move, etc. So it is the address bus which is used to carry the address information of the data operations. If a bus has 8 lines, it can address a memory of 256 locations and similarly if the address bus has 16 lines, then it can address 65536 locations.

Data Bus Similar to address bus, the data bus is used to carry the data for the operations required by the CPU. It means if a processor is termed as 8 bit, then it can handle the operations on 8 bit numbers and can generate the output on 8 bit numbers.

Control Bus The control bus is used by the CPU to send the control signals to various sub systems. The control bus is used for sending and receiving the information and also to carry the timing signals for synchronization.

System Bus The system bus is used for communication with the input and outputs. The data, input and outputs to the external world outside the PLC use the system bus.

9.2.3.2 Memory

PLCs read only memory (ROM) is used for the data that requires permanent storage such as operating system and some information that needs to be retained. Similarly, random access memory (RAM) is used for storing the program in the memory and data. The status of input and output devices, values from the timers, counters and other internal data for temporary storage. Sometimes this part of RAM is used in portions of memory or blocks of portions. The programs in the PLC are also written in the EEPROM (erasable read only memory) and is used to boot the PLC after the restart and also provides flexibility to rewrite with modifications. The programs in RAM can be edited and PLC can provide some blocks of RAM allocated for storage of the programs alone.

9.2.3.3 Input/Output Unit

The input and output modules are the means for connecting the PLC system to the outside environment through electrical connections. The input and output channels can receive and provide signals from the switches, valves, solenoids and motor starters, etc. Programs are entered from a program panel through the input/output unit. Every input/output point has a unique address which can be used by the CPU.

Input Module Input modules convert process level signals from sensors (e.g. voltage face contacts, 0–24 V dc, 4–20 mA), to processor level digital signals such as 5 V or 3.3 V and also accept direct analog inputs from thermocouples or RTDs and limit switches or encoders in the digital case. Modules used for capturing thermocouple/RTD/encoder inputs are often referred to as special modules as they are exclusively used for capturing these signals. Naturally, these modules include circuitry for isolation such as those using optocouplers. Primary purpose of such isolators is to protect the card from the faults in the field instruments. Without these circuits if any instrument gets shorted it will directly damage the I/O card.

Analog Input Modules Analog input modules convert analog process level signals to digital values that are subsequently processed by the digital electronic hardware of the programmable controller. The typical parameters that define an analog input module are shown in Table 9.1.

The analog modules sense 8/16 analog signals in the range ± 5 V, ± 10 V or 0–10 V. Each channel can either be single-ended or differential. Only one wire is connected to a channel terminal for a single-ended channel. The analog voltage on each channel terminal that is sensed is referred to a common ground. In the case of differential channels, each channel terminal involves two wires and the voltage between the pair of wires is sensed. Thus, both the wires can be at different voltages and only their difference is sensed and converted to digital. Differential channels are more accurate but consume more electronic resources of the module for their processing. An analog module typically contains:

- Analog-to-digital (A/D) converters
- Analog multiplexers and simultaneous sample-hold (S/H)
- Analog signal termination
- PLC bus ports
- Synchronization

Table 9.1: Characteristics of input modules

Module Parameter	*Type / Number / Typical Value*
Number of input	8/16 voltage/current/ Pt100/RTD
Isolation	Yes /No
Input ranges	±50 mV to ±10 V; ±20 mA; Pt 100
Input impedance for various ranges (ohm)	±50 mV > 10 M; ±10 V > 50k; ±20 mA 25; Pt 100 > 10 M
Types of sensor connections	Two-wire connection; four-wire connection for Pt 100
Data format	
Conversion principle	
Conversion time	11 bits plus sign or 12 bit 2's complement
Integrating /successive approximation	In ms (integrating), μs (successive approximation)

Digital Input Module The digital input modules convert the external binary signals from the process to the internal digital signal level of programmable controllers. Digital input channel processing involves isolation and signal conditioning before inputting to a comparator for conversion to a 0 or a 1. The typical parameters that define a digital input module are shown in Table 9.2.

Table 9.2: Characteristics of digital input modules

Module Parameter	*Typical Values*
Number of input	16/32
Galvanic isolation	yes
Nominal input voltage	+ 24 V dc

(*Contd.*)

Input voltage range "0" signal "1" signal	–33…+7 V +13…+33 V
Input current	Typically in mA
Delay	Typically in µs
Maximum cable length	Typically within 1000 m

Output Module Outputs to actuators allow a PLC to cause something to happen in a process. Common output modules include:

- **Solenoid valves:** Digital output signals drives these valves which can open close a switch and allow a hydraulic or pneumatic flow through the pipe.
- **Lights:** The digital outputs from the PLC that can drive the end devices such as lights often provide a signal to relay which intern drives the light.
- **Motor starters:** Motor starters are used to start the motors and PLC drives them using the digital output and a relay contact.
- **Servo motors:** An analog output signal from the PLC is used to send a command to a servo motor drive which can drive the motor and maintain a speed or position as required by the program.

The outputs from these modules may be used to drive actuators. Alternatively, the output module may include circuit for current or power made of power electronics such as solid state relays or Triacs to drive the output actuators. Continuous outputs require output cards with digital-to-analog converters. Sometimes they also provide potential free relay contacts (NO/NC that may be used to drive higher power actuators using a separate power source. These modules must provide isolation as they straddle across the processor and the output power circuit. However, most often the output modules act as modulators of the actuator power that is actually applied to the equipment or plant. External supply is provided to the output cards and the contact in the card can switch on or off the supply to the external device. Generally used voltages are 120 V ac, 24 V dc, 12–48 V ac/dc, 5 V dc (TTL) or 230 V ac. The cards are available with various options in terms of the number of channels such as 8 channel, 16 channel or 32 channels. The options can include with different current ratings and also with options for relays or transistors, etc. The mostly commonly used option being relays due to the fact that they can be used for driving both ac and dc voltages and hence with wider options of actuators. However, they are slower, expensive and wear out after a large number of cycles. Relays can switch high dc and ac voltage levels while maintaining isolation. Transistors are restricted to dc outputs and triacs are restricted to ac outputs and thus are known as switched outputs respectively.

Analog Output Module Analog output modules convert digital values from the PLC processor module into an analog signal for the process. These modules therefore require a DAC for providing analog outputs. However, servo-amplifiers for power amplification (required for driving high current loads directly) are not integrated onboard. Front panel connectors are used for signal cable terminations. Mostly, both the modules in the rack or the front connector to the module can be connected or disconnected while under power. This is commonly referred to as removal and insertion under power. The output signals can be disabled by means of an enable input. The last value then remains latched in the output. Typical parameters that define an analog output module are shown in Table 9.3.

Table 9.3: Characteristics of analog output modules

Number of Outputs	*8 (Voltage and Current Output)*
Isolation	Yes
Output ranges (rated values)	± 10 V; 0…20 mA
Load resistance • For voltage outputs minimum • For current outputs maximum	 3.3 k 300
Digital representation of the signal	11 bits plus sign
Conversion time	In μs
Short-circuit protection	Yes
Short-circuit current approximately	25 mA (for a voltage output)
Open-circuit voltage approximately	18 V (for a current output)
Linearity in the rated range	±0.25% + 2 LSB
Cable length maximum	200 m

Digital Output Module As discussed earlier, the digital output modules convert the output from the processor of the PLC to a binary signal. The level of the signal will be such that it can drive an actuator in the process. Output can be dc or ac in multiples of 8 and can be connected in parallel. Indication for short-circuits, fuse blowing, etc. are often provided. The typical parameters that define a digital output module are shown in Table 9.4 along with typical values.

Table 9.4: Characteristics of digital output modules

Module Parameter	*Typical Value*
Number of outputs	16/32
Galvanic isolation	Yes
Rated value of supply voltage	+24 V dc
Permissible range	20–30 V
Max. output current for “1” signal	0.5 A

(*Contd.*)

Short-circuit protection	Yes
Maximum switching frequency for resistive loads, lamps, inductive loads, respectively, in Hz.	100/11/2 Hz (at 0.3 A)
“0” signal level maximum “1” signal level maximum	+3 V V_{pp} – 1.5 V
Max. cable length (unshielded)	400 m

Special Modules

Encoder Encoder modules are normally preferred for high-speed applications and precise motion sensing applications. A classic example is that of controlling the motion arms in a packaging industry. For example, movement of robotic arm by certain degree for holding an item is typically done through an encoder combined with servos. Similarly, if a light weight platform has to move to certain height for transferring a material at faster rate, encoder is used for precise positioning. Hence, its application lies in both translational and rotational motion control. These made them more popular in faster moving packaging/automobile lines. Therefore, a dedicated hardware often called as high-speed counter is present for capturing its signal and special blocks such as pulse input block in a PLC.

Counter Module The PLCs are provided with modules that can count the pulses from the counters upto 32 bits. Since the pulses are high in speed, a normal PLC scan may not be able to count them. Such cases use the counter module wherein the module itself can measure the inputs such as 1-phase input, 2-phase inputs, etc. The counter modules count in up count/down count methods. For 1-phase input, the program is used to differentiate and count the direction of the counting such as up and down or a combination of both. For 2-phase input, the counting and the direction of the counting is calculated based on the program logic such as difference in the phases of the signals.

The counter module is also used for achieving some additional logical information in the programs such as counter clear, latch the counter, frequency measurement, counter disable, etc. These functions are self-explanatory and once students gets conversant with any of the counter functions in PLC, counter functionality remains same throughout. However, for the speed of operations this data capture happens in a different cycle at a faster rate.

RTD Module The RTD input module is to convert the temperature data (°C) input by the temperature sensor. Normally, Pt100 is converted into a signed 16-bit digital output data. In such a connection module, the temperature data (resistance) is directly measured by the module and is converted to the digital information for processing in the PLC. In addition, the degree of precision required in the digitization can be controlled by the program in the PLC.

Normally, one module can be connected to 8-point (channel) temperature sensor. The RTD input module has cable burn-out function at their every channel. It is nothing but open wire detection capability. It detects the out-of-range temperature that is input by sensor. The typical characteristics of an RTD module are listed in Table 9.5.

Table 9.5: Characteristics of RTD modules		
Characteristics	*Numerical Value*	
Connectable RTD	Pt 100	
Temperature input range	Pt 100	: –200.0°C to 600°C (18.48 Ω to 313.59 Ω)
Digital output	Digital conversion value (scaling value): 0 ~ 16,000 Detected temperature value: -2000 to 6000	
Open wire detection	Each of three wires at every channel has a detection function	
Accuracy	±0.5 % (full scale)	
Maximum conversion speed	50 ms per channel	
Number of temperature input device points	8 channels per module	

Serial Interface Module Serial interface modules are used in the PLC for interfacing with the intelligent devices outside the PLC. This is widely used practice as an automation system, multiple intelligent devices needs to be integrated. The interface module is used for establishing communication with other PLCs from different suppliers, computers using different communication protocols, may be the same physical interface. It can also be used to emulate as a communication modem to exercise a control on a remote PLC.

Serial interface module has the following characteristics:

- User can specify the communication speed and communication mode (protocol) using laptop-based tool application. This helps to achieve the integration with third party devices with less complexity. The tools help to set the communication speeds/baud rates such as 300 bps to 115200 bps for RS 232 and 300 bps to 115200 for RS 422, etc.
- The serial interface modules are available to support multiple physical interfaces and port combinations such as RS-232C-2Port, RS-422(485)-2Port, RS-232C-1Port/RS-422-1Port. This is an example only and in practice there are wide varieties of combinations to suit different needs of the integrations.
- The communication of the data using the interface module is largely controlled by the program executed in the PLC which is defined by the application engineer. The granularity of the control can be extended to each channel in the serial interface module. This method of communication helps improving the reliability of the system and also helps to replace the modules online without any re-engineering.
- The communication interface module allows the program to read, write and read/write to the system to which it is integrated. Multiple devices can be connected to the same interface module in the form of a bus with multidrop. In the case of an RS422/485, the protocol and the module allows to have 32 devices connected in the same bus.
- The module supports full-duplex (RS-422/RS-232C) as well as half-duplex (RS-485) communication.

It is worth mentioning the parallel and serial I/O bus in this case. A parallel I/O bus comes out of the processor and the I/O modules are plugged into this interface. Most popular ones are the digital and analog (4–20 mA/0–5 V) that serve as perfect examples of parallel I/Os. In majority of the cases, parallel I/Os stays closer to PLC. If there is a separation, then their location is placed on another board (often referred as extended I/O) and they participate in critical control.

In case of serial bus, they are distributed throughout and widely spread across the plant. Normally, serial buses carry signals over single wire to the main control processor and they confine their sensor wiring locally thereby avoiding the costs arising due to wiring distribution over long distances along with signal losses. However, the baud rate on serial bus is not so fast and hence normally preferred for non-time sensitive applications of supervision purposes.

9.2.4 PLC Configuration

PLC configuration refers to the physical organization of the components. Typical configurations are listed next from largest to smallest.

9.2.4.1 Rack

A rack is often large and can hold multiple cards. A bus, often called a backplane, connects these cards that realize the CPU, power, communication, I/O and special function modules. Multiple racks can be connected together by bus extenders if needed. Each channel in a card can be addressed by a rack-slot-channel-addressing scheme that varies across vendors. Though the cost tends to be high, they are very flexible and easy to maintain. The functional architecture of such a rack mounted PLC system is shown in Figure 9.5. The figure shows the various types of functional subsystems that may or may not be on the same board connected through a backplane. However, this does not reflect the physical organization of the various modules that make a PLC system. For extension over longer distances, special bus extension units are needed to provide the necessary drives for reliable signal transmission over a distance.

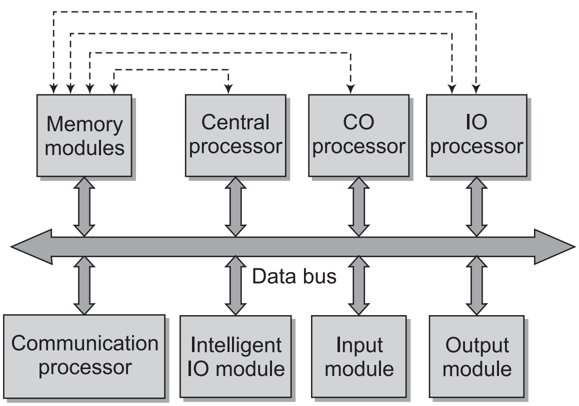

Figure 9.5: Functional hardware organization of a PLC system

9.2.4.2 Mini

A mini is similar in function to a PLC racks and is about half the size. Generally situated completely at one place it may be either floor-mounted or wall-mounted and does not use an extended bus.

9.2.4.3 Compact

A compact is a single standalone unit with fixed units and I/O channels. The unit has limited or no expansion capability. The size and cost of these compact units makes them suitable for applications that are small and usually field-mounted or wall-mounted.

9.2.4.4 Micro

Micro units can be as small as a deck of cards suitable for wall-mounting or table top. They tend to have fixed quantities of I/O and limited abilities but costs are considerably lower. They are used for simple embedded applications and are often not suitable for industrial applications.

9.2.4.5 Software

A software-based PLC requires a general-purpose computer like a PC with an interface card. The software utilizes the operating system resources of the computer to realize control, logic, and I/O functions. An advantage of such a configuration is that it allows the PLC to be connected to sensors, other PLCs or to other computers across a general purpose network such as the Ethernet.

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Checkpoint

✦✦ 1. What is the role of processor in PLC?

✦✦ 2. How the memory of the PLC is divided?

✦ 3. What is the role of the I/O module in PLC?

✦✦✦ 4. What is the purpose of the programming device?

✦✦✦ 5. Explain how the IO's can be increased in a PLC.

✦✦ 6. What is the purpose of communication interface in PLCs?

✦ 7. What is the role of bus in CPU of the PLC?

✦✦✦ 8. What is the purpose of the isolator in input module?

9.3 DIFFERENT PROGRAMMING LANGUAGES AND OPERATIONS OF PLCs

LO 3

Analyze different programming languages and operations of PLCs

9.3.1 Programming PLCs

A programming device can be a handheld device, a desktop console or a computer. A program is transferred to the memory unit of the PLC only after being done on the programming device. The programming devices or tools have built-in memory to store the program and allow the transfer to different locations. In case of a PLC with front panel, the display console has features to program from the keyboard and screen display.

Laptops are widely used as means for development of the application programs, storage and archival of the programs. Some PLCs can be programmed by using a configuration tool installed in a laptop and to have a special communication cards or cables to connect to PLC. The simple and major advantage of using a laptop as a configuration tool is its ability to develop and store the program and move the program to a memory stick, etc.

As discussed earlier, the most common method of programming a PLC is using an application software also called as configuration tool hosted in a laptop or personal computer. The laptop is connected to the PLC using an Ethernet port or serial communication ports such as RS232/485, etc. The software application is used for designing, entering and editing of the logic. The tool or application software is also used for operations such as debugging, troubleshooting and additional operations such as upload and download the program from/to PLC for backup or recovery, etc. The programming methods of a PLC are standardized through an international organization such as International Electrotechnical Commission (IEC). The IEC 61131-3 is the governing document on the different programming languages that can be used in the programming of a PLC. The following are the different types of programming languages used as per the specifications—ladder logic diagram (LD), sequential function charts (SFC), function block diagram (FBD), structured text (ST), instruction list (IL).

There are various advantages of using the standards based programming languages in a PLC in term of skillsets, interoperability, etc. In addition to these benefits, multiple languages support in the same PLC allows the programmer to choose the type based on the application needs and for each of the specific type of logic.

9.3.1.1 *Ladder Logic Diagram*

Ladder logic diagrams are the most widely used programming method for the PLCs. The LD method is similar to the relay logics used in the early industrial control logics. The decision and logics implemented to represent the relay logic is treated as the strategy in the ladder logic. The time needed to improve the skillset for engineers has greatly reduced by selecting ladder logic as the main programming method.

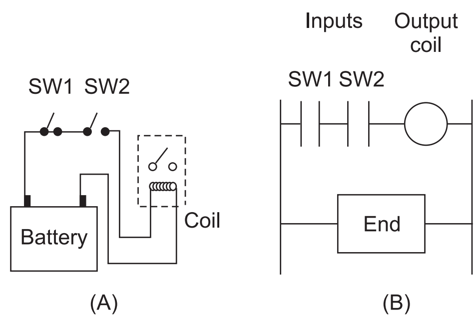

Figure 9.6: (A) Electrical circuit (B) Equivalent ladder logic

Incidentally, the first PLC was programmed with the method based on the relay logic wiring schematic. This method removed the need to train the technicians and engineers on programming. Hence, this programming method has stuck and is the most common technique for programming for today's PLC. Simple electrical circuits and the equivalent ladder logic programs are illustrated in the Figures 9.6 A and B.

9.3.1.2 *Sequential Function Charts*

Sequential function charts are developed based on the flowchart concept of logic development. However, the flow charts were improvised with more powerful features to implement an SFC.

As mentioned earlier, SFCs are very different from flowcharts because they do not have to follow a single path through the flowchart. Figure 9.7 illustrates an example of SFC.

"Start" denotes the starting point of the chart. Double horizontal line indicates that both paths are to be followed. As a result, the PLC follows the branch on the left and right hand sides separately and simultaneously. The functions in the left are power up and power down. It is such that power up starts and runs until it is completed and then the next function starts. Each of them again may be a ladder logic inside and a separate logic is executed such that it does not need to follow a single path in its execution.

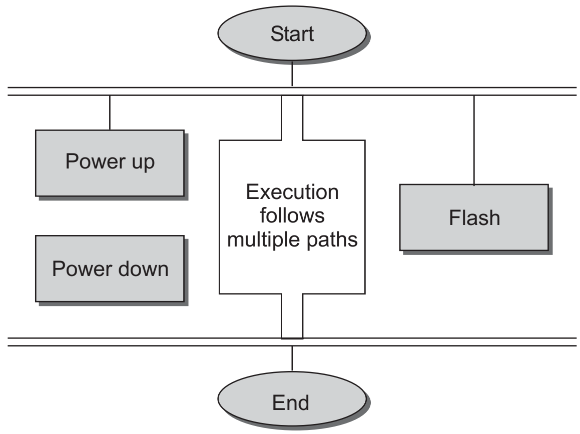

Figure 9.7: An example of sequential flowchart

9.3.1.3 *Functional Block Diagram*

Function block diagram is another powerful programming language of the PLC and is widely used in DCS as well. This is a graphical language and the concept remains centered on the flow of the information from inputs to different blocks. The combination of the blocks defines the logic. The blocks always are represented in rectangles with pins exposed in left and right for the type of the parameters. A sample function block for ADD is shown in the Figures 9.8 and 9.9.

Figure 9.8: Example of FBD instruction

The functionality of the blocks is explained as follows—it is provisioned to accept an input from a parameter variable or a constant or an input signal from the field. It performs the logic on the input received. It can store the results in a register or can drive the output actuator.

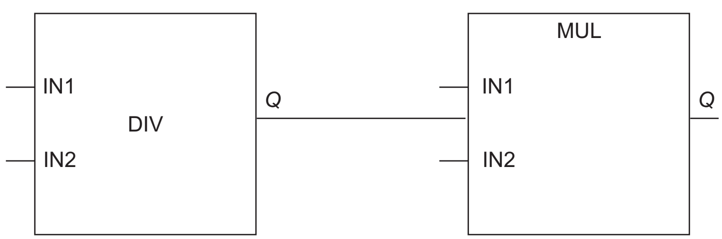

Figure 9.9: FBD example

9.3.1.4 *Structured Text*

Structured text is similar to any high-level programming language such as C, C++. It being high level, provides flexibility and ease of development in developing the control algorithms, parameter assignments, and branching and looping of the variables. It is often considered to be the easiest language to use for programming control logic. When symbolic variables are used, ST logic resembles sentences making it highly intelligible to novice users. A simple structured text programming is given in the example.

Example

```
//AND Logic
            Motor: = Switch_1 AND Switch_2;

//Conditional Logic
            If (Switch_1 OR Switch_2)
            Then
            Start Motor: = 1;
            Motor_Start_Count:= Motor_Start_Count + 1;
            End if;
```

9.3.1.5 *Instruction List*

Mnemonic instructions are one of the earliest techniques used to program the PLCs. The instructions are based on the ladder logic and are used to program the PLC through a handheld programming terminal. It uses very simple instructions similar to the original mnemonic programming languages developed for PLCs. It is being a low-level language; all the high-level languages can be converted to this form either by manual practice or by using suitable tools. The handheld terminals are used even today for any changes to the existing program of the PLC in the manufacturing operations. A simple example of instruction list is as follows:

Table 9.6: Example of an instruction list

Opcode	*Operand*	*Comment*
	Start	
LD	%I: 000/00	(* Load input bit 00 *)
AND	%I: 000/01	(* Start a branch and load input bit 01 *)
OR (ANDN)	%I: 000/02	(* Load input bit 02 *)
ST	%O: 001/00	(* SET the output bit 00 *)
	Start	
LD	%I: 000/00	(* Load input bit 00 *)
AND	%I: 000/01	(* Start a branch and load input bit 01 *)
OR	%I: 000/02	(* Load input bit 02 *)
ANDN	%O: 001/00	(* SET the output bit 00 *)
ST	%O: 001/00	(* SET the output bit 00 *)

9.3.2 PLC Program Scan

The program in the PLC is repeated in a predetermined cycle and is often referred as scan rate. The scan in a PLC is counted from the time it reads the input value or status. The application program reads the input and a decision output is sent to buffers or output channels. Once the program is completed, the PLC starts the internal diagnostics and communications with the peripheral units. The output from the buffers is sent to the output modules. The scan time ends at this point of time. The cycle repeats again for the second scan time. The time of the scan depends on the number of inputs and outputs, speed of the communication (bandwidth) between the input/output with the processor, the length/size of the program. The scan rate and different activities involved in the scan are shown in Figure 9.10.

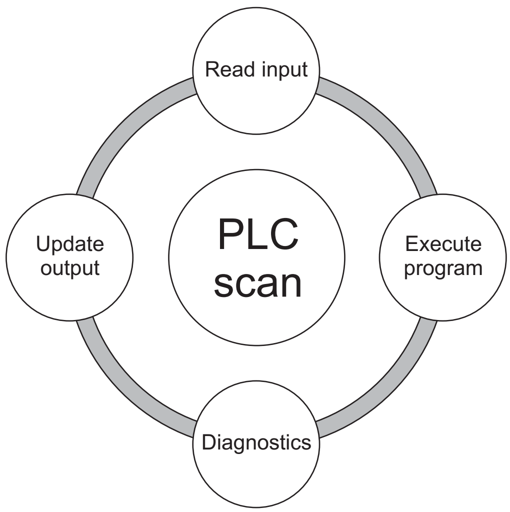

Figure 9.10: PLC program scan cycle

A user program can be executed in many ways. Normally, a cyclic execution program is preferred and these cyclic operators are given due priority. Program processing in a PLC happens cyclically in the following manner:

1. Once the PLC is initialized, the processor reads the individual inputs and the status of the input is stored in the process image input table (PII).
2. The CPU runs the program stored in the memory which is set of logical instructions in a specific sequence. The input status and values are read before the program is executed and the output is written in to the specific memory addresses after the execution of the instructions. The other reserved areas for the instructions such as counters and timers are executed based on the instructions from their locations.
3. Once the instructions are executed and output is written in the specific locations, the output variables and status is transferred to the output modules for actuating the switches and solenoids, etc. The process starts for the next step after this activity is completed.

9.3.3 PLC Program Operation

The following example illustrates a PLC program operation for a simple application, i.e. motor control. A push button with normally open (NO) contact is connected to the first input at address I0.0. Similarly a push button of the type normally closed (NC) is connected to the second input at address I0.1. A overload relay is connected as the third input at address I0.2. These inputs are used to control the logic which is programmed into the PLC. While using discrete signals, "I" and "Q" conventions are normally used for input and output signals. "I" represents a digital input and "Q" represents a digital output. Analog signals and calculations uses memory areas dedicated for those purposes.

For example, some PLCs in the market uses "M" memory for calculating intermittent calculations for users, "K" memory area is dedicated for PID loop-related calculation, "L" is dedicated for high-speed calculations so on and so forth. Though the memory space for alphabets may change, fundamental memory organizing methodology nearly remains the same.

In order not to restrict by dedicated memory areas, a new technique called "tag declaration" was introduced. For example, if "M" memory above support 32767 address spaces, it may get used up for the calculations and user may not be able to proceed further with usage of other spaces as machines restrict them. To avoid this, "tag-based declaration" was introduced where the user gives tag name rather than addresses and system will take care of the allocating memory and optimizing the space.

If the start button is "On", the CPU receives the signal from the address I0.0 and initiates the logic accordingly (Figure 9.11). The CPU sends logic 1 to output Q0.0. The motor starter is energized and the motor starts.

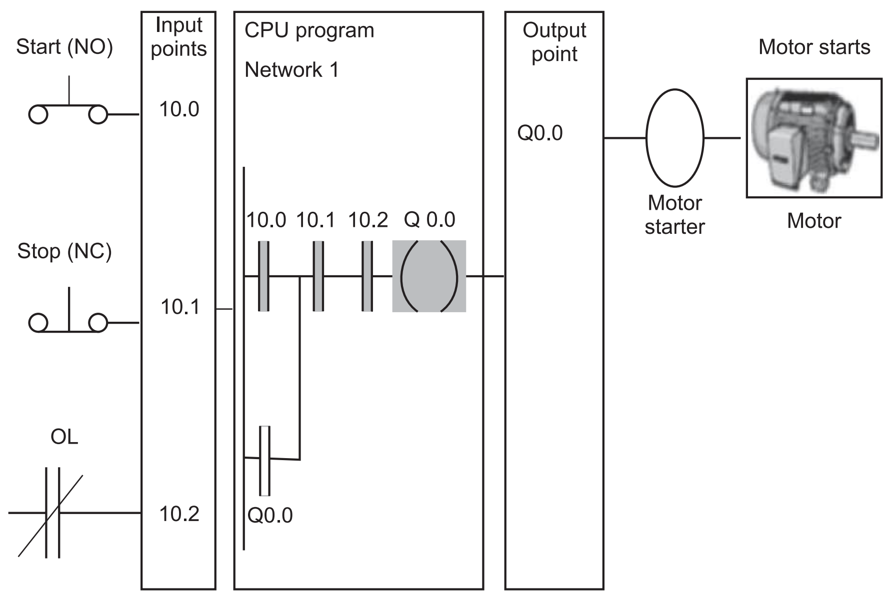

Figure 9.11: Sample program 1

Once the program executes with the above, the output status becomes "1" at address Q0.0. Once it is on, during the next cycle it continues to latch even if the input status at address I0.0 is changed to "off" condition (Figure 9.12).

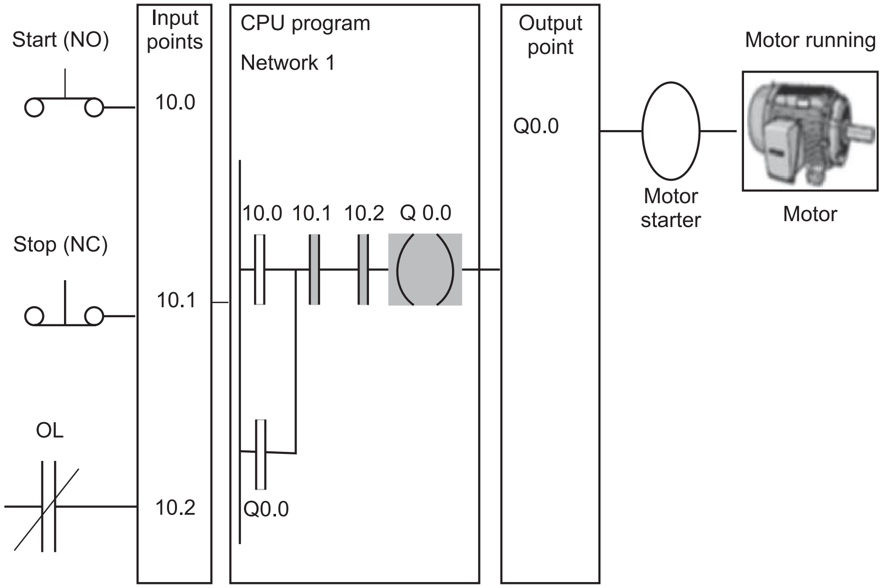

Figure 9.12: Sample program 2

If the push button for stop connected at input I0.1 is "On", then the output at Q0.0 deenergises and motor will turn off (Figure 9.13).

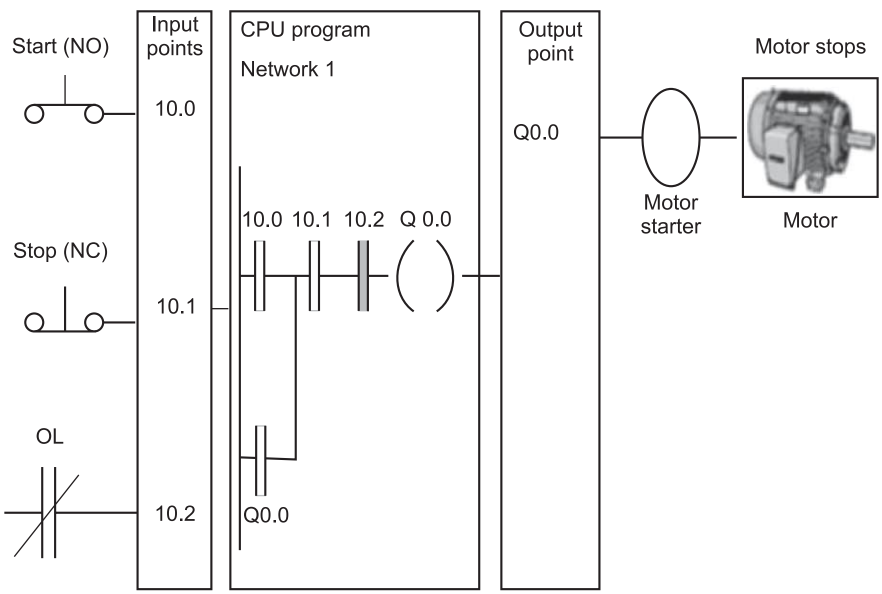

Figure 9.13: Sample program 3

The same logic is extended here to show some lights for "on", "off" conditions of the outputs which are mapped to appropriate output addresses such as Q0.0 and Q0.1 in this scenario. Refer to Figures 9.14 and 9.15) for the ladder logic.

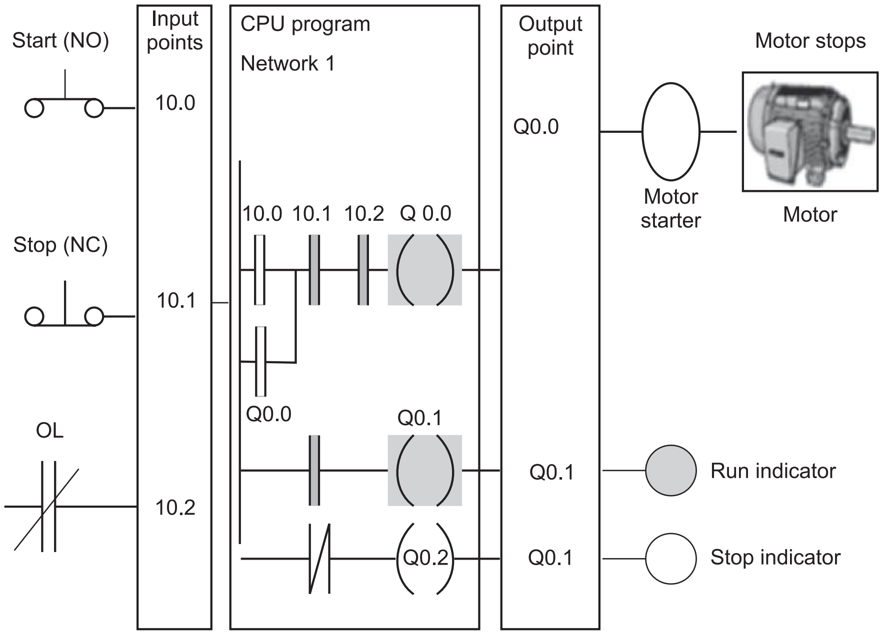

Figure 9.14: Sample program 4

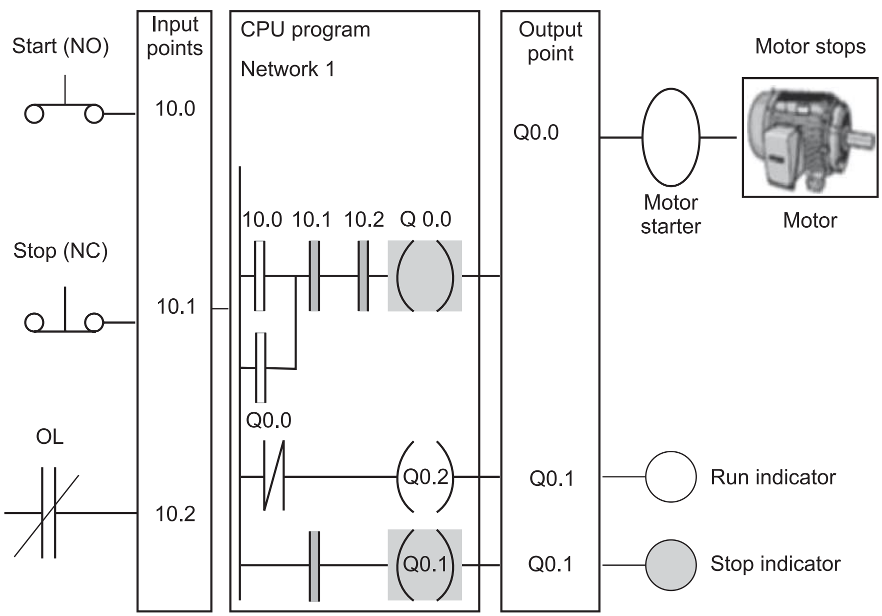

Figure 9.15: Sample program 5

9.3.4 Advantages of PLC

The following are some of the advantages of a PLC:

- **Flexibility:** PLC is scalable from a small modular device to a large system with multiple PLCs. A single PLC system can control many machines and processes in the plant.
- **Correcting errors:** In relay panels, a change for an additional line or improvement to the existing logic is costly and takes more time. In case of PLC, the changes are easy using the programming languages and there is no rewiring and sequencing in the logic. The troubleshooting and improving the logic is much simpler in the case of a PLC.
- **Space efficient:** The PLC can provide many functions required for coils, relays and counters. Implementing the same in a relay panel will be costly and takes large space and is inefficient.
- **Low cost:** Cost of PLC is scalable and is available in various configurations and options. However, when compared to the cost of a relay panels with so many relays and contacts, the PLC is much affordable. In addition, the PLC gives benefits in saving the cost of installation, shipping, etc.
- **Testing:** The logic of the program can be tested in the lab without the equipment. This method saves time and avoids the last minute changes to the programs.
- **Visual observation:** The run time view of the program helps to see the program execution and state changes and processing of the values in a step-by-step model on the display. This is very helpful for troubleshooting the program very quickly without having to shutdown the process or machine.
- **Security:** The PLC cannot be altered unless it is unlocked and programmed. An unauthorized person cannot change the PLC program as it is locked.

Table 9.7 provides some of the inherent features in the PLC and their benefits to the industry.

Table 9.7: Benefits of a PLC

Inherent Features	*Benefits*
Solid-state components	High reliability
Programmable memory	Simplifies changes Flexible control
Small size	Minimal space requirements
Microprocessor-based	Communication capability Higher level of performance Higher quality products Multifunctional capability
Software timers/counters	Eliminate hardware Status changes can be easily counted

(*Contd.*)

Software control relays	Reduce hardware/wiring costs Reduce space requirements
Modular architecture	Installation flexibility Easily installed Reduces hardware cost Expandability
Variety of I/O interfaces	Controls a variety of devices Eliminates customized control
Remote I/O stations	Eliminates long wire/conduit runs
Diagnostic indicators	Reduces troubleshooting time Signal proper operation
Modular I/O interface	Neat appearance of control panel Easily maintained Easily wired
Quick I/O disconnects	Service without disturbing wiring
System variables	Useful management/maintenance
Stored in memory data	Can give an output in report form

Checkpoint

✦✦✦ **1.** List the programming languages as per IEC.

✦✦✦ **2.** Which is the IEC standard for programming languages of PLCs?

✦✦ **3.** What are the different functions of application program software of a PLC?

✦✦ **4.** What was the mimic for the ladder logic?

✦✦ **5.** What is the most common language for programming a PLC?

✦✦✦ **6.** How an SFC is different from a flow chart?

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Summary

LO 1: Describe programmable logic controllers and their evolution

- Programmable logic controllers also known as programmable controllers or PLCs are members of the computer family that use integrated circuits instead of electromechanical devices to implement control functions.
- The term "logic" is used because programming is primarily concerned with implementing logic and switching operations.
- PLC is a special purpose industrial microprocessor-based real-time computing system which performs the following functions in the context of industrial operations—monitors input/

sensors; executes logic, sequencing, timing, counting functions for control/diagnostics; drives actuators/indicators; and communicates with other computers.

LO 2: Explain the architecture and functionality of PLCs

- The central processing unit (CPU) or the processor unit contains the microprocessor which interprets the input signals and carries out the control actions, according to the programs stored in its memory, communicating the decisions as action signals to the outputs.
- The memory in a PLC is divided into program and variable memory.
- At the input and output sections the processor receives and transmits information from/to the external devices.
- A programming device is needed to enter, modify, and troubleshoot the PLC program or to check the condition of the processor.
- Expansion units are additional modules that are used to increase the number of input/output lines for a PLC controller.
- The communication interface is used to receive and transmit data on communication networks from or to other remote PLCs. The communication interface is responsible for device verification, data acquisition, synchronization between user applications and connection management.
- Buses the physical communication means/path for the signals to communicate within a PLC. The information is transmitted in binary form, i.e. as a group of bits with a bit being a binary digit of 1 or 0, i.e. on/off states. The term "word" is used for the group of bits constituting some information.
- The input/output unit provide an interface between the system and the outside world enabling connections to be made through input/output channels to input devices such as sensors and output devices such as motors and solenoids.
- Primary purpose of such isolators is to protect the card from the faults in the field instruments. Without these circuits if any instrument gets shorted it will directly damage the I/O card.
- The analog voltage on each channel terminal that is sensed is referred to a common ground. In the case of differential channels, each channel terminal involves two wires and the voltage between the pair of wires is sensed.
- Relays are the most flexible output devices that are capable of switching both ac and dc outputs. However, they are slower, expensive and wear out after a large number of cycles.
- In case of serial bus, they are distributed throughout and widely spread across the plant. Normally, serial buses carry signals over single wire to the main control processor and they confine their sensor wiring locally thereby avoiding the costs arising due to wiring distribution over long distances along with signal losses.

LO 3: Analyze different programming languages and operations of PLCs

- SFCs are very different from flowcharts because they do not have to follow a single path through the flowchart.
- FBD instruction is represented as a rectangle with inputs entering from the left and outputs exiting on the right.
- It is very flexible and intuitive for writing control algorithms and uses operators such as assignment, logical branching and loops.

Questions

I. Objective-type questions

✦✦ **1.** In Modbus application commands and relay ladder logic (RLL), a single output bit describes a:
(a) Coil (b) Register
(c) Force (d) Mask

✦✦✦ **2.** The ANSI/ISA-95.00.03-2005 standard functional hierarchy defines equipment control and equipment monitoring of PLCs in:
(a) Level 1 (b) Level 2
(c) Level 3 (d) Level 4

✦✦✦ **3.** For programmable controllable hardware ports, the main power interface/port must:
(a) Connect with the interface functions to the sensors and actuators portion of a programmable logic controller.
(b) Include snubber networks to prevent current leakage from triacs.
(c) Open for third-party devices such as personal computers instead of PADT.
(d) Maintain intelligent input devices during power up, power down, and power interruptions.

✦✦✦ **4.** All of the following programming languages could be used to facilitate communication in an HMI except:
(a) Java (b) Relay ladder logic
(c) BASIC (d) C/C++

✦✦ **5.** Which of the following is true of programmable logic controllers (PLCs)?
(a) PLCs have generally adopted the ladder logic standard.
(b) PLCs are usually configured in groups, with one PLC covering multiple functions.
(c) PLCs did not historically support redundancy.
(d) PLCs did not historically support use in a work cell.

✦✦✦ **6.** Which of the following is NOT a shortcoming of relay ladder logic and function block languages?
(a) Complex data addressing uses real addresses instead of symbolic variable names.
(b) Language implementations vary between different systems.
(c) Poor feedback loop integration exists, such as for PID controllers.
(d) Standard software elements are difficult to reuse because there is no object orientation.

✦ **7.** Which of the following would allow an individual with a minimal programming background to set a PLC to handle feed forward controls?
(a) Analog hardware (b) Function block
(c) Configurable digital system (d) Relay ladder logic

✦✦ **8.** To which of the following should a user refer if looking for specifications on structured text?
(a) IEC 61131-1
(b) IEC 61131-2
(c) IEC 61131-3
(d) IEC 61131-8

✦✦ **9.** What is controller scan time?
(a) Time taken to scan the inputs and outputs.
(b) Time taken to run the logic.
(c) Time taken to scan the inputs and generate the alarms.
(d) Time taken on scan the inputs, run the logic and update the outputs.

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II. Short-answer questions

✦✦ **1.** List three advantages of using PLCs compared to traditional panel wiring.

✦ **2.** How the analog voltage is sensed in each channel?

✦✦ **3.** How does the output module provide contacts?

✦ **4.** What is the purpose of relays in digital outputs?

✦✦ **5.** What is the purpose of analog output module?

✦✦ **6.** What is the purpose of digital output module?

✦✦ **7.** Define the scan rate of a PLC.

✦✦✦ **8.** What are the contributing factors for the cycle time of a PLC?

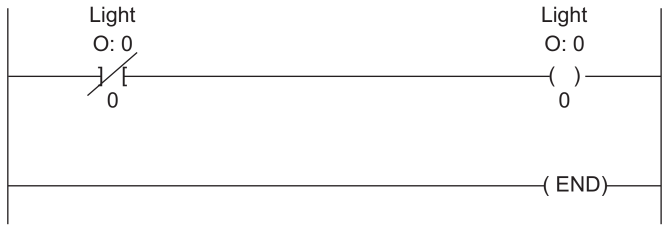
✦ **9.** List three advantages of PLCs.

✦ **10.** How an FBD block is represented?

III. Unsolved problems

✦ **1.** Draw a PLC ladder diagram which exhibits the behavior of XOR logic gate.

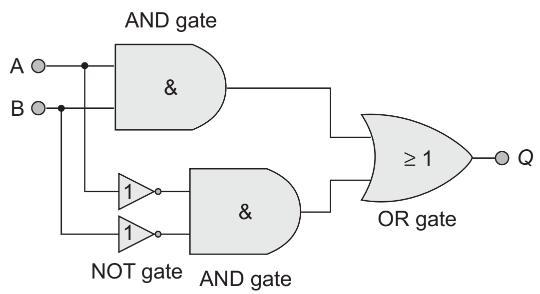
✦ **2.** Draw the output timing diagram (light) when the following ladder logic is loaded and started in PLC. The PLC scan order is: scan input—update output—execute logics and its execution period is 100 ms. The light 0:0 is output here.



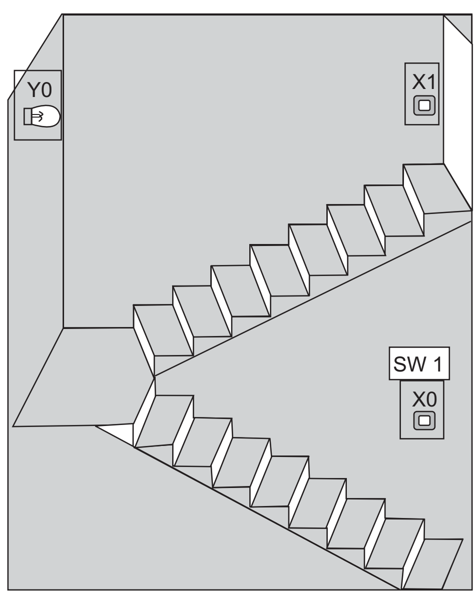
✦✦✦ **3.** A PLC has a digital input card which can accept only wet contacts (24 V dc). Draw how you would connect a pressure switch which provides a mechanical dry (potential free) contact.

✦✦ **4.** There are three sensors A, B, C used in an application to detect the flame. Design a ladder logic circuitry to detect if any one of the sensors does not agree with the other two.

✦✦ **5.** Realize the following logic in ladder diagram:



✦✦✦ **6.** Complete the ladder logic diagram for the following staircase lighting. The light should be able to turn On/Off using both bottom switch and top switch.



✦✦ **7.** Draw a ladder program to energize a burner lit with tag name Burner_Lit only if at least two out of the three normally closed sensors detecting the flame are normal (closed) with the tag names Sensor_A, Sensor_B, Sensor_C.

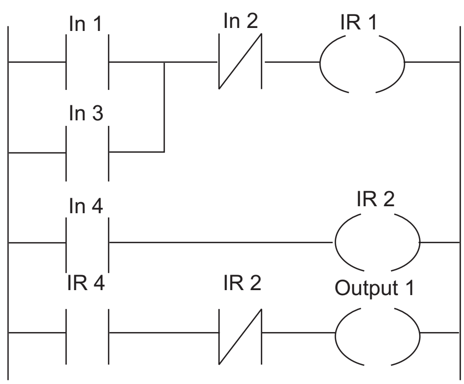
✦✦✦ **8.** One normally open and one normally closed push buttons (PB_On and PB_Off respectively) are used to make a lamp (LAMP) On/Off in an application. Draw the ladder diagram for the same.

✦✦✦ **9.** Draw the ladder rungs to represent:
(a) Two switches are normally open and both have to be closed for a conveyer to operate.
(b) Either of the two normally open switches has to be closed for a motor to be energized and operate an actuator.
(c) A motor is switched on by pressing a spring-return push button start switch, and the Motor should remain on until another spring-return push button stop switch is pressed.
(d) A fan is to be switched on if there is an input from sensor A or sensor B.
(e) A motor is to come on if there is no input to a sensor.
f. A fan is to be activated if sensor A gives an input.

✦✦ **10.** There are three push buttons located at different places. Motor has to run if any one of these three push buttons are pressed. Write a ladder logic for above application.

✦✦ **11.** Decide whether each of these statements is True (T) or False (F):

For the ladder diagram shown in the figure, the internal relay R1 is energized when:
i. There is an input to In 1.
ii. There is an input to In 3.
(a) i. T, ii. T (b) i. T, ii. F
(c) i. F, ii. T (d) i. F, ii. F



✦✦✦ **12.** A motor has to turn after 10 s of pressing On push button. Same motor has to switch off after 5 s of pressing Off push button. Write a ladder diagram using timers.

✦✦✦ **13.** Write a ladder program to switch on a motor in sump to fill overhead tank. Motor has to switch off after reaching 90% of the tank level and switch On when tank level is around 10% of tank level. Consider a level T/x which gives level in % to PLC.

✦ **14.** Draw the ladder logic to power on the light. Consider that there are three different switches and if any one switch is on, light should get on.

IV. Critical-thinking questions

✦✦✦ **1.** What is the difference between a PLC and DCS?

✦✦ **2.** What is programmable automation control?

✦✦ **3.** Can we perform a batch control using PLC?

✦✦ **4.** What is the purpose of encoder modules in PLCs?

✦✦✦ **5.** List the types of operators used in structured text programming language.

✦✦ **6.** Which is the most fundamental level programming language used to program PLC?

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SCADA System

10

LEARNING OBJECTIVES

After reading this chapter, you will be able to:

1. Describe SCADA system
2. Illustrate the basic elements of SCADA system
3. Analyze the architecture of SCADA system

Supervisory Control and Data Acquisition Systems, also called as SCADA Systems are one of the earliest form of industrial automation. They are used for monitoring the process/instruments distributed in a large geographical area such as pipelines and power distribution lines, water distribution, etc.

In this chapter the evolution of the systems in terms of the features and architectures are discussed. The major components of a SCADA systems are remote transmission units, telemetry systems and HMI systems. The remote transmission units also called as RTUs are discussed in detail with their various forms and features.

The human machine interface (HMI) systems are discussed in terms of the various features provided to the users to ease the operations of the process and systems. The SCADA systems are installed in different locations, the communication protocols become a key feature. Modbus is one of the communication protocol in additional to many others. In order to provide an understanding on the communication protocols, modbus is discussed in detail.

Finally the chapter provides the information required for the student to understand the SCADA systems, their various configurations and architectures, functions and features.

Keywords:
SCADA, HMI, communications, operators, RTU, Modbus, distributed SCADA systems, networked SCADA

"Synergy means behavior of whole systems unpredicted by the behavior of their parts"
Richard Buckminster Fuller

10.1 SCADA SYSTEMS

LO 1
Describe SCADA system

How would you imagine a plant? Here is the answer, a combination of simple to complex machines and devices spread over kilometers working in coordination to achieve a common outcome. The outcome is commonly a product expected because of the automation, in other words a result of coordinated device operation as can be a petrochemical product or a car or purified water. Now what do people in such plant do when the abovementioned machines are working? The answer is quite simple they monitor the entire process. As you know, controls are distributed geographically; hence, there should be a location from where they can view the process and understand how various controls are connected and operating. This location is called control room and in the control room people observe the processes as they happen in the plant from a single location although the systems are miles apart. Viewing of this can be done by means of specialized hardware and software or only specialized software with common hardware. However, a SCADA can be installed on any windows platform with basic configuration and the graphics can be designed to monitor the process. In order to monitor a process and making it simpler a system called as SCADA (Supervisory Control and Data Acquisition) evolved.

10.1.1 Definition of SCADA

It is a system for monitoring live and old industrial processes as they happen in a way perceivable by humans for controlling it. The key take away points from this explanation are:

- SCADA is a system for monitoring and controlling plant processes.
- It provides knowledge to humans about a process in a way which can be perceived easily by means of graphics and trend.
- People can also pull out old data of the events that have occurred in the past.

Underlying technology that makes the above features possible for a SCADA system is called as protocol. Since it specifically caters the purpose of serving a SCADA system, it is often referred as SCADA protocol. Hence, whatever look and feel of a system that an operator sees is because of the underlying protocols. Role of SCADA systems is to monitor and control a plant or equipment in automated industrial processes and these systems find applications in industries such as water and waste control, oil and gas refining, municipal water supplies, steel manufacturing, telecommunications, transportation, and power generation. SCADA has usage in large scale process facilities where the inputs and outputs received will range from thousands to several thousands such as nuclear power fusion testing, etc. However, SCADA systems are rapidly evolving and penetrating the market of plants with several thousand I/O channels.

The large scale SCADA systems can be provided with a central host system connected with several RTUs, PLCs, and analyzers over a network. The operator terminals are provided in the central control room for monitoring purpose. In this case it is an integration project wherein multiple systems from multiple places are integrated into one single system. SCADA systems are typically used to control assets that are geographically dispersed and are dispersed over thousands of square kilometers.

SCADA system collects the information from different places (for example a leak in water pipeline) while monitors at a central location. The information received and analyzed at the central location is then transferred back to the local station for an action. The events are displayed as alarms in all the locations to create the alerting to the engineers attending the station. The information collected from different locations is displayed in an organized way based on the locations and based on the types of users, etc. These systems can be simple such as the ones that monitor the electrical consumptions of building to a large scale river monitoring. The SCADA systems were traditionally built on telephone networks for communications and matured as the technology evolved. Today options are available to have a SCADA communication backbone built on ethernet [local area network (LAN), wide area network (WAN)], internet, wi-fi, cellular, satellite, etc.

Checkpoint

✦✦ **1.** What is a control room?

✦ **2.** What is the full form for SCADA?

✦✦ **3.** Define SCADA?

For answers to checkpoint, scan the QR code

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10.2 BASIC ELEMENTS OF SCADA SYSTEMS

LO 2

Illustrate the basic elements of SCADA system

A SCADA system has certain basic elements which work together to get the desired functionality. These basic elements or subsystems are represented in Figure 10.1:

- A field interface unit is an intelligent device that connects to the field instruments such as sensors, actuators, and has the ability to connect with the central systems using the communication technologies. Usually these devices are installed in a panel of small local control rooms in the field. These devices are called RTUs and sometimes PLCs can also meet the purpose.
- The other major element in the SCADA is its communication backbone. The communication backbone is the method of transferring the data from the field interface units, such as RTUs and PLCs, to the central hosts located remotely in central control rooms. The communication backbone constitutes telephones, wired copper cables, cellular or satellite, etc., or mix of them.

Note: ✦ Level 1 & Level 2 category
✦✦ Level 3 & Level 4 category
✦✦✦ Level 5 & Level 6 category

- The central host computer or central host server is the means of connecting and collecting the information from all the field interface units using the communication backbone. These systems are hosted remotely from the place of measurement and are generally in a central place where the data is analyzed. These systems are also called master stations or master terminal units. These systems are either server application software hosted on a general purpose server with operating systems or embedded, purpose build machine interfaces to the network on both collection and sharing side of the network.
- A set of software applications hosted on a general purpose hardware and operating systems are used to provide real-time information to the SCADA operators. These are generally called the operator stations and the application software is called human machine interface (HMI) or man machine interface (MMI). These systems have the capability to engineer the system in such a way that it is easy to understand the process and collect the real-time information from the central host. These are connected to the same communication backbone to which the central host and field interface units are connected. The HMI can provide the information in the form of a real-time values, graphs, trends and faceplates.

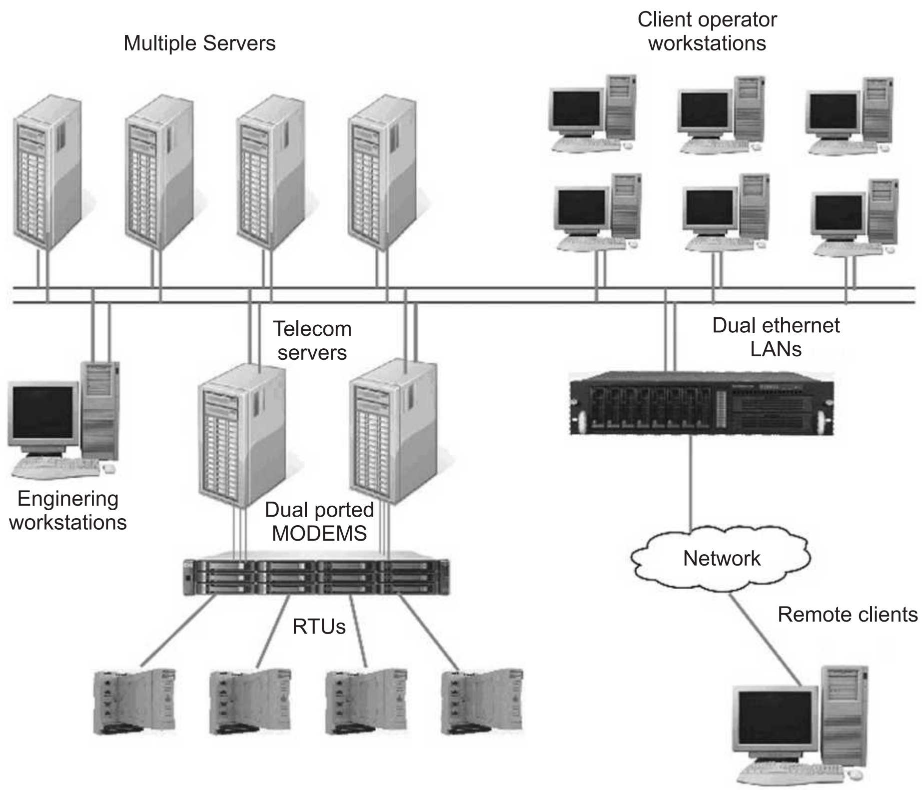

Figure 10.1: Typical SCADA system

10.2.1 Field Data Interface Devices

Field data interface devices form the "eyes and ears" of a SCADA system. For example if the river basin management is the application of SCADA, then the level measurement instruments such as radar level transmitters, ultrasonic level transmitters, flow transmitters, quality analyzers, gate open status switches and whether monitoring instruments are connected to the field data interface units such as RTU and PLCs. Using these information collected by the remote host computer, the HMI hosted in operator station can see the status. The information provided in the graphics in the operator stations can help assess the situation and take appropriate steps from central locations. However, before the end state can be reached, the process instruments, and measurement and actuating equipment shall be compatible to exchange information with the field interface units such as RTUs. The process instruments thus selected should be provided with matching signals, protocols and electrical interfaces suitable for RTUs and SCADA systems. These are primarily electrical signals. Once it is processed by the RTU the digital form of exchange takes place between RTU and SCADA central host. The logic for the control, if any, is executed at local processor of the RTU and only set points or actions are received from the central host. These types of mechanisms are used largely due to their limited bandwidth of communication between the FIU or RTU to the central host systems.

To explain it in a better way, consider a construction of building where the bricks or material to construct a wall is mixed in one area and transferred over multiple hands to reach its destination. Contrary to this, if the signal goes from the central control station every time to RTU, there is significant delay in providing the control for multiple devices over multiple locations that ultimately loads the system and network, resulting in poor control. To avoid this, controls are made local and a centralized system is used to supervise them. However, this centralized system does have the capability to send a control signal, however only used when it is really needed. Hence, control/logic instructions are traditionally held within the RTUs/PLCs. As discussed earlier, PLC is meant for automating the monitoring and control needs of the processes. The PLC can be a part of SCADA system and can integrate and interoperate with SCADA along with other RTUs in the network. The PLCs are also connected with the field instruments for communication with SCADA. Since PLCs can execute the logic locally and transmit the data remotely to central locations via communications backbone, the combination becomes a powerful use case where the breadth of monitoring for a large-scale system alongwith the depth of control with PLC is achieved locally. This does not mean that PLCs are replacing RTUs—both have different applications based on the type of needs. The traditional concepts as outlined in the following section are slowly getting obsolete.

In earlier times there was a perception that PLCs are mainly used for controlling and RTUs are used for telemetering/transferring the data. As PLCs were used mostly to replace relay switching logic control systems, telemetry was increasingly used with PLCs at remote sites. There arose a necessity to use a remote signal to influence the program within the PLC. This is in effect the "supervisory control" part of the acronym SCADA. In other words, due to SCADA there is a need of devices capable of telemetering as well as controlling. In earlier days, the RTUs or field interface units used to store a limited amount of programs in the local systems. The traditional PLCs coupled with a communication module can interface with the communication backbone of the SCADA systems with limited bandwidth as required. Thus, there is a thin gap between these two types of equipment as the vendors are competing for the same market. Academically we can say that RTU is a device that can be programmed and can interface with the SCADA systems.

10.2.2 Communications Network

The communication networks or communication backbone in the SCADA network connects different subsystems participating in the usage. The backbone connects the central server, field interface units and operator stations. The communication is achieved through cables, telephone networks, or cellular networks and data transfer can be bidirectional. The use of cables for establishing the communication is limited to specific geographical locations. However, the same concept is not practical in systems that are spread across the sites at different geographical locations and sometimes are not possible for human occupancy. The cost of wiring to such places is too high. Such are the conditions which drive the usage of the public telephone networks, cellular or satellite communications. Some of them are leased line and some of them are data transfer based which is very economical and is charged based on the usage. The leased lines and dedicated satellites are costly because they require a dedicated line and the costing is done based on the fixed amount instead of the usage. But the SCADA systems do not require a permanent connection as it is a request-response based communication mechanism and data is needed only when requested. Sometimes, the option is to have a dial-up connection or data transfer cellular cards or broadband internet packages.

The SCADA network can be used along with the office network to save cost for the company as it can be used for both the purposes. In addition, the SCADA can exchange information with other office applications such as spreadsheets, workflow management, historian databases and GIS modeling systems.

10.2.3 Central Host Computer

The central host or master station is the computer hardware and server application software hosted in a remote place in a central control room. These are server systems with typically no man-machine interface. The task of these systems is to collect the data from a field interface unit spread across the geographical locations. The host periodically scans the devices for change in the values using the communication backbone. Sometimes a group of devices are clustered together for scanning them together. The purpose of this scanning is to use the minimum time, minimum bandwidth, fast scan and every device to be scanned in the specified amount of time. The real-time database in these central host systems can store the run-time values and can be stored in the database. The hardware, operating systems were used to be proprietary in nature and do not communicate with other systems except the own man- machine interfaces and operator stations. However, the technology has moved to an open-based technology where the hardware becomes a commercial off-the-shelf (COTS). The operating systems are general windows based. The central host is server application software with open interfaces to communicate with other systems. With these interfaces and ability to share the same networks, many powerful automation tools such as GIS, office applications, workflow management systems, databases and modeling software such as hydraulic modeling software can exchange the information.

10.2.4 Operator Workstations and Software Components

Operator stations, also called HMI stations, are networked to the same backbone and act as client systems to the central host server. These client systems together with the application software can request the information and can represent the data in a mimic format. The trends, alarms and faceplates appear in the system. The actions as required by the operator are accepted in these systems and carried out via the host system to the backbone network to the field interface units. While the central stations oversee the entire process, these operator workstations have the provision and permission only to monitor limited geographical locations/areas. The advantage with operator workstations is to give the operator a view of the process that is closer to the physical location of the workstation, wherein if any operator action is needed they can attend it quickly.

The major component in the operator interface is the application software package for man-machine interface. The packages are generally installed in multiple systems installed in the network. All these systems share the same information from the central host server. Since there are multiple packages which need to be purchased based on the size, complexity and number of logical units of control. The cost of these packages can become a costly item. Ultimately, well-designed, developed and tested software is the key for success of the SCADA projects.

Many of the application software are developed by the proprietary system and work on specific hardware and do not share the information with other systems. However, the proprietary software has a defined and definite performance associated with it as they are well-tested and optimized for this hardware. The software packages are also available in a COTS model and can be installed on any commercially available hardware. They have open interfaces with other systems and are flexible in terms of configuration and development. The limitation with such models is their performance and inadequate reliability due to too many variables.

In general the software from proprietary means are functionality centric for control applications, while COTS software focus on types of instruments and interfaces supported, etc. Hence, it is important to choose the right type of software application based on the needs, skill sets available, etc. The software packages are available in different forms and need to be purchased separately. The most common types of packages are as follows:

- **Central host computer operating system:** This software package is used to host the application server. The operating system can be a windows or Linux-based system and is dependent on the type of hardware. Sometimes this software is purchased along with hardware, but the optimization of this software for the server may not be available with the hardware vendor. So it is wise to purchase the operating system and add the optimizations required for the server from the application server vendor.
- **Operator terminal operating system:** The operator-station operating system is generally a client operating system and is light weight so as to handle the desktop applications. This is typically used by operators and this operating system hosts the application software in the operator station.

- **Central host computer application:** This software application is used for the server for collecting the real-time data from different field instruments. The software package is installed on the operating system hosted on the server hardware. This package is connected to other packages in a client and server mode for sharing the data over the network. This software also communicates with the RTUs and PLCs and shares the information with the mimic software installed in the client systems.
- **Operator terminal application**: The software packages used in the operator stations are typically a subset of server application software. These are used to render the information to the operator as client systems from the central host. Generally in a typical plant the number of operator stations is based on the number of sites controlled, number of operators and number of critical geographic locations controlled, etc.
- **Communications protocol drivers**: The drivers are self-executing software applications that can communicate with the PLCs and RTUs in the network. These drivers are selected based on the type of RTUs selected and their method of communication. The drivers are installed in the host computer based on the types of PLCs and RTUs. They can read, control, translate and interpret the information received from the communication link.
- **Communications network management software**: The communication network is monitored on a continuous basis as this is critical part for the operations of the SCADA systems. The typical metrics used to measure the health of the network is its bandwidth, the successful transactions and failures, retries post the failure are measured.
- **RTU automation software**: The most widely used term is configuration tools. These are used to configure the RTUs and PLCs and are used by the engineering staff to monitor the application logic and also to troubleshoot and diagnose the problems. Generally, these tools will be different for each type of the controller and will be same if the controllers and PLCs are purchased form the same vendor or same family of the controllers in the same vendors.

The preceding software products provide building blocks for application-specific software, which must be defined, designed, written, tested, and deployed for each SCADA system.

For answers to checkpoint, scan the QR code

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Checkpoint

✦ **1.** What is RTU?

✦ **2.** What is MTU?

✦✦ **3.** What is HMI?

✦✦ **4.** Define RTU.

10.3 SCADA ARCHITECTURE

LO 3
Analyze the architecture of SCADA system

SCADA systems have evolved parallely with the modern computing technology. The SCADA systems are divided into the following three generations: first-generation—monolithic; second-generation—distributed; third-generation—networked. These are described in the following sections.

10.3.1 Monolithic SCADA Systems

The early days of computing were based on mainframe computers and the SCADA software developed were based on these machines. These mainframe machines were centralized with no networking concepts. Each of the system is a standalone on its own with no networked digital connectivity with the others. The RTUs were connected to these mainframe computers using wide area networking concepts. However, these networks were developed for the sole purpose of communicating the RTUs with the mainframe computer and there were no open protocols or there was no sharing with the other systems.

The communication means were proprietary in nature and there was no open protocols and even the proprietary was very lean in nature with functionality to scan and control the points in RTUs. There was virtually no diagnostics, network management or multi-vendor interoperable systems, etc.

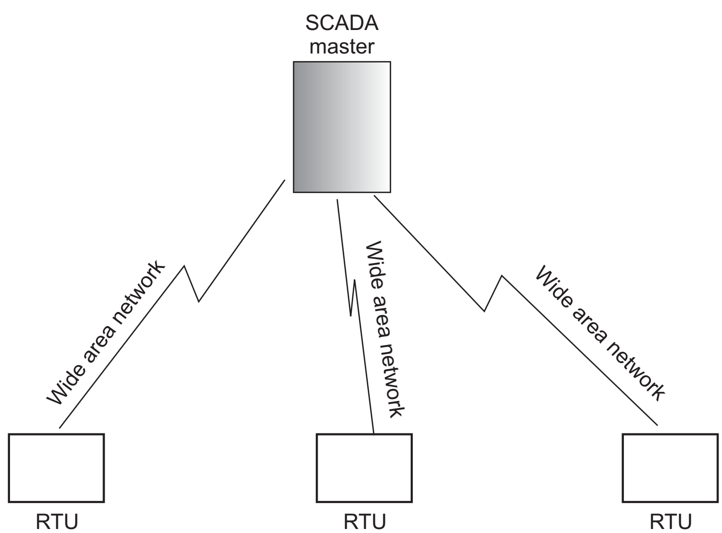

Figure 10.2: First-generation SCADA architecture

The connectivity with the host computer in the mainframe controller itself is very limited in nature. The interface cards which are developed by the vendors for this purpose are plugged and special drivers are executed to make them operational. This means not only the hardware, but some level of hardware also needs to be purchased from the SCADA system supplier for its operations and maintenance.

Redundancy in the first-generation systems was achieved by using two similar machines with the same software installed. The backup machine or backup mainframe computer keeps watching the primary and once the event is received on the failure of the primary, the secondary will take over. The secondary backup mainframe computer is not used until the primary fails. Figure 10.2 illustrates the typical first-generation SCADA architecture.

10.3.2 Distributed SCADA Systems

The second-generation systems adopted the technologies of the time and came with SCADA with miniaturization and computer networking. The systems were architected with multiple personal computers connected over LAN and the processing is distributed over multiple computers. The information exchange reached very near to real time across the systems. The operator stations were mini computers which are many in number and are small in size and less in cost compared to the previous generation. The distribution means the computation power is distributed across multiple systems which are connected over network. This generation of SCADA systems had the advantage of using improved local area network (LAN) technology and system miniaturization to distribute the processing across multiple systems.

The servers in the network played different roles based on the application software loaded in it—some became a communication server whose primary role is to establish the communication with field interface devices and collect the data in a frequency defined by the user; some others became operating stations for providing HMI functions; some others became the processors for calculations; and some for the storage of data. There are some other classes of servers meant for supervisory control in a SCADA system.

The individual functions of individual processors when integrated became powerful SCADA. The systems were integrated by LAN for real time transfer of information with the bandwidth rates upto 1 GBPS. Some of the vendors had optimized the LAN with the proprietary protocols which are further optimized for real-time information exchange with more reliability, determinism and fault tolerance. But the disadvantage with these proprietary layers on the ethernet is their inability to interoperate with other servers sharing the same networks. Figure 10.3 illustrates typical second-generation SCADA architecture.

The major advantage with the distributed system is its improvement in the reliability and redundancy of the system. In this architecture, a single system failure does not halt the operation of the entire system. It is much different from a single primary and backup system operation of maintaining the redundancy as was the case in the first-generation systems. In this scheme all the systems are maintained at the same state and all of them share the information with the same set of servers. If a single HMI station fails, the user is free to use other stations which will be in the same state and there may be a need to enter the credentials for loading specific functionality based on the role. In this scheme there is no concept of primary and redundant backup for the operator stations.

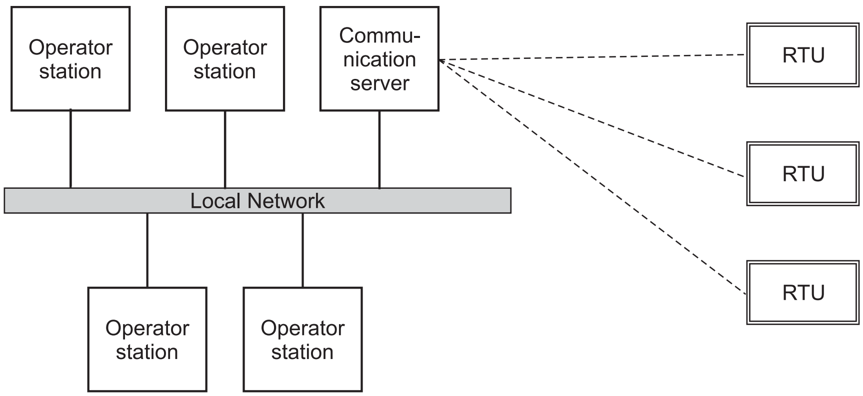

Figure 10.3: Second-generation SCADA architecture

The second-generation systems does not provided a major improvement in the WAN technologies and hence the SCADA central host continue to communicate with the RTUs and PLC located in the field as was the case in the first-generation systems. The external communication was still limited by the protocol used by these embedded devices and their limited bandwidth options.

10.3.3 Networked SCADA Systems

The third/current-generation SCADA systems appear same as second-generation in terms of the architecture and look and feel except these being open in nature and are controlled by the standards rather than the individual vendors. These are a combination of multiple networks and networked systems connected to one or multiple central host systems in the central locations. The RTUs are still available in the market which are proprietary in nature, but there are open RTUs in the systems that can share the same WAN can distribute the functions of the RTU over the network. So the distribution has crossed the boundaries of LAN and reached WAN and hence to the field devices.

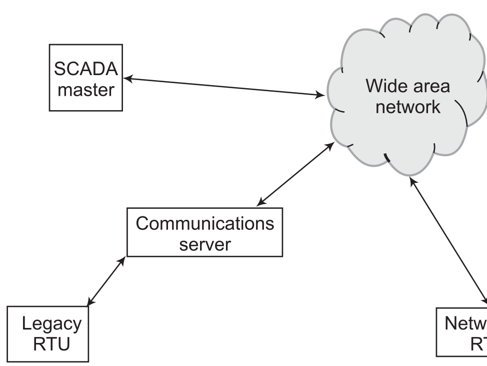

Figure 10.4: Third-generation SCADA system

The advantage with the open standard-based system and communication is that it opens the networks to interoperable with the best device for each of the application, which was a significant limitation in the previous generation. The open-based system also helps in connecting any third party peripherals such as monitors, keyboards and printers to the systems. With the open standards, the dependency of the software on the hardware platforms and operating systems is removed. The SCADA user has got the advantage to choose the hardware based on the local conditions, support needs, etc. The networks and the networking devices are open for any devices which is selected based on the local site conditions and maintaining them becomes easy. The change allowed the SCADA system suppliers to come with more value added features that help in monitoring the systems much more efficiently and easy to troubleshoot features. The SCADA systems also comes with the software-based host controller or master stations to be separate from the communication servers. There are RTUs that can communicate with the master stations in internet and also over ethernet. Figure 10.4 represents a networked SCADA system belonging to the current generation. An open based networked SCADA can be explained by using an open protocol such as modbus. The salient features of the protocol are explained next.

A company called Modicon developed a message structure in late seventies which is called modbus protocol. It is used today to establish a master slave/client server communication between the devices. The protocol is open and widely adopted. One of the reasons for its adoption is its simplicity and ease of development. The data between the devices is transferred in the form of analog, digital and registers. The protocol is also widely used in wireless applications where the RTUs need to communicate with the central host controller using wireless technologies.

The physical medium used for Modbus is:

- **Modbus serial:** The modbus serial communication is established using the physical interfaces such as RS-232 (or) RS-485.
- **Modbus TCP:** The modbus TCP uses the ethernet as the transmission medium and has the transmission modes for Modbus RTU where the messages are coded in hexadecimal.
- **Modbus ASCII:** The Modbus ASCII uses messages which are coded in ASCII characters (Only 0–9 and A–F characters are used)

As per the OSI model, modbus fits in the following layers as per the Table 10.1.

Table 10.1: Modbus communication layers

OSI	*Modbus serial*	*Modbus TCP/IP*
Application layer	Modbus application protocol client/server	Modbus TCP
Presentation layer	NULL	NULL
Session layer	NULL	NULL
Transport layer	NULL	TCP
Network layer	NULL	IP

(*Contd.*)

Data link layer	Modbus serial line protocol	IEEE 802.3/IEEE 802.2 ethernet
Physical layer	EIA/TIS-485(232)	10/100 base T

As per the modbus protocols the limitations of stations and other specifications is as follows—normally as per Modbus protocol, each RTU/device is treated as a station, for Modbus serial following is the specification listed in Table 10.2 .

Table 10.2: Modbus RTU specifications	
Network type	Simple master slave communication
Topology	RS232: Peer to peer communication between master and slave
	RS485: Line topology with segments up to 32 devices, each segment is terminated at the end.
Installation	Shielded twisted pair cables, line length depends on physical media and baud rate
Data rate	User selectable, depending on physical media
Max stations	1 master and up to 246 slaves
Data	0–252 byte per telegram frame
Network features	Simple master slave network for peer-to-peer (RS-232) or multidrop (RS485) communication

Modbus RTU has a master slave mode of communication and host controllers in the SCADA is always the master whereas the RTU becomes the slave. The master initiates the communication where it sends the requests in modbus messaging format. The slaves responds with the same format. In case of Modbus TCP, the same mechanism except the messages are packaged in ethernet format and use the switches and ethernet network as the transmission medium. In addition, specifications are as per the Table 10.3.

Table 10.3: Modbus TCP specifications	
Network type	Ethernet TCP/IP based simple client/ server network
Topology	Very flexible with star, tree or lime structures
	All topologies that can be implemented with standard ethernet technology including switches networks are applicable
Installation	Standard 10.100 or 1000 Mbits/s ethernet technology based on copper cables, fiber optics or wireless standards can be used
Speed	10, 100, 1000 Mbits/s
Maximum stations	Nearly unlimited

(*Contd.*)

Data	Upto 1,500 bytes per telegram frame
	Total: neatly unlimited
Network features	Simple client server network based on standard ethernet technology and TCP/UDP/IP technologies at level 3–4

SCADA sends the request to the server in Modbus messaging format. Subsystem-Modbus TCP server responds to the request in Modbus messaging format. It uses TCP port number-502 for the communication (Figure 10.5).

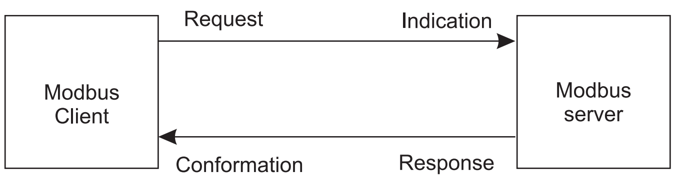

Figure 10.5: Modbus communication request/response

The client server model of the modbus has four types of messages which are request, confirmation, indication and response. *Request* is the message sent by the client to initiate the communication and *Indication* is the message received at the server which is intiated from the client. *Response* is the response from the server to the client and *Confirmation* is the message received from the client. The client server model is used for information exchange in real time between the devices; between devices and third party devices; between the HMI stations and also between the configuration tools and the device while connecting and downloading programs. Figure 10.6 displays the architecture of the Modbus client/server TCP communication.

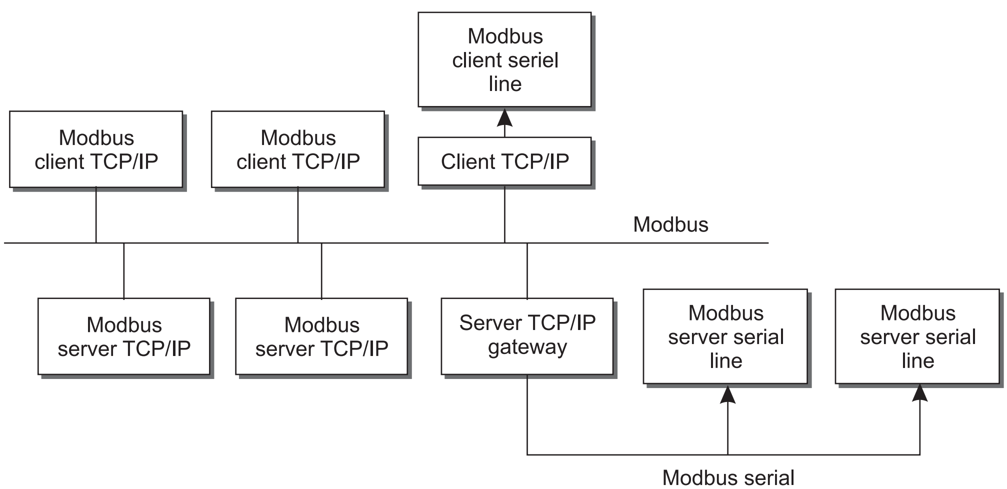

Figure 10.6: Architecture of systems with Modbus

Coils are mainly used for digital inputs and outputs, inputs and output registers are used for reading and writing analog data. Each register type and whether it supports only read or both read and write is given in Table 10.4.

Table 10.4: Modbus communication layers

Category	*Access Type*	*Address Range*
Input coils	Read only	10000–19999
Output coils	Read/Write	00000–09999
Input register	Read only	30000–39999
Output register	Read/Write	40000–49999

Checkpoint

✦✦✦ **1.** How redundancy is achieved in the first-generation SCADA architectures?

✦✦ **4.** What is the advantage of distribution of individual SCADA system function across multiple systems connected over network?

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Summary

LO 1: Describe SCADA system

- In the control room, people see process as it happens in the plant from single location although the systems are miles apart. Viewing of this can be done by means of specialized hardware and software or only specialized software with common hardware. However, a SCADA can be installed on any windows platforms with basic configuration and the graphics can be designed to monitor the process.
- These systems encompass the transfer of data between SCADA central host computer and number of RTUs and/or PLCs, and the central host and the operator terminals. SCADA systems are typically used to control geographically dispersed assets scattered over thousands of square kilometers.

LO 2: Illustrate the basic elements of SCADA system

- A collection of standard and/or custom software systems, such as human machine interface (HMI) software or man machine interface (MMI) software, application software that provide real-time values to the SCADA central host and therefore to the operator terminal application or operator stations. This helps in supporting the communications system, and monitoring and remotely controlling field data interface devices.
- RTUs, also known as remote terminal units, provide this interface. They are primarily used to convert electronic signals received from field interface devices to the communication protocol used to transmit the data over a communication channel.
- SCADA systems have origins in early telemetry applications, where it was only necessary to know basic information from a remote source. The RTUs connected to these systems

does not need control engines inside as the relay switch logic in the field is used to do the same.

- Modern SCADA systems can exist in traditional computer servers as well. This has opened a range of possibilities linking SCADA systems to office-based applications such as GIS systems, drawing management systems, hydraulic modeling software, information databases and work scheduling systems.
- The advantage with operator workstations is to give the operator a view of the process that is closer to the physical location of the workstation, wherein if any operator action is needed they can attend to it quickly.

LO 3: Analyze the architecture of SCADA system

- Redundancy in these first-generation systems was accomplished by the use of two identically equipped mainframe systems, a primary and a backup, connected at the bus level. The standby system's primary function was to monitor the primary and take over in the event of a detected failure.
- The distribution of individual SCADA system functions across multiple systems connected in a network provides more processing power for the system as a whole than would have been available in a single processor based monolithic systems.
- Distribution of system functionality across network-connected systems helps in increasing processing power and improving the reliability and redundancy of the system as a whole.
- The major improvement achieved in third-generation SCADA systems is the use of WAN protocols [internet protocol (IP)] for communication between the master station and the communication equipment.

Questions

I. Objective-type questions

✦✦ **1.** Which of the following is true of traditional SCADA?
(a) SCADA was the original method of referring to systems of PCs linked with PLCs within a plant.
(b) RTUs using microprocessors are considered "smart" and do not need a master termination unit (MTU).
(c) Large distances require that remote process control must be standalone control.
(d) Systems consist of MTUs located at each end element

✦✦✦ **2.** Which of the following would be applicable for remotely controlling gas pipelines located beyond the plant itself?
(a) Supervisory control and data acquisition
(b) Single loop controller
(c) Data acquisition and control
(d) Control in field

✦ **3.** SCADA means:
(a) Scope of Data Acquisition
(b) Superior Control and Data Acquisition
(c) Supervisory Control and Data Acquisition
(d) Setting Control and Data Acquiring

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II. Short-answer questions

✦✦ **1.** List three application scenarios of SCADA systems.

✦✦✦ **2.** List the different means of communications as used by the SCADA systems.

✦✦ **3.** What are the advantages of third-generation SCADA systems?

III. Critical-thinking questions

✦✦ **1.** Explain the role of communication networks in SCADA.

✦✦✦ **2.** What are the different office-based applications that can be interacted to SCADA.

✦✦✦ **3.** What is the advantage of an operator workstation?

✦✦✦ **4.** List at least three software products used in a SCADA system.

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Distributed Control Systems

11

Introductiontothedistributedcontrolsystems,different types of controls and evaluation of such systems over a period of time are discussed in this chapter. Different types of controllers used in distributed control and relative advantages and disadvantages of such systems have also been discussed. The subsystems used in the DCS, hardware, and software components are elaborated. The functional components are further discussed individually for the components and the topologies of the DCS along with the engineering guidelines for the implementation are also presented. Various subsystems used in industrial automation with DCS as the central system are outlined and the details of such systems are explained. The functional components on the DCS explained in this topic become the basis for all the future systems and for adoption of these technologies. Applications of DCS are briefly introduced to give an idea to the reader about the wide usage of DCS. Finally, some pointers to help the users choose between DCS and PLC are discussed briefly.

Keywords:
PLC, direct digital control, central control, networked systems, hardware, architectural components of the DCS, subsystem performance, reliability and availability, HART, foundation fieldbus, profibus, pneumatic communication, digital communications, hybrid communications

LEARNING OBJECTIVES

After reading this chapter, you will be able to:

1. Describe the concept of distributed control systems
2. Review the evolution of communication in distributed control systems
3. Analyze different modes of distributed control systems
4. Illustrate the architecture of distributed control systems
5. Identify the functional components of distributed control systems
6. Summarize the applications of distributed control systems

"Unity makes strength, and since we must be strong, we must also be one"
Grand Duke Friedrich von Baden

11.1 CONCEPT OF DISTRIBUTED CONTROL SYSTEMS

LO 1

Describe the concept of distributed control systems

Automatic control, typically involves the transmission of signals or commands/information across different layers and the calculation of control actions for decision-making. The term DCS stands for Distributed Control System. They were used to be referred to as distributed digital control systems (DDCS) earlier, implying that all DCS are digital control systems. They use digital encoding and transmission of process information and commands. DCS are deployed today not only for all advanced control strategies but also for the low-level control loops.

As the name suggests, the control is distributed in a plant; DCS has evolved with the main intention of avoiding failure of a process/plant or part of it due to failure of a single controller. Therefore, on a higher level a DCS is a superset on plant control having PLCs, controllers specific to DCS, field instruments, control, SCADA, protocols, supervisory systems under it. A detailed explanation of components and architecture is given in the subsequent sections of this chapter.

DCS controllers are distributed across the plant and they communicate amongst themselves and with operator terminals, supervisor terminals to carry out all necessary control functions for a large plant/process. The scope of control is limited to the part of the plant it is distributed in. DCS is most suited for a plant involving large number of continuous control loops, special control functions, process variables, alarms, etc. DCS architectures are generally similar in the way they are designed and laid out. Operator consoles are connected to controllers housed in control cubicles through a digital, fast, high integrity communications system. The control is distributed by the powerful and secure communication system. The process inputs are connected to the controllers directly or through IO bus systems such as Profibus, foundation fieldbus, etc. Some systems also use proprietary fieldbus systems. With advancing technologies, DCS has rapidly expanded their capabilities. The DCS available today can perform very advanced control functions, along with powerful recording, totalizing, mathematical calculations, and decision-making functions. The DCS can also be customized to carry out special functions as mentioned by the user. An essential feature of modern day DCS is the integration with ERP and IT systems through exchange of various pieces of information.

To understand DCS, it is a good idea to review the evolution of control systems. This includes hardware elements, system implementation philosophies and the drivers behind this evolution. This helps in understanding how process control, information flow, and decision-making has evolved over the years.

Checkpoint

✦✦✦ 1. Explain the way a DCS performs transmission of process information and commands.

✦ 2. Explain how DCS has evolved with the main intention of avoiding failure of a process/plant or part of it due to failure of a single controller.

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11.2 COMMUNICATION IN DISTRIBUTED CONTROL SYSTEMS

LO 2

Review the evolution of communication in distributed control systems

As discussed in the previous section, communication is the key subject on the evolution of the control systems in the industrial automation. Let us review the evolution of the communication subsystems in the DCS.

11.2.1 Pneumatic Communications

Earliest implementations of automatic control systems involved pneumatic transmission of signals. They used compressed air as the medium for signal transmission and actuation. Actual control commands were computed using elements such as springs and bellows. Plants used local, pneumatic controllers, which were large mechanical structures. These later became miniaturized and centralized onto control panels and consoles. The principles of pneumatic controls are beyond the scope of this book.

A pneumatic controller has a high margin for safety and since it is explosion proof it could be used in hazardous environments. However, they have slow response and are susceptible to interference. The pneumatic signals range from 3 psi to 20 psi. The 3 psi represents the lower range limit (LRL) and 15 psi represents the upper range limit (URL).

11.2.2 Electronic Analog Communications

Over a period of time, electronic analog control was introduced. In these systems electrical signals were used as a means for communication. They are significantly different from their predecessors where in pneumatic signals were used in mechanical controllers. Electrical signals to pressure signals converter (E/P transducers or I/P converters) and pressure to electrical (P/E transducers or P/I converters) are used to transmit signals to enable coexistence of

Note: ✦ Level 1 & Level 2 category
✦✦ Level 3 & Level 4 category
✦✦✦ Level 5 & Level 6 category

pneumatic and electrical signals. Analog signals have a weakness as they are susceptible to contamination from stray fields leading to degradation in signal quality over long distances.

The analog communication is standardized at 4–20 mA current signals. The signals are carried in a pair of copper wires and if the current passing through them is 4 mA, it means the process variable is at LRV and if the current is at 20 mA then the signal is carrying a process variable which is at URL. Other common standard electrical signals include the 1–5 V signal and the pulse output.

11.2.3 Digital Communication

In this mode, the transmission medium is still an electrical signal, but the signals are transmitted in binary form. Digital signals are separate levels or values that are combined in specific ways to represent process variables and carry diagnostic information. The method of digital communication is referred as a protocol where the transmission used a proprietary means or an open standard based communication methods. The proprietary methods are property of the company that developed it and needs to pay the license for usage or their permission to use in the products. Open protocols such as HART®, foundation fieldbus®, Profibus®, Modbus®, etc., which are standard based and are governed by nonprofit organizations. Digital signals are far less sensitive to noise. In digital signaling, we look for two levels of signals (the two states of digital signal either 1 or 0), magnitude of the signals is expressed as a combination of 1 and 0 corresponding to the magnitude expressed as a binary number. Therefore, the impact of noise is reduced compared to an analog signal. The digital signals are used by the device directly which is equipped with microprocessors. These devices are flexible as they allow programming to function as per the user needs. The devices also get additional processing power and can process most complex logics in the device itself. The limitation is on the computing power of the computer, how many computations it can perform in a given unit of time. In some cases, if the processing in a single device is not possible or not economical, then multiple devices connected in the networks are used to execute the function as a collection of devices.

The sensors produce the electrical signals for the measurements and these signals are converted to digital format for processing and then back to analog for communication with the host systems. The host systems again convert the analog signals to digital for further processing. It is possible to implement many sophisticated control strategies at very high speeds with the development of digital implementation systems on which DCS is based.

For answers to checkpoint, scan the QR code

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Checkpoint

✦✦✦ **1.** Why a pneumatic communication is advantageous in safety hazardous applications?

✦✦✦ **2.** What is the common industry standard pneumatic signal range?

✦ **3.** What is the most common standard electrical signal with which a transmitter sends a small current through a set of wires?

11.3 DIFFERENT MODES OF DIGITAL CONTROL SYSTEMS

LO 3
Analyze different modes of distributed control systems

Computer control is usually carried out in following modes:

- Direct digital control (DDC)
- Supervisory control
- Hierarchical computer control system

11.3.1 Direct Digital Control

In DDC, a digital computer develops control signals that directly operate the control devices. A single computer digitally performs all signal processing, indication, and control functions, and therefore the name "direct digital control". Initially computers were very large and housed in large buildings with substantial environment controls. As the electronics evolved, and MSI (medium scale integration) and LSI (large scale integration) integrated circuits (ICs) became available, powerful, and relatively small mini computers became a reality. These minicomputers were first deployed to realize DDC (Figure 11.1). Therefore, the cycle of control process is:

1. The system performs input/output (I/O) scan and takes the input from controller to system

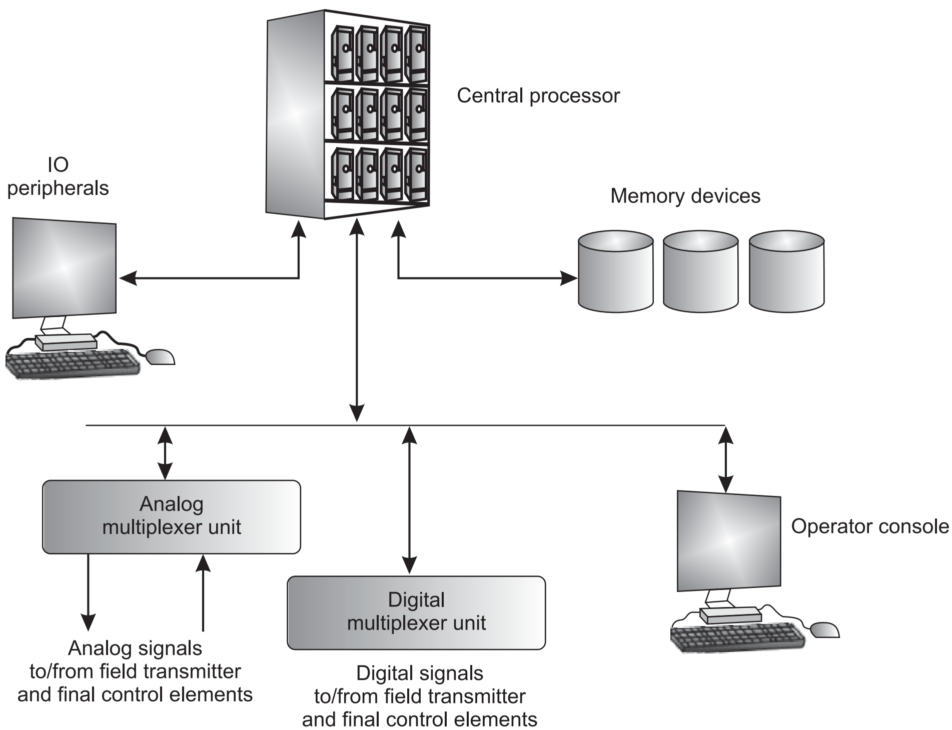

Figure 11.1: Architecture of DDC

2. The system has specialized software which is capable of processing the signal and as per the algorithm defined in the system
3. The control is given to the destined output or set point or any chosen destiny. This control logic generally holds true for any of the controls however, the mechanism of scanning the IO and processing the signal and sending it back may differ.

11.3.3.1 Disadvantages of DDC

The following are some of the disadvantages of the direct digital control:

- **Centralized control**: A single central processor is used to perform following tasks necessary for control:
  - I/O scanning
  - Data logging
  - Control execution
  - Alarm generation
  - Database update
  - Serving operator display updates
  - Periodic and on-demand report generation
  - Serve peripherals such as printers and recorders
  - Process optimization
- It is costly and complex, and there is a difficulty in troubleshooting.
- Creating customized software for advanced process control and optimization was cumbersome. In addition, DDC systems support software systems (compilers) used for configuration and engineering functions. CPU memory requirements and management were challenges.
- Poor system reliability and performance: Single failure is catastrophic to plant control, with no provision of redundancy in DDCS.

11.3.2 Supervisory Control

In a supervisory control, a set point to the analog controllers are sent from the application software in digital computers. This is described in the block diagram in Figure 11.2. The inputs are sent to the computer and the control outputs are sent from the computer to the actuators such as control valves. The process continues in a time known as scan time which is defined by the sampling time. In supervisory control, the input signals and instrumentation are interfaced to the supervisory controllers' computer through an interfacing hardware. SCADA provides systems to monitor the process variables that mimic the process. The operator station provides features for process display, alarms, and history.

11.3.2.1 Advantages of Supervisory Control

The following are the advantages of supervisory control:

- In supervisory control, the primary control still be executed by the analog control where only the set point adjustments are done at the supervisory computer. In this way the computer is not used for time critical control functions and hence is not time

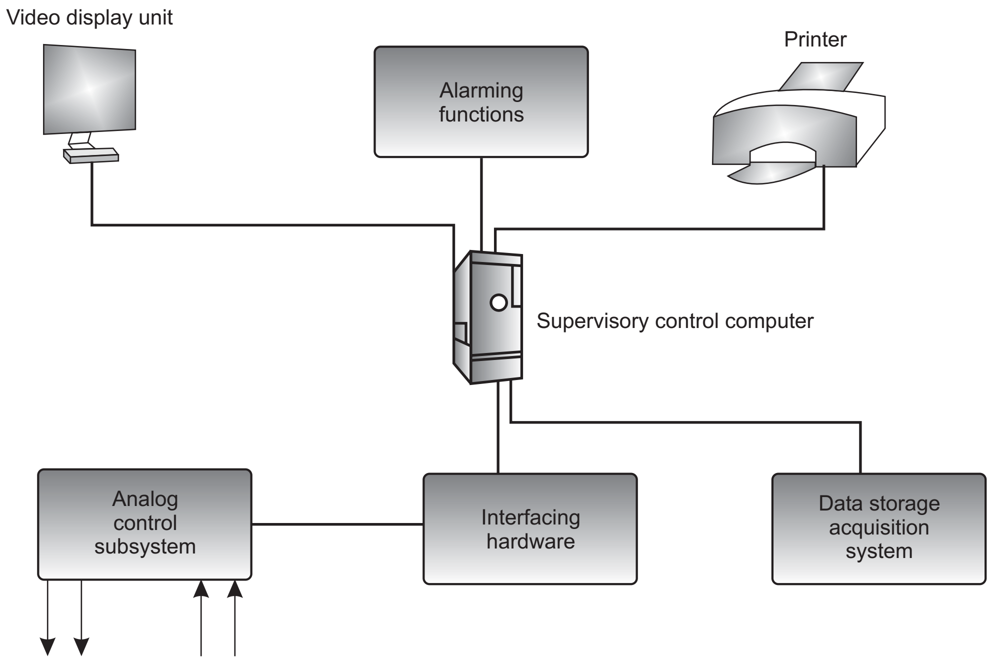

Figure 11.2: Architecture of supervisory control

intensive and can be used for functions which are computation intensive such as process optimization and plant management functions.

- Sometimes the analog controllers added to the direct digital controller add reliability to the overall systems.
- Control algorithms, which provide the set point to the analog control subsystem, accommodate higher complexity.

11.3.2.2 Disadvantages of Supervisory Control

The following are some of the disadvantages of supervisory control:

- Extensive wiring is required between the analog controllers and the supervisory computer, and between other instrumentation and the computer system.
- Interfacing equipment from multiple vendors (interfacing one vendor's computer system to another vendor's analog instrumentation) is difficult.
- Supervisory control is costlier than DDC.

All vendors who later started offering DCS offered both DDC and supervisory control options. In the earlier versions, both versions coexisted with the DCS. A lot of the current DCS control technologies had their origins in DDC and supervisory control systems. However, DDC is rarely used in current industrial automation scenarios.

Therefore, the fundamental difference between DDC and supervisory control is explained as follows. In DDC, the computer directly operates on the controller output directly. Therefore while DDC is controlling plants, controllers are taking the values from computers that are not too smart and just accept the inputs and respond accordingly. When supervisory controls have evolved, field instruments have also evolved and they have become smarter to have certain level of local control and thereby reducing the load on monitoring computer. Hence, by just providing the set point, controller is smart enough to regulate the process accordingly and computer purpose has shifted from core control to mimic and partly control the controller.

11.3.3 Hierarchical Computer Control System

In this system, multiple processors and systems are connected in a network within a limited geography, such as plants, and all of them work for common purposes such as monitoring, control and optimization, information storage, etc. These are typically applied in large refineries or power plants and fertilizer plants, etc. A representative depiction of hierarchical computer control system is shown in Figure 11.3. The understanding on the hierarchical control becomes easy once we know the operations of the plants or industrial facilities. These systems follow a bottom-up approach in design and functionality. The level of access to the control system increases from operator to supervisor to engineer to manager. The role of each person is defined as follows:

- **Operators** are normally people who are confined to a specific location in a plant and have limited access to the allocated area. This is mostly limited to one or two control panels per plant. They do not have much control over the process as they can only view alarm or notifications in the system and change the set point of few loops based on the instructions given by people above them.
- **Supervisors** have control over few more areas and have slightly better privileges to perform few basic operations and control limited loops.
- **Engineers** normally own part of the plant and have very good control over the loops/alarms and process.
- **Managers** have complete access of the system. They can normally over ride capabilities for control. Managers have the capability to utilize the system's data for decision-making. For example, a manager can use the data of how the process variable change of a few loops has impacted the product quality, and then instruct people to change the parameters for better outcome; typically this is done by usage of sophisticated analysis tools.

Information is passed up and down between primary level of process monitoring and control, through supervisory levels, to decision making/top management level.

The computer network architecture usually parallels the organizational structure of a company itself with hierarchical systems primary computers providing direct control of process and this could be a combination of DDC, supervisory control or microcontroller-based controllers.

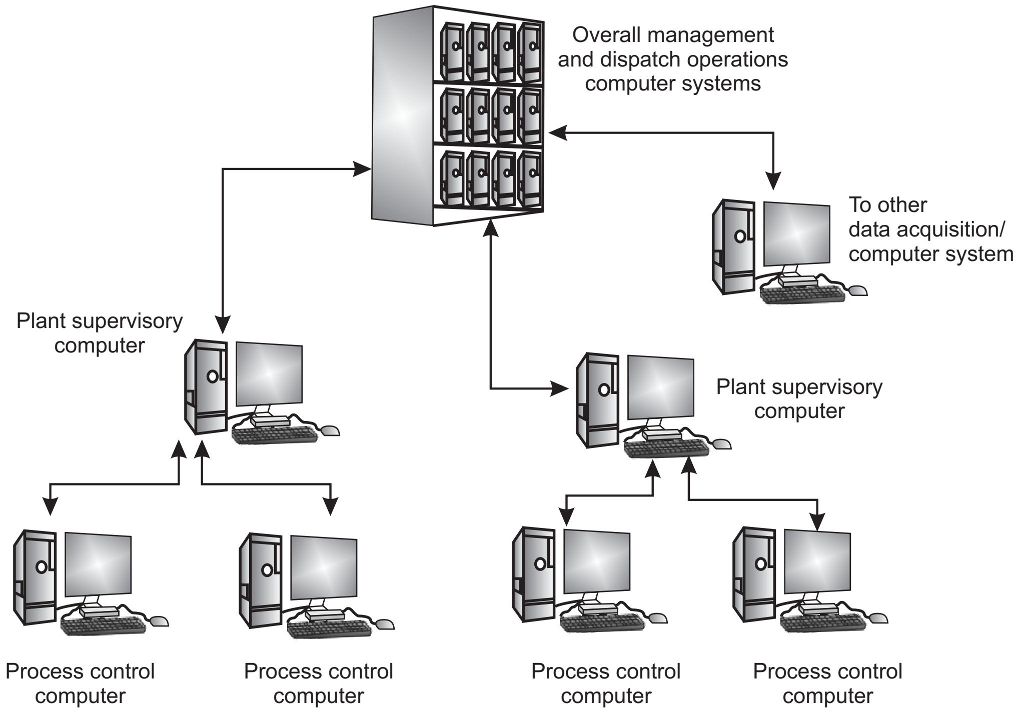

Figure 11.3: Architecture of hierarchical computer control

Checkpoint

✦✦✦ **1.** What are the three key process steps that take place in direct digital control?

✦✦ **2.** Name the three disadvantages of using direct digital control.

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11.4 ARCHITECTURE OF DISTRIBUTED CONTROL SYSTEM

LO 4

Illustrate the architecture of distributed control systems

With the advent of microcontrollers, individual controllers became powerful. They could execute more number of control algorithms and more complex algorithms. They could also control a larger set of control steps. It became easy to move the intelligence involved in controls to lower levels and improve the signal processing in transmitters. Powerful microcontrollers also enabled the design of faster networks. Together with microcontrollers the concept of DCS turned into a reality.

11.4.1 Programmable Logic Controllers

Programmable logic controller (PLC) was the first manifestation of a distributed controller. A PLC is specialized for process control of noncontinuous systems such as batch processes or discrete manufacturing systems that encompass equipment or control elements that operate discontinuously. A PLC is programmed to execute the desired Boolean logic and implement a sequence of operations. Therefore, a PLC is used in many instances where interlocks are required. For example, a flow control loop must not be actuated unless a pump, responsible for the flow has been turned on. In the same note, during the startup and shut down or emergency shut down of the plants, there is a definite sequence to be followed for the safety of the people and equipment. For example during the startup, the upstream flow and level must be stabilized before the motors/pumps in the downstream are started. Similarly, during shutdown, the upstream pressure must be reduced and the line pressure must be vented before shutting off the stream. These well-defined logics are generally implemented in PLC/safety systems to exercise a better control on the process.

As discussed in Chapter 9, the inputs to the PLC are a set of relays, sensors representing the state of the process or the equipment and output from the PLC are actuators and solenoids, lights such that the system can drive the process and machine to a controlled state.

Though PLCs were initially conceived to implement simple binary logic, they started using powerful microcontrollers and could therefore handle comparatively complex functions such as proportional integral derivative (PID) controls. Currently, PLCs can handle thousands of digital I/O and hundreds of analog I/O and continuous PID controls. However, PLCs lack the flexibility for expansion and reconfiguration. The choice of operator interfaces to PLC systems is also limited. The programming of the PLC is as defined in the standard and hence does not have the flexibility to programming them using higher level programming languages or implementing advanced algorithms meant for control. However, PLCs are overcoming several limitations and are today positioned for many complex control tasks.

PLCs are not typically applied in traditional continuous process plants. However for operations, such as sequencing, and interlocks, the speed and power of PLCs can be used very effectively. Where sophisticated process control strategies are needed, PLCs are a cost-effective alternative to DCS. The advancements in the PLC architectures are focused on adding more flexibility, speed of operation and ease of maintenance. The technology maturity allows it to have added process control features such as PID, feedforward, etc. With these advancements if we combine the PLC and an HMI package, it may look like DCS, except that there is mapping of the points across the systems, and single point integrity will still be missing.

PLCs and DCSs can be combined by design in a hybrid system where PLCs are connected through a link to a controller forming part of a larger DCS, or are connected directly to network of the DCS.

11.4.2 Commercial Distributed Control Systems

A DCS is defined as a system comprising of functionally and physically separate automatic process controllers, process monitoring and data logging equipment all of which are interconnected through a fast, digital network. This ensures sharing of relevant information for optimum control of the plant. In large scale manufacturing plants, there are hundreds of control loops to be monitored and controlled. For such large processes, the commercial DCS is normally the control system of choice.

The hardware and software of the DCS are quite flexible and easy to modify and configure. They are capable of handling a large number of process control loops. Modern DCSs are equipped with optional software elements for optimization, and various controls based on process models. They also come with tools for defining high-performance models.

As signified by the term “distributed”, DCS architecture enables distribution of the controllers and the operator input elements through the data highway, which connect all the different parts. Elements closest to the process transmit and receive raw data between them and the local computers while those farther away from the process exchange mostly processed data at fewer frequencies but for a wider set of consumers of the data. All data exchanged such as the presentation information for the multi-displays on various operator control panels, historical data to and from archival storage have to pass through the data highway.

Normally data in the plant is historized and archived in order to use it for business decisions and designing better performing models. The data helps in business decision making because change in the process variables can affect the production and there by affecting the revenue of business. By analyzing this data, people can understand the process dynamics and conclude if they can be optimized for getting a better performance. Normally historizing is must for archiving the data over extremely longer periods varying from months to years and it is stored in servers with very high capability and tightly integrated with DCS.

Coming back to the importance of data highway, it can be said that data highway is the backbone of the DCS system. A supervisory computer is normally at the top of the hierarchy and is responsible for performing many higher-level functions in the common DCS architecture systems which directly interact with processes, are usually less sophisticated equipment employed for low-level functions and have set of electronics which typically employ a microcontroller. One such example is an I/O module. Generally the I/O modules acquire the data from the sensors, transmitters, and perform a signal processing and engineering unit conversion. The processed information is updated to the controller in a scheduled manner using process control network. The controllers accept these information and process the advanced control algorithms.

The block set or function library is so rich and the DCSs have evolved with better speed of response. They are not only limited for the regulatory control, but also to the logical control which was traditionally managed using a PLC. A range of functions are designed into the controllers, such that the entire general plant control operation functions, whatever the type, could be carried out by the DCS. These functions include continuous control, cyclic control, logic control, motor control, batch control, etc. One key difference is in the processing speed of sequence functions. The scan times for the PLC will be in the range of 10–30 ms, based on the program and number of inputs. The scan rates of a DCS will be in the range of 100 s of milliseconds with the fastest being used in 250 ms. The speed provided in a DCS is adequate for process control applications which might be not suitable for some special applications such as compressor surge control or turbine speed control, etc. The typical industry practice is to use a PLC to do such fast control operations and these PLCs are integrated to DCS for the rest of the activities such as monitoring and control, etc.

However, it calls for using different engineering tools for the DCS and the PLC. On some DCS, the need for higher speeds is addressed with a high-speed controller and I/O cards and these provide the speed of execution necessary for special applications. These controllers come with a cost premium and are used judiciously to ensure cost-effectiveness of the solution.

Therefore, the standard elements of functionality available with DCS today are sufficient to provide an integrated control system capable of controlling most processes, either by themselves or through integration with other controllers. They are also capable of providing necessary information for the overall management of the production facility.

11.4.3 DCS Design Considerations

Any modern DCS is expected to meet the following requirements. These form the considerations during the design of the DCS.

11.4.3.1 High Reliability

Any control or hardware component failure can have devastating consequences leading to loss of life and property. So, reliability of the control system is a life-critical requirement. During manufacture, all electronic components of the DCS are subjected to extensive periods of cycling at temperatures exceeding the extremes listed in equipment specifications. This process weeds out the components that are most likely to fail. Suppliers provide redundancy in their design without which reliability is still probable. Power supplies, data highways, traffic directors, and controller electronics are important single points of failure in the system and are considered as candidates for having redundancy. The transfer between the redundant partners should be automatic and fast, such that there is no disturbance to the plant operation or to the output of the system. Sometimes it is referred as bumpless transfer. The other requirement is that alarm should be provided to the system operators on the failure such that a corrective action can be taken immediately.

11.4.3.2 High Availability

Availability is another characteristic of the DCS and is as critical as the reliability of the system. It is the ratio of mean time between the failures (MTBF) to the mean time to repair (MTTR) and MTBF. This means the system is highly reliable and if it fails then it is quick to repair the system. Since the DCS is offered in a modular fashion with multiple cards sharing the racks, or multiple racks sharing the bus, etc. It is easy to replace the modules or racks with the similar equipment and this repair does not impact the rest of the process control. In case of redundancy, this replacement does not impact the current process as well since the redundant module will take care of the counterpart being repaired. Once the repaired modules are replaced, the software tools can update the firmware and system can update the configuration from the central repository. These automated processes reduce the time to repair and hence the availability of the system will be high. All these activities do not create any disturbance to the control functions.

11.4.3.3 Low Cost

The cost in general to be considered are the initial purchase cost, the cost of implementing them in the project, maintenance costs such as maintenance contracts, spare parts, etc. Considering all these costs, DCS is a proper solution that will cost less for a plant of moderate size. This will provide the long-term goal of effective control, ease of implementation and scalability to grow the system as the plant gets expanded. The comparison is with the alternatives such as SCADA system with multiple PLCs or single-loop controllers across the plant operations etc. Any other options requires significant integration work and associated cost and mean time to repair will be high as multiple vendors has to provide the support for any downtime which is costly for services as well the loss incurred in the production either dues to loss of production or poor quality products.

11.4.3.4 High Alarm Management Capability

DCS systems must be capable of intelligent alarm management to aid in abnormal situation management. Alarm management is necessary in a manufacturing process environment using a control system, such as DCS or a system of PLCs. The large scale DCS are generally configured with hundreds of alarms on a per point basis. If there is an upset in the plant or shutdown, many alarms will come to the console which might have the same common root cause. The psychology of humans, as studied, can pay attention to a few alarms only at any given time. The automation system engineering ensures that few critical alarms only are presented to the process operators. This is a critical condition to be aware of during the emergency situations. The presented alarms should also be in an order in which the operator can quickly reach the condition which was the root cause of the disturbance. Sometimes the alarms can be listed in the order of priority so that critical actions are attended first to maintain the safety of the plant. The capabilities of alarm management in the system must go beyond the basic level of utilizing multiple alarm priority levels. It is to be noted that alarm priority itself is often dynamic. Likewise, disabling an alarm based on unit (also referred as location at times) association or suppressing audible annunciation based on priority do not meet operational requirements in a complex plant. We need dynamic, selective alarm annunciation in such cases. Most DCS are provided with an alarm management function either as a built-in package or an additional package which can filter the alarms based on the current plant conditions and allows the operator to act on critical alarms and also the alarms that cause the plant disturbance.

11.4.3.5 Scalability

In general, a PLC/SCADA based system is easy to configure and deploy. However, the complexity grows as the system becomes bigger and the cost of doing so, including the labor hours increase exponentially and if not managed well, the size of the system leads to failure of the system, meaning not meeting the objectives of the control. It also increases the risks of errors creeping into the process of engineering. It is easy to design and implement a single loop PID controller in a SCADA/PLC system and it can be done quickly. However, to design and implement the base layer control for a refinery using a SCADA/PLC system can be a daunting endeavor. One of the chief considerations in the design of the engineering tools for a DCS is that engineering time for system expansion and other changes must be considerably less. Features, such as batch updates, replication of application programs with suitable substitution, etc., are provided in the engineering tools.

11.4.3.6 Distributed Systems

A DCS has to share real-time data across a network, despite the fact that the components are geographically distributed. The need for a seamless transfer of control signals amongst the distributed controllers, the supervisory controllers, operator workstations, plant computers, etc. can never be overstated. This makes networking a major component in the DCS architecture. The objectives of a networking topology in industrial automation systems include the following:

- Enable wide distribution of the components
- Connectivity to different machines and nodes
- Reliable data gathering and sharing
- Redundant communication medium
- Deterministic transmission and receipt of data
- Sufficient speed to match the plant requirements

11.4.4 Advantages of DCS

Traditionally, DCS is seen as more expensive considering the initial purchase price, compared with PLC for similar number of points. The same is true from a production point of view—sometimes a PLC based control is good enough for the small facilities. But when the objectives of the control cross the production yield to safety, regulatory compliance and total cost of ownership, then the DCS needs to be considered. Demands on manufacturing companies have risen and the purchase price of the DCS has come down. Yet, DCSs do have advantages over PLC systems.

The DCS is architected and designed with the focus on control distributed across the geography for the plant, and operators (either in central control room or local control room) can monitor and interact with the process by connecting to the same network. It is based on the basic foundation of systemic approach to control, overall synchronization and coordination of the plant operations on a reliable and deterministic network.

The major advantages of functional distribution of hardware and software characteristic of DCS are:

- Flexibility in system design
- Ease of expansion
- Reliability
- Ease of maintenance

- Local control can be maintained even if central components fail or are degraded functionally to a substantial extent.

We then say the plant is operating as a set of "islands of automation". The architecture of the automation system based on DCS is such that there is no complete loss of production due to loss of any subsystem. Even if the data highway fails, the local control units can continue to operate the plant with no loss of production, but with some loss of functionality which can be recovered very fast and does not extend for long periods of time. This greatly enhances the availability and reliability of the system.

The control network, which is a built-in feature of data highway, is the most important component of DCS. The manufacturers of the systems will test the DCS with largest capacity and topology to ensure maximum reliability. The test will be conducted with large volumes of data transferred in relatively fast cycles which are the demanding conditions of the system. The systems are provided with redundant configuration and the networks constantly fail to see the behavior of the system during failures and its recovery mechanisms. The systems are fine tuned to manage these adverse conditions such that the highly available system is built on the commercial off-the-shelf components. The networks are provided with diagnostic capabilities that they can send an alarm to the system operator and is recorded and tracked as a process failure alarm. The control performance is another critical area in the design of DCS. Unlike PLC, where speed matters, in DCS repeatability of the control matters for the process. This quality of control is directly proportional to the quality of the product. The control library of the DCS is provided with enough algorithms which are parameter based. Using these function blocks any complex control logic can be built using the documentation available. The application engineers can build any logic using these control blocks in the library. It is more like connecting the function blocks and achieving the control, rather than creating the control from scratch by programming.

DCS system allows having a diverse set of networking options and also a flexible mode of control. For example, a loop can be configured in the system and can be operated in multiple modes such as manual/auto/supervisory, etc. In manual mode of operation, the operator can directly control the final control element whereas in an automatic mode, the set point is received from the operator while the control is exercised by PID control in DCS. In the supervisory mode, a supervisory controller sitting a level above the process controller selects the set point to the low-level controller such as PID. This mode of control is used in advanced process control where the set point is based on various conditions and inputs which are not available in the low-level controller of the DCS. The set point for the advanced controller can either be set by the operator or can be the outcome of steady state optimization.

DCS vendors also supply all of the control ware, a data historian, trend objects, business integration software, and graphics needed to run a plant as a single package that can be easily deployed on the DCS. Purpose of data historian is to historize and archive data. DCS allows only the control applications that are correctly designed and tested. In other words enough mistake proofing is built in such that proper configuration only can be downloaded and the versions of the application software can be tracked. The versions allow the users to check in the final version and do modifications on top of it in a controlled manner. If required, the same can be reverted. This becomes very significant when DCS stays deployed for longer periods and are expanded to meet changing plant requirements. Since it is designed as a single system, various tools and systems, controllers and IOs share the common data model and data model is not changed based on where it is used by the engineering and where it is viewed by the process operators. This is the reason for the DCS to have a common point name across the systems and there is no need to map the points with controllers and HMI and historians, etc.

That is a significant advantage given the integrated nature of a typical industrial automation system. DCS costs less compared to the features it provides and it provides user the option to start out at a low-level of investment. Finally, DCSs have been flexible in assimilating new technologies in hardware, firmware, and software. This provides great advantage as the systems and plants evolve over a period.

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Checkpoint

✦✦ **1.** How PLC is evolved to handle complex functions such as PID controls?

✦✦ **2.** What is a hybrid system?

✦✦✦ **3.** Define distributed control system.

✦✦ **4.** What are the different types of controls possible with DCS?

✦ **5.** What is the scan time of PLC and DCS?

✦✦ **6.** Why it is essential to perform an automatic transfer between redundant parts? Explain why the MTTR of a DCS is short?

11.5 FUNCTIONAL COMPONENTS OF DISTRIBUTED CONTROL SYSTEM

LO 5

Identify the functional components of distributed control systems

Distributed control systems are made of several components (Figure 11.4), namely:

- I/O buses
- I/O cards
- Controllers
- Control technology (control function libraries and software)
- Plant control network
- Workstations
- Operation and control software
- Plant information network
- Gateways where applicable
- Engineering/configuration software

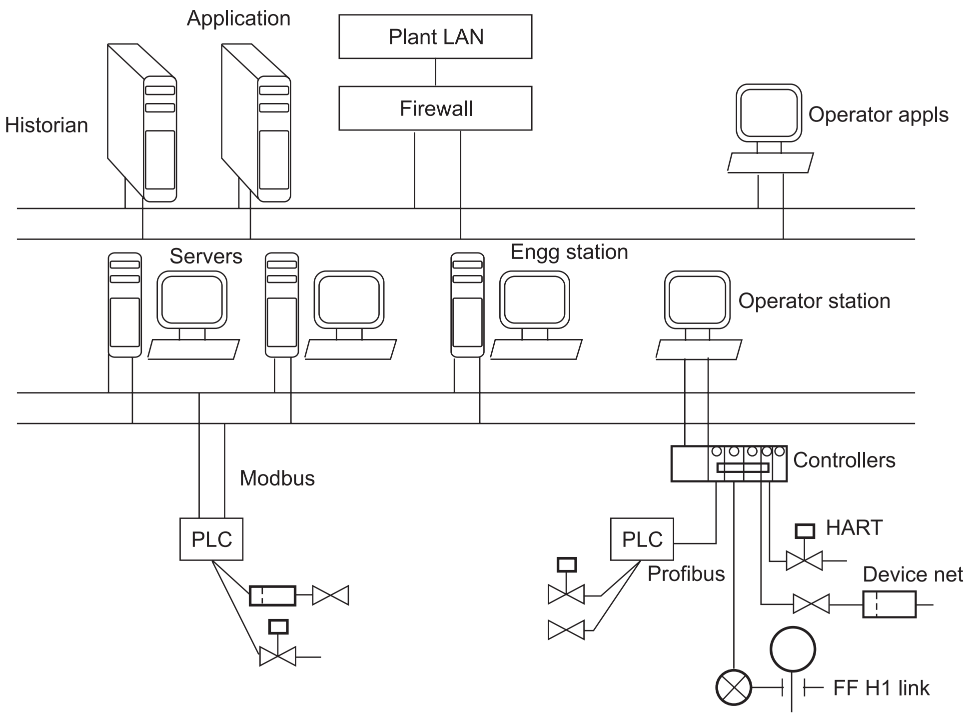

Figure 11.4: Architectural features of DCS

The controllers are connected to field devices in various ways. Majority of the field devices even today are hardwired to the controllers. They can also be connected using analog, digital, or combined analog/digital buses. Valves, valve positioners, switches, and transmitters or direct sensors, are located in the field. The smart field instruments can communicate on field sensor bus such as foundation fieldbus etc., while the signal processing, alarming and engineering unit conversions are performed locally. In case the control systems are located locally in the field where the control strategy is executed, the system is hardwired to the central controller by means of copper or fiber cables. The sensor buses such as foundation fieldbus can also send the controlling signal to the actuators directly without having necessity to be controlled from the central controllers.

I/O cards perform a variety of functions such as analog to digital conversion, conversion to engineering values; limit checking, quality tagging and so on. They also enable assignment addressed to the field signals for use by the controllers.

Controllers execute the control logic once every set interval of time, which constitutes the controller cycle time. During the engineering process, the tools ensure that the given package of control logic can be executed in a deterministic way within the cycle time of the controller.

The controllers consist of a base firmware, which enables the controllers to communicate on the network, exchange data and commands amongst themselves or with the operator and supervisory interfaces. The application programs are plant specific and are engineered to suit the plant where the DCS is being implemented. The engineering tools enable the creation and validation of the application program. The application programs are downloaded into the controllers after the validation process and are typically stored and executed from a separate and designed memory area in the controller. The information from the field devices is available to the plant control network which makes it available to the servers, workstations and historians, database servers. The same data is used for generating reports and create annunciations for the operator attentions.

The operator stations are hosted with application software packages that helps to perform a variety of operations meant for monitoring and controlling the plant. An operator may interact with the system through the displays and keyboards to change control parameters, view the current state of the process, or access and acknowledge alarms that are generated by field devices and controllers. The operator can also change the control software executing in the controllers and in some of the field devices. In some cases, the system may support process simulation for the purpose of training personnel or for testing the process control software.

Operator workstations pass on information to other workstations, which execute a variety of higher-level applications. The operator workstations and the supervisory workstations exchange data through the plant information network. The plant information network could also be part of the enterprise network, though there are substantial safeguards to ensure that unauthorized access to the networks in the realm of the control systems is entirely prevented.

Gateways can be made available on any of the networks to enable data exchange. The primary purpose of a gateway is to support integration of different protocols or a standard-based device to communicate with mainline DCS and its controllers. For example, if a DCS controller has to communicate with OPC/foundation fieldbus or Profibus they normally reach the device operating on above standards/protocols through a gateway only. In the abovementioned example, OPC is a standard where others are protocols. Normally, OPC is a de-facto standard for communicating across DCS from various vendors. They could alternatively use to share data from the DCS with other plant/business systems. Gateways by design allow two-way data transfer.

DCS is always sold as packages because the parts function together as a system. Since all the subsystems share a common bus, even if there is change in the control application of one system, does not require reengineering or rewiring in the same system or other systems. However, standards have enabled interoperability between components from different vendors. DCS users are no longer tied to a single vendor. It is not uncommon to come across a plant with field devices from Rosemount®, operator software from Foxboro®, controllers from Yokogawa®, and advanced applications from Honeywell® with network infrastructure provided by Cisco®.

In this concept animation, various components of a distributed control system (DCS) including the networks, operator stations, engineering stations, controllers, and inputs and outputs are presented. It also explains the DCS as used in most systems in today's industries.

For process-related video, scan the QR code
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The major features of any DCS comprise of the following:

- System configuration
- Communications
- Control
- Alarms and events
- Diagnostics
- Redundancy
- Historical data
- Security
- Integration

11.5.1 System Configuration/Programming

Every DCS controller is a computer, with limited peripherals of a computer system. The controllers therefore need instructions to execute the control actions. Two distinct terms must be distinguished here—programming and configuration. Every controller comes with inbuilt firmware. In addition, an application program is downloaded into another partition of the controller memory and this is called the application program. In some cases, manufacturers provide the application programs also and provide a way to set certain parameters to make the generic logic work in a particular plant. For example, the DCS manufacturer may provide an application program for control of a set of three compressors. The same vendor may sell the same controller with another application program for control of a set of pumps. At the field, it is just a matter of defining the minimum and maximum pressures, the number, and type of relay contacts to be operated and the measurement range for field signals. This process is called configuration. Consider the case where the DCS vendor provides the controller with the application program memory in a blank state. The user of the DCS can write his own application program to cater to his specific logic. This process is termed programming.

Engineering tools provide facilities to configure and program controllers, depending on the applications. Licensing mechanisms may control the actual features. The engineering tools also hide the complexities of programming the microcontrollers (which would have their own specific instruction sets) by providing a common programming language with suitable user interfaces. Therefore, application and process engineers mostly describe the control logic graphically, which are translated into the instruction set of the microcontrollers.

The control strategy constitutes a combination of blocks connected together. The strategy also constitutes the sequential function charts with a view of the equipment and units represented in a hierarchical manner. The SFC can act on the inputs that can also be acted on by the control modules or control strategies. The function blocks also provide outputs to other function blocks and/or physical I/O within the control scheme. Normally, the DCS vendor provides the set of function blocks as libraries. This overcomes the need for any special software language to program the microprocessors used in the system. In addition, the users themselves can create their own function blocks by combining the pre-defined function blocks to more complex library of functions. The function blocks are pre-tested by DCS vendor and this enables a DCS to be applied to any plant quickly, cutting down the debugging required on programmed software.

The engineering tools invariably follow ISO standards on the types of function blocks, the representation of the blocks and the accepted form of interconnection. The programmed control schemes are stored as files/control programs in a configuration database. Using the engineering tool users can download these strategies via the control network to distributed controllers, consoles, and devices.

In addition to the configuration of the software, there is an element of hardware configuration also. This involves activities such as setting the addresses of the I/O modules and controllers. Sometimes depending upon the type of connections, different links might have to be connected to adopt the same card to suit different field interfaces. While the hardware configuration needs the actual hardware in the field, software programming can be carried out separately and downloaded to the controllers at the plant.

The configuration/engineering application also allows a designer to create or change operator interfaces, such as plant schematics, process control diagrams viewed on the operator displays through a viewing application. These diagrams enable the operator to change settings within the process control system.

The DCS systems can be reconfigured without a need to switch off or take the system away from the control. Some parts of the system may require a downtime but will be minimum compared to other downtimes in the plants. The precautions and checklists will be available from the suppliers such that the downtime is avoided while performing changes in the DCS. This facility can be of particular use in applications where the process is continuous and shutdown maintenance periods are short or limited.

11.5.2 Communication

DCS systems vary in size from very small to very large, depending on the size and complexity of the plant being controlled. Today's DCS are available with services enabled to view the plant outside in internet applications and are supported with open protocols such as OPC to share the information with third party packages.

The communication infrastructure including control network supports the following as a minimum in all the systems:

- Connections between nodes in the system
- Unsolicited communications for real-time data changes in the process

- Synchronous and asynchronous read/writes
- Configuration downloads to nodes, controllers and devices
- Auto-sensing of workstations, controllers, I/O cards, devices
- Diagnostics of system components and control strategies
- Online upgrades of system in operation
- Hot/warm/cold restart of control models from the previous backup or a recent checkpoint
- Secure information exchange with external systems and controlled exchange with the internal systems in different networks.
- Alarms and events for attention to the operator and also for audit purpose. The alarms and events are recorded not only for process, but also for the system and its health. Normally devices and equipment in the system generate the device alerts
- Time synchronization across nodes, devices, and I/O
- Deterministic communication of plant data so that data exchange is guaranteed in the system.

The data highway is the communication device that enables a DCS to distribute the controlling function throughout a large plant area. The length of the data highway varies, depending on the speed of transmission, supported bandwidth, and physical characteristics of the medium of the data highway. However, data highways are designed as segments with suitable bridges/extenders connecting segments so that the length of a segment of data highway is not a limiting factor. The most popular physical medium is ethernet CAT5 cable. However, several suppliers still offer communication over twisted and shielded coaxial cables. Several modern DCS implement the data highway using fiber optic cables. Some of them have also successfully incorporated wireless exchange of data.

Optic fiber cables are used most commonly for point-to-point connection between switches and hubs. Optical fiber is used if the distance to communicate is larger than a traditional copper cable can handle. This medium provides advantages such that it eliminates the interference from other sources on the signal quality and avoids ground loops. These are safe to operate in hazardous areas. Optical fiber can carry more information than copper conductors can. Optical fiber is inert to most chemicals, is lighter and easier to handle than coaxial cable. However, special equipment and skilled labor is needed to terminate and connect optical fibers.

11.5.3 Control

The DCS is connected to field sensors and actuators and commonly uses set point control to control the process in the plant. Common example is a set point control loop consisting of a pressure sensor, controller, and control valve. Through transmitted and signal conditioning I/O cards pressure or flow measurements are transmitted to the controller. If the measured value reaches certain value above the set point entered by the operator, then action is originated from the controller in a direction to correct the measurement. The action signals are transmitted to the actuators such as valves or drives which are connected to the process. Thousands of such loops are deployed in a refinery for controlling various such loops. The application need not be limited to process applications in refinery, but virtually to all the processes such as drum level in a boiler, paper quality in pulp process, etc.

DCS constitutes a combination of subsystems such as I/O modules, controllers distributed functionally and geographically and can still act on a single loop over the network without the loss of integrity of the loop. The control can be extended to a simple PID to sequential control to most advanced combination loops or neural and fuzzy controllers. In this case the I/O modules can be installed close to the field and the IO network connects to the controller. Sometimes the controller is installed in the field control station and participates in the main data highway or process control network of the plant.

11.5.4 Alarms and Events

A critical part of the DCS is the integrated alarms and events processing subsystem. Using the engineering software, notifications can be configured for significant system states. The states can be monitored and acknowledged. Priorities may also be associated to the events, and events in the plant can be monitored. Events are recorded as a change in state of the process at a specific time for a specific unit. Sometimes events are not meant for initiating action but only to save the activity or status. The events are represented with their current status and are recorded even if the condition is removed. When an operator has seen the message and acknowledges the same, the event enters the acknowledged state.

Event types can be defined in DCS. For various states of alarms, it is possible to configure the text as instructions to the operator. The attributes of such an event can be the date and time, priority of the alarm, the equipment to which it is associated, and number of times it occurred in the previous hours, etc.

Device and equipment alerts are supported by DCS systems. Alerts can have priorities assigned to them like process alarms, and convey information related to the condition that caused them. Unlike process alarms, DCS hardware or devices and equipment external to the DCS generate the alerts. To the operators in alarm banners and summaries, these alarms and alerts are presented. Operators can observe and respond to conditions using these particular interfaces.

Operators can navigate to a specific display in which additional details can be viewed and appropriate actions can be taken. Operators can also suppress and filter alarms.

To temporarily remove alarms from the system, alarm suppression is used for which some condition exist that the operator knows about (a piece of equipment is shut down or is under maintenance). Alarm filtering provides a way for the operator to view collections of alarms and efficiently manage alarms when there is a flood of alarm messages and to suppress several alarms which result as a consequence of a basic alarm condition.

11.5.5 Diagnostics

An important feature of DCS is integrated diagnostics. The diagnostics comprise of hardware, redundancy, communications, control, and the software that makes DCS. Usually a system alarm is reported on the failure or malfunction of any of these components and the necessary log messages are recorded.

The tests built into the control room equipment are designed to analyze a high proportion of all failures, diagnose problem and isolate the replaceable unit without intervention by the operator or a maintenance technician while the system is on line and controlling the process.

11.5.6 Redundancy

Redundancy is an important requirement for any critical process control application using DCS. Several DCS redundancies built at the level of communication media, controllers, I/O cards, and I/O communications/connections. In critical applications where the failure of the loop is associated with significant loss of control and loss of production, safety and environmental pollution, it is possible to have a redundant system. In such systems where the safety integrity levels are high, multiple inputs feed the signals such as two out of three or three out of four, etc., to decide the faulty measurement. In such voting only the critical and right ones are considered and rest are discarded. Sometimes the redundancy is planned where an upgrade to the plant is necessary without a downtime to the process. In either case, safety of the plant, downtime and associated cost of loss of production and cost of purchasing the redundancy needs to be evaluated.

11.5.7 Historical Data

The ability to collect batch, continuous, and event data is done by the DCS. For the storage of historical data, a central defined history database is made available. The value of attributes like alarm or any control strategy, alert, or process condition can be recorded in database along with its status. As an integrated feature of the system in modern control systems, the data values are collected. In some cases down to a resolution of few milliseconds, events are also collected and time-stamped at their source. In a time-ordered fashion, users and layered applications can retrieve the batch, continuous, and event data. Without leaving behind an audit trail, ensuing security; values cannot be edited. The engineering tools and operator tools enable selection of points for history storage.

11.5.8 Security

In process control, security is very essential. DCS system should be able to limit access to different parts of the control system to authorized people. By establishing user, plant area, and workstation this can be achieved. Before applications are allowed access into the system layered applications have to establish a session. In addition to the normal physical security measures, there are several aspects to security:

- **Authentication**: Password-protected user accounts are created for access to the DCS for human users and layered application users.
- **User:** The operators or engineers or technicians of the DCS are provided with an account to gain access to the system. Every user has a unique name and definite area of control or scope of control associated to the same. To start a DCS session, all user accounts should have a password, which must be provided along with account name.

- **Plant area security**: The user account can be controlled from the administrator where the access can be permitted or denied or changed based on the role and responsibility of a particular individual.

The user account can also be denied access to any of the plant areas. Sometimes the access can be restricted at run time, which means while the plant is operational such configuration changes to the system may be limited to specific site and unit of the plants. The user account can be provided or denied access to view or modify user account and privilege information. In some machines, authorization can be enabled as an additional security mechanism.

Users in some cases need to confirm the password for changing certain parameters, starting/stopping a batch. This is in addition to the password used for logging on to the system.

In addition, access to specific areas of the plant or specific field equipment is governed by permissions form operations personnel and interlocks are created in the control room to ensure safety of plant personnel.

11.5.9 Integration

To provide a coordinated operation, for any additional plant units added to the existing plants the information needs to be exchanged between these two units. This is essential for coordinated operations in a manner similar to all the units. If the existing DCS is extended to new units, the sharing of the information becomes seamless with no additional integration efforts. To integrate systems several techniques are used. For accessing information within a control system, the OPC Foundation has defined an industry standard. Therefore, many control systems offer OPC server capability in workstations designed for interfacing to the plant local area network (LAN). Several DCS also communicate using several other hardware connections (RS232, RS485, USB etc.) and software protocols (Modbus, Devicenet, etc.) including hardwired serial and parallel communication lines.

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Checkpoint

✦ 1. What is the purpose of IO cards in a DCS?

✦✦ 2. What is the purpose of an engineering tool in DCS?

✦✦✦ 3. Which network is used to exchange the information between different workstations such as operator workstation and supervisor workstation?

✦✦ 4. What is the primary role of a gateway in DCS?

✦✦ 5. List the three major functions of communication infrastructure in control network.

11.6 DCS AND PLC DIFFERENCES AND CONVERGENCE

LO 6
Summarize the applications of distributed control systems

Process manufacturers are facing challenges in selecting the best technology due to the union of PLC and DCS. To make the assessment successful, one must start by developing a clear picture of the requirements of application and the needs of the engineering, maintenance, and operations. The major differences between the systems is represented in Table 11.1.

Table 11.1: Difference between PLC and DCS systems

PLC	*DCS*
Local control	Distributed over entire plant
Less network intensive	Highly network intensive, mostly operates over LAN
Faster scan rate due to which control is faster	Scan rate varies across controller which DCS hosts
Needs to be integrated with SCADA separately	SCADA/control protocols are integral part
PLCs are capable of being standalone controllers	DCS can have its own controller, PLCs can be part of DCS network
Very less computing/storage and control capabilities. Control is limited especially with respect to regulatory control	Extremely high computing/storage and control capabilities
Limited capability of providing business decisions	Capable of providing data for business decision making

11.6.1 Selecting the "Right" Automation Technology

In the current global markets with products from different parts of the world, the process industries are facing challenges in maintaining productivity at low cost and high quality. In order to achieve these goals, the right automation strategy is key factor which can help increase the yield and reduce the variability in product and hence increase in the cost. The importance of the strategy is much more critical than the cost of DCS itself. In this way, having the right technology and a supplier to support, the plant can quickly respond to the dynamic market situations and can maintain the competitive advantage, the total cost of ownership or life cycle cost of the system can be minimized, develop a system that can be maintained, supported and upgraded over the life of the plant and meet the future plans of the plants.

11.6.2 Type of Process

It is fundamental to determine the requirements of the application to make a best fit automation system. The system selection is influenced by the way a product is manufactured, the amount of performance needed along with any physical limitations in the process. The applications in the manufacturing industries which involve machines and movement of materials from one place to another demand a PLC-based automation system. As the things move through the manufacturing line, the operator can usually monitor the "things" visually. The process is run based on a well-defined logic and speed of the execution is treated as yield of the production line. Such requirements calls for a PLC with an HMI installed for the operator to view the line.

Another process, different from the one mentioned above, is process automation where the materials are processed to create a different material. Usually the process includes some reactions, heat transfers, distillations, fractionations, and movement of liquids from one tank to another. Different units or processes are connected by means of pipes and pressure, and temperature needs to be maintained to keep the physical properties of the material as desired. The process sometimes is hazardous and flammable for the electrical ignitions. Such process-control applications involve a large number of controllers installed with PID controllers and other advanced control systems. The response times are faster for the process that require but more than a PLC can do. But complex algorithms are programmed in the DCS using the function block programming and are flexible for changes as and when required. These types of process are automated using a DCS where the analog input and outputs are high and size of the plant is large. Sometimes the sequential control needs of the processes such as batch control in a pharma needs more complex logic and flexibility to manage the units, recipes and batches. These applications call for DCS for the automation.

11.6.3 Value of the Product and the Cost of Downtime

PLCs are used for independent machines, which manufacture a product independently and cost of downtime is less with less or no damage to the equipment. In case, cost of downtime is high and cost of lost product is high, DCS becomes the choice due to inherent characteristics of reliability and availability. Sometimes the loss of production and associated damage to the raw materials and cost of waste product, and its impact on the environment becomes too high to manage. Sometimes a refinery operated by a DCS if produces a wrong product if a bad level is not managed well, the amount of loss to the refinery is too huge compared to the cost of the system itself.

In case of a bottling plant where it is run for few hours of the day to produce or clean the bottles and is kept for maintenance for the rest of the time can be automated with PLC, where the impact is less on the machines and there is no need to invest on large controllers.

In case of the process applications which are required to operate throughout the year, the failure in the system can cause the downtime and loss of production but much more than this are the safety systems which are required to be in place for such situations. For example, the flare control in the refinery needs to run continually to burn the excess gas in the system irrespective of the plant running and downtime conditions. Similarly, in the case of a power plant, the furnace in the boiler needs to be managed for the time even if there is a downtime in the power generation process.

11.6.4 Central Controller

The controller (PLC) is the heart of a factory automation control system that contains all of the logic to propel the product through the assembly line. A PC-based station that provides the operator with supplemental or exception data is the HMI (an on-machine panel). Normally for factory automation applications the requirement is operational information that results from data analysis which is the driving demand for more sophisticated HMI.

HMI is considered by most to be the heart of the system in process automation, where the environment can be volatile and dangerous, and where operators cannot see the actual product. In such situations, the operator console which is hosted with application software package for monitoring the process is used to know the state of the process, such as pressures and temperatures in the pipes, levels in the tanks, etc.

11.6.5 Operator Actions

In the PLC environment, the operator main part is to handle exemptions. Status updates and exception alarms help the operator in knowing the changes in the process, which in most cases can run lights out.

The process is monitored and managed by an operator who makes the decision and interact with the process as required. It is the operator's knowledge that is key for the success of the process operations for efficiency. The changes in the feedstock or modifications to the existing vessels calls for a change in the operator actions such as different set points, open, close of valves or manual actions to move the produce from tank to tank. The HMI provides live values, trends, faceplates and work flow management to deal with different activities to deal with the production goals. If an HMI fails, the modern architectures provides means for having provisions to handle the operations from other HMIs. If such provisions are not made, then a failure of an HMI calls for a forced shut down of the plant operations. This is the primary reason for an upfront buy-in for the screen designs and navigation philosophy.

11.6.6 System Performance

The speed of control execution is a key metric to differentiate the products. As discussed earlier, the PLCs are designed for high-speed execution of the logic in a sequential manner. The PLCs can be used for applications that require fast scan rates such as 10 ms or less which include reading the input, executing the logic and writing the values in the output devices, etc. Fast scan is necessary for some applications such as purge control in a compressor. If the system cannot measure the surge within the duration, it leads to failure of the compressor. In case of DCS, the fast execution is not required for regulatory control. The most widely used scan rates range from 100 ms to 500 ms. For the processes that do not respond fast, if the speed of execution is too high, then it leads to a wear and tear and noise introduced by the valves on the process. These outcomes lead to an early maintenance and harmful disturbance to the process.

The additional reliability due to the redundancy and availability due to modular installation makes DCS a choice for selection.

PLCs can be used in applications where offline configurations and engineering changes do not create any impact on the machine. On the other hand, the DCS is not meant for doing changes with a shutdown options. The processes such as blast furnace are expected to run on a continuous basis and changes to the system are done without impacting the process. The

DCS are originally designed to handle the analog control and they continue to mature in this industry while improving the libraries for logic execution. Similarly, PLCs are designed for discrete control while maturing now to handle the PID controls, cascade control, ration and feed forward, etc.

11.6.7 Customization

The extent of customization required for each type of controllers are different based on the application.

Since a PLC is a general purpose controller, it is customized for different applications. The applications may constitute some routines and functions and a combination of them attached to the logic. The system integrators will use the PLC for a machine with one application today say in an automobile application for one type of car today and change the program for the other where there is a change in the line. In the case of DCS, the library contains the rich set of algorithms and application engineer can connect them in a group to meet the needs. Sometimes the prebuilt custom blocks, templates for building the application code. As discussed earlier, in the case of DCS, the concentration is to build the application that is to control in a reliable way and the process parameters should be repeatable for the same set of inputs.

11.6.8 Engineering

The automation engineers for PLC needs tools to program the PLC. Most generally since they operate on small systems, the engineer can directly start working on the program with little information on the inputs and outputs and the logic expected from the machine. This is also treated as bottom-up approach and is suitable for small applications. The DCS systems on the other side need a top-down approach with all the details upfront before the start. This helps to reduce the cost of developing the application software and reduce problems in the site while commissioning. The engineers use the standard ways to program the system such that the logic and applications are proven and there are no surprises and costly rework. Process engineers and DCS engineers always use tested libraries and defined logics for the process operations to drive repeatability and save time. On the other hand a PLC engineer can have flexibility to have his own programs meant for different applications as required and can include the interlocking of control of motors and drives. The function block program in DCS can use the alarm functionality to drive the safety and improving the operator alerting systems.

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Checkpoint

✦✦✦ 1. Which type of controller is better suited for a simple batch application?

✦✦✦ 2. What is the expectation out of a plant operator using DCS system?

Summary

LO 1: Describe the concept of distributed control systems

- The term DCS stands for distributed control system. They were used to be referred to as distributed digital control systems (DDCS) earlier, implying that all DCS are digital control systems. They use digital encoding and transmission of process information and commands.
- DCS has evolved with the main intention of avoiding failure of a process/plant or part of it due to failure of a single controller.
- DCS controllers are distributed across the plant and they communicate amongst themselves and with operator terminals, supervisor terminals to carry out all necessary control functions for a large plant/process.
- An essential feature of modern day DCS is the integration with ERP and IT systems through exchange of various pieces of information.

LO 2: Review the evolution of communication in distributed control systems

- A pneumatic controller has a high margin for safety and since it is explosion proof it could be used in hazardous environments.
- The common industry standard pneumatic signal range is 3–15 psig where 3 psig corresponds to the LRV and the 15 psig corresponds to the URV.
- The most common standard electrical signal is the 4–20 mA current signals. With this signal, a transmitter sends a small current through a set of wires.
- Digital signals are discrete levels or values that are combined in specific ways to represent process variables and also carry diagnostic information.

LO 3: Analyze different modes of distributed control systems

- The cycle of control process is:
  - the system performs IO scan and takes the input from controller to system;
  - the system has specialized software which is capable of processing the signal and as per the algorithm defined in the system; and
  - the control is given to the destined output or set point or any chosen destiny.
- SCADA provides systems to monitor the process variables that mimic the process.
- Analog controllers added to a DDC computer system enhanced the overall reliability.
- Interfacing equipment from multiple vendors (interfacing one vendor's computer system to another vendor's analog instrumentation) is difficult.
- Manager has complete access of the system; he normally has over riding capabilities for control. The manager has the capability to utilize the systems data for decision-making.

LO 4: Illustrate the architecture of distributed control systems

- Though PLCs were initially conceived to implement simple binary logic, they started using powerful microcontrollers and could therefore handle comparatively complex functions such as PID controls.
- PLCs and DCSs can be combined by design in a hybrid system where PLCs are connected through a link to a controller forming part of a larger DCS, or are connected directly to network of the DCS.
- A distributed control system is defined as a system comprising of functionally and physically separate automatic process controllers, process monitoring and data logging equipment all of which are interconnected through a fast, digital network.
- A range of functions are designed into the controllers, such that the entire general plant control operation functions, whatever the type, could be carried out by the DCS. These

functions include continuous control, cyclic control, logic control, motor control, batch control, etc.

- A PLC's scan time (the time taken to scan the inputs) is in 10 s of milliseconds, while the same for a DCS could be in 100 s of milliseconds or seconds (typical fastest speed 0.25 s).
- It is essential to have automatic transfer between redundant parts, so that if one fails the other takes over without disturbance of the operation or output. At the same time, there must be some form of alarm to alert the operator to draw his attention to the fact that a failure has occurred.
- Since distributed control equipment is highly modular and contains many printed circuit cards, time to repair can be very short if sufficient spare parts are available and the components can be quickly brought into service and the necessary software updated online without affecting the control functions in any way.
- These total costs turn out to be lower in case of DCS compared to providing comparable level of functionality using PLCs because the built-in functions and inherent integration capabilities available in a DCS enable implementation and maintenance of a more effective system with reduced labor, plant lifecycle cost while avoiding degradation in functionality over time.
- DCS systems must be capable of intelligent alarm management to aid in abnormal situation management.
- In the manual mode of a control loop, the operator manipulates the final control element directly. In the auto mode, the final control element is manipulated automatically through a low-level controller usually a PID. The operator provides the set point for this control loop.

LO 5: Identify the functional components of distributed control systems

- IO cards perform a variety of functions such as analog to digital conversion, conversion to engineering values; limit checking, quality tagging and so on.
- The engineering tools enable the creation and validation of the application program.
- The operator workstations and the supervisory workstations exchange data through the Plant Information Network.
- The primary purpose of gateway to support integration of different protocols or a standard based devices to communicate with mainline DCS and its controllers.
- An event priority type defines the priority of an event for each of its possible states.
- Alarm suppression is typically used to temporarily remove alarms from the system for which some condition exists that the operator knows about (e.g. a piece of equipment has been shut down or is under maintenance). Alarm filtering provides a way for the operator to view collections of alarms and efficiently manage alarms when there is a flood of alarm messages and to suppress several alarms which result as a consequence of a basic alarm condition.
- Usually a system alarm is reported on the failure or malfunction of any of these components and the necessary log messages are recorded.
- Redundancy at various levels helps the user to upgrade components online in the control system.

LO 6: Summarize the applications of distributed control systems

- A PLC can be used effectively for "simple" batch applications, while a DCS is typically better suited for "complex" batch manufacturing facilities that require a high level of flexibility and recipe management.
- If the value of a batch is high, either in raw material cost or market value, and downtime not only results in lost production but potentially dangerous and damaging conditions, the selection should be DCS.
- The DCS plant requires an operator to make decisions and continuously interact with the process to keep it running.

Questions

I. Objective-type questions

✦✦ **1.** An operator needs to review historical trend data to evaluate significant changes exceeding a specific value. Which HMI parameter is BEST suited for this task?
(a) Server filtering
(b) Dead band
(c) Active X graphic controls
(d) Aggregates

✦✦✦ **2.** Which of the following industrial automation networks provides a widely used backbone bus for integrating controllers and I/O systems through simple-to-write drivers that use standard PC serial ports?
(a) Foundation Fieldbus HSE
(b) Profibus-PA
(c) Interbus
(d) Modbus

✦✦ **3.** The three basic data interfaces found in open information architecture are:
(a) Alarm summary, trending, and report viewing
(b) Dynamic data exchange, alarm management, and data historian
(c) Data access, alarms and events, and historical data access
(d) Alarm capture and viewing, plant queries, and assets viewing

✦✦✦ **4.** Which of the following describes a distributed control system as opposed to a central control room system?
(a) Longer wiring runs and more wires in total
(b) Can gradually scale up system without excessive cost
(c) Operator no longer has to tour the plant
(d) Operator can make set point and output changes remotely

✦✦✦ **5.** A small heat-treating plant with stand-alone processes needs a system that combines a few process control loops with some discrete interlocking. Which of the following would provide such capabilities to the small business?
(a) Hybrid control
(b) Distributed control system
(c) Programmable logic controllers
(d) Control in field

✦✦✦ **6.** Which of the following is true of different types of controller and control systems?
(a) Older control system types have been made obsolete by newer types.
(b) Engineers are "logical" and select controller types based solely on function.
(c) Application requirements dictate the "best" controller type.
(d) Controller types follow a distinct hierarchy from worst to best.

✦✦✦ **7.** One of the differences between PLC and DCS is:
(a) Only the name differs but both are same
(b) System with distributed Controller is DCS and Single Controller is PLC.
(c) The communication networks are different in these systems
(d) None of above

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II. Short-answer questions

✦✦ **1.** Name at least two digital communication protocols used in industry.

✦✦✦ **2.** Name two advantages of supervisory control.

✦✦ **3.** List two disadvantages of supervisory control.

✦✦✦ **4.** Name the three roles of control systems operations.

✦✦✦ **5.** Define an event priority.

✦✦ **6.** Define alarm suppression.

✦✦✦ **7.** Define alarm filtering.

✦✦✦ **8.** Which type of alarm is generated for the malfunction of the DCS system components?

III. Critical-thinking questions

✦✦ **1.** Explain why DCS controllers are distributed across the plant and they communicate amongst themselves with other nodes to carry out all necessary control functions?

✦✦ **2.** Why an integration of DCS with ERP and IT systems through exchange of various pieces of information is important?

✦✦ **3.** Explain why the total costs turns out to be low in case of DCS compared to providing a comparable level of functionality using PLC.

✦✦✦ **4.** How DCS plays a role in abnormal situation management

✦✦✦ **5.** List the objectives of network in DCS architecture.

✦✦✦ **6.** What are the major advantages of functional distribution of hardware and software characteristics of DCS?

✦ **7.** What is the difference between a manual and auto mode in DCS?

✦✦ **8.** Explain how the redundancy in system components helps in upgrade of the system?

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