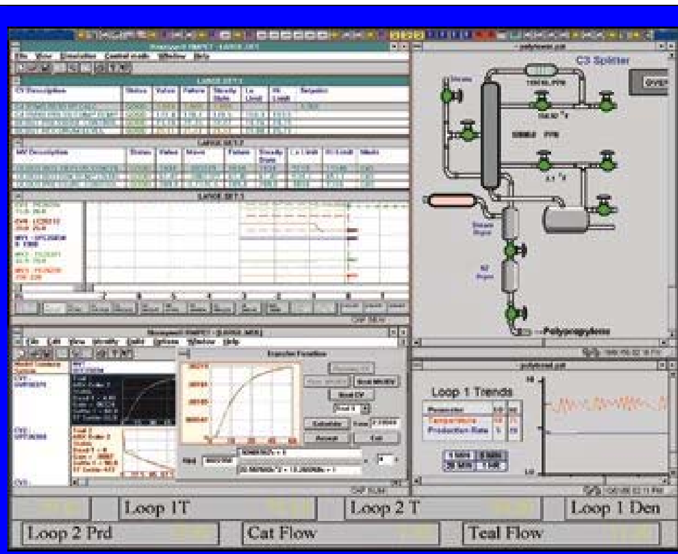

Operator's Training

PROCESS CONTROL FOR OPERATORS

Honeywell

Student Course Workbook

5725

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Contents

List of Tables

List of Figures

Process Control for Operators

5725

Course Objective

At the completion of this course you will be understand the basic principles of process control used in industry today. You will cover the following topics:

- Basic Control Concepts
- Basic Instrumentation
- Instrumentation Diagrams and Symbols
- Temperature Measurement
- Pressure Measurement
- Level Measurement
- Flow Measurement
- Humidity Measurement
- Analytical Measurement
- Final Control Elements
- Process Dynamics
- Types of Process Controllers
- Multi-Loop Controllers

Course Introduction

Today many teenagers are taught to drive in small compact cars and, for the most part, become fairly good drivers. But then they are handed the keys to a full-size car or truck, it seems that they have forgotten everything that they learned in driving school. They find that the characteristics of driving a small compact car are much different than driving a full-size car or truck. The principles of driving are the same for the compact car as they are for the full-size car or truck. In fact, each vehicle has an engine, a steering wheel, and 4 tires. But if you try and turn a full-size truck like you can turn the compact car, you will most likely flip the truck over.

Just like there are basic principles of driving regardless of the type of vehicle, there are some basic principles of process control. From the manufacture of toilet paper or plywood, to the refining of oil or gas, to the generating of steam or electricity, still requires the use of the basic principles of process control. Even though modern industrial sites are extremely complex and there is virtually no limit to the degree of sophistication and complexity a control system can reach, the basic principles of process control are unchanging.

The operation of a modern industrial plant involves many processes that work together to produce final products. The control room operator is responsible for keeping these processes working properly and within process limits. With the rapidly changing technology of control systems, the control room operator has to understand how to optimize the process for the most economical operation. A good understanding of the basic principles of process control will assist the operator in making informed decisions affecting a plant’s efficiency and safety.

This course will cover these principles of process control and our discussions will focus on the practical application of process control loops.

Lesson 1
Introduction to Process Control

Lesson Objectives

At the completion of this lesson, you will be able to understand the basic concepts, terminology, instrumentation, and drawing symbols used in the Process Control Industry.

Basic Concepts of Process Control

Sometimes it seems as if a process control engineer, technician, or mechanic is talking a foreign language in their communication with operators about some plant process. The different vendors are no better with all their equipment specific acronyms and terminology. But, it behooves the operator to learn the technological language so that they can better communicate, verbally or in writing, with those who maintain the plant's control systems.

The process that we want to control is called the *process variable*, sometimes referred to by its initials of *PV*. This variable can be the pressure of a tank, the temperature of steam, the amount of flow out of a tank, the level of water in a reclaim pond, or the analytical measurement of a chemical.

This process variable *(PV)* is measured by the appropriate type of instrument in the field and is called the *primary element*. The process variable value is then sent to a device called a *measuring element.* This measuring element is sometimes part of the same instrument as the primary element and sometimes it goes directly to the control system as an input. A *transmitter* is a good example of the combination of primary element and measuring element. The transmitter contains a sensor that will measure the process variable that then is converted to an appropriate signal type by the measuring element, which is the electronic head of the transmitter. T*hermocouples* or *resistance thermal devices (RTD)* are good examples of primary elements that can be connected directly to a special type input card in the control system.

The next element in the basic process control loop is the *controlling element*. The controlling element receives an input from the primary/measuring element and compares that value against the controller's set point. The controller then computes the difference between the measured value and desired set point to produce a corrective signal. This corrective signal is then fed through the controller's output to what is called the *final control element*. In some of the more complex *multi-element* control loops the controller output may not go a final control element that is in the field but become an input to another controller. We will cover more of this type of controller in a later section of this course.

The *final control element* converts a corrective signal from the controlling element and drives a field device, such as a control valve, to manipulate a process variable and return the process variable to set point.

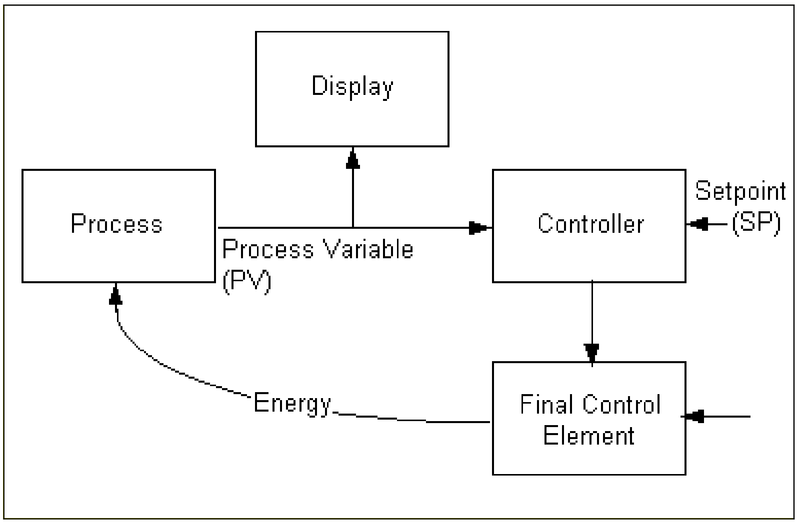


Figure 1.1 Single Loop Basics

What has been described above is considered a typical *single-element* control loop that consists of one primary element. A control loop that has more than one primary element is considered to be a *multi-element* control loop and can become quite sophisticated and complex. These multi-element control loops will be discussed in detail in a later section of this course.

Basic Instrumentation

The stability and accuracy of a control loop is dependent upon the stability and accuracy of the measured value of the process and the final control element. Field instruments such as transmitters, transducers, thermocouples, RTDs, and digital indicators often obtain the information about a process. The final control elements are usually valves, dampers, or motors.

Transmitters

Transmitters are devices used in instrument systems to sense and measure process variables and generate signals that represent the values of those process variables. Today, the majority of the transmitters in plants are electronic and provide an analog signal of 4-20 milliamps for the range of the process variable. Many plants are installing Smart Transmitters, which provide a digital signal that is less susceptible to noise and provides a more accurate and faster signal.

Transducers

In some plants more than one type of signal is used in field instruments, such as a pneumatic signal. To be able to talk to the digital control system a transducer is used to convert from one type of signal to another. An example of where a transducer would be needed is to convert the electronic signal from the controlling element to a pneumatic signal that moves a positioner on a control valve.

Valves

A valve is a device that is used to regulate the flow of a process in a plant. Many have an actuator that moves the valve stem. Sometimes a valve positioner is used to control which direction that the valve moves in response to the controlling element’s signal. Some controller’s signals will go directly to an actuator from a transducer.

Dampers

Dampers are a different type of final control element used in today’s plants to control air flow. These dampers will usually have an actuator and positioner.

Motors

In many plants, variable speed motors are used to control certain processes in a system. The motors can control the amount of liquid flow that is provided or it can control the speed of a conveyor belt. The controllers usually feed a signal to the variable speed drive to either speed up or slow down.

Characteristics of Instruments

Before we leave the subject of instruments, we need to discuss some of the characteristics of these instruments and how they can affect the control of a process. There are two categories that these characteristics fit into. One is called *static characteristics* and one is called *dynamic characteristics*.

Static Characteristics

Static characteristics refer to variables when they are not changing. These characteristics are *accuracy*, *reproducibility*, and *sensitivity*.

Accuracy

Accuracy in an instrument is its ability to measure the actual value of the process variable. Manufacturers specify the percentage of accuracy either plus or minus of the total range of the instrument.

Reproducibility

Reproducibility in an instrument is its ability to measure identical values of a process variable each time the conditions are present. In other words, can it repeat its accurate measurement of the process variable.

Sensitivity

Sensitivity in an instrument is its ability to measure the smallest change in the value of the process variable. Most instruments will have a small *dead zone* in which the instrument will not respond.

Dynamic Characteristics

Dynamic characteristics refer to variables when they are changing. These characteristics are *responsiveness* and *fidelity*.

Responsiveness

Responsiveness in an instrument is its ability to follow changes in the value of the process variable.

Fidelity

Fidelity in an instrument is its ability to correctly measure a change in the value of the process variable.

Each of these characteristics can affect how well the control system is able to control the process. We will cover more about these and other characteristics in more detail in the Process Dynamics section of this course.

Instrumentation Diagrams and Symbols

Just as there is a special language for the process control industry, there is also a set of symbols used to communicate in process control diagrams. The Instrument Society of America has prepared two standards, one entitled, *Instrumentation, Symbols and Identification, S5.1*[1] and the other entitled, *Graphic Symbols for Distributed Control/Shared Display Instrumentation, Logic and Computer Systems, S5.3*[2] for individuals in the field of instrumentation. While each plant determines how the standards are applied at their site these standards provide consistency in the process control industry regardless of the particular type of industry. This course will cover the basic standards used in drawings for the majority of the process control industry.

The Identification System

General

Each instrument is identified first by a system of letters used to classify its functionally. To establish a loop identity for the instrument, a number shall be appended to the letters. This number will, in general, be common to other instruments of the loop of which this instrument is a part. A suffix is sometimes added to complete the loop identification. A typical tag number for a temperature-indicating controller is shown below.

T	I C	2175	A
First Letter	Succeeding Letters	Loop Number	Suffix (If needed)
Functional Identification		Loop Identification	
Instrument Identification or Tag Number			

The instrument tag number may include plant specific coded information that may designate plant unit, area, drawing location, and equipment number.

The following examples give you an idea how the standard can be modified to include plant specific information.

1PS2103 = 1 / PS / 21 / 03 = Unit / Pressure Switch / P&ID # / Equipment #
1MR2103 = 1 / MR / 21 / 03 = Unit / Motor Run / P&ID # / Equipment #
1YR2103 = 1 / YR / 21 / 03 = Unit / Start Run / P&ID # / Equipment #
1AH1C07 = 1 / AH / 1 / C / 07 = UNIT / Air Heaters / SAMA SHEET / Control / Equipment #

[1] *Instrumentation, Symbols and Identification, ISA-S5.1,* (1984). Instrument Society of America, 67 Alexander Drive, P.O. Box 1227, Research Triangle Park, North Carolina 27709.
[2] *Graphic Symbols for Distributed Control/Shared Display Instrumentation, Logic and Computer Systems, S5.3* (1983).). Instrument Society of America, 67 Alexander Drive, P.O. Box 1227, Research Triangle Park, North Carolina 27709.

Functional Identification

The functional identification of an instrument shall consist of letters from Table 1.1 shown below, and shall include one first-letter, covering the measured or initiating variable, and one or more succeeding letters covering the functions of the individual instrument. An exception to this rule is the use of the single letter ***L*** to denote a pilot light that is not part of an instrument loop.

Table 1.1 Identification Letters

	Measured or Initiating Variable	***Modifier***	***Readout or Passive Function***	***Output Function***	***Modifier***
A	Analysis		Alarm		
B	Burner, Combustion		User's Choice	User's Choice	User's Choice
C	User's Choice			Control	
D	User's Choice	Differential			
E	Voltage		Sensor (Primary Element)		
F	Flow rate	Ratio (Fraction)			
G	User's Choice		Glass, Viewing Device		
H	Hand				High
I	Current (Electrical)		Indicate		
J	Power	Scan			
K	Time, Time Schedule	Time, Rate of Change		Control Station	
L	Level		Light		Low
M	User's Choice	Momentary			Middle, Intermediate
N	User's Choice		User's Choice	User's Choice	User's Choice
O	User's Choice		Orifice, restriction		
P	Pressure, Vacuum		Point (Test) Connections		
Q	Quantity	Integrate, Totalize			
R	Radiation		Record		
S	Speed, Frequency	Safety		Switch	
T	Temperature			Transmit	
U	Multivariable		Multifunction	Multifunction	Multifunction
V	Vibration, Mechanical Analysis			Valve, Damper, Louver	
W	Weight, Force		Well		
X	Unclassified	X Axis	Unclassified	Unclassified	Unclassified
Y	Event, State, or Presence	Y Axis		Relay, Compute, Convert	
Z	Position, Dimension	Z Axis		Driver, Actuator, Unclassified Final Control Element	

The functional identification of an instrument shall be made according to the ***function*** and not according to the construction. Thus, a differential-pressure recorder used for flow measurement shall be identified as an ***FR***, a pressure indicator and a pressure switch connected to the output of a pneumatic level transmitter shall be identified as ***LI*** and ***LS***, respectively.

In an instrument loop, the first letter of the functional identification shall be selected according to the ***measured or initiating variable*** (primary element) and not according to the manipulated variable (controlled element). Thus, a control valve varying flow according to the dictates of a level controller is an ***LV**,* not an ***FV***.

The succeeding letters of the functional identification designate one or more readout or passive functions, or output functions, or both. A modifying letter may be used, if required, in addition to one or more other succeeding letters. Modifying letters may modify either a first-letter or other succeeding letters, as applicable.

The sequence of identification letters shall begin with a first-letter. Readout or passive functional letters shall follow in any sequence, and output functional letters shall follow these in any sequence, except that output letter ***C*** (control) shall precede output letter ***V*** (valve); e.g., ***FCV***, a flow control valve.

The number of functional letters grouped for one instrument should be kept to a minimum according to the judgment of the user. The total number of letters within one group should not exceed four. The number within a group may be kept to a minimum by these means:

1. The functional letters are arranged into subgroups. This practice is used for instruments having more than one measured variable or output, but it may also be done for other instruments.
2. If an instrument indicates and records the same measured variable, then the ***I*** (indicate) may be omitted.
3. All letters of the functional identification should be in the uppercase format.

Refer to your plant's standards for drawings to determine how your plant identification is set up.

Loop Identification

The loop identification of an instrument generally uses a number assigned to the loop of which the instrument is a part. Each instrument loop will have a unique number. A single sequence of loop numbers should be used for all instrument loops of a project or sections of a project regardless of the first letter of the functional identification of the loops. A loop numbering sequence may begin with the number ***1*** or with any other convenient number, such as ***175*** or ***1201***, that may incorporate coded information such as a plant unit or area designation.

If a given loop has more than one instrument with the same functional identification, then, preferably, a suffix shall be appended to the loop number, e.g., ***FCV2175A, FCV2175B, FCV2175C,*** etc., or ***TE-25-1, TE-25-2, TE-25-3,*** etc. The suffixes may be applied according to the following guidelines:

1. Suffix letters should be displayed in the uppercase format, i.e., ***A, B,*** **C**. etc.
2. For an instrument such as a multi-point temperature recorder that prints numbers for point identification, the primary elements may be numbered ***TE-25-1, TE-25-2, TE25-3,*** etc. The primary element suffix numbers should correspond to the point numbers of the recorder. Optionally, they may or may not correspond.
3. Further subdivisions of a loop may be designated by alternating suffix letters and numbers.

An instrument can perform two or more functions and may be designated by all of its functions. For example, a flow recorder ***FR-2*** with pressure pen ***PR-4*** is preferably designated ***FR-21PR-4***. Alternatively, it may be designated ***UR-7,*** a two-pen pressure recorder may be ***PR-718,*** and a common annunciator window for high and low-temperature alarms may be ***TAHIL-9***.

Symbols

Symbols are intended to depict instrumentation and their application on flow diagrams, process control diagrams, mechanical diagrams, and instrumentation system drawings.

The symbols shown in Figure 1.2 represent those symbols typically shown on P&IDs and control logic diagrams called SAMAs.

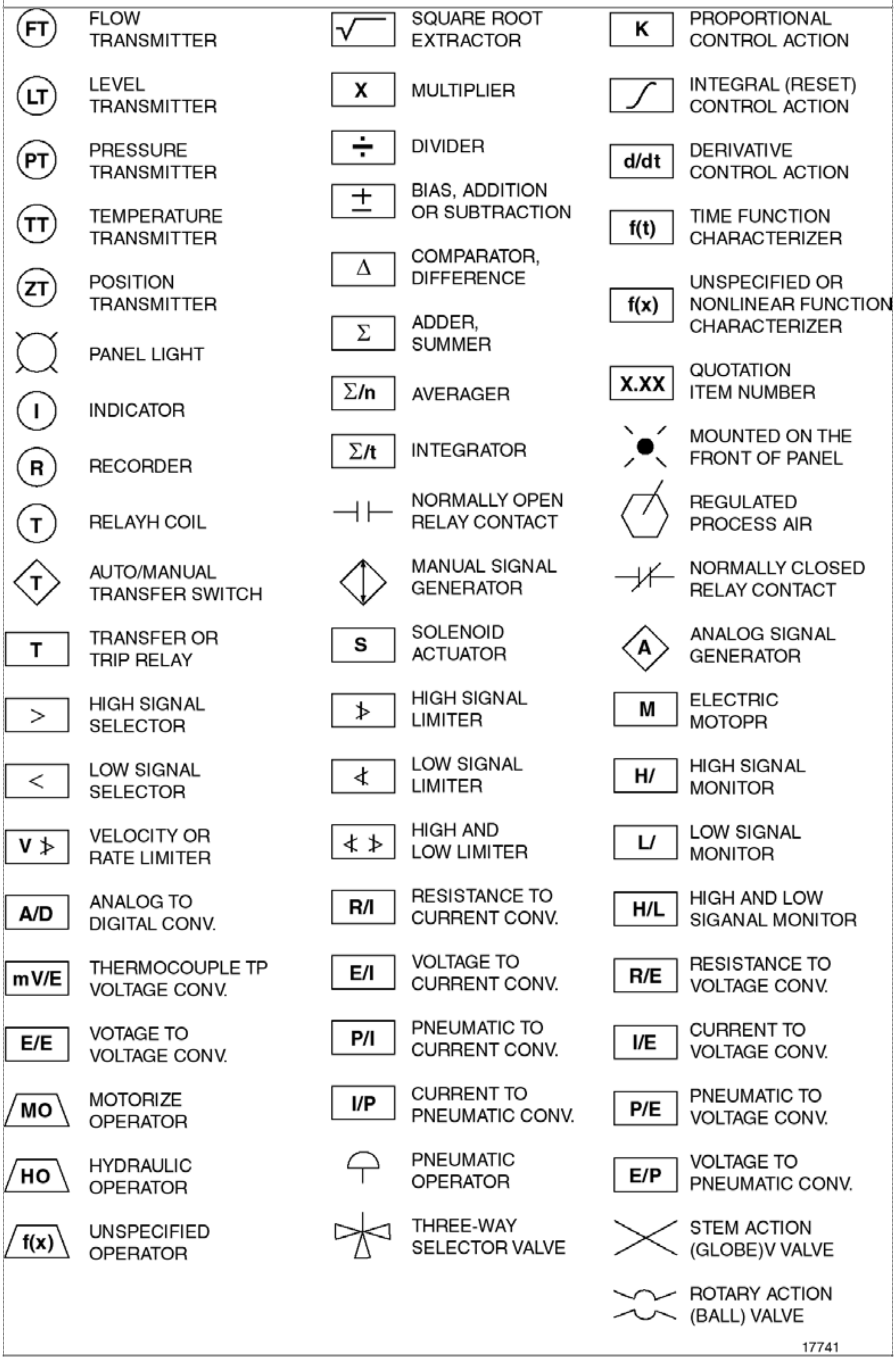


Figure 1.2 P&ID Symbols

Advances in control systems permit shared functions such as display, control and signal lines. The symbols in Figure 1.3 illustrate the principles of the methods of symbolization and identification.

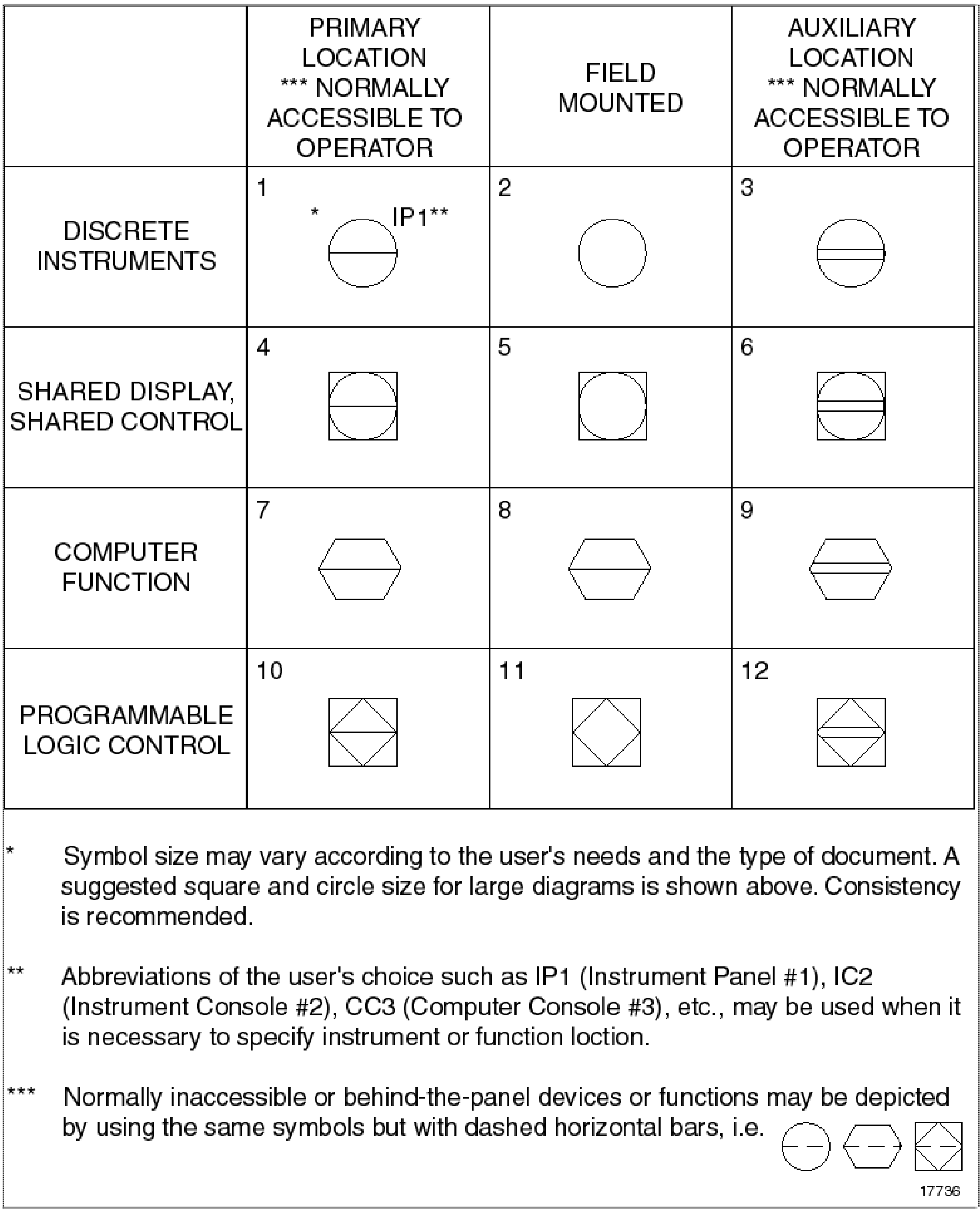


Figure 1.3 Principles of Symbol Identification

Additional symbols that adhere to these principles may be devised or modified as required.

The sequence in which the instruments of a loop are connected on a flow diagram shall reflect the functional logic. This arrangement does not necessarily correspond to the signal connection sequence. Thus, a loop using analog voltage signals requires parallel wiring, while a loop using analog current signals requires series wiring. But the diagram in both instances shall be drawn as though all the wiring were parallel. This will clearly show the functional interrelationships while keeping their aspect of the flow diagram independent of the type of instrument system installed. The literal and correct wiring interconnections are shown on a suitable electric wiring diagram.

Symbols are also used in depicting the type of instrument lines that are used to send the signals from the field equipment to the control equipment. Figure 1.4 shows the most common used types of signals and their associated symbol.

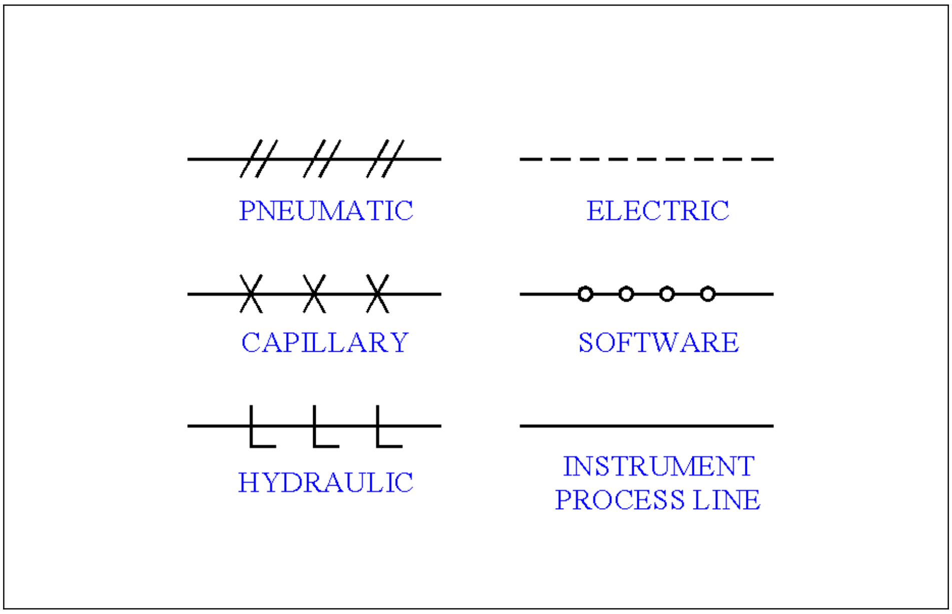


Figure 1.4 Instrument Line Types

P&IDs

The Process and Instrumentation Diagram (P&ID) shows all process fluid lines, equipment, and valves and will represent the general operating strategy for an installation by the use of standard symbols. Most P&IDs depict only that instrumentation that is needed for the operation of the actual process. Minor instruments and loop components, e.g., pressure gages, thermometers, transmitters, converters, may thus be eliminated from the diagrams. An example of a P&ID is shown in Figure 1.5.

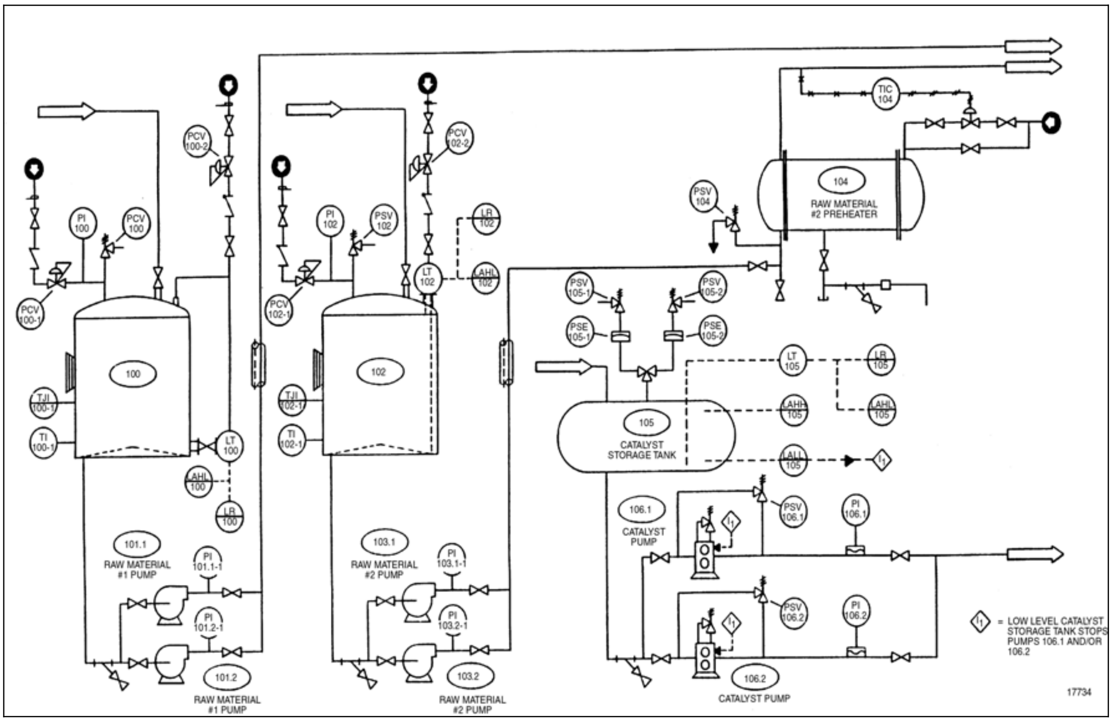


Figure 1.5 P&ID Example

Listed in Table 1.2 are a few of the identification numbers and symbols used in Figure 1.5 and the description as per the standards.

Table 1.2 P&ID Symbol Numbers

Control Panel Instrumentation	
Symbol	**Instrument Function**
PCV100-1	Pressure Control Valve 1 in loop 100.
PCV100-2	Pressure Control Valve 2 in loop 100.
LT100	Level Transmitter of Raw Material #1 Storage Tank, which is loop 100.
LAHL100	Level Alarm High Limit for loop 100.
LR100	Level Recorder for loop 100.
TIC104	Temperature Indicating Controller for loop 104, which is the Raw Material #2 Preheater.

Control Diagrams

The process control loop logic or functionality is shown on diagrams commonly referred to as SAMA drawings. SAMA drawings use standard symbols to represent the analog configuration of the control scheme and standard logic symbols to represent the binary digital logic of the control scheme. These SAMA diagrams assist individuals in understanding the functional configuration of the control loop.

Honeywell uses SAMA style diagrams that have had the standard symbols modified to better represent the Honeywell system. The following figures represent the modified symbols and how they are used in SAMA and binary logic diagrams.

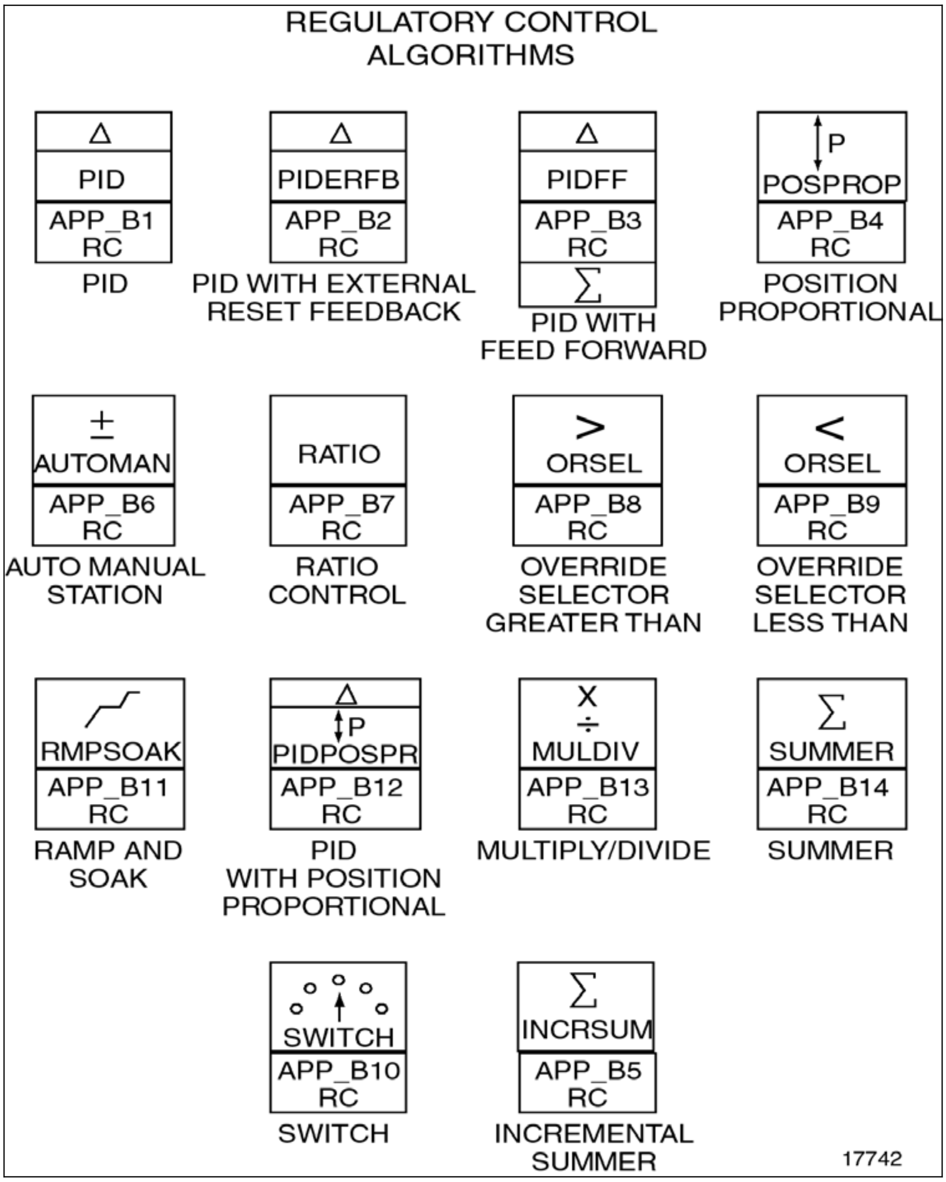


Figure 1.6 SAMA Regulatory Control Algorithm Symbols

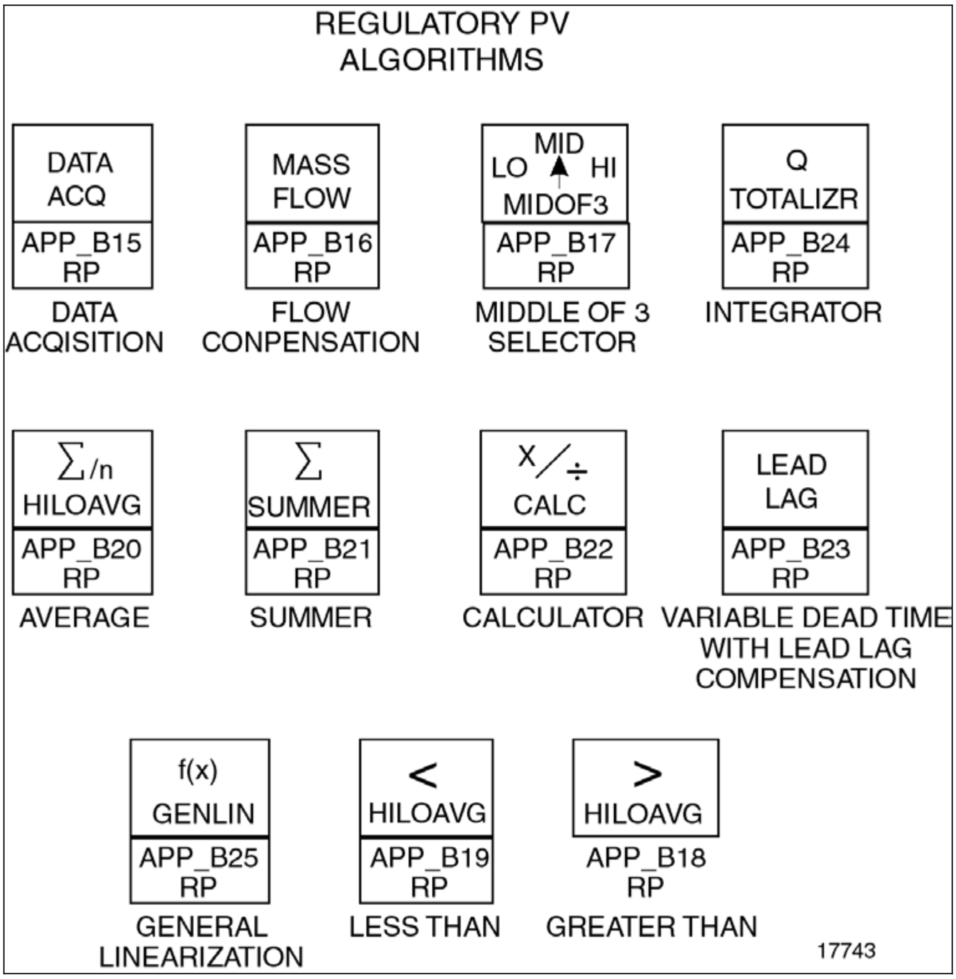


Figure 1.7 SAMA Regulatory PV Algorithm Symbols

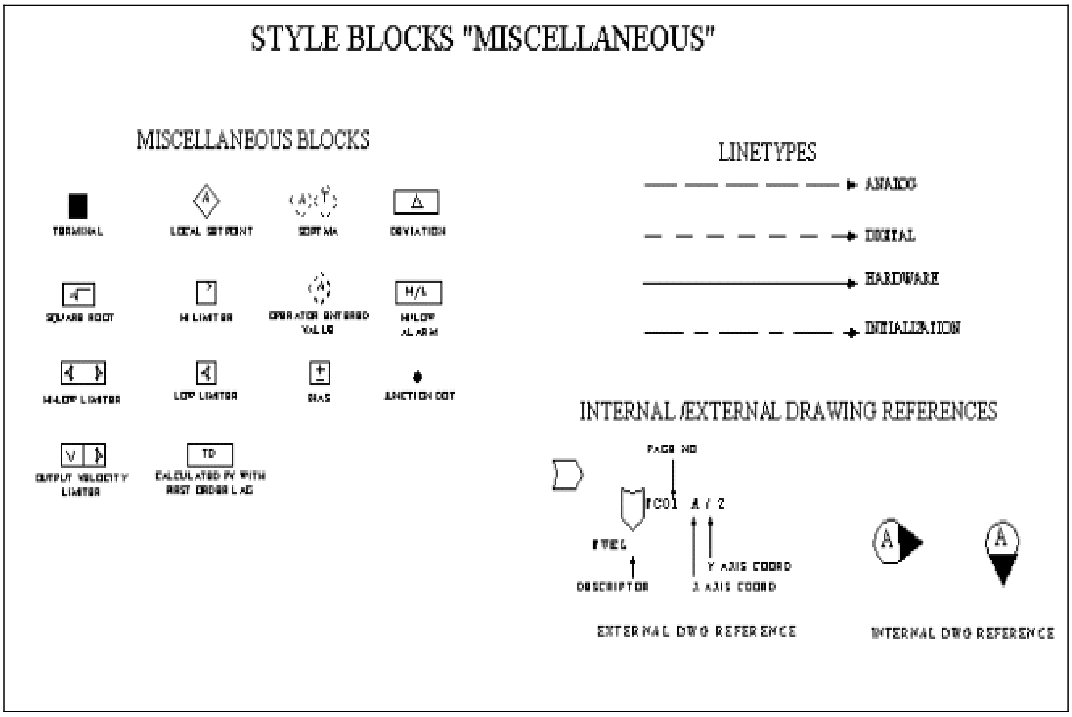


Figure 1.8 SAMA Style Blocks

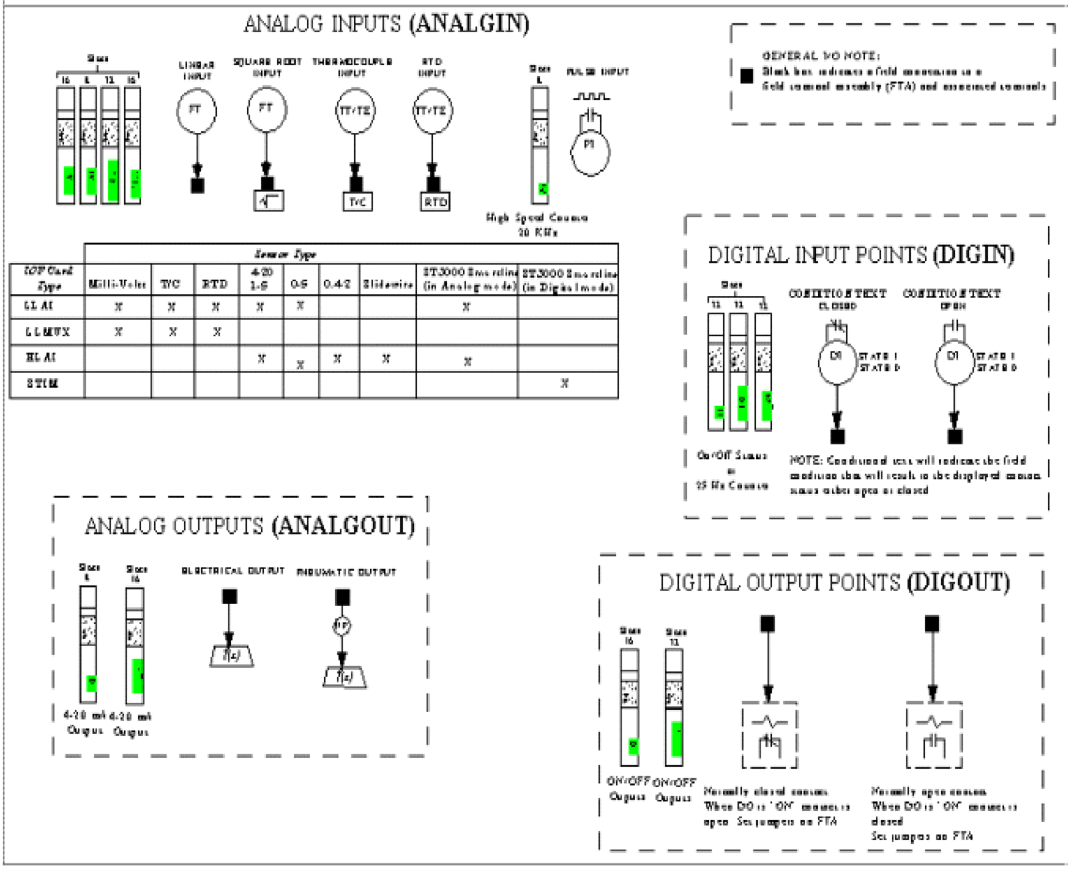


Figure 1.9 SAMA Analog Input Symbols

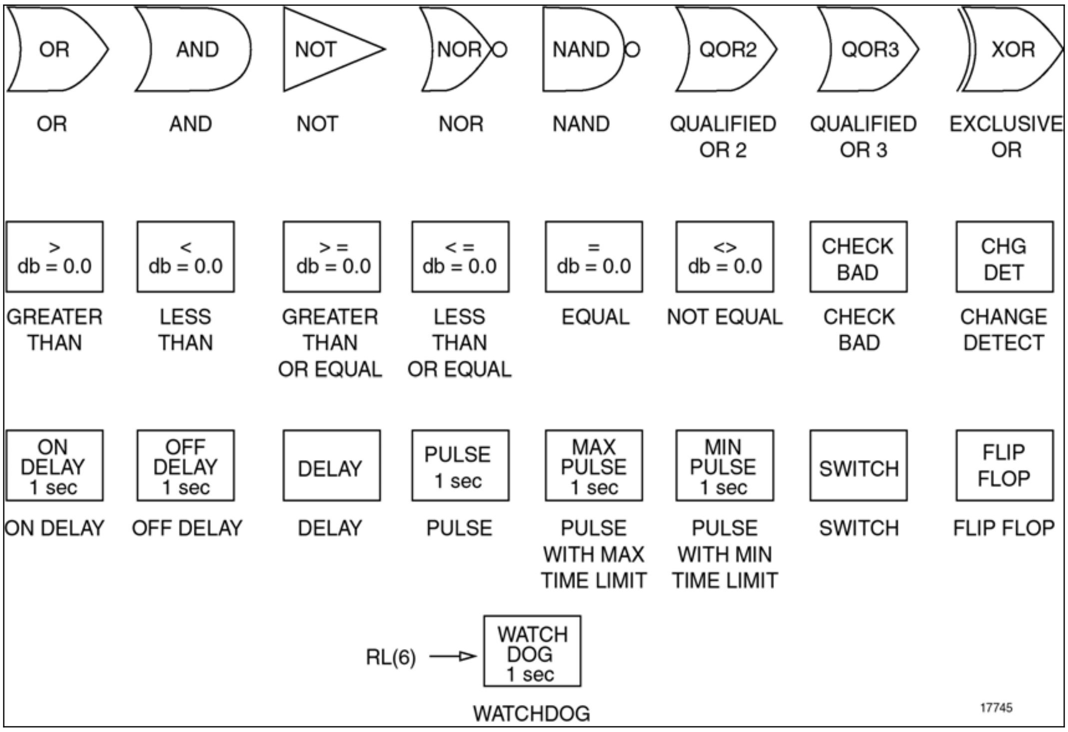


Figure 1.10 SAMA Digital Logic Symbols

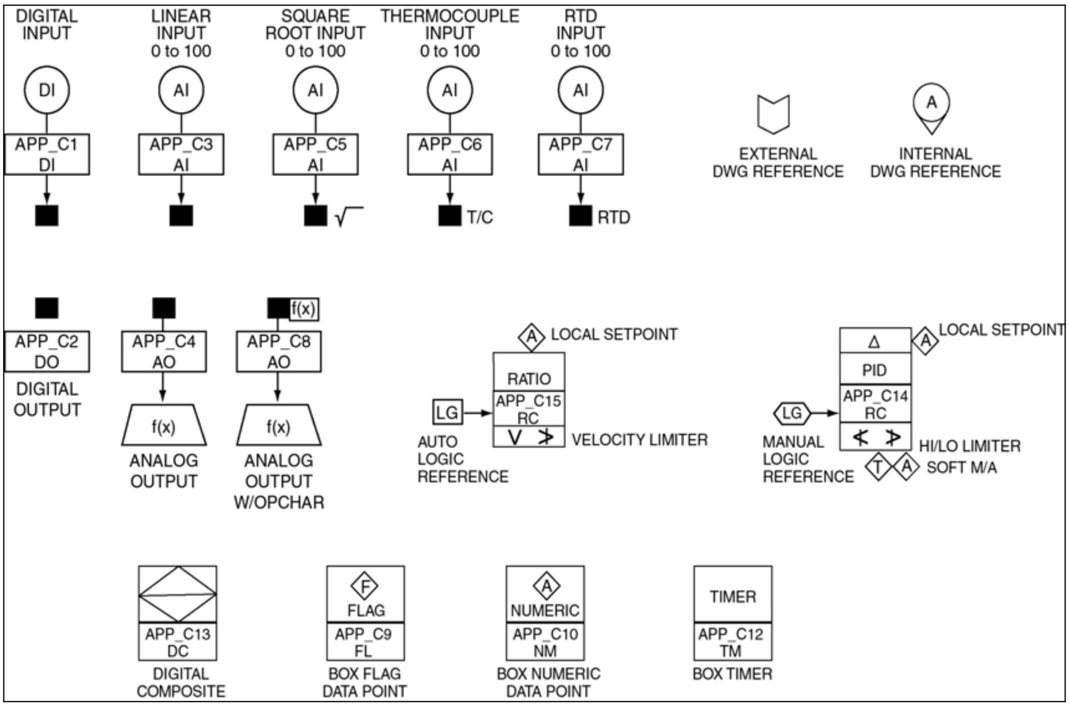


Figure 1.11 SAMA Miscellaneous Input/Output Symbols

Figure 1.12 is a typical SAMA style drawing that represents the analog portion of the control loop.

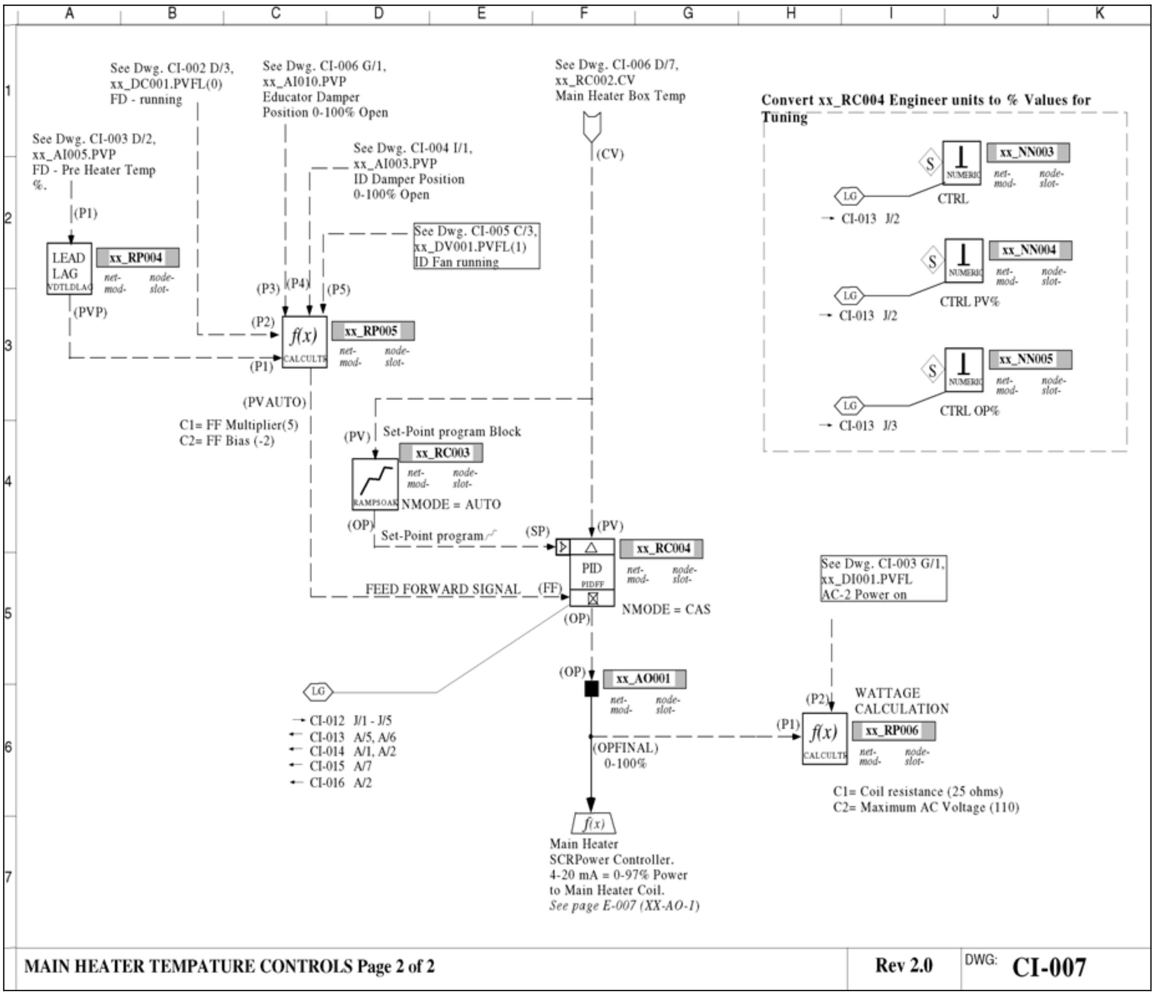


Figure 1.12 Sample SAMA Drawing of Analog Portion of a Control Loop

The binary digital portion of the control logic is represented with standard symbols that convey, in simple form, the sequence of operations that takes place in the process that is being controlled. Figure 1.13 is a typical SAMA style logic drawing that represents the binary digital portion of the control loop.

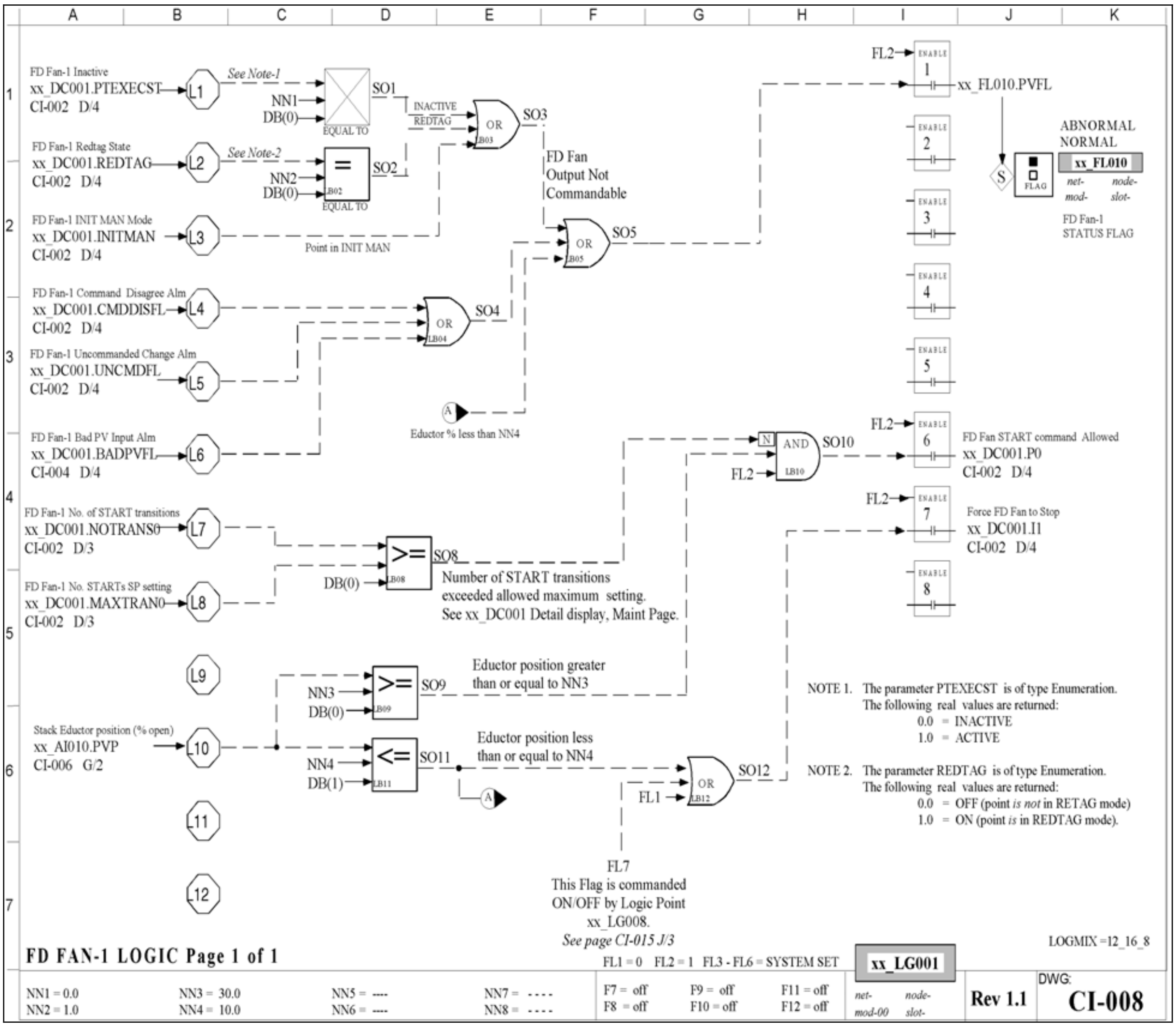


Figure 1.13 Sample SAMA Drawing of Digital Portion of a Control Loop

Lesson Summary

In this lesson, you have been introduced to the basic concepts, terminology, instrumentation, and drawing symbols used in the Process Control Industry. These subjects will enable you to communicate effectively with the engineering and maintenance groups.

In the next lesson you will learn about temperature measurement, instrumentation, and control.

Lesson 2
Temperature Measurement and Control

Lesson Objectives

At the completion of this lesson, you will be able to understand the basic principles of temperature measurement and instrumentation.

Introduction: Evidences of Heat

The dictionary definition of temperature is "the degree of hotness or coldness measured on a definite scale." Temperature can be defined in terms of thermodynamics, also but our fundamental concept of it is obtained from our sensation of warm or cold, which we experience all the time. The concept of temperature leads to the concept of heat, which is a form of energy.

Under normal circumstances, man can exist only within a narrow span of temperatures somewhere between the freezing point and boiling point of water. His comfort is dependent upon the attainment of an even narrower band of temperatures in the 60 to 80 degree Fahrenheit zone. Since ambient conditions in our universe vary from the almost absolute zero of black space to the millions of degrees in the nuclear fusion process inside stars, how delicate an organism man really is and how ideal his thermal environment is are evident.

For centuries man was content to wrap animal skins about him when cold, fan himself when overheated, and make rough tools by chipping or grinding materials available in a natural state.

Fire enabled him to cook his food, fashion metal or ceramic objects to improve his lot, and keep him warm at least on the side next to the fire. He thought of objects as being either hot or cold with respect to his own body temperature. He had no need for precise temperature measurement, although most of his food was either raw or burnt and many of his tools were ruined with improper tempering during their manufacture.

Through the ages, activity eventually turned toward a factual cataloging of the nature of things. It became increasingly important to measure temperatures in order to duplicate previous conditions.

Newtonian mechanics is the basis for the theory that heat is energy associated with the activity of the molecules of a substance. Since these minute particles are assumed to be in continuous vigorous motion, their activity is sensed to a greater or lesser degree as heat. In this classical kinetic theory, molecular activity ceases at absolute zero. Modern experiments indicate that a minimum amount of activity remains, and that absolute zero is impossible to attain, but the classic theory has been the oasis for virtually all experimentation.

The amount of heat a body holds is related to its temperature. This amount of heat is described in other terms, such as Btu, of which temperature is one part while mass is the other. Temperature is a thermopotential comparable to a pressure head or an electrical voltage.

Heat will flow from a point of higher temperature to one of lower through the intervening medium. In order to have a standard for identifying or comparing the temperature of objects, scales were devised. One of these, the Celsius or centigrade scale, uses the freezing point of water as its zero degree point and the boiling point of water as its 100° point. The Fahrenheit scale locates the water freezing point at 32 degrees and the boiling point at 212 degrees.

It is often necessary to convert temperature readings from one scale to another and there is an easy calculation that you must perform.

Changing from Fahrenheit scale to Celsius scale.

$°C=100/180\ (°F-32°)$ or

$°C=5/9\ (°F-32°)$

Example: Change 77°F to °C

$°C=5/9(77°-32°)$

$°C=5/9 \text{ X } 45°$

$°C=25°$

Changing from Celsius to Fahrenheit scale.

$°F= (180/100°C) + 32°$ or

$°F= (9/5°C) + 32°$

Example: Change 10°C to degrees Fahrenheit

$°F= (9/5°C) + 32°$

$°F= (9/5 \text{ X } 10°) + 32°$

$°F= 18° + 32°$

$°F= 50°$

The science of thermodynamics however, requires a temperature scale, which locates the zero point at absolute zero. The Kelvin scale fulfills this requirement with Celsius degrees, i.e. 100 degrees between ice and boiling points of pure water. The temperature at the ice point on this scale is 273.16 degrees.

The Rankine scale also locates its zero point at absolute zero, but measures in Fahrenheit degrees. The ice point temperature on the Rankine scale is 491.69 degrees, and the boiling point temperature is 671.69 degrees.

Having established a basis for reading temperature, and having observed that various chemical elements and simple compounds, like water, have predicable solidifying and vaporizing points, with proper sensors man could achieve repeatable results in his processes. Since temperature is a fundamental condition of all matter, it will affect many physical and electrical properties. Indeed, the radioactive decay of the atom is about the only phenomenon not affected by temperature.

Some of the ways in which temperature can be inferred in the practical world are:

- Changes in volume or (or pressure. viscosity, density, etc.)
- A chance in electrical resistance
- The EMF created at the junction of two dissimilar metals
- The intensity of the total radiation emitted
- Change in state (solid to liquid: liquid to gas)
- Chemical change

Sensors

Any one of the above effects may be used as the principle of operation for a temperature sensor. But a sensor must have other qualities beyond responding to temperature changes. It must not upset the temperature it is measuring by conducting heat to or from the area, and its response must be capable of being translated into temperature terms. In addition, simplicity, ruggedness and sensitivity are also desirable qualities.

Figure 2.1 illustrates the useful temperature range of different sensors. The operating principles of some of the many temperature sensors used in the laboratory and in industry are given in the following sections.

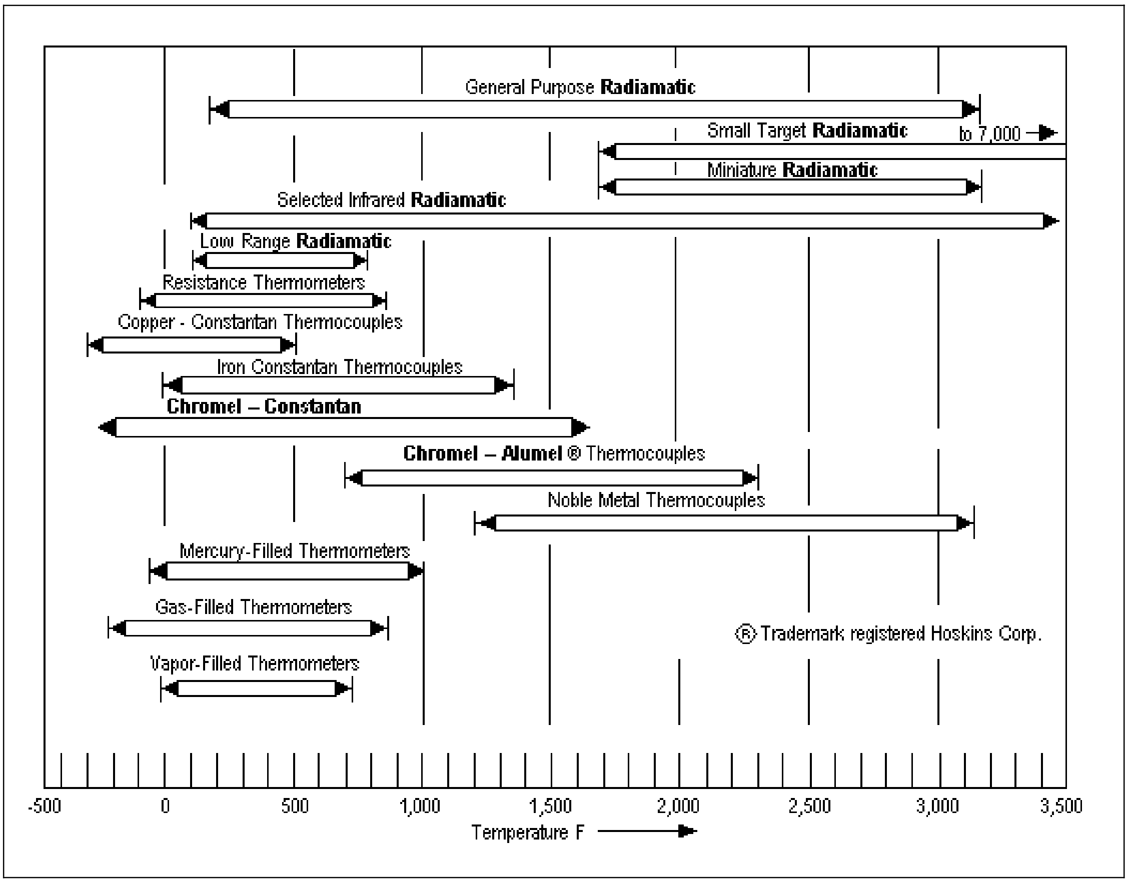


Figure 2.1 Spectrum of Temperature Measuring Instruments

Mechanical Sensors

Visible Liquid Column

Perhaps the simplest thermal expansion instrument is the glass stem thermometer, in which a liquid such as alcohol or mercury expands with increasing temperature up a graduated closed end glass tube. The system has a fixed volume and the vapor pressure above the liquid is reduced to near-zero. A bulb containing the bulk of the liquid is part of the system. When it is immersed in the medium whose temperature measurement is wanted, the liquid expands up the glass tube and indicates the temperature on the graduations on the tube. The limitations of the glass stem thermometer are obvious — hard to read, no recording or control, local measurement only, etc.

Filled Thermal Systems

With a filled thermal system, some of the disadvantages of the glass stem thermometer are eliminated. A filled thermal system is basically a pressure gage to which has been added a bulb and a length of small-bore connecting tubing. The system is filled and maintained pressure tight (see Figure 2.2). Several different fills are used, each having its own characteristics. Gas filled systems, which use nitrogen, can be used at process temperatures between — 125°F and 800°F.

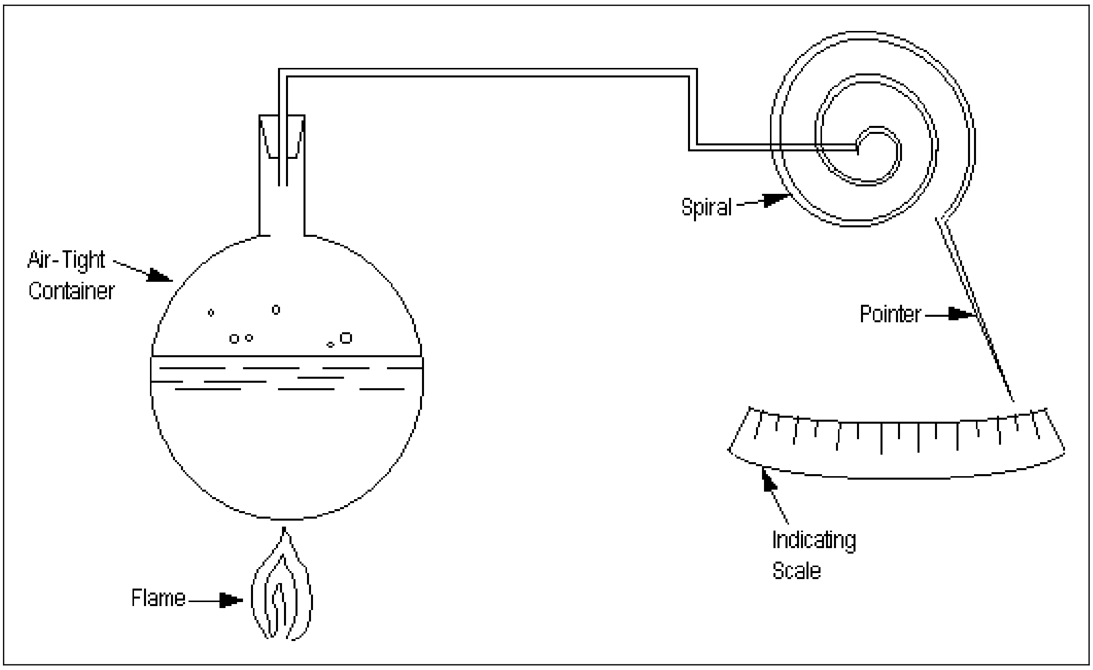


Figure 2.2 Principle of a Filled Thermal System

It is sometimes necessary on these systems to provide compensation for ambient temperature changes at the case so that these changes will not affect the reading of the instrument. Gas-filled systems have a relatively large measuring bulb, which also reduces the effect of ambient temperature changes.

Vapor filled systems are used to measure temperatures ranging from –40°F to 600°F. No case compensation is required since the pressure in the system is strictly a function of the temperature at the liquid-vapor interface, which is always in the bulb of the system. Vapor systems must be calibrated, however, with the bulb at the elevation with respect to the pressure spiral at which it is going to be used, since vertical displacement of the liquid-vapor interface will cause a head effect on the pressure. Also, this type of system should not be used to measure across ambient temperature.

The mercury filled system can measure a wide range of temperatures: -40°F to 1000°F. It is manufactured to produce high internal pressures. Mercury is unusable in some applications because of the danger of contamination if the system leaks or ruptures.

Filled systems are used in conjunction with rectangular case mechanical instruments that are frequently used as low-cost indicators. Their main advantages lie in simple mechanical operation, low maintenance, and low initial cost. However, their speed of response is slower than that of electrical sensors.

Bimetallic Elements

The bimetallic thermometer is made by bonding together strips of two materials that have different coefficients of thermal expansion. As temperature changes, the element bends.

The major advantages of this group of sensors are simplicity, ruggedness and economy, while the disadvantages are limited sensitivity, confined environment, and inability to adapt to recording and control without further limiting the accuracy. The operating range of these elements is -300°F to 800°F.

Chemical Sensors

Pryometric Cones, Crayons, Paper, Etc.

Cones made of certain ceramic will deflect at a specific temperature. They are obviously one shot devices. Crayons and paper that change their color or texture with temperature have limited use in certain industries where economy is necessary and sensitivity of measurement is not critical.

Electrical Sensors

Resistance Temperature Detector (RTD)

Several types of electrical sensors are in use today where the resistance is a function of temperature. The resistance thermometer consists of a length of wire coiled into a small volume. It may be open to the atmosphere or protected by a well. Resistance is measured by passing a small controlled current through the wire with an electrical bridge. The current is kept below a value that would cause self-heating.

The resistance thermometer is used as a standard over part of the International Temperature Scale. The platinum resistance temperature detector has been accepted as a reference below 630.5°C. However, it can be used beyond that point with good results. In many places, the resistance thermometer and the thermocouple will be alternate choices. Why would a user choose this larger, more fragile device over the thermocouple or thermistors?

Primarily, the choice is based on accuracy in a given area. A nickel RTD can be accurate to 0.6°F in the 0 to 300°F range. Industrial quality platinum RTD's, when used with a suitable bridge unit, can provide accurate readings to better than 0.1°F. Also, narrow spans of 20°F are common practice in industrial applications and a 10°F span can be supplied with little difficulty. Short-term reproducibility is better than that of the thermocouple. However, long term drift of 0.2°F can be expected for the nickel RTD.

Because of their construction, resistance thermometers are more likely to be affected by environments than thermocouples, thermistors or radiation detectors. Therefore, it is common practice to supply them with protective covers, or wells. This makes their size a factor in some installations, and cuts down speed of response, while making mounting more difficult.

Resistance thermometers can be either ac or dc powered, involving the usual precautions against strays. While they require no cold junction compensation, as do thermocouples, lead wire resistance is sometimes a consideration.

Principle of Operation

The RTD is usually connected to a measuring instrument incorporating a Wheatstone bridge (Figure 2.3). This measuring instrument interprets changes in resistance at the thermometer bulb in terms of temperature.

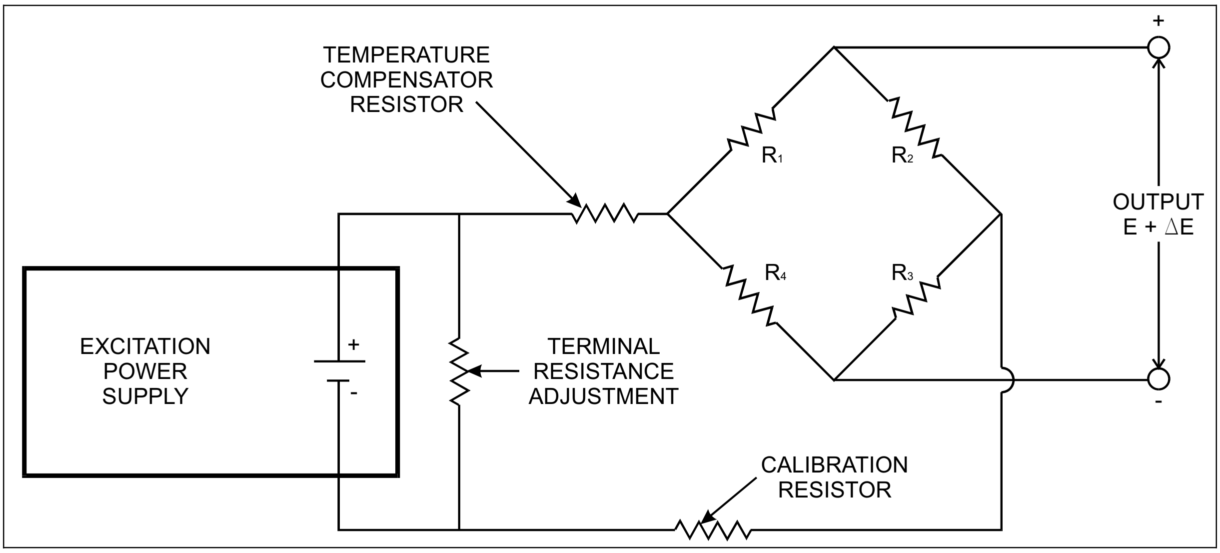


Figure 2.3 Wheatstone Bridge Circuit

In a typical balanced type Wheatstone bridge resistance thermometer, a coil of platinum or nickel wire, which comprises the RTD, is connected into one branch of a DC bridge circuit. In another branch, there is a variable resistance in the form of a slidewire. The RTD, suitably protected, is placed in the medium to be measured. Variations in the temperature of the measured medium causes change in the resistance of the RTD and consequent imbalance of the bridge circuit.

A self-balancing Wheatstone bridge recognizes the condition of unbalance, determines its direction and magnitude, and positions the slidewire contactor to rebalance the bridge and to indicate or record the temperature on a suitable scale or chart.

Thermistors

The thermistor is constructed from semiconductor material.

Thermistors are made from specific mixtures of very pure oxides of nickel, manganese, iron, cobalt, copper, magnesium, titanium, and other metals. The name is derived from the term "THERMally sensitive resISTORS". Their distinguishing characteristic is a large negative temperature coefficient that makes them extremely sensitive at normal ambient or lower temperatures.

In the past, thermistors varied greatly as to resistance at a particular temperature and also as to rate of change, which made individual calibration a requirement. Production of probes interchangeable to within 0.03°C is now common, making them extremely useful in applications requiring very narrow-span temperature recording a control, as for example, in constant temperature rooms.

The interchangeability enables them to be used in Wheatstone Bridge circuit instruments without the need for special zero and span adjustments on spans over 15°C. Their small size makes then particularly adaptable to physiological temperature measurements, insuring a quick response (some 30 seconds for body temperature with certain probes). In other media such as a well-stirred oil bath, response time may approach one second. The probes are best used between -80°C and + 150°C. Although the negative temperature coefficient is an advantage in low-temperature measurements, thermistors are not used much below -100°C. They can be used to about 300°C, but stability at this part of the range is questionable.

Since thermistors are ceramic-like in mechanical properties, chemically stable, and physically small, they can be used in many environments. Their resistance is a function of absolute temperature, making cold junction compensation unnecessary. Large resistance changes also make contact or leadwire resistance negligible.

The large resistance changes per unit of temperature are unwieldy for wide spans. Scale shapes are very non-linear for nominal span, making temperatures difficult to read at the high end of the scale without modification. Drift is a real problem. Properties may be altered by exposure to radiation.

Thermocouples

T.J. Seebeck discovered in 1821 that if a circuit consisting of two dissimilar metallic conductors were formed it would develop an emf if one of the junctions were heated. Since then, the thermocouple has become the most widely used electrical temperature sensor.

In today's thermocouple, two wires of dissimilar material are welded together to form what is commonly called the measuring junction. The other ends are connected to a millivoltmeter or potentiometer. The emf generated by the temperature difference between the measuring junction and the other ends, or reference junction, is measured by the millivoltmeter or potentiometer, and if the temperature at the reference junction is known, this emf can be converted to give the temperature at the measuring junction. Commercial thermocouples generate on the order of 20 to 50 millivolts through the range of their ordinary operating temperatures.

The measuring junction is placed in the medium whose temperature is desired. The reference junction is at the instrument. To prevent errors due to emfs produced by variations in the temperature of the reference junction, compensation for these emfs must be provided. One method, often used in laboratories, is to hold the reference junction at a constant temperature in an ice bath. However, most often compensation is provided by using resistors whose combined temperature resistance coefficient curves match those of the voltage-temperature curves of the reference junction, canceling out the effect of any temperature variations of the reference junction.

Thermocouples are the most widely used electrical temperature sensors for a variety of reasons. They are capable of long life, they are of relatively low cost, and have relatively high accuracy. Some industrial thermocouples can provide accuracy as high as ±.25 %. Emfs are independent of the length and diameter of the extension wires between thermocouple and instrument as long as the wire material is homogeneous. Thermocouples can be made very small, which expands the number of locations in which they can be used, and which reduces the effect they might have in conducting heat to or from the environment they are measuring. Their small mass also allows them to respond rapidly to temperature changes.

Accuracy can be adversely affected by stray pick-ups in the measuring circuits. It is the best practice never to run thermocouple wire in the same conduit with electric power wires. Errors can also be introduced by improper choice of extension wire. To guard against mistakes in connections, industry practice is to color code the wires so that the negative lead always contains red.

Two Basic Laws of Thermoelectricity

There are two laws of thermoelectricity that become important for they govern both thermocouple theory and practice. They are known as the Law of Intermediate Temperatures and the Law of Intermediate Metals.

Law of Intermediate Temperatures

In most industrial installations, it is not practical to maintain the reference junction of a thermocouple at a constant temperature. Therefore, means must be provided to bring the emf developed under existing conditions at the reference junction to a value equal to that which would be generated with the reference junction maintained at a standard temperature, usually 32°F.

The Law of Intermediate Temperatures states that the sum of the emf's generated by two thermocouples; one with its junctions at 32°F and some reference temperature, the other with its junctions at the same reference temperature and the measured temperature; is equivalent to that produced by a single thermocouple with its junctions at 32°F and the measured temperature.

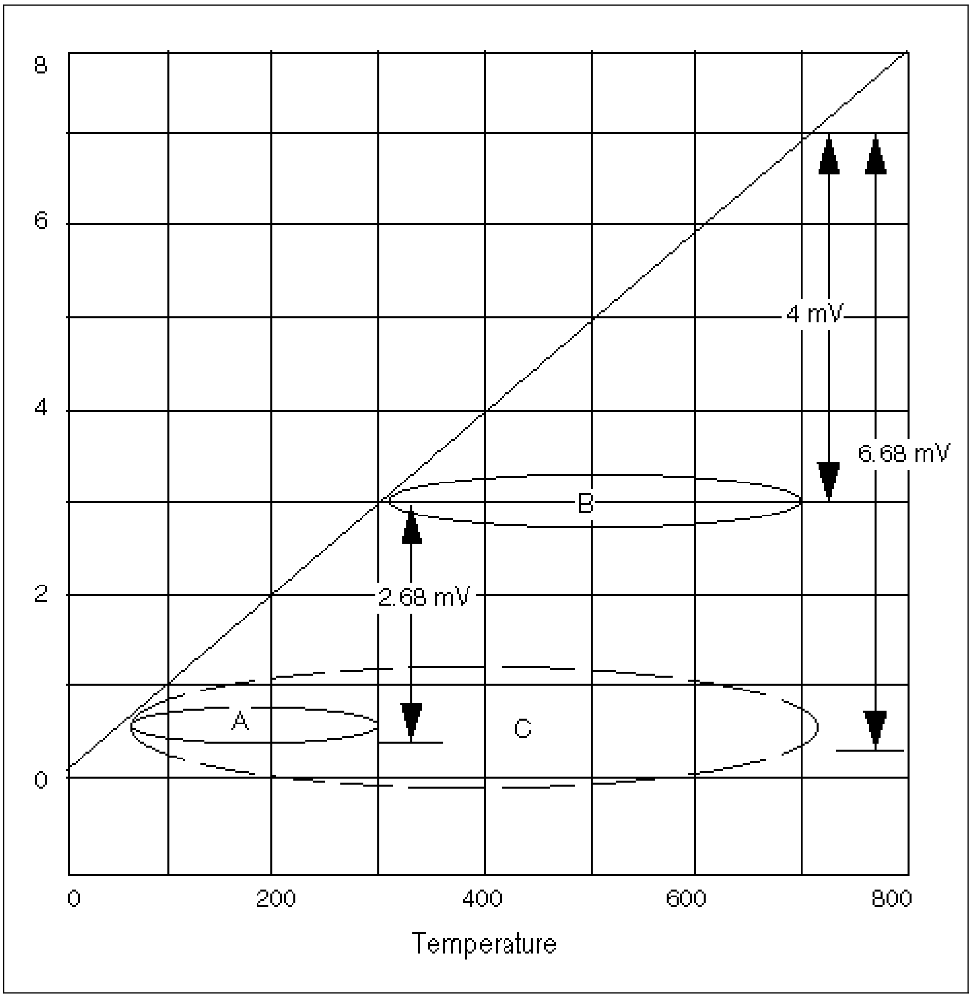


Figure 2.4 Law of Intermediate Temperatures

This is represented in Figure 2.4 where the measured temperature is 700°F. By adding an emf equal to that produced by thermocouple A in Figure 2.4 with its junctions at 32°F and the reference temperature to that of thermocouple B, a total emf equivalent to that generated by the hypothetical thermocouple C results. In most pyrometers, this is done by a temperature-sensitive resistor, which measures the variations in reference junction temperature caused by ambient conditions, and automatically provides the necessary emf by means of a voltage drop produced across it. Thus, the instrument calibration becomes independent of reference temperature variations.

Law of Intermediate Metals

When thermocouples are used, it is usually necessary to introduce additional metals into the circuit.

It would seem that the introduction of additional metals would modify the emf developed by the thermocouple and destroy its calibration. However, the Law of Intermediate Metals states that the introduction of a third metal into the circuit will have no effect upon the emf generated so long as the junctions of the third metal with the other two are at the same temperature.

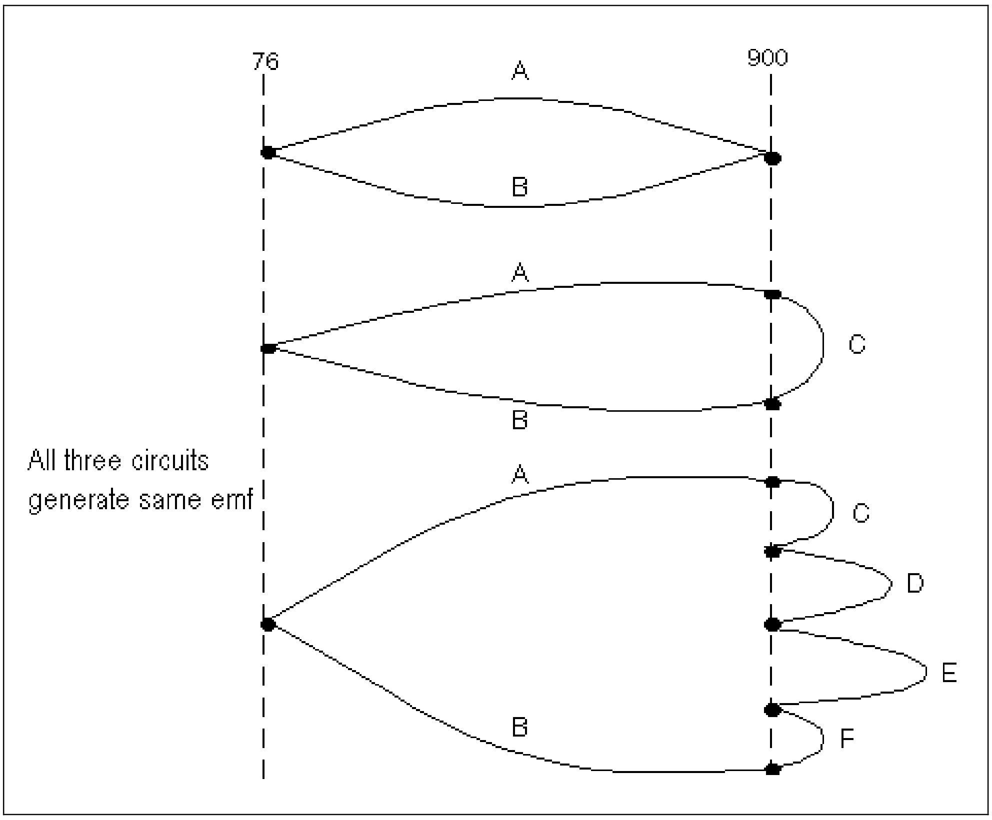


Figure 2.5 Law of Intermediate Metals

Any number of different metals can be introduced, providing all the junctions are at the same temperature. In Figure 2.5, the circuits shown all generate the same electromotive force, even though the second and third circuit diagrams show materials C, D, E and F inserted between A and B. In practice, this means that if the temperature inside an instrument containing a number of different metals in the thermoelectric circuit is maintained uniform, the net emf generated by the thermocouple itself will be unaffected.

Construction and Operation

Figure 2.6 illustrates schematically the incorporation of a thermocouple into a typical system. The basic components are: (1) the thermocouple, attached to (2) a connection head which is located near the point of measurement and is in turn connected by (3) extension wires to (4) an instrument which incorporates (5) internal extension wire and (6) the thermocouple reference junction. The thermocouple reference junction is extended to the instrument, which usually contains a temperature-sensitive resistor or other device to compensate for minor variations in the reference junction temperature.

The thermocouple is an expendable unit and must be replaced periodically. Since the extension wires are part of the thermoelectric circuit, they must be made of either the same material as the thermocouple or materials having essentially the same temperature-emf curve.

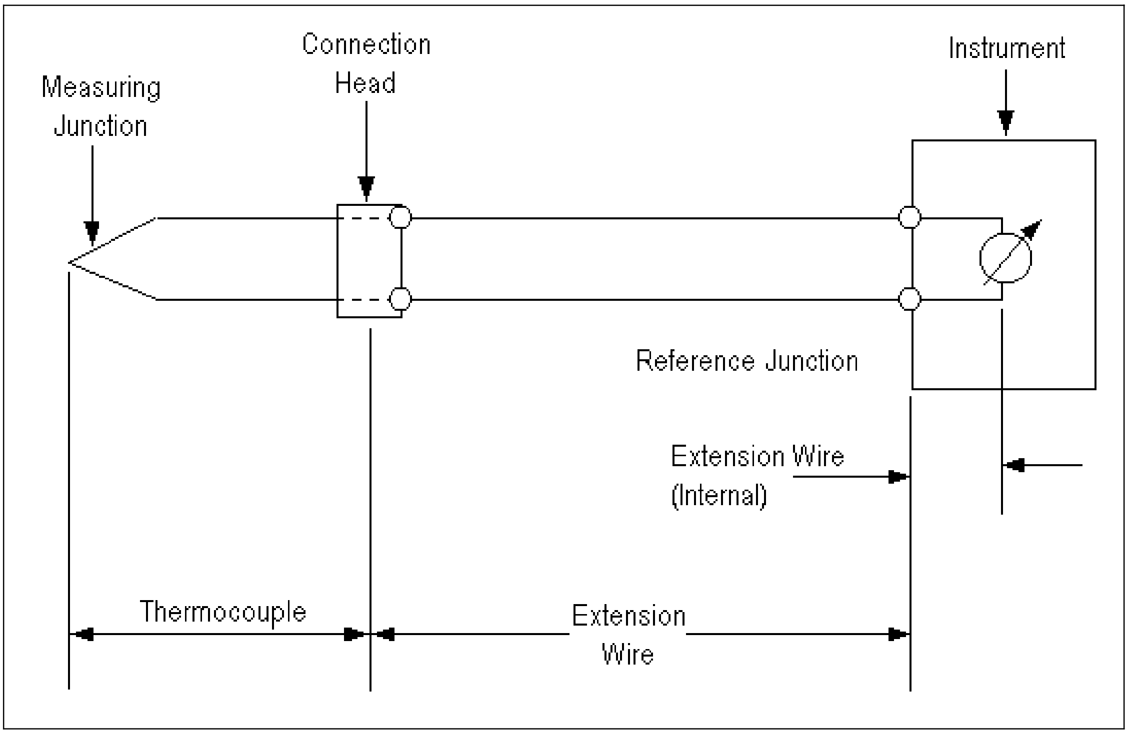


Figure 2.6 Incorporating a Thermocouple Into a System

The actual reference junction is inside the instrument, so internal extension wires of these same materials must be used between the instrument terminals and the reference junction. Therefore, there are really three thermocouples in the circuit, one in the thermocouple assembly, one in the external extension wire, and one in the internal extension wire. But the actual temperature at the connecting head and at the terminals of the instrument has no influence (the Law of Intermediate Temperatures).

Thermocouple Accessories

In addition to these basic components, actual thermocouple assemblies and installed systems usually contain protecting tubes or wells, ceramic insulators on the thermocouple wires within protecting tubes (or insulation on the thermocouple and extension wires), and certain accessory fittings for specific installations. These fittings are often provided to make it easy to mount the assembly in a pipe line, through a furnace wall, or in other processing equipment.

With very few exceptions, thermocouples must be equipped with suitable protection in the form of wells or tubes, particularly at high temperatures. The term protecting tube refers to a closed-end tube attached to the connection head.

A well is a pressure tight receptacle with external threads for attachment to a vessel or pipeline. Hundreds of varieties of these tubes and wells in various metals, alloys and refractory materials are on the market today to meet special job requirements.

A protecting tube or well is used for one or more of the following reasons:

1. to protect the thermocouple from harmful atmospheres (oxidizing, reducing, or contaminating)
2. to protect a thermocouple from corrosive liquids
3. to provide a suitable installation in a pressurized vessel (the thermocouple can be withdrawn, leaving the well in place)
4. to protect the thermocouple from mechanical damage
5. to support the thermocouple (particularly if it is installed horizontally at high temperatures)

A protecting tube interferes with ideal temperature measurement and control, and often complicates installation. It decreases the sensitivity of measurement and increases installation space and cost. A protecting tube or well should have:

1. Resistance to high temperatures and to sagging at operating temperatures
2. Resistance to action of oxidizing and reducing atmospheres
3. High thermal conductivity to insure prompt transmission of temperature changes to the couple
4. Resistance to the thermal shock caused by sudden temperature changes
5. Ability to withstand mechanical shocks
6. Resistance to corrosion by chemicals
7. Low porosity at operating temperature (to prevent gas leakage to couple)
8. Resistance to erosion

Base metal couples are used with metal protecting tubes, and noble metal (Platinum content) couples are used with ceramic protecting tubes.

Thermocouples can be furnished with full-length ceramic or metal protecting tubes with adjustable mounting flanges or mounting threads. Angle type thermocouples, in which the thermocouple is formed in the shape of an "L" for convenient mounting in tanks or pots are obtainable.

Two important facts that bear on accuracy are:

1. Thermocouples do not measure an absolute temperature, but rather measure the difference in temperature between two junctions.
2. The accuracy is dependent upon how closely any given thermocouple and its extension wire match the accepted emf curve.

Common Types of Thermocouples

The seven most commonly used thermocouples are:

1. Copper-Constantan (Type T)
2. Iron-Constantan (Type J)
3. Chromel-Alumel* (Type K)
4. Chromel-Constantan* (Type E) Noble Metal Thermocouples
5. Platinum-13% Rhodium/Platinum (Type R)
6. Platinum-10% Rhodium/Platinum (Type S)
7. Platinum-30% Rhodium/Platinum-6% Rhodium (Type B)

*Trademark - Hoskins Mfg. Company

The type in parenthesis after each is the letter symbol adopted by the ISA in 1948. The features of the most commonly used thermocouples are described below:

Copper-Constantan (Type T)

These thermocouples have a pure copper wire for the positive conductor and copper-nickel (constantan) alloy for the negative conductor. They are particularly suited for measuring temperatures from minus 300°F to plus 600°F.

They are excellent for use in measuring sub-zero temperatures because of their high resistance to corrosion from atmospheric moisture or moisture condensation.

Copper-constantan thermocouples are generally more accurate than other commercially available thermocouples for the measurement of temperatures from minus 300°F to plus 300°F. Originally used in the laboratory and pilot plant, they are now being employed more and more in industry for low-temperature work, and can be used in either oxidizing or reducing atmospheres in their recommended temperature range.

Iron-Constantan (Type J)

These thermocouples use iron for the positive conductor and constantan for the negative conductor. They are used to measure temperatures from about zero to 1,400°F and are suitable for use in oxidizing or reducing atmospheres.

Above 1000°F the rate of oxidation of the iron wire increases rapidly and the use of No. 8 gauge wire is suggested. No. 8 gauge Iron-Constantan protected thermocouples are generally considered satisfactory and economical up to 1400°F.

Chromel-Alumel (Type K)

The Type K thermocouple is made up of a positive conductor of nickel-chromium alloy and a negative conductor of nickel-aluminum alloy. It is generally recommended for temperatures from 1,000-2,000°F, although an upper temperature limit of 2,300°F is given by ISA. The best service is obtained when this couple is used in oxidizing atmospheres, but it can be used in reducing atmospheres or atmospheres that are alternately oxidizing and reducing, if it is supplied with a ventilated protecting tube.

Chromel-alumel thermocouples nicely complement iron-constantan thermocouples in coverage of the range of temperature measurements, but their cost is somewhat higher (although not sufficiently so to discourage their wide use).

The Type E Thermocouple

The Type E Thermocouple is used primarily for oxidizing atmospheres. It does not corrode at subzero temperatures and it is recommended up to 1600°F.

Platinum/Platinum-Rhodium Thermocouples (Types R and S)

Platinum/Platinum-Rhodium Thermocouples also called noble metal thermocouples, are made of a pure platinum negative conductor, and a positive conductor of either 87% platinum and 13% rhodium (Type R) or 90% platinum and 10% rhodium (Type S). Suitably protected, they are recommended for temperature measurements up to about 2,700°F. They are easily contaminated and protecting tubes must always be used with them. Silicon, as well as hydrogen and metallic vapors, will contaminate these couples. (Even the rhodium in the positive thermocouple wire can vaporize somewhat at high temperatures and contaminate the companion platinum wire: thus a full-length, double-bore, ceramic insulator must be used over the pair of wires.) Because of their comparatively high cost and also the low emf produced, practical industrial application of the Type R and Type S couples is limited to the measurement of temperatures beyond the range of chromel-alumel couples.

Yet, as a calibration standard, nobel metal couples are used extensively because of:

1. the reproducibility of their calibration curve
2. availability of the metals in purer forms
3. chemical stability of the metals
4. the high accuracy over a wide temperature range

They have been adopted as the standard for the International Temperature Scale between 1,167°F and 1,945°F.

Type B

Platinum 30% Rhodium/Platinum 6 % Rhodium thermocouples are recommended for use in oxidizing atmosphere. It is easily contaminated in any other atmosphere, so caution should be used in these cases. Type B is recommended up to 3100°F.

Lesson Summary

In this lesson you have learned the basics of temperature measurement and instrumentation found in industrial plants.

In the next lesson you will learn about pressure measurement and instrumentation.

Lesson 3
Pressure Measurement

Lesson Objectives

At the completion of this lesson, you will be able to understand the basic principles of pressure measurement and instrumentation.

Pressure Measurement

Pressure is a fact of life on this planet. Water, a fundamental necessity of life, is supplied to most of us under pressure. In the typical industrial plant, pressure affects boiling point temperatures, condensing point temperatures, and process economics. The measurement of this pressure, or lack of it *(vacuum)*, in the plant is critical.

Pressure is defined as force divided by the area over which it is applied. The mathematical formula is expressed as $P = F/A$, where P is pressure, F is force, and A is area. Let's look at an example of what this statement means.

If we have an object that weighs 100 pounds and rests on one square inch of the earth's surface, it is exerting a pressure of 100 pounds per square inch. Figure 3.1 illustrates this point.

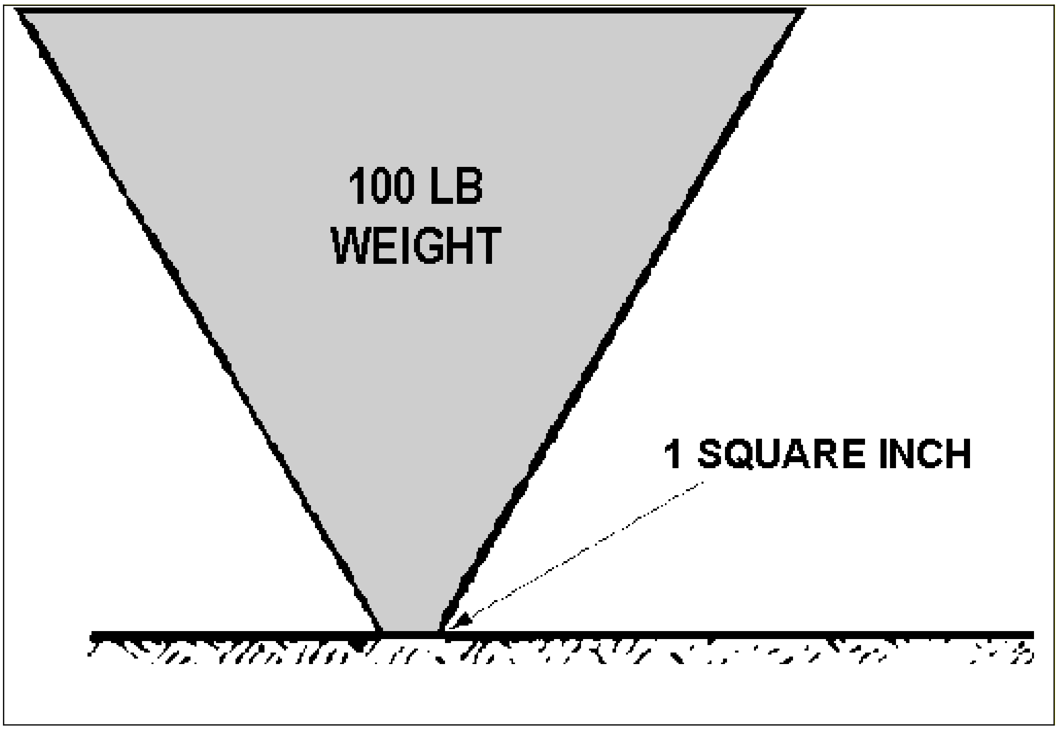


Figure 3.1 Pressure Example

A container of liquid exerts a pressure on the earth just as a solid object does. This is known as *hydrostatic pressure*. Different liquids will exert different amounts of pressure.

Water is used as the reference liquid in comparing the density of liquids or solids.

Density is the mass per unit volume of material. To show this difference look at the comparison between the inches of mercury and water needed to exert a pressure of one pound per square inch (1 psi) in the table below.

Table 3.1 psi Comparisons

Type of liquid	Inches needed to exert 1 PSI
Water	27.7
Mercury	2.04

Air is used a reference in comparing the density of gases. This comparison is called *relative density* and is sometimes referred to as *specific gravity.* The table below lists some common materials and their densities and specific gravity.

Table 3.2 Common Materials Densities and Specific Gravities

Substance	Density lb/ft^3	Specific Gravity
Liquids		
Water	62.43	1.00
Crude	48.70 - 57.43	0.78 0.92
Gasoline	42.45	0.68
Fuel Oils	51.19 - 59.31	0.82 - 0.95
Mercury	849.04	13.60
Solids		
Aluminum	168.56	2.70
Lead	706.46	11.35
Gases		
Air	0.076	1.0
Hydrogen	0.005	0.069
Oxygen	0.084	1.10

Pressure Measurement Scales

There are three scales for pressure measurement:

- Gage pressure (PSIG)
- Absolute pressure (PSIA)
- Vacuum

The location of the zero point is the difference between gage pressure and absolute pressure. On gage pressure the zero point is at atmospheric pressure, which is 14.7 PSI at sea level. Atmospheric pressure is the pressure exerted by the air surrounding the earth. The higher one gets above sea level the less atmospheric pressure there is as seen by the comparison table below. Most pressure gauges will read zero when open to the atmosphere even though there is really 14.7 PSI present.

Table 3.3 Elevation to psi Comparisons

Elevation	Pressure Reading
Sea Level	14.7 psi
5,000 feet above sea level	12.2 psi
10,000 feet above sea level	9.7 psi

Absolute Pressure

In the previous sections, various types of hardware were discussed. The elements mentioned all measured pressure with reference to atmospheric pressure In other words, the pressure being measured was in addition to the pressure already being exerted by atmospheric pressure. Atmospheric pressure (also called barometric pressure) is that which is exerted by the blanket of air surrounding the earth, and is approximately 14.7 psi or 30 inches (760 mm) of mercury. It varies with elevation and weather conditions. When a measured pressure is referenced to atmosphere, it is called “gage pressure”.

In some industrial or laboratory applications, it is necessary to measure a pressure, which is referenced to an unchanging, absolute value rather than atmospheric pressure. We call this absolute pressure. A chart showing the relationship between absolute pressure and gage pressure is given in Figure 3.2.

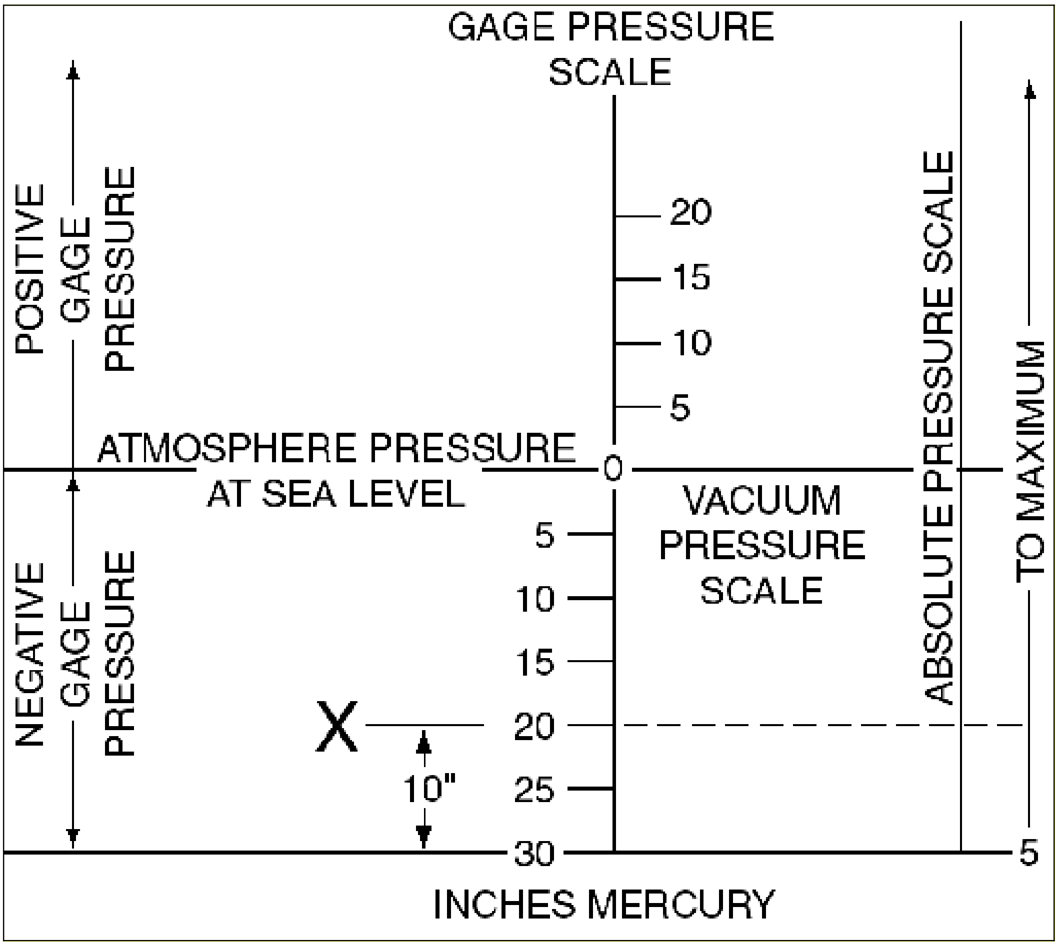


Figure 3.2 Pressure Chart

Importance of Pressure Measurement in Industry

Measurement of pressure in the process industries is important for a variety of reasons. Differential pressure is the driving force in fluid dynamics; pressure is one of the fundamental terms in the ideal Gas Law and its modifications. Pressure is one of the determining factors in vapor-liquid equilibria (it is estimated that about 75% of the processing in a petroleum refinery involves distillation); and pressure is a consideration in the safe operation of process equipment.

Remember we defined Pressure as force per unit area. It is expressed in a wide variety of units. Table 3.4 at the end of this module is a pressure conversion table, which relates the most common units to the SI unit, the Pascal. From a very broad standard point we could say we are interested in measuring pressure from 0 psi absolute to infinity, At present, however, equipment is available only to measure pressures from about 10-12 mm Hg to 6,000,000 psi. A wide variety of measuring devices are used in the process industries.

Where pressure is monitored as opposed to being controlled, measurement is generally made by directly actuated mechanical elements. In plants where economies can be realized by extensive automatic instrumentation, and where precision of control, automatic data processing or quick analysis of operations are important, electronic instrumentation meets these needs.

Pressure Instrumentation

Gages

Helix and Spiral Gages

Helix and spiral elements are made from thin-walled tubing that has been flattened to produce a long narrow elliptical cross section. This flattened tubing is then formed into a helix or spiral as required, with one end sealed. It pressure is applied to the open end, the tube tends to uncoil and the resulting motion, through a suitable linkage, drives a pen or pointer.

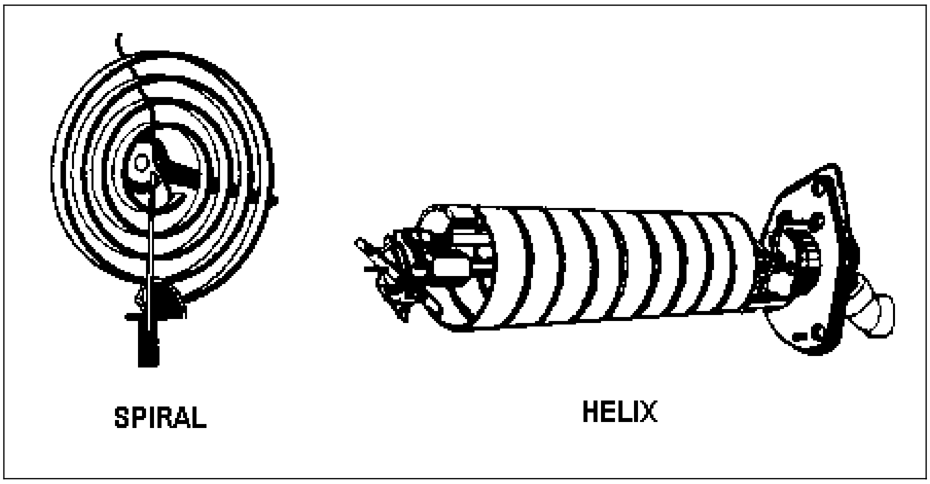


Figure 3.3 Spiral and Helix Gage Example

Since these two elements (illustrated in Figure 3.3) provide large movements of the free end, they are ideal for use in direct actuated instruments of the recording and/or indicating type.

The spiral is normally used for pressure ranges from 0-20 to 0-4000 psi and the helix from 0-100 to 0-80.000 psi.

Helix and spiral gages are made from bronze, steel, stainless steel or special alloys, depending on the pressure range and application.

Bourdon Tube Gages

The bourdon tube is made from a thin-walled tube, which may be flattened a small or large amount depending on the material and pressure range. One end is sealed and closed. This tubing is then formed into a C shape, and with pressure applied to the open end, the tube tends to straighten out. The bourdon tube, as shown in Figure 3.4, can be used for pressure ranges from 0-15 to 0-100,000 psi. Bourdon tube gages are normally made of stainless steel, copper alloy or special alloy. The bourdon tube-measuring element is most widely used on concentric indicating pressure gages.

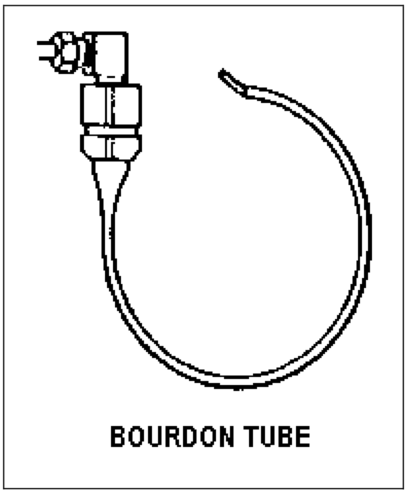


Figure 3.4 Bourdon Tube Example

Spring and Bellows Gages

Pressures in what are termed the intermediate and low ranges cannot be measured satisfactorily with the spiral. The type of spring-opposed bellows element illustrated has been developed for these lower pressures (Figure 3.5).

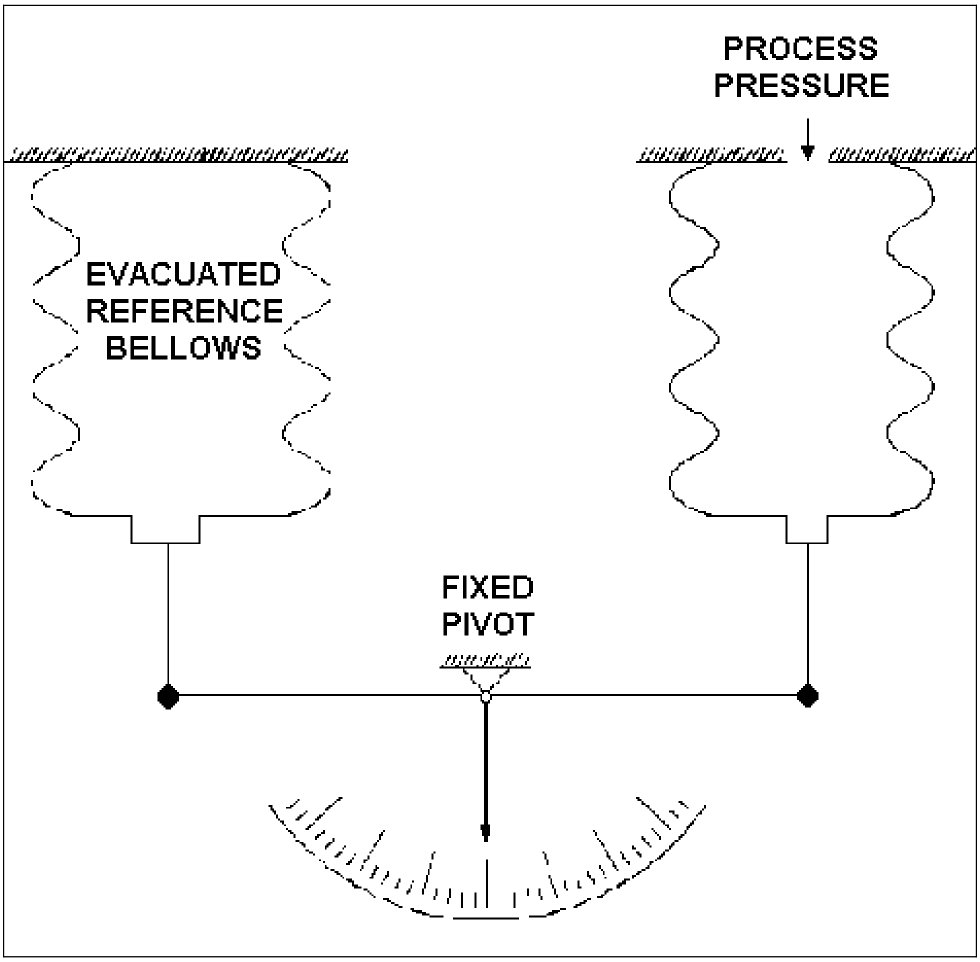


Figure 3.5 Bellows Example

The intermediate range unit, with either brass or stainless steel bellows, is used to measure pressures with full-scale values between 5 and 25 psi. The unit is made up of a metallic bellows enclosed in a shell. Pressure acting on the inside of the bellows, expands the bellows, and moves its free end upward against the opposing force of the spring. A rod resting on the bottom of the bellows transmits this vertical motion through a linkage into linear pen or pointer movement.

For lower pressures and vacuums, a second type of spring-opposed element is employed. In this unit, mounted on the back of the receiving instrument case, the pressure is connected to the inside of a larger bellows. For the measurement of vacuums or combinations of vacuum and pressure, this element is also equipped with a spring that opposes the collapsing bellows. This low-pressure element, a brass bellows, is generally used for minimum full-scale pressures of 5 inches of water up to 90 inches of water, and vacuums of 5 inches of water.

These elements are characterized by an extremely long life, as proved by tests, which indicate the bellows and springs will withstand millions of cycles of flexing without rupture. Phosphor bronze is commonly used for the bellows, and the springs are made of carefully heat-treated alloy steel.

The bellows gradient is small in comparison to the spring gradient and has little effect on the calibration of the unit. The bellows, which generally does not have too linear a gradient, merely serves as a pressure enclosure. With such a construction, a change in range can often be made simply by replacing the spring with one of a different gradient.

Diaphragm Capsule Gages

The diaphragm capsule, shown in Figure 3.6, is made up of a number of circular metal diaphragms, which are welded together at both their inner and outer edges around their complete periphery. The complete unit becomes a flexible container, closed off at one end and open to a piece of connecting tubing at the other. The diameter and number of diaphragms used to make up the complete capsule assembly depend on the pressure span required. The process pressure is applied to the inside of the capsule through the connecting tube, and expands the capsule.

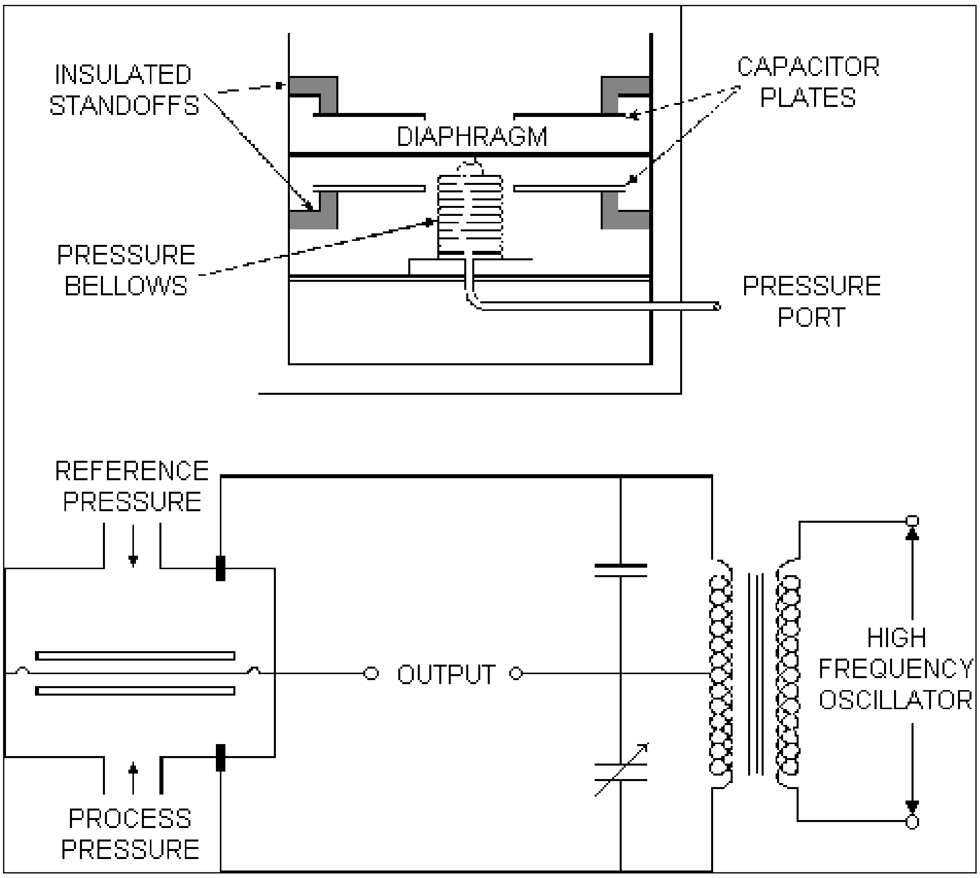


Figure 3.6 Diaphragm Example

This unit can be used for pressure ranges from 0-10 inches of water to 0-100 psi. The materials may be stainless steel or alloys of any type.

Inverted Bell Pressure Gages

The inverted bell type of pressure gage (Figure 3.7) is confined to applications requiring a sensitive, small-range pressure gage for relatively low pressures and vacuums. It is available in a single inverted bell model for measuring static pressures (where the instrument is located at the point of measurement and atmospheric compensation 'is unnecessary), or in a double inverted bell model for differential pressure measurement and control where compensation is required.

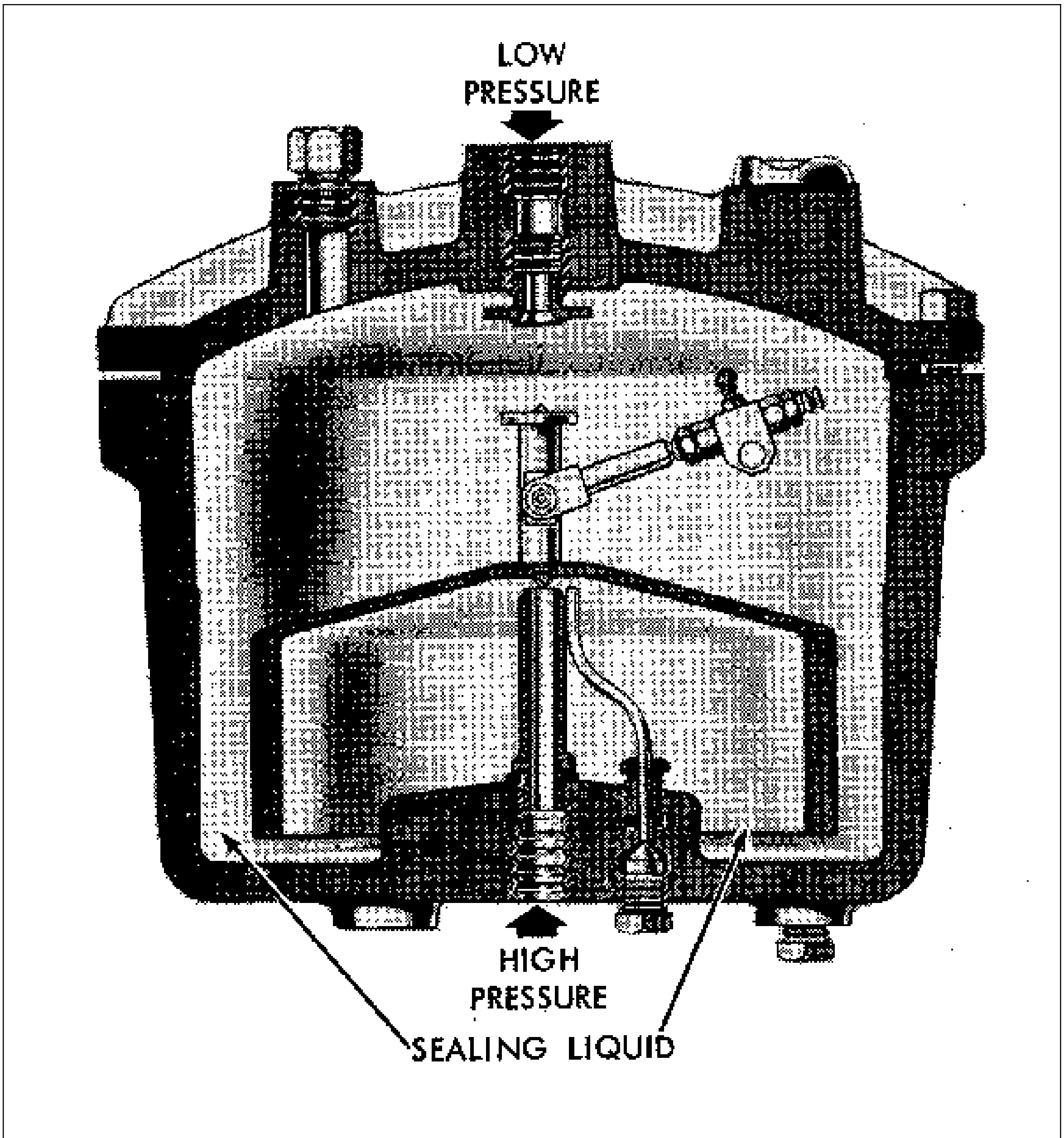


Figure 3.7 Inverted Bell Pressure Gage

The single bell model consists of an inverted bell suspended in such a way that it is immersed in oil, and arranged so that the measured pressure raises the bell and moves a balance beam which has a counterweight on the opposite end. Movement of the balance beam is transmitted through a mechanical linkage to a pressure indicating assembly.

A wider field of application is found for the double bell model which incorporates two inverted bells, partly immersed in oil which acts as a liquid seal, supported from the opposite ends of a balance beam and arranged so that a pressure can be introduced under each bell.

In effect, this arrangement weighs the most minute difference in pressure between the two pressure lines. As a result, the instrument is particularly adaptable to the measurement and control of furnace and heater draft conditions, particularly where atmospheric pressure compensation is necessary. (One of the lines may be exposed to atmosphere, the other connected to the interior of a furnace, so that the instrument will indicate the pressure differential.)

Inverted bell type pressure instruments are sensitive to within ± .0005 inch of water and are available in scale ranges inches of water pressure with spans as of 0-2 inches of water vacuum to 0-5 low as 0.2 inch of water.

Absolute Pressure Gages

The use of absolute pressure gages is generally confined to the accurate measurement and control of pressure low enough to be seriously affected by variations in barometric pressure. Today, many industrial processes require such control to assure a uniform product or to attain the highest yields.

The importance of compensating for variations in atmospheric pressure can be illustrated by considering control of a distillation column, which is to operate at 50mm Hg absolute. If controlled by a vacuum gauge, the set point would be set by reading atmospheric pressure on a barometer and subtracting 50mm from it. So, if atmospheric pressure were 760mm Hg, the set point would be 710mm Hg vacuum. As long as atmospheric pressure remained 760mm Hg, control would remain at 50mm Hg absolute. If atmospheric pressure should rise to 775mm Hg, however, the control system, continuing to control at 710mm Hg, would actually raise the absolute pressure to 65mm Hg, or 30% over that desired.

This error, which is sufficient to seriously impair the effectiveness of a process, could be corrected by periodic readings of the barometer, but this would have to be done frequently and the main advantage of automatic control would be sacrificed. Absolute pressure measurement is the ultimate answer to control problems of this type.

The absolute pressure gage uses an upper evacuated bellows, which is sealed at very nearly a perfect vacuum, and an opposed lower actuating bellows, which is connected to the measured pressure. The adjacent end of each bellows is attached to a movable plate, which transmits the bellows movement to the recording pen through a mechanical linkage.

The method of operation is identical to that of a conventional spring-opposed bellows element insofar as the actuating bellows is concerned. However, a difference in the resultant operation of the actuating bellows is obtained from the action of an evacuated bellows which expands and contracts in accordance with variations in barometric pressure. This action prevents any movement of the pen or pointer with changes in atmospheric pressure by the application of an equal but opposite force to the actuating bellows. The evacuated bellows functions like an aneroid barometer in its response to changes in atmospheric pressure.

Bellows of brass or stainless steel are available in pressure ranges for 0-100 mm of mercury absolute to 0-60 inches of mercury absolute.

Electronic Transmitters

There are a number of industrial applications where it is either impractical or unsafe to bring process information directly into the control instruments.

These include:

- Distances — The process variable would lose amplitude or be distorted
- Safety — High pressures or dangerous chemicals are best kept out of a control room
- Compatibility — The control instruments require a standard signal for their input

In such cases, a process variable transmitter is used. A PV transmitter is a device that measures a process variable (either directly or with a remote sensor), converts this process information into a standard signal (typically 4-20 mA or 3-15 psi), and transmits this signal to the display or control instrumentation.

Principles of Transmitter Operation

As noted above, the output from a PV transmitter can be either a standard pneumatic or electronic signal. The majority of transmitters today are electronic, but some pneumatic transmitters do exist in plants today. When pneumatic, the principle of operation is fairly universal. When electronic, the principles on which it can operate are incredibly diverse.

Pneumatic transmitters operate from a 20 psi supply, from which a 3-15 psi output is produced. The process pressure, through a motion-balance or force balance mechanism, sets the position of a movable flapper against a fixed nozzle. At minimum process pressure, the space between the nozzle and the flapper is maximum and the output pressure is minimum (3 psig). With maximum process pressure, the space is minimum and the output is maximum (15 psig). Normal full-scale travel of the flapper is about 0.003 in. (See Figure 3.8.)

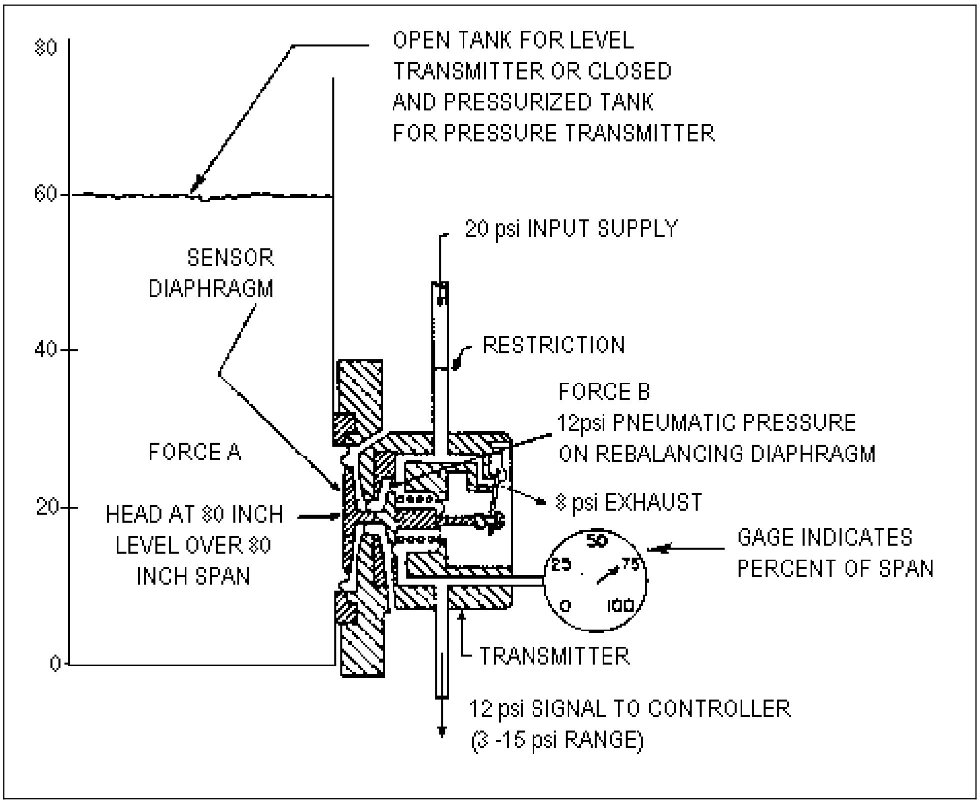


Figure 3.8 Diaphragm Transmitter in Force Balance System

In electric transmitters, some of the sensors used are strain gage, diffused silicon, electromagnetic, ultrasonic, piezoelectric, capacitance, variable permeability and several other types. Only the strain gage principle and a state-of-the-art pressure transmitter that operates on it will be discussed here.

In strain gage type instruments, either a metal wire or a semiconductor chip can be used as the pressure-sensing element, whose resistance varies as incoming process pressure deflects it. This change in resistance can be measured using a bridge circuit.

The Honeywell standard pressure transmitter uses a chip of piezoresistive silicon. The sensor (Figure 3.9) is a fully active Wheatstone Bridge of resistors diffused into a single crystal silicon chip, hence the name Diffused Silicon Transmitter. The direct conversion of pressure into an electrical signal is achieved by a minute deflection of the sensor, which changes the resistance of the bridge with the applied stress. Changes in pressure cause a corresponding change in the transmitter amplifier output.

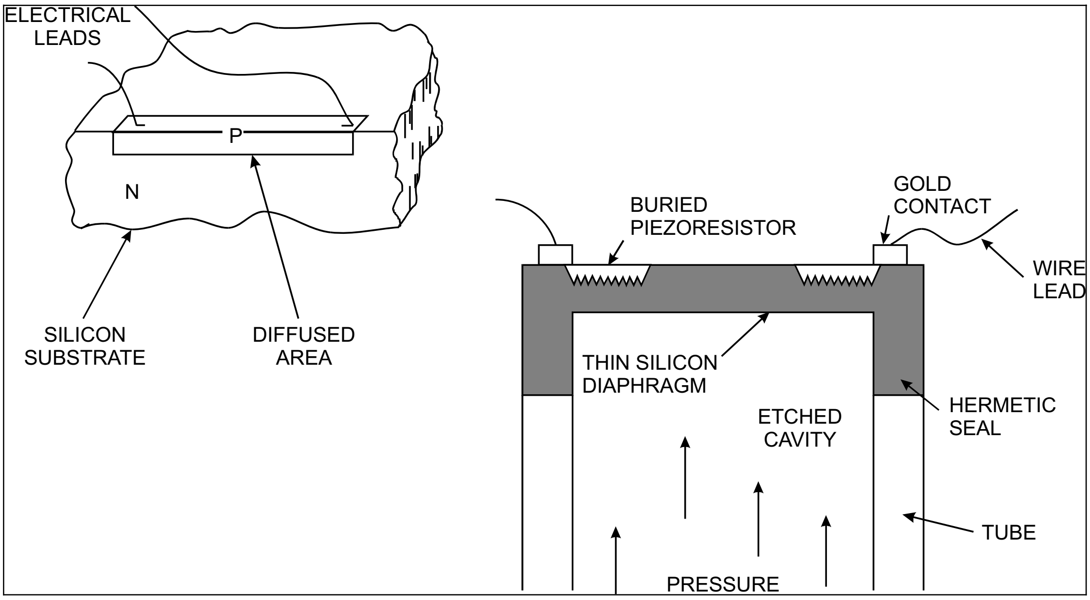


Figure 3.9 Pressure Transmitter with Piezoresistive Silicon Chip

This output, in addition to being the 4-20 ma transmission signal proportional to pressure, is fed back through the feedback resistor into the bridge as shown in Figure 3.10. This feedback balances the bridge and provides stability. In essence, the transmitter has a sensitive and accurate null-balance measuring circuit.

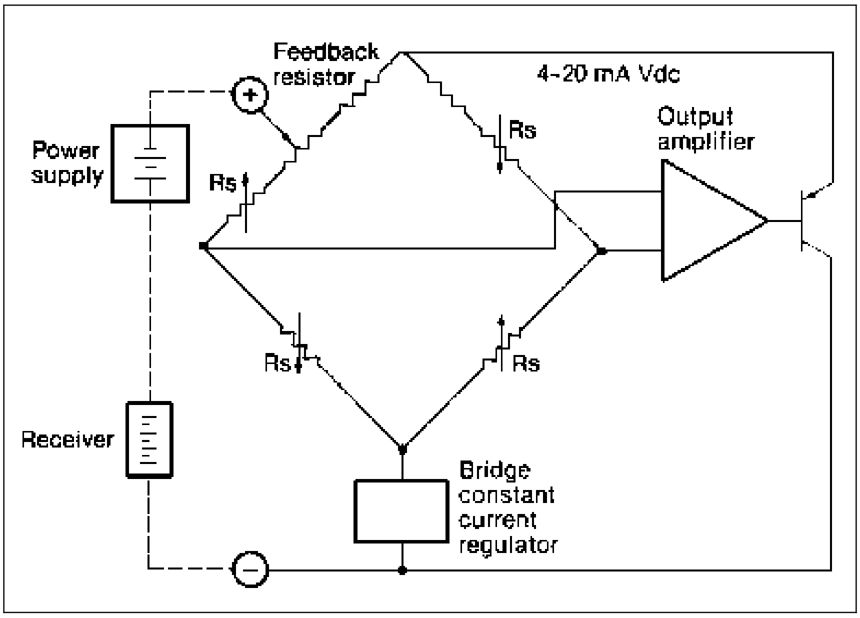


Figure 3.10 Balanced Bridge/Amplifier Circuit

The sensor is permanently sealed in a silicone fluid in the center section of the meter body and protected from the process by an internal metal diaphragm (Figure 3.11). Pressure is applied to the diaphragm and transferred through the protective fluid to the strain gauge. A flexible tape circuit strip connects the bridge elements to the amplifier circuitry on the electronic circuit board. No mechanical linkages, levers or pivots are required. All adjustments are electrical.

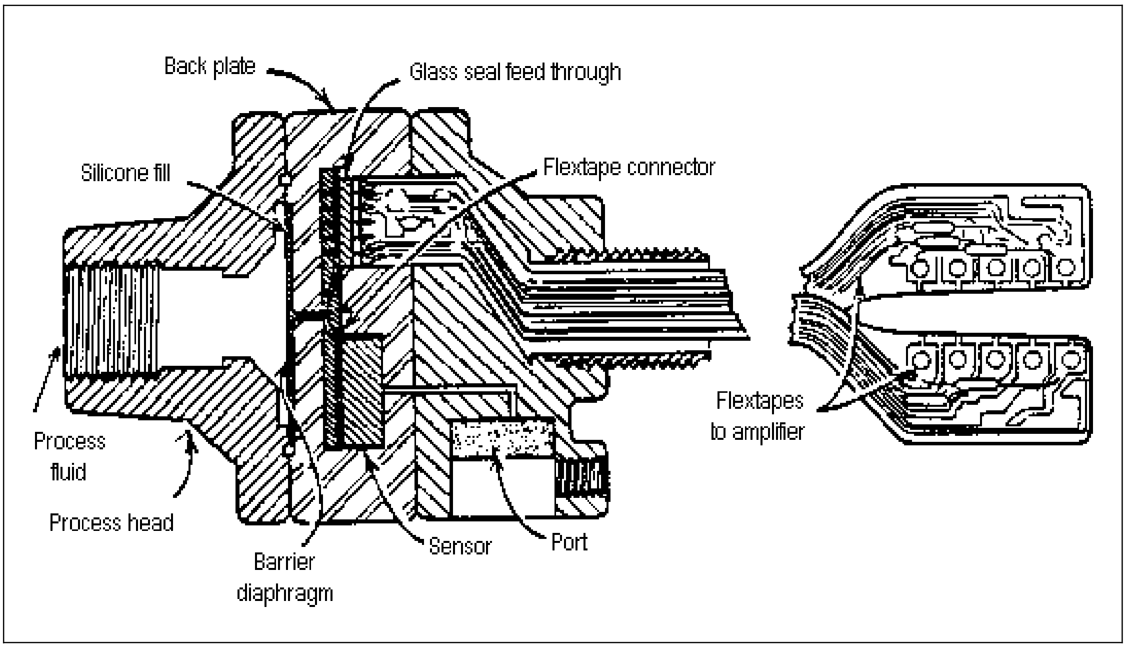


Figure 3.11 Cutaway View of Process Pressure Meter Body

Today there are transmitters that use *"smart"* technology, which was invented by Honeywell. An instrument is smart when it takes full advantage of microprocessor technology to provide:

- Bi-directional digital communication between transmitter and controller or the PC-based or Field Communicator.
- Diagnostics of the transmitter electronics, sensor and loop.
- Reliable and proven design.
- Broad rangeability.
- Characterization for stable outputs under varying operational and environmental conditions.

Smart Transmitters deliver the highest standards of accuracy, stability and repeatability. These features, along with their inherent smart capabilities, enable these products to deliver more precise measurement signal thereby improving control.

Table 3.4 Conversion of Pressure Units to the SI Unit[a]

To convert from	*To*	*Multiply byb*	
atmosphere (normal = 760 torr)	pascal (Pa)	1.013 25	E+05
Atmosphere (technical = 1 kgf/cm^2)	pascal (Pa)	9.806 650*	E+04
bar	pascal (Pa)	1.000 000*	E+05
centimeter of mercury (O°C)	pascal (Pa)	1.333 22	E+03
centimeter of water (4°C)	pascal (Pa)	9.806 38	E+01
decibar	pascal (Pa)	1.000 000*	E+04
dyne /centimeter^2	pascal (Pa)	1.000 000*	E-01
foot of water (39.2°F)	pascal (Pa)	2.988 98	E+03
gram-force/centimeter^2	pascal (Pa)	9.806 650*	E+01
inch of mercury (32°F)	pascal (Pa)	3.386 389	E+03
inch of mercury (60°F)	pascal (Pa)	3.376 85	E+03
inch of water (39.2°F)	pascal (Pa)	2.490 82	E+02
inch of water (60°F)	pascal (Pa)	2.488 4	E+02
kilogram-force/centimeter^2	pascal (Pa)	9.806 650*	E+04
kilogram-force/meter^2	pascal (Pa)	9.806 650*	E+00
kilogram-force/millimeter^2	pascal (Pa)	9.806 650*	E+06
kip/inch^2 (ksi)	pascal (Pa)	6.894 757	E+06
millibar	pascal (Pa)	1.000 000*	E+02
millimeter of mercury (O°C)	pascal (Pa)	1.333 224	E+02
poundal/foot^2	pascal (Pa)	1.488 164	E+00
pound-force/foot^2	pascal (Pa)	4.788 026	E+01
pound-force/inch^2 (psi)	pascal (Pa)	6.894 757	E+03
torr (mm Hg, O°C)	pascal (Pa)	1.333 22	E+02

[a]Rel. Metric Practice Guide, A5TM Bulletin E380-79, American Society for Testing and Materials, Phila, Pa., 1979

[b]E = exponent, base ten (eg, E + 02 = 10^2). Asterisk means conversion is exact.

Lesson Summary

In this lesson you have learned the basics of pressure measurement and instrumentation found in industrial plants.

In the next lesson you will learn about level measurement and instrumentation.

Lesson 4
Level Measurement

Lesson Objectives

At the completion of this lesson, you will be able to understand the basic principles of level measurement and instrumentation.

Liquid Level Measurement

The measurement of liquid level enables us to locate the surface of a liquid with respect to some reference level. It is a necessary measurement in the process industries in order to:

- Maintain safe operating levels in steam boilers, storage tanks, reservoirs, process cushion tanks, reflux towers, a vacuum stills, etc.
- Determine by inference the quantity of liquid in a tank, or the quantity flowing in or out of the tank

Inferential Method

One of the most flexible and convenient means of measuring liquid level, especially where there is a considerable change in level, is the static pressure or inferential method. It employs conventional industrial instruments which are readily available and which can easily be equipped for control.

This method is based upon the fact that the static pressure exerted by any liquid is directly proportional to the height of liquid above the point of measurement, irrespective of volume. Thus, any instrument that measures pressure can be calibrated in terms of the height of a given liquid and used to measure liquid level in vessels under atmospheric pressure.

Pressure Gage Method

The simplest method of measuring liquid level in an open tank is shown in Figure 4.1, where a pressure gage having a range equal to the liquid head being measured is used. When the pressure gage cannot be located at the minimum level, the range of the instrument must be shifted to compensate for the head pressure on the gage at minimum level. For corrosive or viscous liquids, or where sediment might clog the pipe to the gage, a seal is necessary, as is shown in the Figure 4.1.

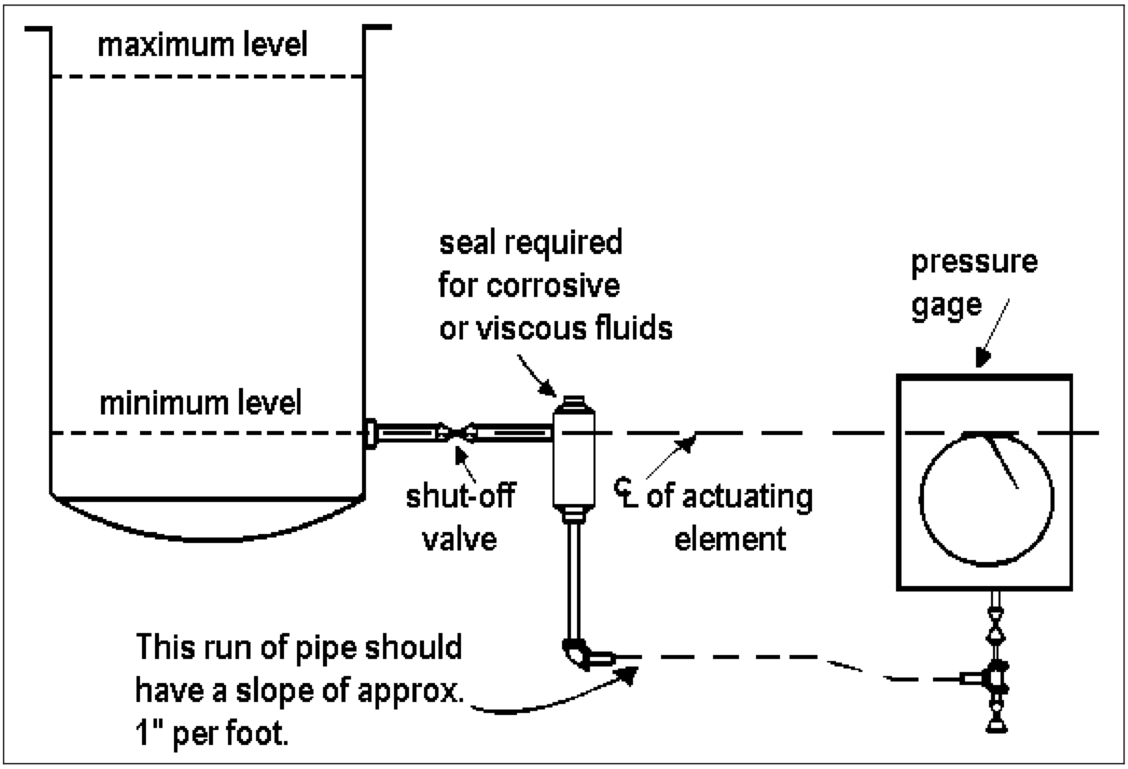


Figure 4.1 Liquid Level Measurement by Pressure Gage Method

This method of level measurement makes possible the use of non-indicating pressure controllers for "high-low" level control. One type that actuates a mercury switch, for example, can turn on an electric inlet pump when the level drops to a low limit and turn the pump off when the high limit is reached.

Diaphragm Box Method

Another pressure-gage level system employs a diaphragm box (Figure 4.2). This box, connected by a tube to the pressure gage, contains a relatively large amount of air, which is retained by a flexible diaphragm. The pressure exerted by the head of liquid against the underside of the diaphragm compresses the air within the box until the air pressure on the upper side is equal to the liquid pressure. The gage measures the air pressure but is calibrated in terms of liquid level.

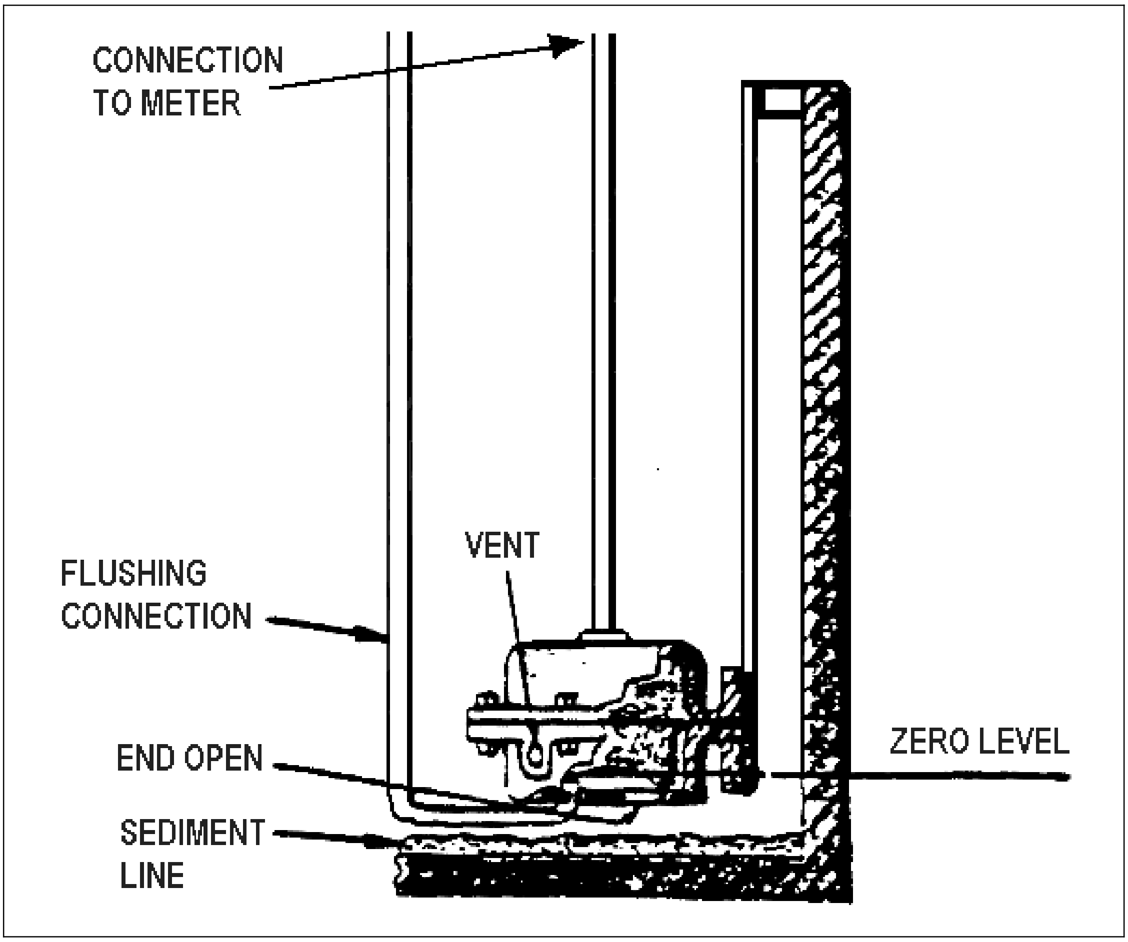


Figure 4.2 Open Type Diaphragm Box

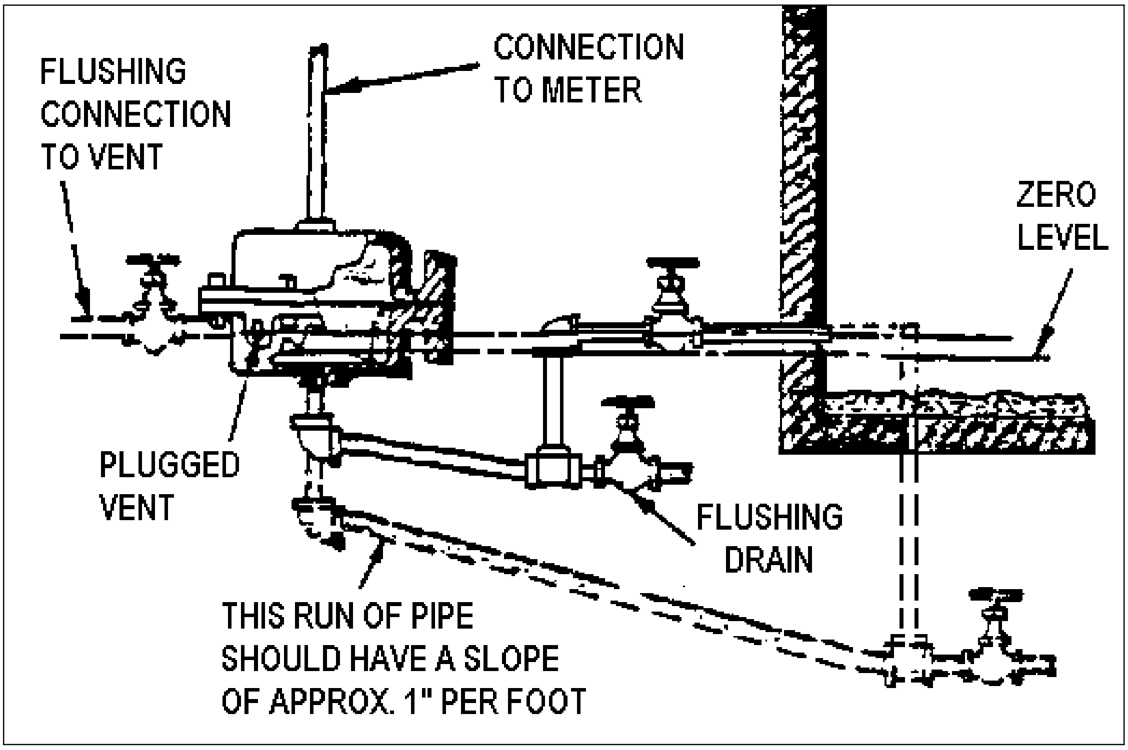


Figure 4.3 Closed Type Diaphragm Box

There are two types of diaphragm boxes — the open type (Figure 4.2), which is immersed in the liquid in the vessel; — and the closed type (Figure 4.3), which is mounted externally and connected to the vessel by a short length of piping. The open box can be used with liquids containing some suspended matter, but the closed box is used only with clear liquids. Neither box should be located more than 50 feet from the gage. Figure 4.4 shows a closed type diaphragm box with a seal pot for use with corrosive fluids.

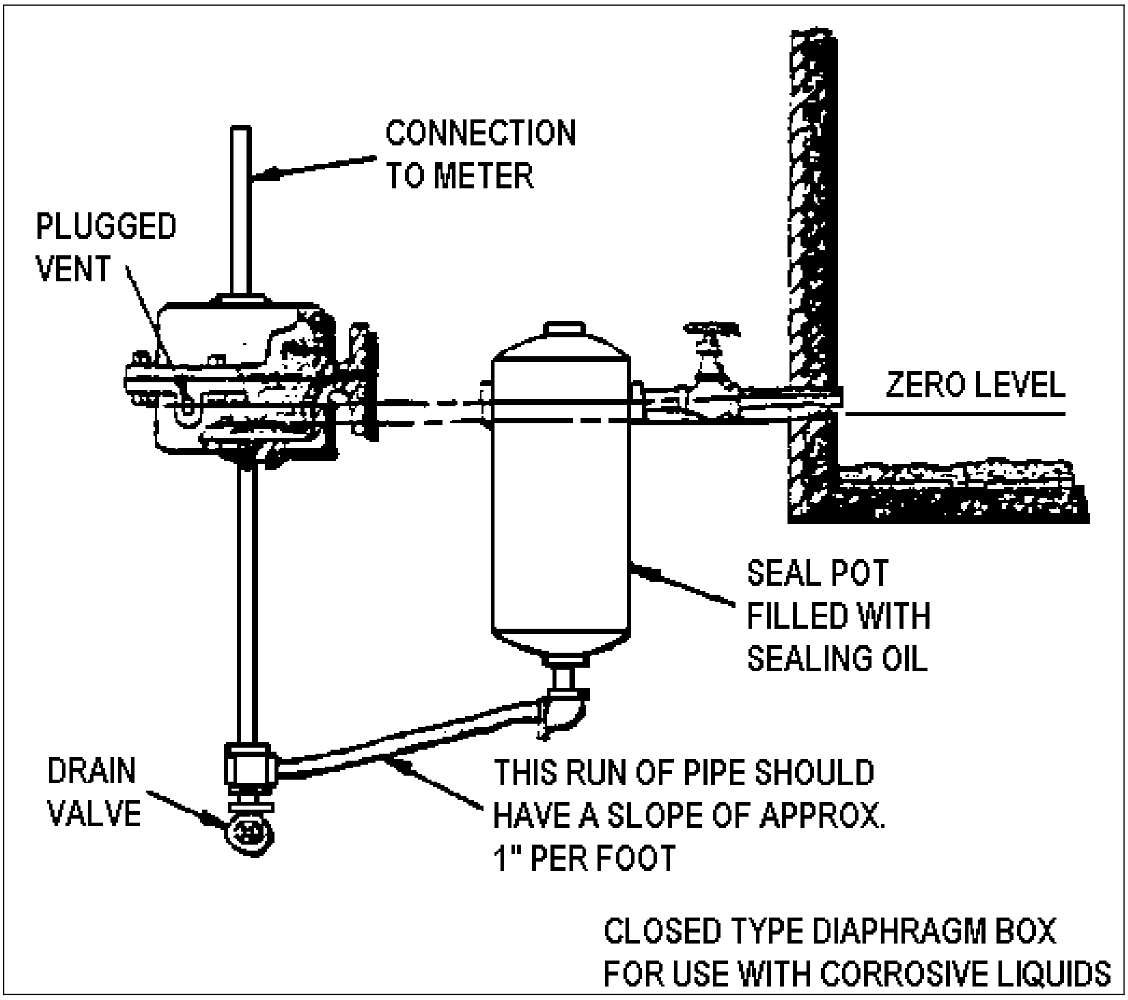


Figure 4.4 Liquid Level Measurement by Diaphragm Box Method

Air Purge Method

This system, shown in Figure 4.5, also involving a pressure gage, does not limit the location of the gage and can be used for corrosive liquids even with relatively large amounts of suspended matter. An air line is immersed in the liquid to the minimum level, with the pressure and volume of air supply controlled by a rotameter with differential regulator so that slow bubbling will occur when the vessel is filled. The pressure in the air line is then equal to the back pressure exerted by the head of liquid. Measurement of this air pressure is, therefore, equivalent to measurement of the static pressure of the liquid — i.e. the liquid level. Where immersion of the air line is not desirable because of agitator blades or for other reasons, the air line can be tapped into the side of the vessel at the point of minimum level.

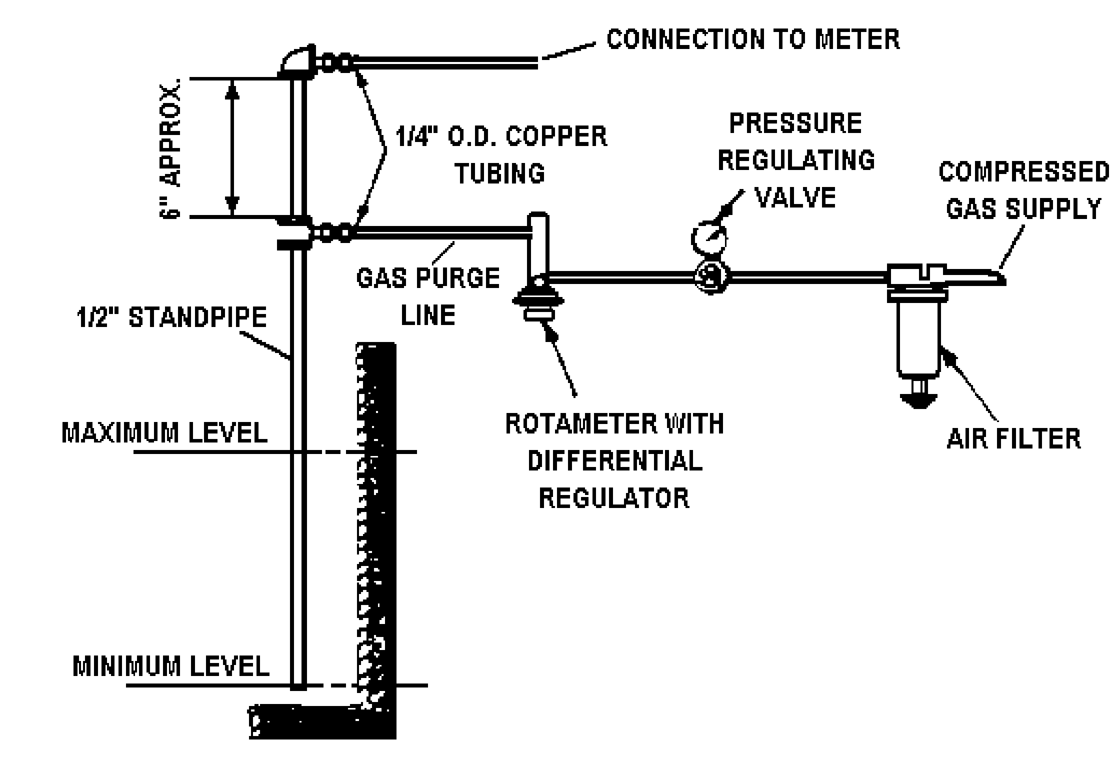


Figure 4.5 Liquid Level Measurement by Air Purge Method

Air purge systems have several limitations. In addition to limited accuracy, one of their major drawbacks is that they must introduce foreign matter into the process. Liquid purges can upset the material balance of the process, and inert gas purges can overload the vent systems on vacuum processes. Because of the large number of components, maintenance is frequently needed and whenever the purge media fails, the detecting instrument is exposed to the process material, causing plugging, corrosion, freezing or other problems. In short, these devices should be avoided where the measurement is critical or where high accuracy is needed. At the same time where economics is the overriding consideration and clean, easy to handle liquids are involved, air purge systems are useful.

Meter Body Method

Liquid levels in open vessels can also be measured with standard type differential pressure meter bodies. The state-of-the-art differential pressure transmitter is the Diffused Silicon Transmitter, whose principle of operation is discussed in the Pressure section (piezoresistive silicon chip) and the flow section (differential pressure meter body operation).

Open Tank Applications

The conventional direct action differential pressure transmitter measures level in open tanks. Measurement can be made directly (with measured liquid or sealing liquid in the meter) or indirectly (using an air or gas purge). Liquid level in elevated open tanks can also be measured, but requires a transmitter with a suppressed zero range. On elevated tanks, the minimum level head can be canceled out by connecting a stand-pipe with an equal head to the LP side.

The liquid head, or with gas purge systems its equivalent gas pressure, is applied to the HIP side. The LP side is vented to atmosphere.

Direct Measurement

Figure 4.6 shows an open tank application. The transmitter should be mounted as close to the tank as feasible. The high-pressure connection on the transmitter meter body is made at the minimum level on the tank to be measured. The low-pressure connection is open to atmosphere. The range of the transmitter is dependent on the height of the level variation to be measured and the specific gravity of the liquid.

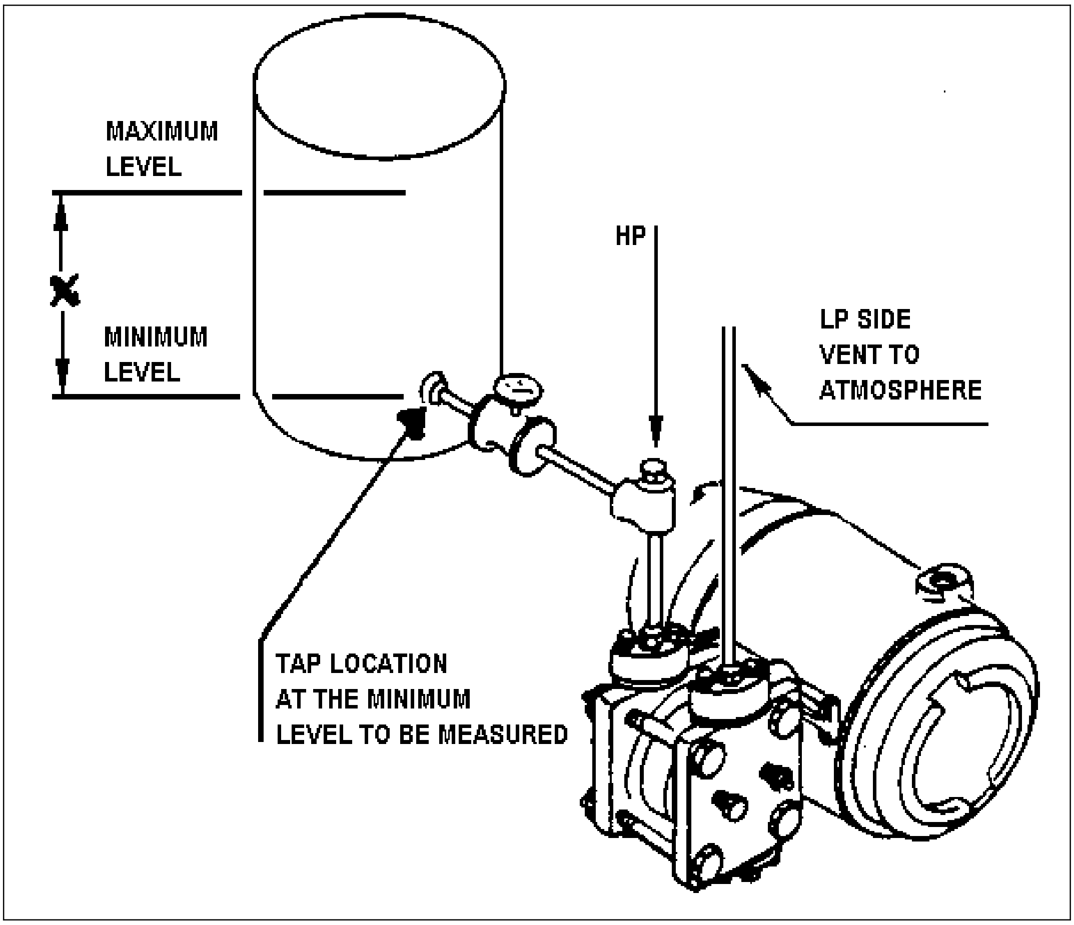


Figure 4.6 Open Tank Application

When measuring liquid level in an elevated open tank (Figure 4.7 and Figure 4.8) elevation E must be canceled out by using a transmitter with a suppressed zero range or balancing with a fixed head equal to E. If E is not canceled out, the transmitter will measure E + X. Since E is often much greater than X, only a small portion of the transmitter's range may be used.

In Figure 4.7, the transmitter is operated with a suppressed zero range. The transmitter is calibrated such that with E felt on the high pressure side and atmosphere felt on the low pressure side the transmitter output will indicate zero differential. Thus, E is cancelled by a strictly electrical manipulation.

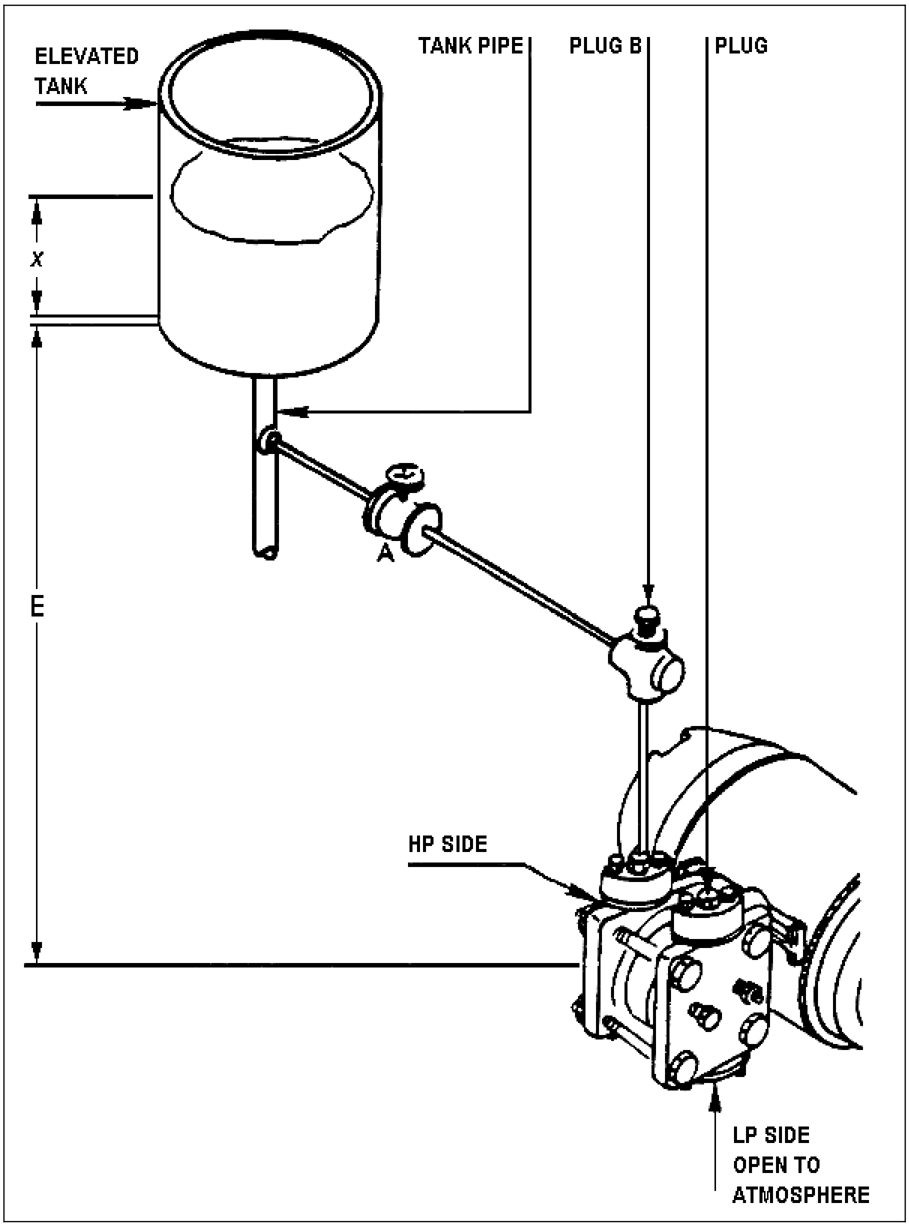


Figure 4.7 Transmitter Uses Suppressed Zero Range Cancel Effect

In Figure 4.8, the effect of elevation is cancelled using a filled reference leg whose height is equal to E. The low pressure side will always feel this head and therefore, when the tank is empty will read zero differential. Care must be taken to ensure that this low-pressure head level is maintained.

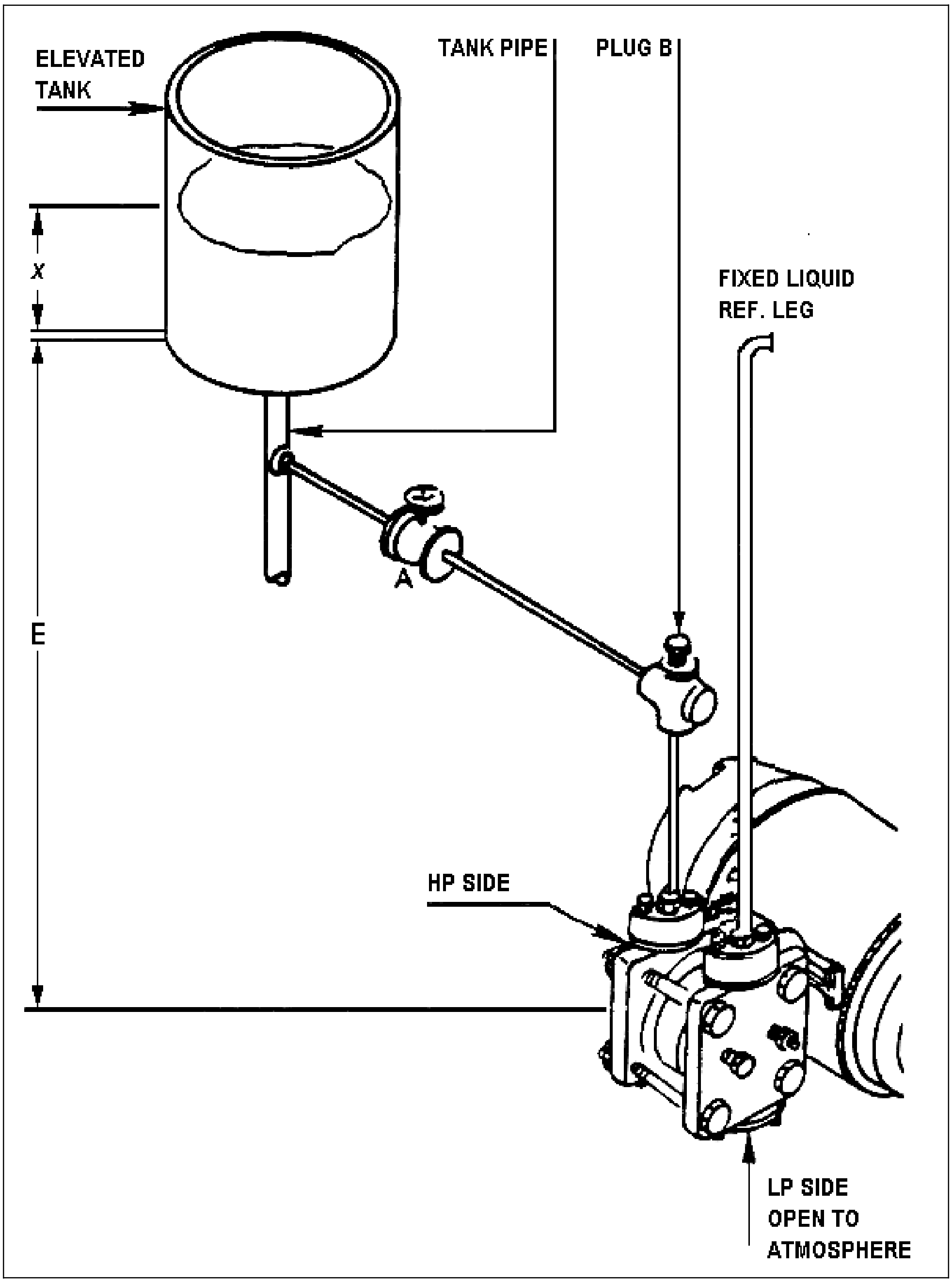


Figure 4.8 Canceling Effect of Elevation with a Filled Reference Leg

It should be mentioned that one advantage of using a transmitter on an elevated tank is that it can be mounted at the minimum level, thereby eliminating the need for suppressed zero range.

Indirect Measurement (Air or Gas Purge)

Purge systems are used on applications where it is impossible or undesirable to connect the transmitter directly to the tank. A purge system is shown in Figure 4.9. Air is usually used, but any dry, non-corrosive gas can be used also. The fluid being measured may be corrosive, may contain suspended solids, may have other properties making its use in the body unfeasible, or the tank draw off may be the only meter fitting on the tank.

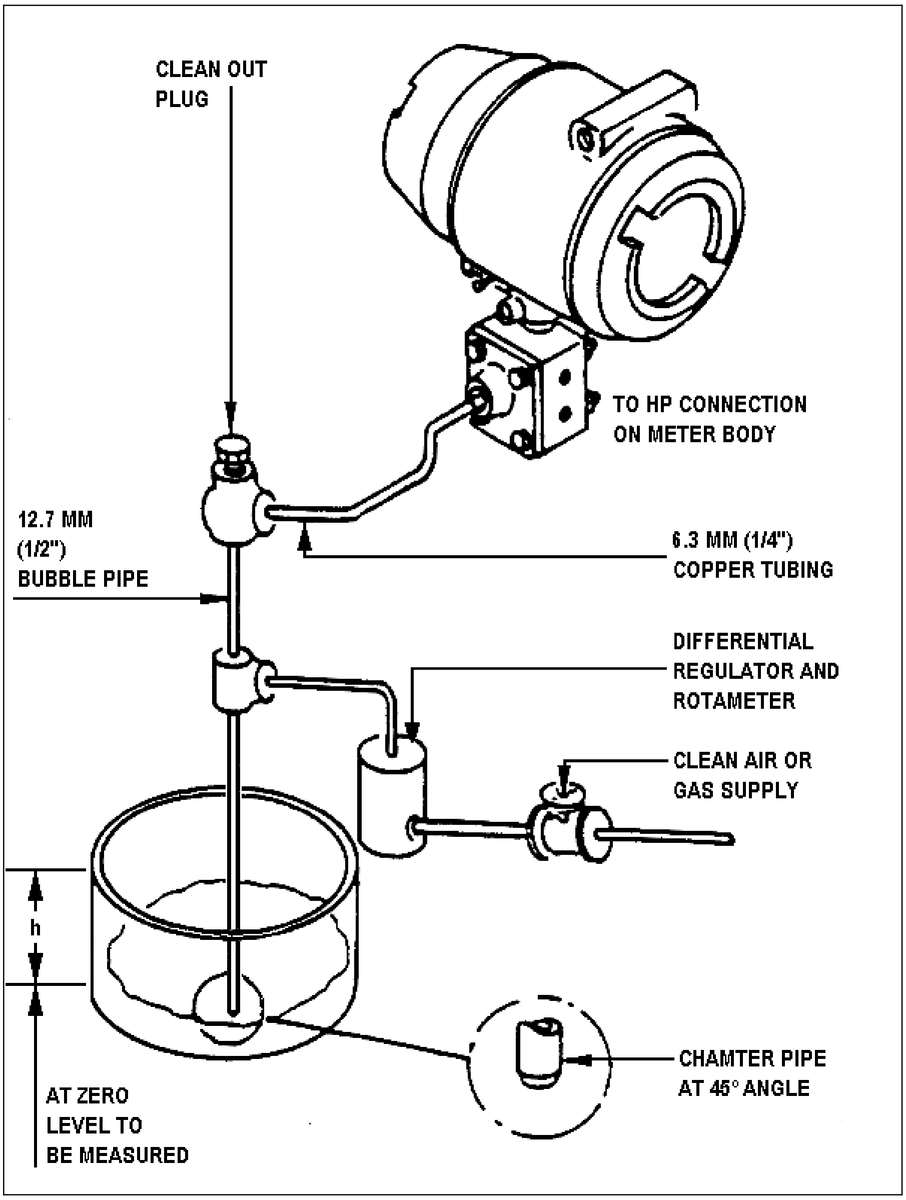


Figure 4.9 Purge System

No liquid enters the meter body. The HP connection is piped as shown in Figure 4.9. The open end of the pipe (often called a bubble tube) or the tank fitting is at the minimum level to be measured. To prevent the body from filling with fluid in the event of purge failure, it should be installed above the maximum tank level. If the transmitter must be installed below the maximum level, the vertical bubble pipe should extend above maximum level before descending to the meter connection.

The transmitter measures the back pressure of air or gas required to balance the head of liquid in the tank. As the head increases, more pressure is required to keep liquid out of the pipe Supply pressure should be slightly greater than the equivalent of the maximum level to be measured to ensure that all liquid is purged from the pipe or tank connections. A differential regulator (one that maintains a constant rate of flow regardless of back pressure is used to control purge rate, otherwise flow would increase as the liquid level drops. introducing errors due to friction loss in the pipe.

A rotameter is a convenient means of indicating flow rate; it also provides indication of purge failure.

Closed Tank Applications

Liquid level in closed tanks (tanks under pressure) may be measured by differential pressure meter bodies also. In these applications, the reference cannot be atmospheric pressure, but must be the pressure in the tank over the liquid, so that the differential pressure measured will be independent of any pressure changes other than those due to changes in level.

Direct Measurement

In its most elementary form, this would require that the LP side of the meter body be connected to the tank above the maximum liquid level. In this manner the pressure above the liquid would be felt on both the LP & HP sides of the meter body and changes in this pressure would not be seen as changes in level.

In practice, however, it is found that liquid from the system frequently finds its way into the reference leg either due to condensation or splash-over, and a changing head due to this liquid is felt on the LP side of the meter body. This causes a zero shift in the measurement. A practical solution to the problem is to fill the reference leg with either the vessel liquid, or if necessary, a sealing liquid. This ensures a constant reference head. This type of system is shown in Figure 4.10.

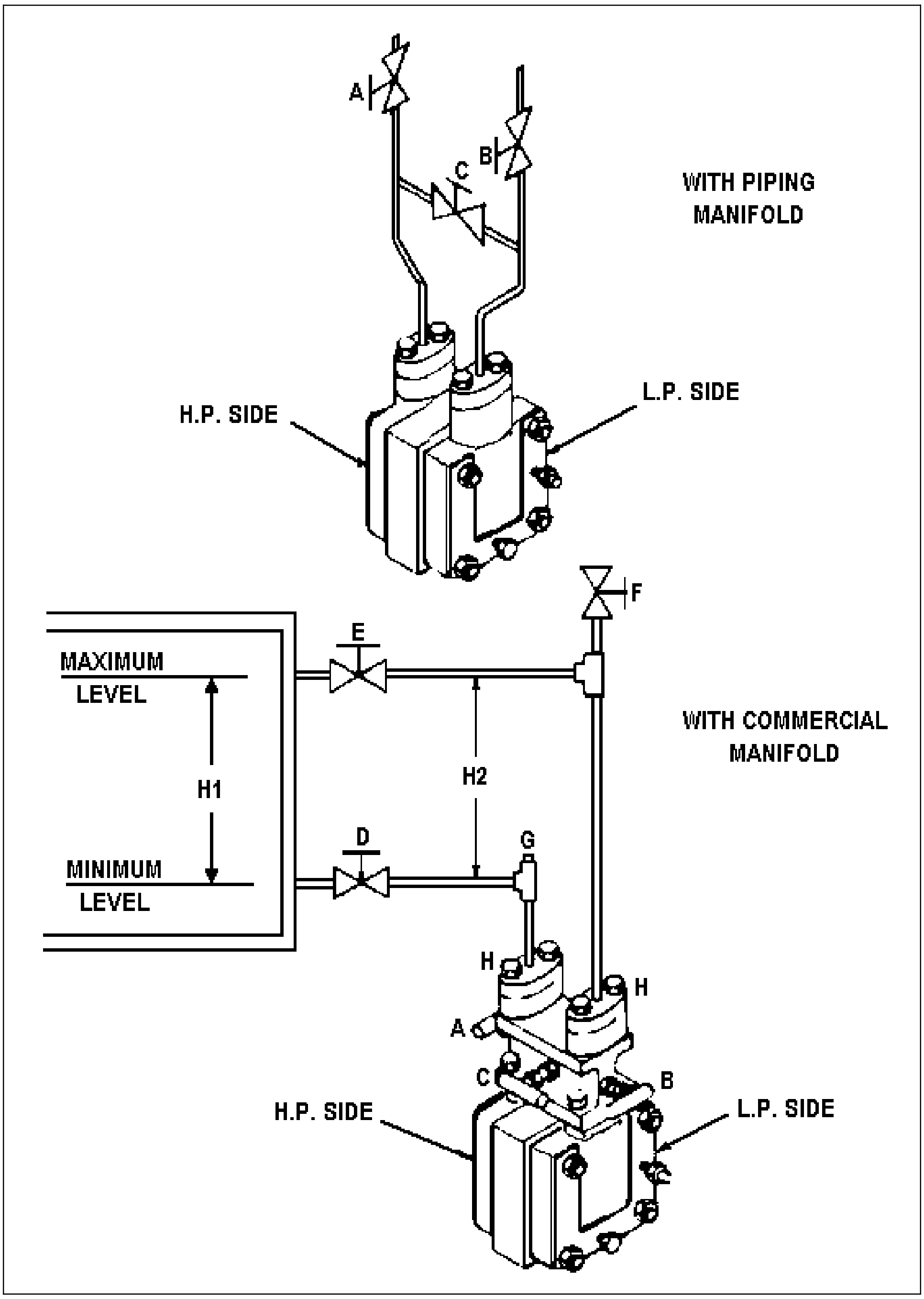


Figure 4.10 Closed Tank Measurement with Empty Tank

As can be seen in Figure 4.10, with the tank liquid at minimum level, the pressure on the tank side connection to the meter body is the tank pressure plus the liquid head in the connecting piping. On the reference leg connection to the meter body the pressure will be the tank pressure plus the liquid head in the reference leg plus the liquid head in the piping below the minimum level. The tank pressure and the connecting piping head cancel out because they are present on both connections to the meter body, and the only differential pressure present is from the liquid head in the reference leg, H^2.

As the tank level increases, the liquid head on the tank side connection increases, and the differential pressure on the meter body decreases. When the tank is full, the liquid head on the tank side connection is equal to the liquid head from the reference leg and the differential pressure is zero.

Several methods of converting the decreasing differential pressure into an increasing output are used in various meter designs. One method uses a different meter body, a mirror image of the standard differential pressure body, which will give an output motion the reverse of the standard body. Another method is to connect the HIP side of the meter body to the tank connection and the LP side to the reference leg and bias the meter body mechanically to be at zero output with max differential pressure (empty tank), which is really a reversed differential (LP > HP). Then as the tank level increases and the differential pressure decreases, the output will increase. Still another method, available on the more recent electronic transmitter is to bias and reverse the electrical output, a relatively simple matter on these instruments.

Indirect Measurement (Air or Gas Purge)

Purge systems can be used where it is impossible or impractical to admit the measured liquid to the meter body and connecting piping. Corrosive liquids and liquids with solids in suspension are two typical examples. Another example is a liquid which, when cooled in the meter body or piping, would solidify or precipitate solids. Some substances such as cryogenic fluids vaporize at relatively low ambient temperature, and cannot exist as liquids at the working temperature of the meter body.

Since only gas or vapor enters the meter body and piping, there is generally a reduced requirement for cleaning. Purge systems also eliminate the need for a fixed reference leg so that direct acting transmitters can be used.

In air or gas purge systems, the meter body and connecting piping are filled with gas or air. This is shown in Figure 4.11. The only liquid head in this system is in the vessel level to be measured. When this vessel head is at the minimum level, the pressure on both the H.P. and L.P. side of the meter body is the vessel pressure and the differential is zero. With the liquid at the maximum level, the pressure on the H.P. side is equal to the vessel pressure plus the liquid head H' and the pressure on the L.P. side is equal to the vessel pressure. The differential pressure on the meter body is therefore equal to the liquid head H, and a standard type meter body with a differential range equal to the head of liquid H can be used. The gas purge pressure must always be greater than the vessel pressure.

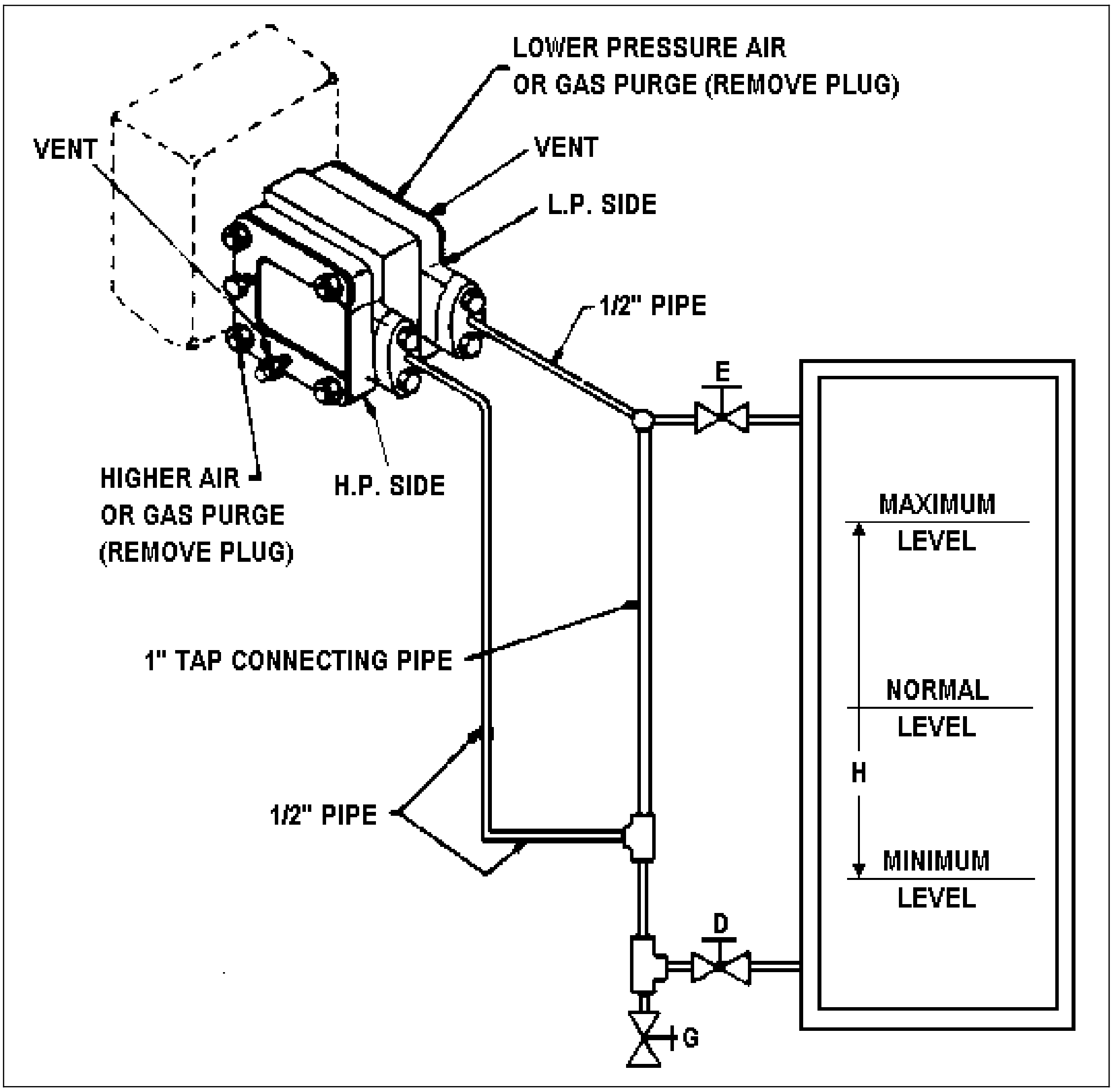


Figure 4.11 Purge System with Meter Body and Connecting Piping

Flange-Mounted Liquid Level Transmitters

In this model of differential pressure transmitter, the meter body is available with a flush mounted diaphragm (Figure 4.12) or an extended diaphragm (Figure 4.13).

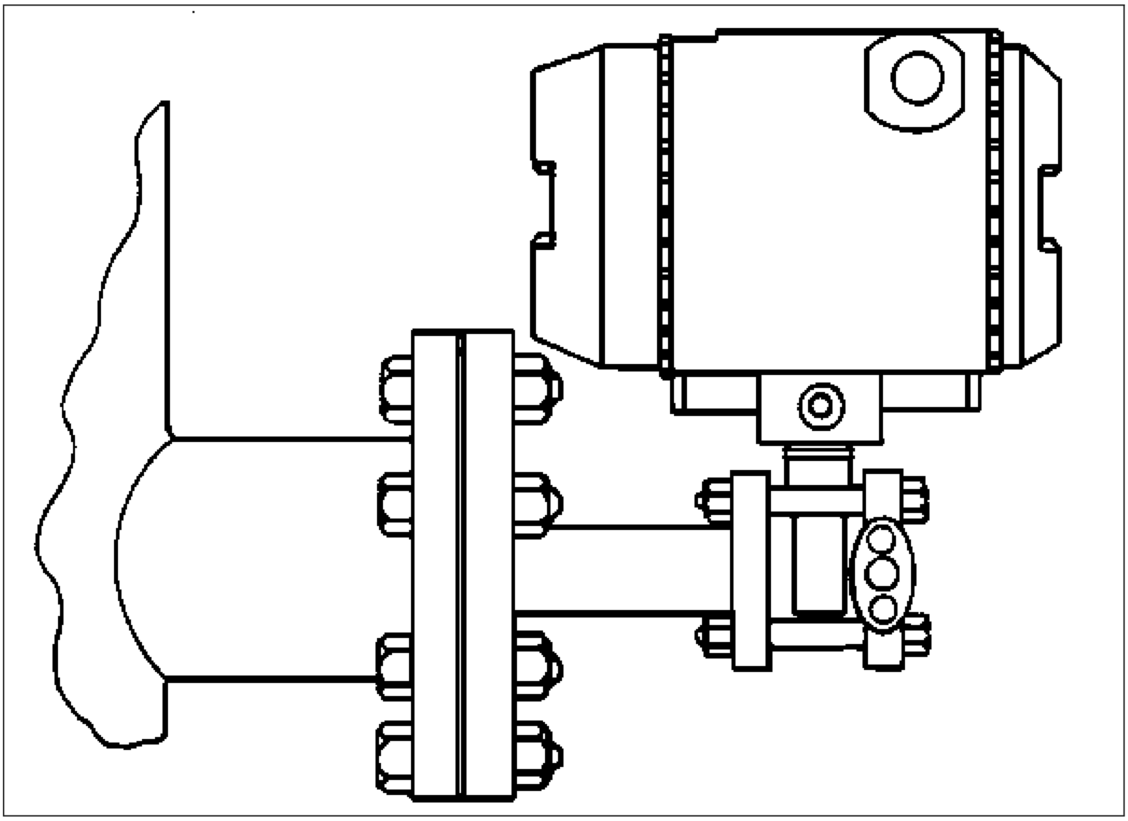


Figure 4.12 Flange-Mounted Model with Flush Diaphragm

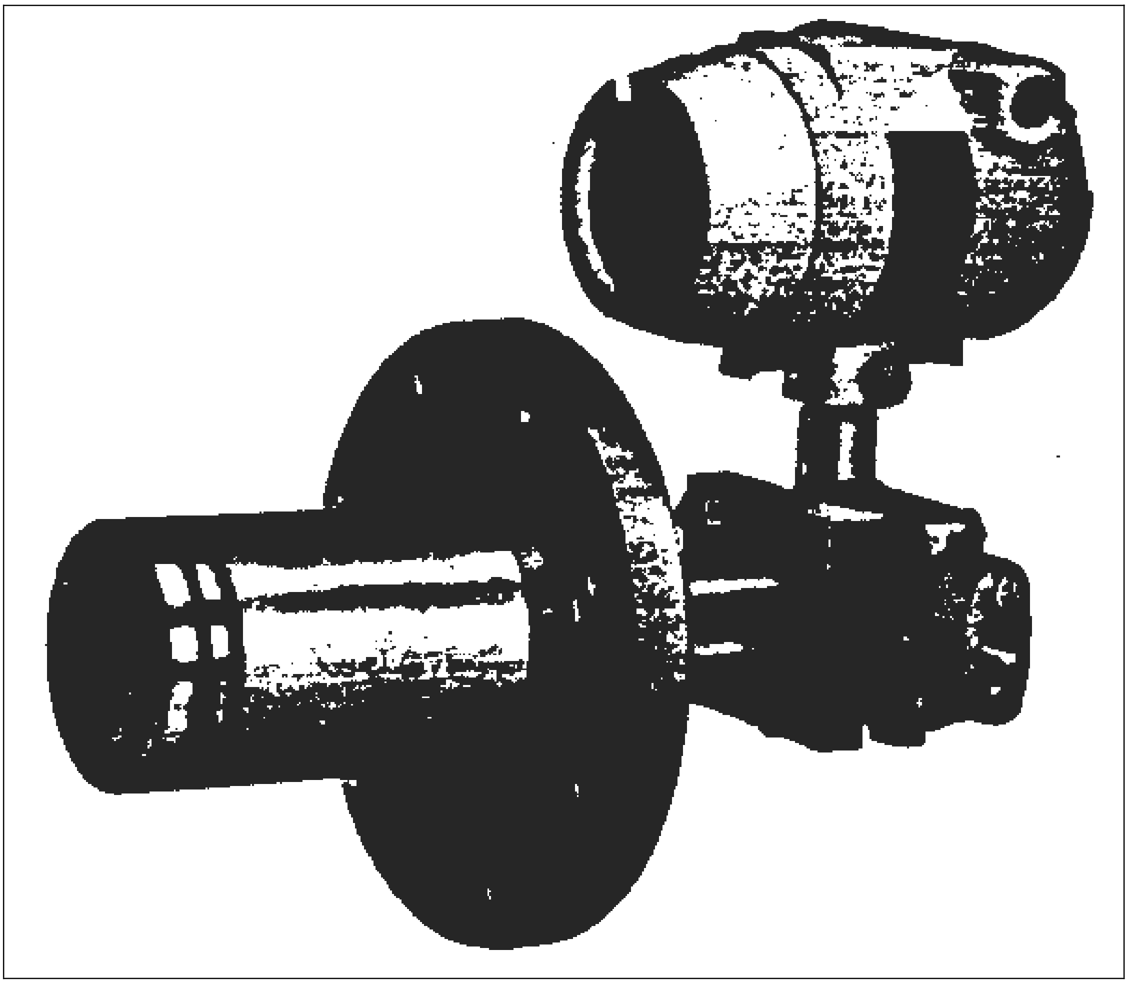


Figure 4.13 Flange-Mounted Model with Extended Diaphragm

The only difference between this model and the conventional one is that the H.P. diaphragm is removed from the center section and placed at the mounting flange or at the end of the extended section. The volume between this diaphragm and the center section is filled with the same liquid as the standard meter body. Thus, there is a metal barrier (diaphragm) between the vessel liquid and the meter body actuating element that obviates the need for a purge system or liquid seals on many applications. This unit is suitable for level measurement of liquids which are highly viscous, contain solids in suspension. slurries, paper pulp, etc. The diaphragm is mounted on the vessel at or below the minimum level to be measured. On application with open tanks, the second pressure connection is open to atmospheric pressure. On closed tank application, the second connection must be made from the vessel above or at the maximum level to be measured and this connection must terminate on the L.P. side of the meter body. In this manner, the vessel pressure is impressed on both the H.P. and L.P. meter body chambers and the differential measured will be equal to the vessel liquid head or level. The L.P. side and its connecting tubing must be either gas purged or filled with a sealing liquid and the operation will then be the same as explained in the previous sections.

Figure 4.14 shows a flange-mounted transmitter on an open tank with the dotted in lines indicating a reference leg to be used in a closed tank application.

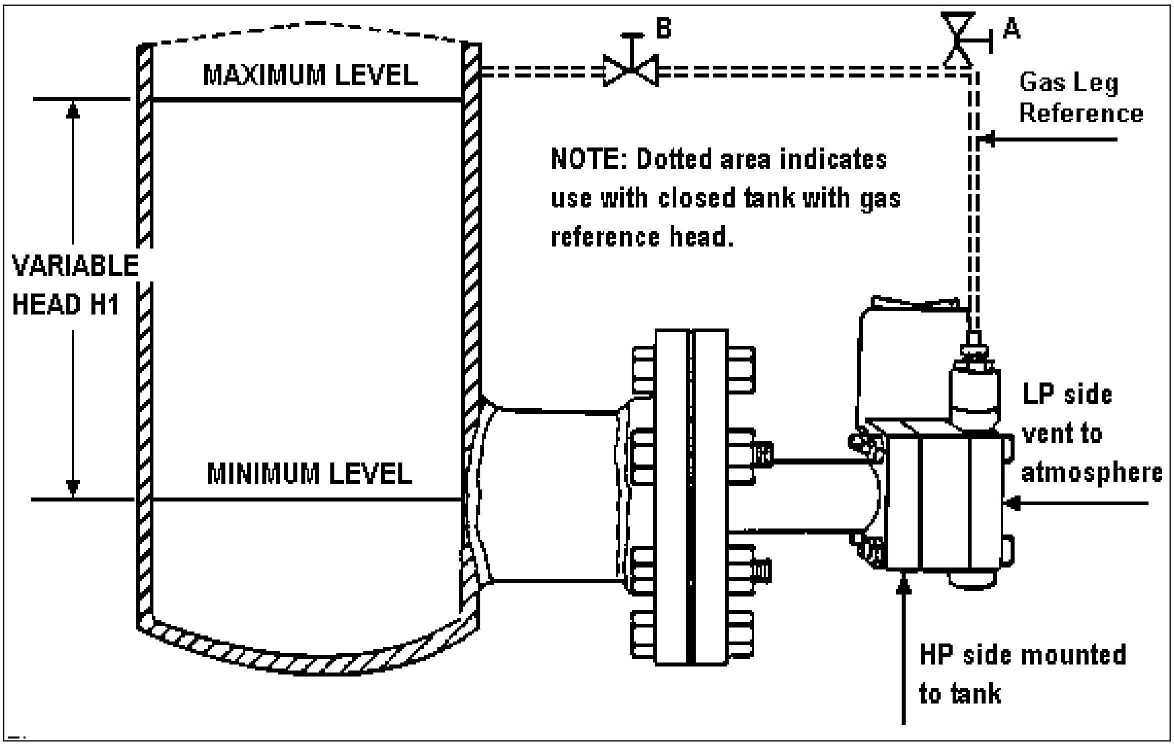


Figure 4.14 Flange-Mounted Transmitter Installation with Open Tank

Figure 4.15 shows a model that uses remote seal flanges. Armored, stainless steel capillary tubing connects the remote seals to the meter body, the seals connect directly to the flanged process connections, and the meter body is mounted at a remote distance determined by the length of the capillary tubing. The remote seals eliminate the need for any special piping.

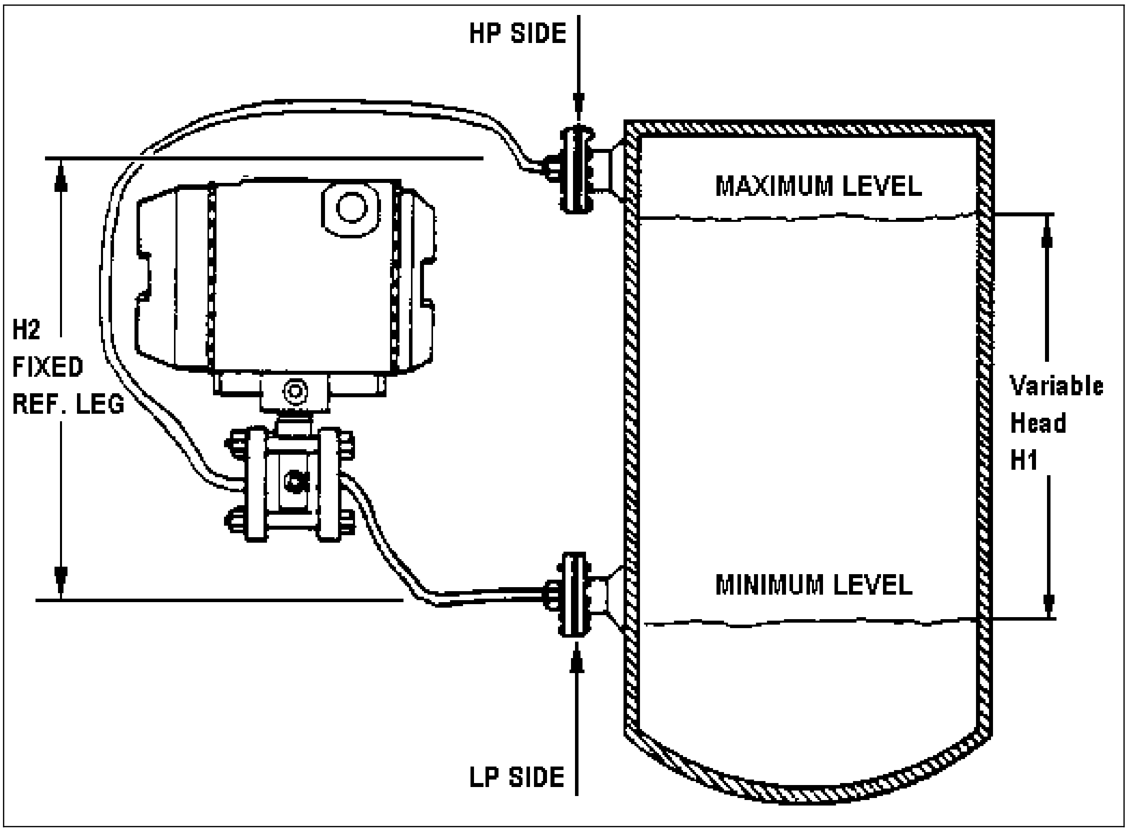


Figure 4.15 Remote Seal Flange Model

Float Operated Method

The float-operated method of liquid level measurement is a direct measurement in which the float rises and falls with the liquid level. In this method, the float, through a cable and counterweight, operates a pulley, which, through a suitable mechanism can actuate a recording pen, indicating pointer, slidewire, etc. (See Figure 4.16.)

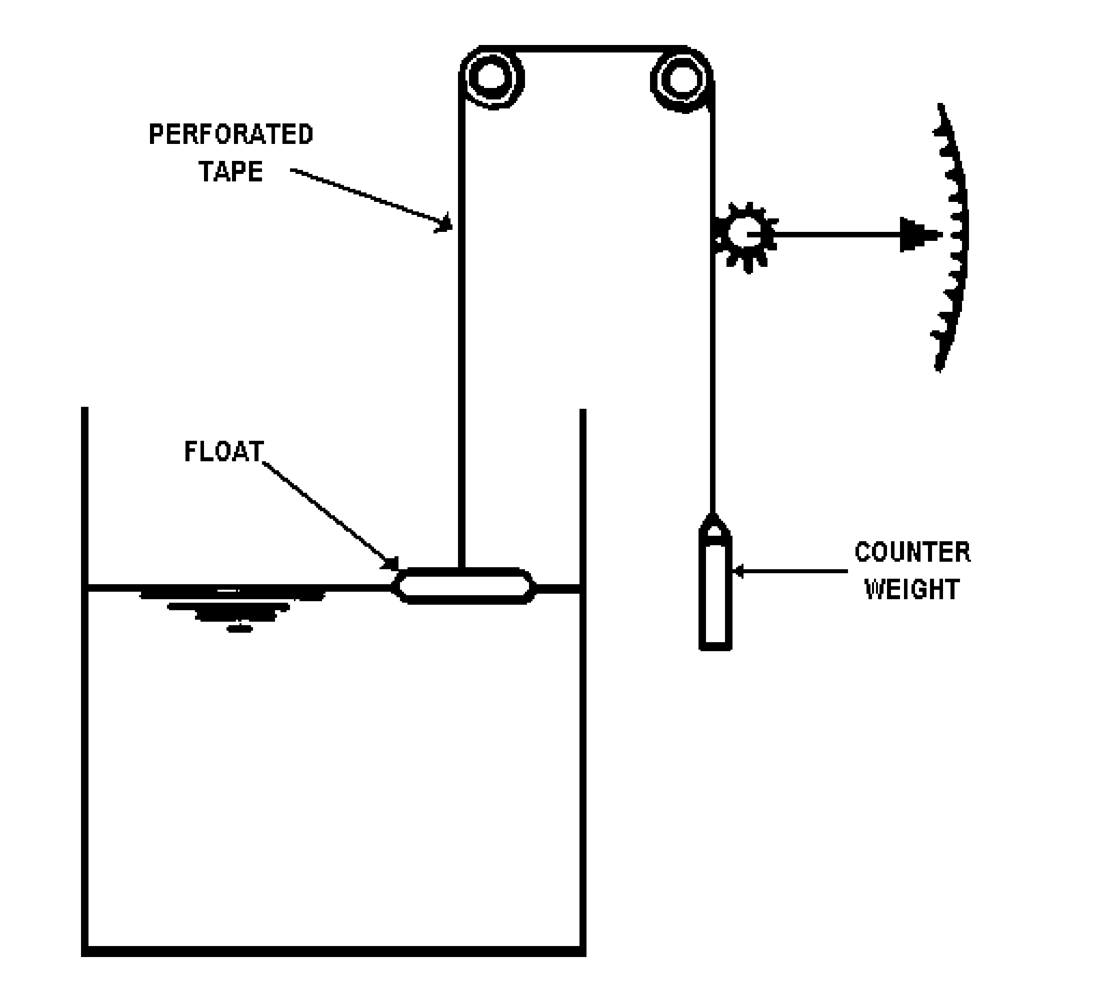


Figure 4.16 Float Operated Level Indicator

There are many different designs of floats. The significant differences among them are the technique used in converting float motion into level reading, and in the isolation of the indicating equipment from the process fluid in the tank.

Electrode Type

The electrode or conductivity probe method of level measurement use the electrical conductivity of the fluid whose level is to be measured. A typical application of this system is illustrated in Figure 4.17. Low-voltage current flows between the tank wall and the electrodes as long as the electrodes are covered by the liquid. When the level drops below the lower electrode, the breaking of the circuit de-energizes a relay, whose contact opens a valve to add liquid to the tank until the level rises to the upper electrode. The two electrodes are connected to the relay so that there is an electrical lock-in action. The relay is not energized until the liquid contacts the upper electrode, then, having been energized, the relay is not de-energized until the level of the liquid falls below the lower electrode.

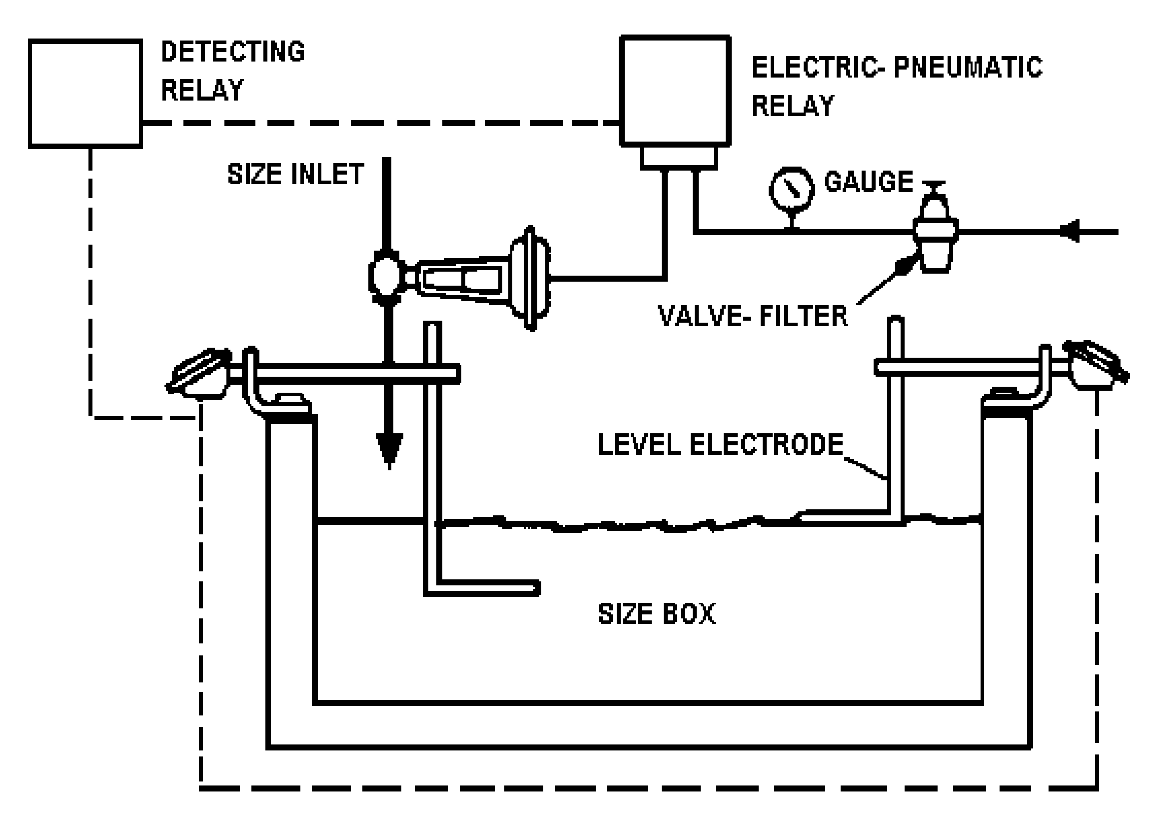


Figure 4.17 Liquid Level Control by Electrode Method

As shown in the above example, on off level control systems can be developed in addition to measurement.

The advantages of the conductivity type switches are their low cost, simple design, and the absence of moving parts in contact with the process material. These units have also been installed to detect the level of moist bulk solids.

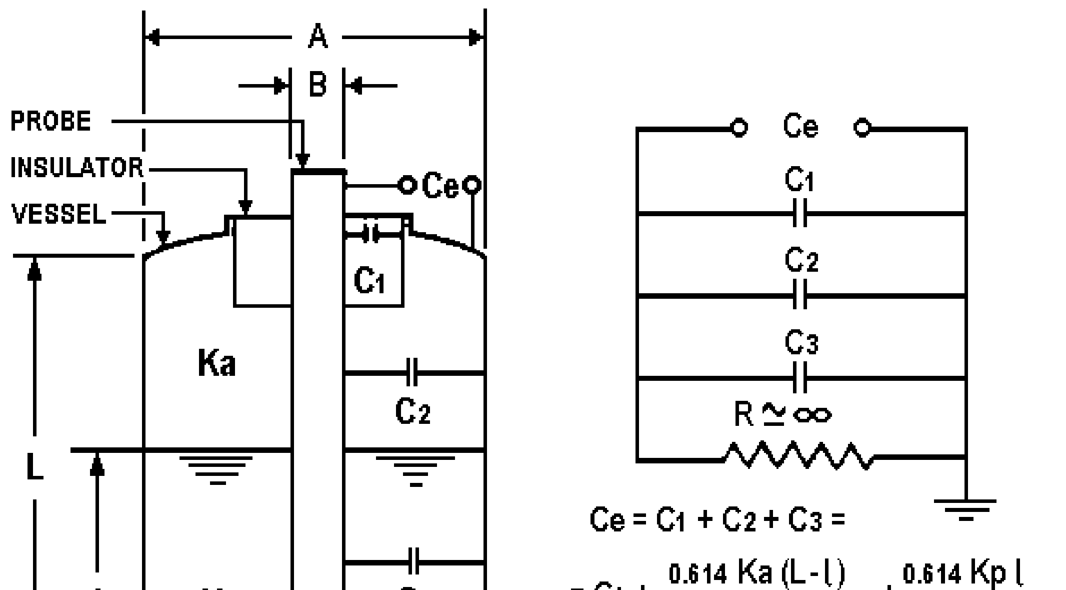
There are also disadvantages. In chemical processing equipment the possibility of sparking. When the liquid level is close to the probe can seldom be tolerated. Some of the solid state designs operate on very low electrical energy levels, and as such can be considered intrinsically safe. This switch is limited in application to conductive (below 108 ohm/cm resistivity) and non-coating fluids. In most processes, electrolytic corrosion at the electrode can have harmful side effects. Electrolysis can be reduced but not eliminated by using AC voltages.

To summarize, conductivity probes are simple and inexpensive devices which are suitable for water level control applications, but which are not desirable in chemical process installations.

Electrical Capacitance Type

This method of liquid level measurement makes use of the electrical capacitance effect of liquids. Variations in the level of the tank will cause a change in capacitance.

Capacitance is measured by a bridge circuit excited by a high frequency oscillator (500KHz to 1.5 MHz). As shown on Figure 4.18, the probe insulated from the vessel is one plate of the capacitor, the tank is the other. The material between the two is its dielectric. As the level rises, vapors with low dielectric constants are replaced by the relatively higher dielectric process materials. The capacitance increases linearly with level. The capacitance changes are detected by an instrument calibrated in units of level. Process pressures, temperatures, and corrosion conditions determine the type of seal used at the insulator, and corrosion conditions determine the desirable probe coating. (The coating conductivity is less than 0.1 micromho/cm^3). For measuring the level of non-conductive materials, the bare metal probe shown in Figure 4.18 can be used. C, in Figure 4.18 is the dead capacitance of the system, and is unaffected by level changes. C_2 is the capacitance in the vapor phase and C_3 is that in the process material. R is the effective resistance between probe and vessel, which varies with the level in the tank. If its value cannot be approximated as infinity, the measurement cannot be made with a bare probe. The capacitance of the system should be affected by changes in level only; therefore, its position, size and the dielectric constant of the process material must remain constant.



$$Ce = C_1 + C_2 + C_3 = $$
$$= C_1 + \frac{0.614\,Ka\,(L-l)}{\log_{10} A/B} + \frac{0.614\,Kp\,l}{\log_{10} A/B}$$

Figure 4.18 Base Capacitance Probe

For measuring the level of conductive materials, insulated (normally Teflon coated) probes are used as illustrated on Figure 4.19. With this installation the measurement is largely unaffected by the effective resistance, and therefore, this probe design is applicable to conductive or non-conductive installations.

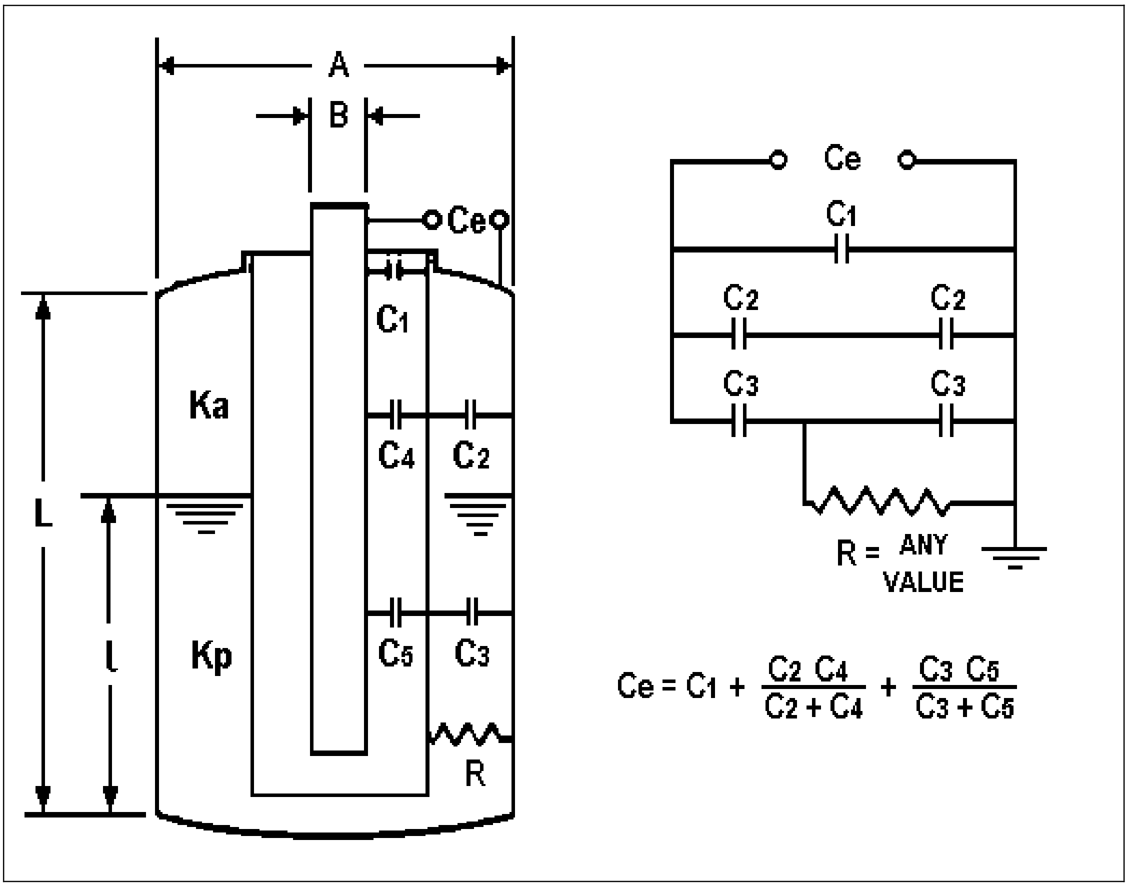


Figure 4.19 Coated Capacitance Probe

If the process material adheres to the probe, a level reduction in the tank will leave a layer of fluid on the probe. If this layer is conductive, the wet portion of the probe is coupled to ground, and therefore, the instrument will not read the new level, but will register the level to which the probe is coated. Other than the changes in process material dielectric constants, this represents one of the most serious limitations of capacitance installations. It should be noted that if the probe coating is nonconductive, the interference with measurement accuracy is much less pronounced.

The advantages and disadvantages of capacitance type level measurement are noted below. On the plus side, the design is simple, there are no moving parts, and the system resists corrosion. The disadvantages are:

- The accuracy is affected by those changes in material characteristics which influence the dielectric constant
- Coating of the probe by conductive materials destroys accuracy
- Proper selection, sizing and installation requires complete understanding of the principles involved
- This method is more expensive than many other means of level measurement

Radiation Type

This method of liquid level measurement makes use of radiation with Gamma Rays. The source of the gamma rays is usually a minute quantity of radioactive material such as radium salts. The rays penetrate the layer of liquid and as the level (layer) increases, the number of rays decrease. This method can include locating the radiation source at or below the minimum level and a Geiger counter at or above the maximum level to be measured. The level varies in proportion to the number of rays. In another system, the radiation source is placed in a float on the top of the liquid, again with the Geiger counter at or above the maximum level. As the level increases, the distance the rays travel is decreased and actually the intensity varies inversely to the square of the distance between the source and the counter. If desirable or necessary, both the radiation source and the Geiger counter can be mounted outside the vessel with the rays passing through the vessel wall and the liquid. The locations of sources and detectors are shown in Figure 4.20.

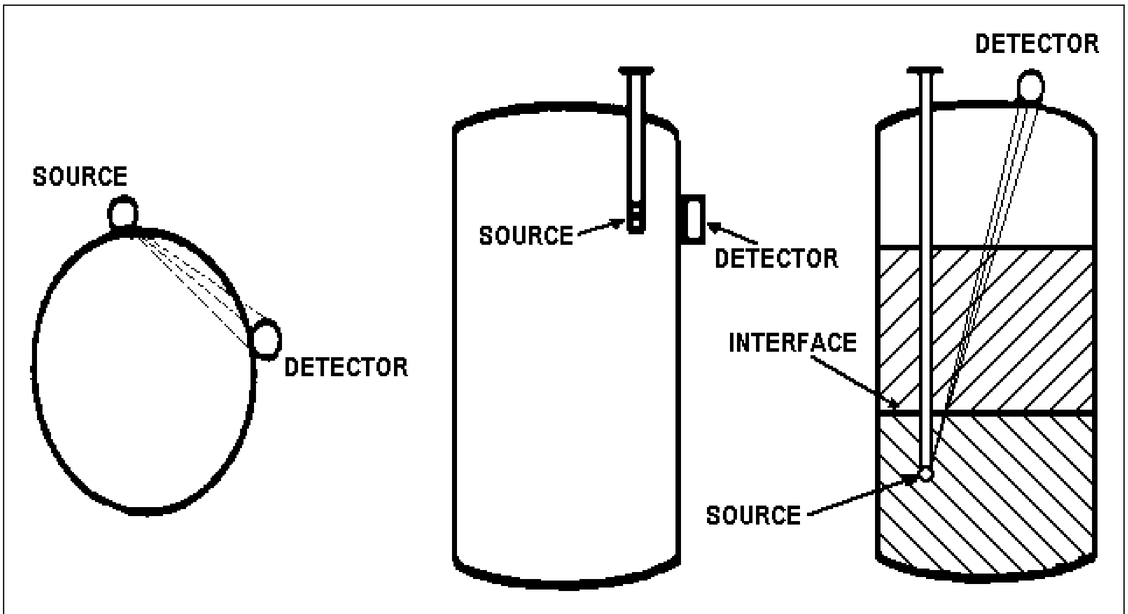


Figure 4.20 Relative Locations of Radiation Sources and Detectors

Ultrasonic Type

An ultrasonic sound wave transmitter is installed at the bottom of a liquid-filled vessel and a sound wave receiver is located beside it. The transit time of a pulse from the transmitter to the surface of the liquid where it rebounds back to the receiver becomes a measure of the height of the liquid column. Suitable electronic gear must be used to transduce these time pulses to a readout of actual level on an indicator or recorder. If it is impractical to use the transmitter and receiver in the liquid, the system can be used with the equipment installed above the maximum liquid level. The ultrasonic sound wave passes through the vapor or gas above the liquid and rebounds from the surface of the liquid back to the receiver.

Lesson Summary

In this lesson you have learned the basics of level measurement and instrumentation found in industrial plants.

In the next lesson you will learn about flow measurement and instrumentation.

Lesson 5
Flow Measurement

Lesson Objectives

At the completion of this lesson, you will be able to understand the basic principles of flow measurement and instrumentation.

Flow Measurement

Flow measurement plays a vital role in today's industrial world. Many consider flow to be the most important process variable, which has to be measured in the industrial plant.

In continuous or batch processes, materials flow through successive operations in which some form of separation occurs; for example, distillation, crystallization, evaporation, extraction. Maintaining a material balance for each separated portion can be critical to process performance. Measuring the rate of flow makes it possible to maintain control.

Knowing total process yields is also important. And, of course, measuring flow rate is vital to the assessment of such material-handling equipment as pumps, fans, and compressors; indeed, of the entire process or plant.

Flow measurement has taken on added importance today with the soaring cost of energy. Accounting procedures for determining the cost of energy bought or sold depend on accurate measurement of the flow of that energy. It is essential to monitor both the rate of flow and the total flow of any energy laden medium both within discrete process loops and over the total system of the plant, for without this information, no serious effort to improve efficiency and reduce energy consumption could be undertaken.

There is no ideal way to measure flow. A host of variables influence the measurements that are made by the commercially available methods. No one measurement system can accommodate them all. The choice of equipment will generally be determined by such requirements as available flow ranges, ability to detect flows of solids, gases or liquids, including clean, viscous or slurry streams, accuracy, linearity, and rangeability limitations, availability of local or remote readouts, totalizers and whether the design is for volumetric or mass flow measurement.

Existing flow measuring instruments operate on a great variety of basic principles. Seven methods of flow metering are discussed below.

Flow Measurement Instrumentation

Positive Displacement Meters

General Features

Positive displacement meters, or volumetric meters, or simply displacement meters, measure the quantity or volume or fluid by filling repeatedly a given container. The total quantity of fluid flowing through the meter in a given time is the product of the volume of the container and the number of fillings. Usually, the number of fillings is obtained by a counter, or register, which is operated by the meter. The registers of most meters for liquids are geared to indicate quantities in gallons, cubic feet, or barrels (42 gal). The registers of gas meters are usually geared to indicate quantities in cubic feet.

Three typical positive displacement meters are discussed below.

Metering Tank

The metering tank is the most elementary form of volumetric meter and embodies an open tank, which is repeatedly filled to a fixed depth and emptied. The number of fillings may be counted by visual observation or by some form of counter. Elaboration of the design could include two or more tanks tilled and emptied in succession.

Bellows Meters

The common name for these meters is dry positive displacement meter, or simply dry meter, and they are used only for the metering of gases. The principle elements of these meters are the flexible partitions or diaphragms of the measuring compartments, valves for controlling and directing the gas flow in filling and emptying the measuring compartments, appropriate linkage to keep the diaphragms and valves in synchronism, and a register for counting the number of cycles. To obtain continuous flow and power for operating the register, it is necessary to have three or more measuring compartments or chambers, with two or more movable walls sealed with a flexible material that is impervious to gas. The movements of the walls or diaphragms are so regulated that the total displacement on successive cycles is the same. The amount of travel or stroke of the diaphragms is regulated in most meters by the radial position of a crank pin to which the diaphragm linkage arms are attached.

Nutating Disk Meters

Other names for these meters are disk or wobble plate meters. Figure 5.1 shows a vertical section through such a meter.

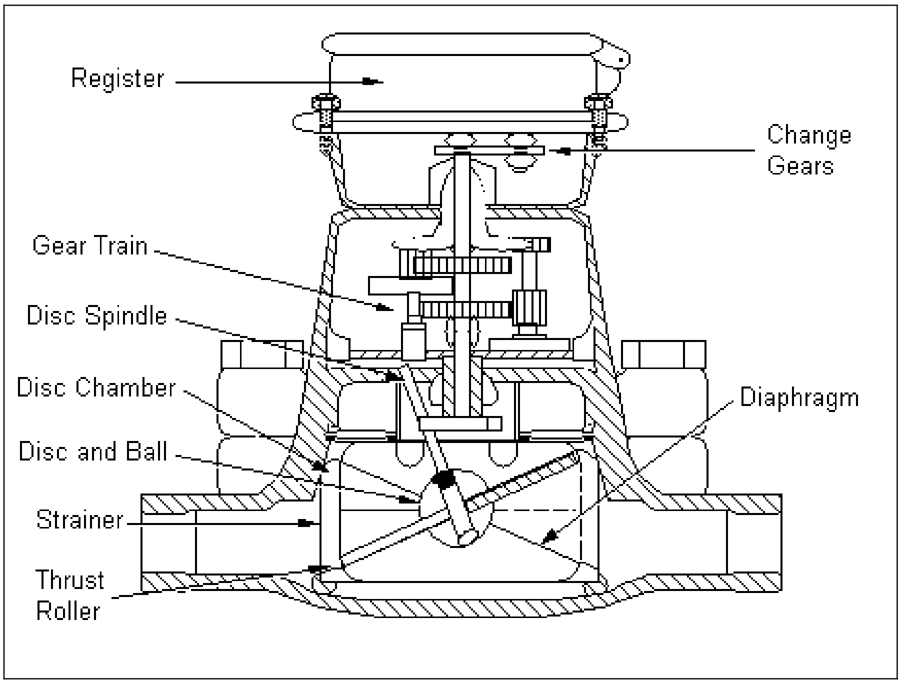


Figure 5.1 Cross Section of a Nutating Disk Meter

The top and bottom surfaces of the measuring chamber are conical, extending inward, and the chamber side-wall is spherical. The movable element is the disk mounted on the central ball, from the top of which a shaft extends that is perpendicular to the disk. This shaft is held in an inclined position by a cam roller so that the disk is in contact with the chamber bottom along a radial element on one side of the ball and in contact with the top in the same radial plane on the other side of the ball. The disk is prevented from rotating about its own axis by a radial partition. The inlet and outlet ports are in the side-wall of the case, adjacent to, and on opposite sides of the radial partition. Liquid enters the measuring chamber alternately above and below the disk and passes around the conical measuring chamber to the outlet port. This movement of the liquid around the measuring chamber, first above, and then below the disk, imparts a nutating motion to the disk (nodding in a circular path without revolving about its own axis). As the disk nutates, the top of the shaft moves in a circular path and, by engaging a crank, operates the meter register. Because of the simplicity of its construction this type of meter can be produced very economically. Partly for this reason, and also because it will maintain a satisfactory degree of accuracy over a long period of time, it is used extensively as a water meter.

Turbine Flow Meters

Principle of Operation

Turbine flowmeters are connected into a pipeline so that the entire stream of fluid in the pipe passes through the meter, and in doing so, causes a turbine rotor to turn. The turbine flowmeter provides a frequency output signal that varies linearly with volumetric flow-rate over specified flow ranges with fluids of given kinematic viscosity. Figure 5.2 is a cross section representation of a typical turbine flowmeter.

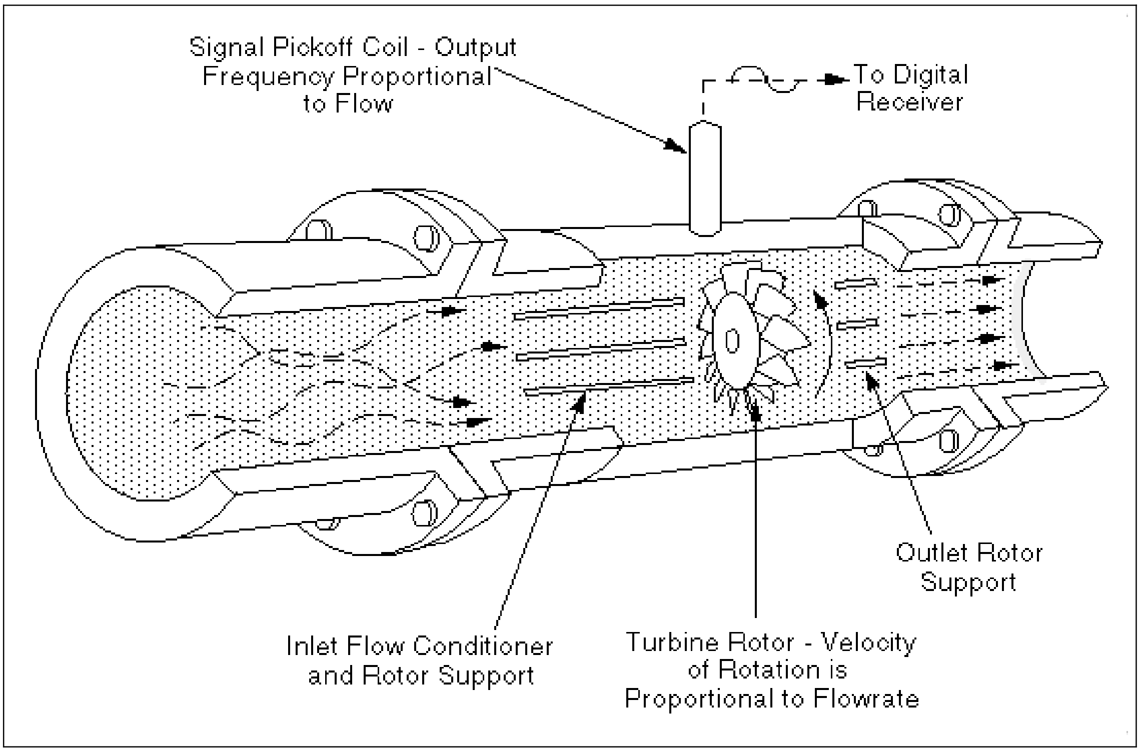


Figure 5.2 Turbine Meter Cross Section

The entire fluid to be measured enters the flowmeter from the left passing through the front rotor support. This support serves the two functions of providing support for the rotor, and conditioning the flow prior to the measurement made by the rotor. The fluid passing the rotor causes it to turn with an angular velocity that is proportional to the fluid linear velocity and, therefore, the volumetric flow-rate. The relationship between rotor speed and volumetric flow-rate is linear within given limits of flow-rate and fluid viscosity. Within these limits the linearity specification is ±0.5% of rate. Repeatability is 0.02% of rate.

The pick-off assembly transduces the rotor velocity to an equivalent frequency signal. Variable reluctance type pick-off assemblies are the most commonly used. In this system the meter housing must be non-magnetic, usually 300 series stainless steel. The rotor must be of permeable material. The pick-off assembly consists of a small powerful permanent magnet and a coil winding. The field of the magnet is influenced by the moving blades of the rotor, which are of permeable material. As a rotor blade passes through the field of the magnet, it provides an easier path for the field and the field distorts, thus moving across the coil winding. The relative motion between the magnetic field and the coil winding generates an AC voltage, the frequency of which is proportional to flow-rate.

Turbine flowmeters develop a precisely known number of pulses for a given volume measured.

Each meter is individually calibrated before shipment. This assures the performance statements of linearity and accuracy claimed for the meter. For flows up to 200 GPM, calibration facilities of some manufacturers are traceable to the National Bureau of Standards. Above these flows, correlation is made generally by using two meters in parallel and using the boot strap method to get to the higher capacities and retain correlation to the reference standard. Turbine flowmeters, because of their high performance capabilities, are used as the transfer standards between manufacturers' facilities and those of the National Bureau of Standards.

To properly select a turbine flowmeter for a given application the following should be known:

1. Process fluid should either be defined by name or its properties completely defined. Any trace of chemicals and particles in the flow stream must be noted. These data are necessary to select bearings properly.
2. The viscosity of the fluid over the operating temperature range must be defined.
3. The linear range necessary
4. The extremes of temperature and pressure over which the meter will be operated.
5. The process connections
6. Signal transmission system
7. The type of totalizer, rate of flow indicator, or other receiver that is to be used.

Receivers and Accessories

Generally, turbine flowmeter information is tallied using totalizer type instruments. For the totalization to be valid the value of each pulse must be essentially constant and, therefore, the turbine flowmeter must be linear.

The turbine flowmeter is generally used over its linear range, which is ± 0.5 % of rate.

Totalizers are available in two general configurations. One form simply totalizes either pulses or does necessary scaling (factoring of the frequency information so that each pulse is equal to a unit volume or decimal part of a volume) and totalizes in direct reading units. A second configuration not only tallies but also predetermines the number of counts or unit volume proportional to a given batch size, and provides a signal, generally a contact closure, to terminate the batch.

Flow-rate indication can be made digitally or in analog form. Digital flow-rate indication is used for test and laboratory work and rarely is used in industrial application. Digital counters with adjustable time base provide flow-rate indication as frequency or in direct reading units (such as gallons per minute) depending on the established time base. Analog indicators require an analog signal proportional to frequency. Frequency-to-current converters are available as accessories or are available complete with milliameter movement. Analog display is generally 2% of maximum, although some units provide analog rate of flow indication within 2% of rate.

Area Meters

Area meters employ a device that moves in response to the rate of flow, and this movement acts to vary, in some way, the cross sectional area occupied by the flowing fluid at a point in the flow line.

The most common form of the area meter is one incorporating a tapered tube and float, usually called a rotameter. In this form, flow is directed through a vertical tapered metering tube, a special glass tube whose cross section increases uniformly from bottom to top. The tube is tightly fitted to metal ends, which form the inlet and outlet connections to the process piping. Flow of the fluid through the rotameter must be from bottom to top. Inside the metering tube is a float, free to move vertically in response to the rate of flow. When there is no flow, the float rests on a stop at the bottom. But as flow increases from zero, a force is exerted on the float, tending to lift it higher in the tube. As the float rises, the area of the annular space between the float and the tube becomes greater because of the taper of the tube. A rotameter is illustrated in Figure 5.3.

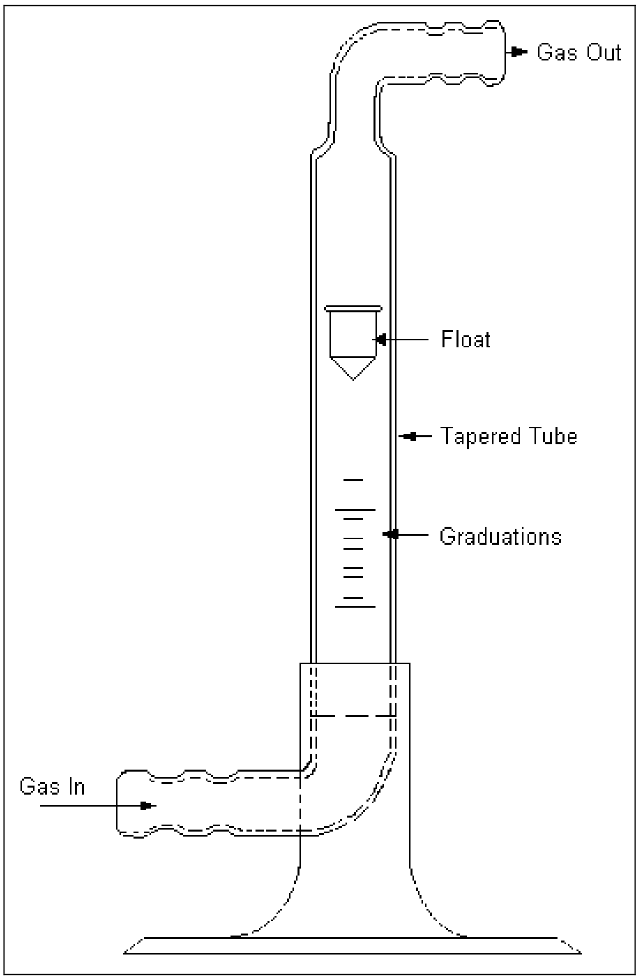


Figure 5.3 Area Meter - Tapered Tube and Float

The shape and weight of the float, the range of the annular area variation, and the variation of the tube area with elevation determine the characteristics of the meter for a particular set of fluid properties. It has been found, for example, that a thin disc float is nearly independent of fluid viscosity effects over a wide range, while a spherical or cylindrical shape may show significant viscosity sensitivity. Generally, tubes of a constant taper angle are employed, and annular areas are kept less than the area of the floating element so that flow rate is approximately linear with elevation.

The most generally used material for tapered tubes is glass, and accurate methods for forming are now available. Other tube materials such as metal and plastics are used; however, an opaque material requires means whereby the float position can be observed or indicated. This is normally accomplished through a magnetic coupling and follower or by having the floating element alter a property such as inductance or capacitance of an electrical circuit. Also, such methods are useful in connection with recording or transmitting the position of the floating element.

Tapered tube and float meters are available in sizes ranging from less than 1/16 in. diameter to over 12 in. Fluid velocities at the tube inlet normally range from 1/2 to 10 fps at maximum design flow rate.

The overall pressure loss will depend upon the friction loss of the particular meter design, plus the practically constant pressure drop across the floating element. The pressure loss depends upon the annular area, and some of the pressure drop across the floating element may be recovered. This pressure drop across the floating element usually will not exceed that calculated from:

$Ap_f \leq (F/A_f)$

where

Ap_f = Pressure drop across floating element

F = Weight of floating element less buoyancy, a force

A_f = Area of floating element at largest section

Vortex Flowmeters

Vortex shedding is the natural effect that occurs when a liquid or gas flows around a non-streamlined object. At a certain velocity, flow cannot follow the shape of the object and the flow lines separate from the object. What happens is that a fluid particle in the boundary layer loses energy because of friction in passing over the front of the object and cannot move very far into the higher pressure region just behind the object. The particle decelerates, stops, and reverses direction, forming a vortex.

The vortex grows in size, separates from the surface, (a process commonly called shedding) and moves downstream. (Figure 5.4) Through interaction of changes in local velocity and pressure, caused by the separation, with the vortex that is forming on the opposite side of the object, an alternating pattern of vorticles is established.

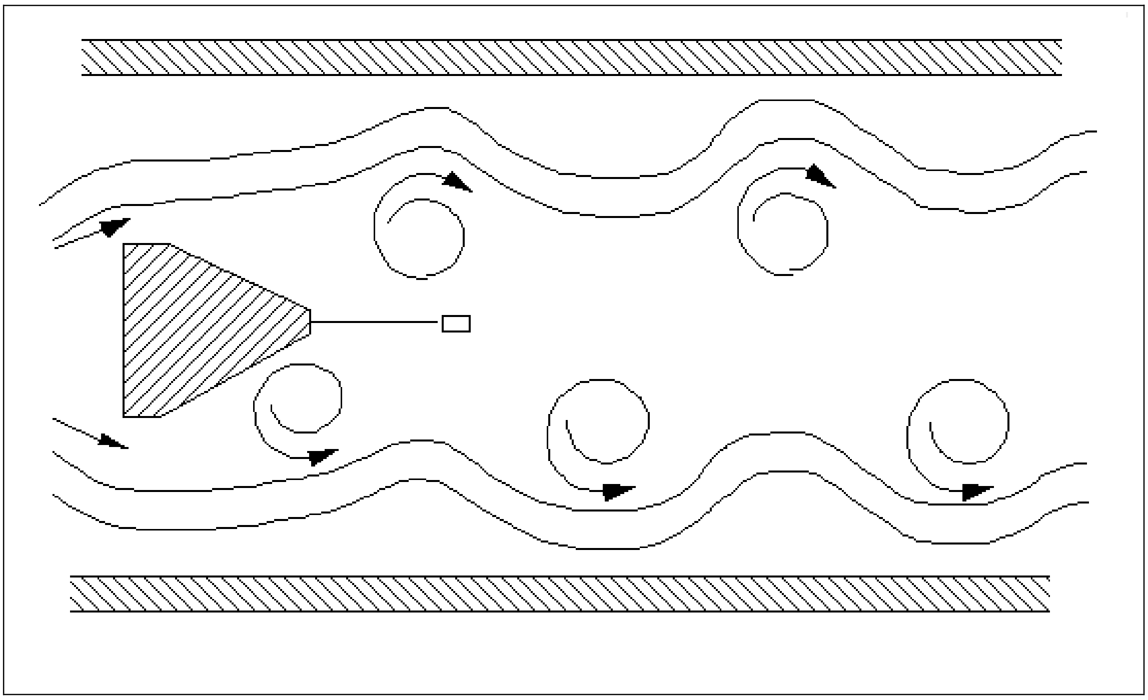


Figure 5.4 Flow Element Creates and Sheds Vortices

As flow rate increases, the speed with which each vortex forms increases at the same rate. Thus, the frequency of vortex generation is directly proportional to the flow rate.

The vortex shedding phenomenon is embodied in a flowmeter by placing a blunt object, the flow element, diametrically across the pipe. Through proper hydraulic design a linear relationship between flow rate and the frequency of vortex generation can be established. And the calibration factor (pulses per gallon or cubic foot) is determined only by the dimensions of the flow element and the pipeline. It is independent of viscosity, temperature, and pressure. Moreover, the measurement is directly digital.

Generating the vortices is only a first step in determining flow; the vortices also must be sensed and counted. Some vortex meters have a vane projecting from the rear of the element. Mechanical motion resulting from the low-pressure vortex passing the vane is transmitted out of the meter, providing complete isolation between the sensing system and the process fluid. The external sensor employs a simple inductive coil to generate a signal resulting from the mechanical motion.

Other manufacturers take different approaches. Heated thermistors are responsive to the cooling effect of flow. Thus, changes in flow velocity across the sensor due to vortex shedding result in changes in this temperature and thus changes in its resistance.

One important advantage of the vortex shedding flowmeter is the fact that it has digital output signal. This is desirable because of an increased requirement to totalize flows that result from energy management programs. It is easier to totalize a digital signal than an analog signal, and there is an order of magnitude difference in integrated accuracy.

Magnetic Flowmeters

Principles of Operation

Magnetic flowmeters use Faraday's Law of Induction for making flow measurement. This law states that relative motion at right angles between a conductor and a magnetic field will develop a voltage in the conductor. The induced voltage is proportional to the relative velocity of the conductor and the magnetic field. This is the principle used in direct current and alternating current generators. The most common magnetic flowmeters are a modified form of alternating current generators. In the magnetic flowmeter, the fluid itself acts as the conductor and must have some minimum conductivity.

Figure 5.5 is a diagram of a representative magnetic flowmeter. The fluid is the conductor which has a length equivalent to the inside diameter of the flowmeter, D. The fluid conductor moves with an average velocity V through a magnetic field B. The voltage E induced in the conductor is proportional to the volumetric flow-rate. The mathematical relationship defining the performance is E = BDV/C.

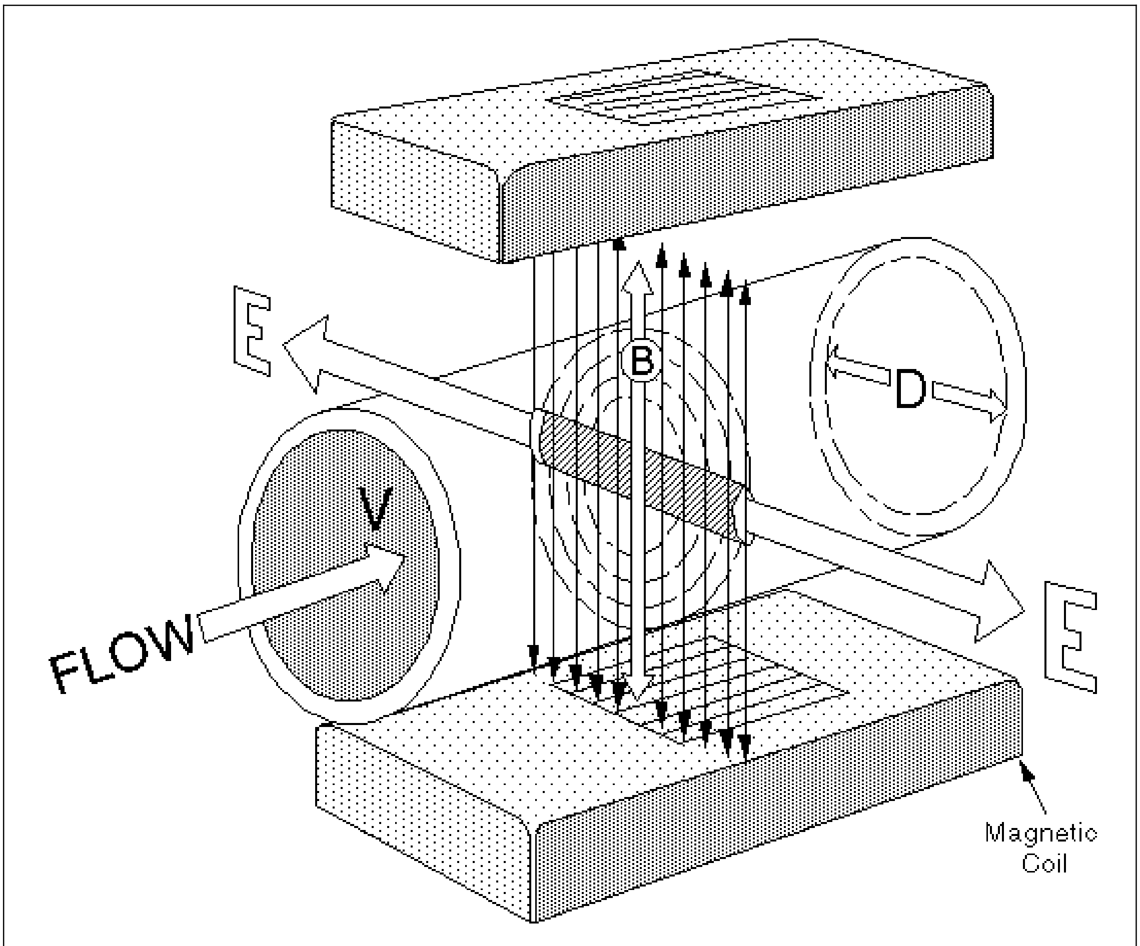


Figure 5.5 Transparent View of a Magnetic Flowmeter

The magnetic field generated is in a plane that is mutually perpendicular to the axis of the meter body and the plane of the electrodes. The velocity of the fluid is along the longitudinal axis of the flow metering body; therefore, the voltage induced within the fluid is mutually perpendicular to both the velocity of the fluid and the magnetic field, and is generated along the axis of the meter electrodes. The fluid can be considered as a series of fluid conductors moving through the magnetic field.

An increase in flow-rate will result in a greater relative velocity between the conductor and the magnetic field and a greater instantaneous value of voltage will be generated.

The instantaneous voltage generated at the electrodes represents the average fluid velocity of the flow profile at the plane of the electrodes at a given instant. Each increment of fluid within the plane develops a voltage proportional to its velocity, the summation of which is equal to the average velocity of the conductor. The output signal of the meter is equal to the continuous average volumetric flow-rate regardless of flow profile: that is, whether the fluid Reynolds Number is within the laminar or turbulent region. Therefore, magnetic flowmeters are independent of viscosity changes. It is essential that the meter be full since the meter senses velocity as proportional to volumetric flow-rate.

Figure 5.6 is a cut-away view showing the construction of a magnetic flowmeter.

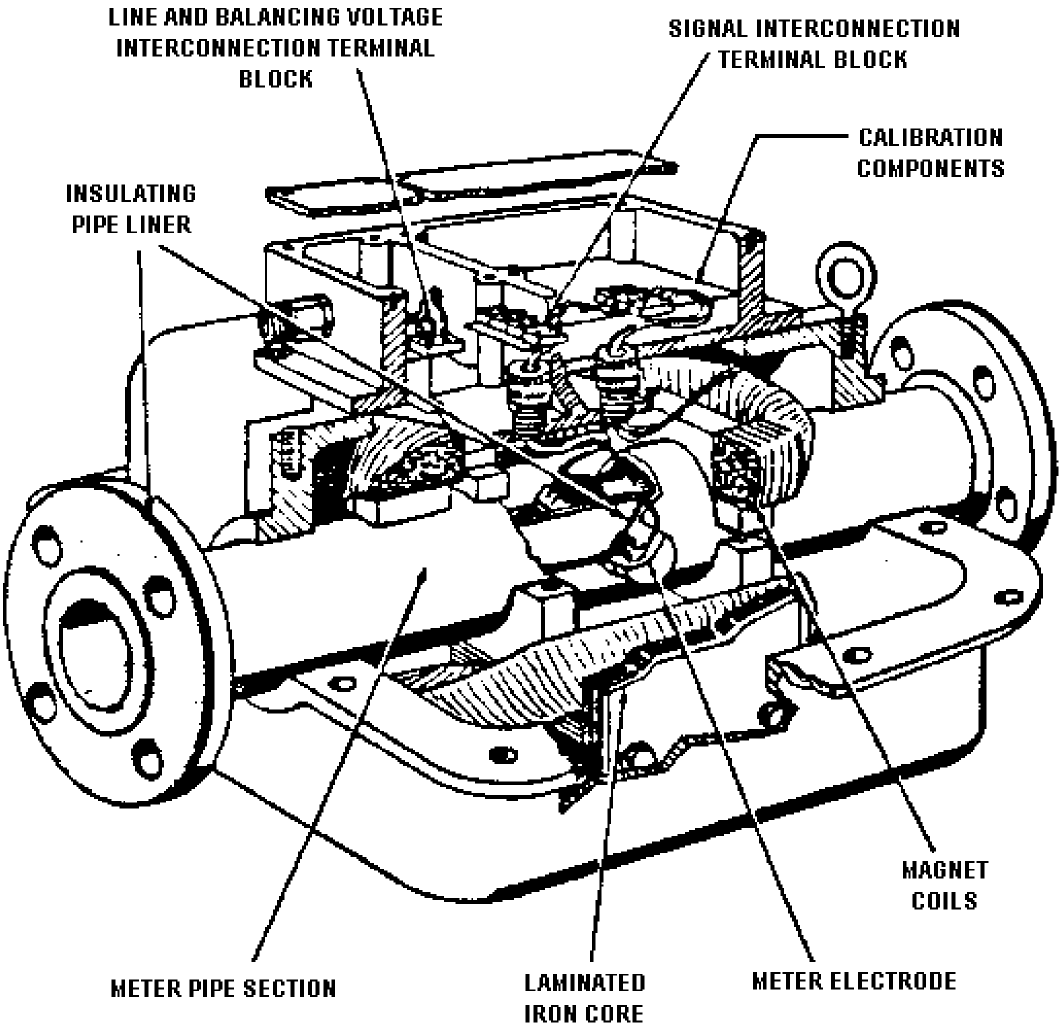


Figure 5.6 Cutaway View of a Magnetic Flowmeter

The magnetic flowmeter is constructed of a non-magnetic tube that carries the flowing liquid, which must have a minimum level of conductivity. Surrounding the metering tube are magnet coil assemblies and cores which, when electric current is applied, provide a magnetic field across the full width of the metering tube. The fluid flowing through the tube is the conductor that moves through the magnetic field. A voltage is generated proportional to the volumetric flow-rate. The voltage generated is mutually perpendicular to the magnetic field and the direction of the flowing liquid.

Magnetic meters are unaffected by changes in fluid density, viscosity, turbulence of the fluid, or by variations in piping.

Generally, any fluid which will conduct an electric current can be measured by the magnetic flowmeter. If the conductivity of the fluid is equal to or greater than 20 micromhos per centimeter, any of the conventional magnetic flowmeter systems can be used. Special systems are available which will measure flow of fluids with threshold conductivity's as low as 0.1 micromhos.

Above the threshold conductivity meter is unaffected by conductivity changes, but the effect of the fluid operating temperature upon the fluid conductivity should be considered. Most fluids have a positive temperature coefficient of conductivity. Certain marginal fluids can become sufficiently non-conductive at lower temperatures as to hamper accurate metering. The same fluid at higher or normal environmental temperatures may be metered with optimum results. The possibility of an adverse temperature conductivity characteristic should be investigated before attempting to meter such a fluid.

Neither viscosity nor consistency has any effect on the meter performance. The signal developed by the magnetic flowmeter is a summation of the incremental voltages across the entire area between the electrodes and will be a measure of the actual average fluid velocity.

The magnetic flowmeter is a bi-directional meter. The output of the meter is the same regardless of the direction of flow. If flows in two directions are to be distinguished, specific systems must be applied.

The meter must always be used with a full pipe to assure proper volumetric measurement. The meter is directly sensing velocity of the fluid and, therefore, the entire cross sectional area of the pipe must be full. Also, the meter must be metering liquids without entrained gas. Any gas bubbles entrained in and carried by the liquid will be measured as liquid and the resultant measurement will be in error.

The magnetic flowmeter develops a voltage signal in the microvolt range; therefore, proper installation and grounding is mandatory to assure proper measurement of flow. The recommendations of the manufacturer are the result of extensive experience and are the proper grounding techniques necessary for the operation of the meter.

Shielded interconnection cable either furnished or recommended by the manufacturer is used to connect the flowmeter to the receiving instrument. This interconnection cable is never to be spliced.

Magnetic flowmeters have many advantages including:

1. Measurement of difficult fluids such as very corrosive and abrasive slurries
2. No obstruction to the fluid flow
3. Pressure drop equal to a straight section of pipe of equal length
4. No special piping arrangement necessary
5. Easily handles bi-directional flow

Receivers and Accessories

The magnetic flowmeter output is an AC voltage proportional to volumetric flowrate. The most commonly used receiver is an AC self-balancing potentiometer specifically designed for use with magnetic flowmeters. These receivers offer many options and accessories, which include:

1. Recording and/or indication
2. Alarms
3. Integral controllers
4. Transmission (pneumatic, electric, resistance, etc.)
5. Totalization

Converters are available, as separate elements or integral with the meter, to convert the AC signal voltage to an equivalent DC signal for use with conventional electronic control systems. Some converters offer pulse outputs and pneumatic output as well as the DC output.

High accuracy totalizers are also available which give totalization within ± 0.5 % of rate within given flow ranges.

Differential Pressure

In a majority of applications, flow rate is determined by measuring the pressure drop across an artificially created restriction in the flow line. This type of metering, commonly known as the differential pressure method, uses various devices for creating and measuring the pressure drop (differential pressure). The relationship between differential pressure and flow rate is explained below.

Principles of Differential Flow Metering

When fluid flows through a pipe, the total energy it possesses at any point is the sum of three different forms of energy:

- Elevation Head
- Pressure Head
- Velocity Head

So the total energy, possessed by the fluid at Point 1 in the process system shown in Figure 5.7 is equal to:

Elevation Head 1 - Pressure Head 1 + Velocity Head

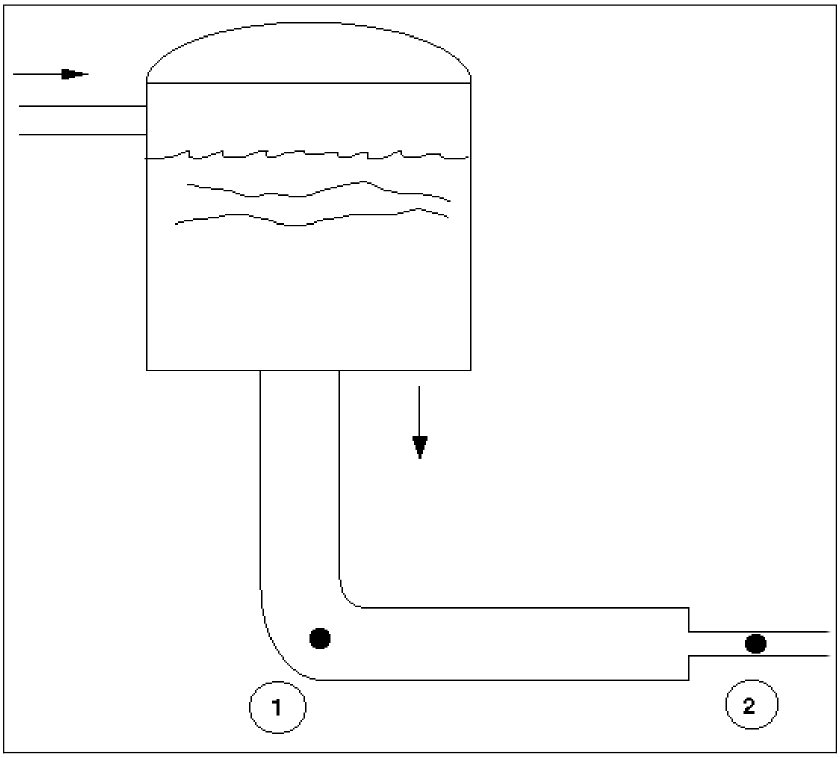


Figure 5.7 Process Piping System

If the pipe is narrowed down to a smaller diameter, as at Point 2, it is apparent that the velocity will be greater than it was at Point 1.

A fundamental law of physics states that energy can change its form but cannot be destroyed. As applied to Point 1 and Point 2, the total energy of the fluid at Point 1is equal to its total energy at Point 2.

Elevation Head 1 + Pressure Head 1 + Velocity Head 1 =

Elevation Head 2 + Pressure Head 2 + Velocity Head 2

Since the Velocity Head for Point 2 has increased, it is evident that one of the other energy terms on the same side of the equation will decrease. The decrease actually takes place in the static pressure energy, or pressure head.

This relationship between velocity and static pressure as the cross section of the pipe changes is graphically illustrated in Figure 5.8. The small tubes connected to the top of the pipe indicate static pressures at various points along the pipe. Whenever the cross section decreases, the velocity increases, resulting in a decrease in static pressure. It is evident that a conversion of energy is taking place. An increase in velocity head takes place at the expense of static pressure head. After the cross section of flow returns to its original full pipe-size, the velocity head returns to its original value, and the static pressure head returns to its original value. (There will actually be a small loss in static pressure, resulting from fluid friction between the two points.)

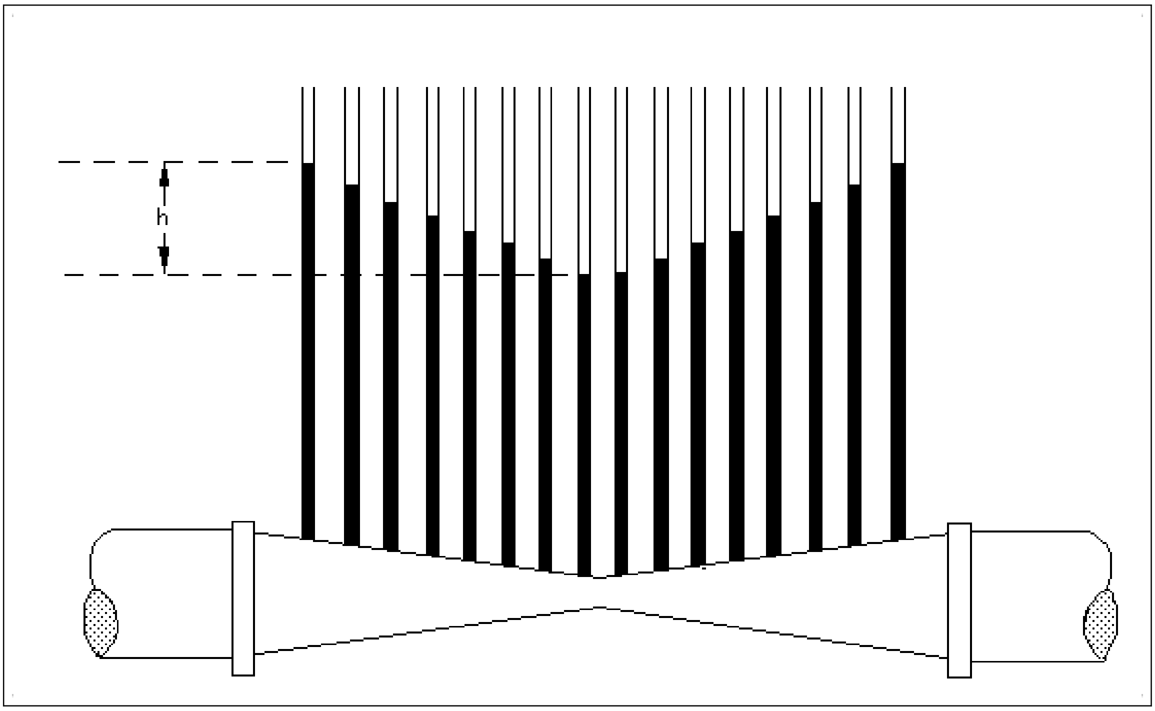


Figure 5.8 Venturi Section of Flow Pipe

This basic pressure-velocity relationship of fluid flow in a pipe (Figure 5.8) was first discovered by Venturi in 1797. However, it was not used for measuring fluid flow until nearly 100 years later when Clemens Hershel demonstrated that a constant relationship existed between the quantity of flow through a pipe and the pressure difference between the inlet and the throat in a convergent-divergent section of pipe. Hershel names this device the Venturi Tube.

A well-known relationship of physics ties this differential in with the velocity and establishes a definite relationship between the two. This relationship is expressed by the formula:

$$V = \sqrt{2gh}$$

Where V = fluid velocity through the restriction

h = the difference of static pressure

g = the gravitational constant 32.2 ft/sec/sec.

The rate of volume flow through any pipe may be readily calculated:

Quantity of Flow = Flow Velocity x Cross-section area

For example, if the fluid is flowing with a velocity of 1 ft. per second, and the pipe cross-section area is 1 square foot, then the volume flowing will be 1 cu. ft. per second.

1 ft. per second x 1 sq. ft, = 1 cu. ft/second

Flow can, therefore, be calculated from the relationship:

$Q = V \times A$

Because of the known relationship:

$V = \sqrt{2gh}$

a substitution can be made for V in the above equation, which then becomes:

$Q = A \times \sqrt{2gh}$

Since in any specific flow meter installation, the area of the throat, or the area of the hole in the orifice plate, is known and unchanging, and since $\sqrt{2g}$ is always the same value $\sqrt{(2 \times 32.2)}$, these terms can be combined into a single constant, K, and the equation then takes its most simplified and most widely used form:

$0 = K\sqrt{h}$

In flow metering, this is referred to as the basic flow equation. It states that as flow varies through a restriction in a pipe, the rate of flow will be proportional to the square root of the differential pressure across the restriction.

In fluid flow through a pipe, the principle on which metering of the flow is based is known as Bernoulli's Theorem which essentially states:

“When a fluid flows in a pipe, the total energy it possesses at any one point is exactly equal to its total energy at any other point, if fluid friction loss between the two points be neglected."

The amount of static pressure lost to velocity is, in actual practice, measured by the difference in static pressure between the two points. In Figure 5.8, for example, the differential between the point before the pipe starts decreasing in size and the point where it is smallest is indicated as h.

Example:

In Figure 5.8, suppose that the differential pressure reading is 2” H_2O for a flow of 10 GPM. If the flow through the pipe were increased to the extent that the differential pressure reading doubled, what would the corresponding flow be? Would it have doubled also?

Solution:

If the differential doubles then the flow will increase by the square root of 2 times the original flow rate.

$$\sqrt{2} = 1.414 \times 10 = 14.14 \text{ GPM}$$

The basic flow principles illustrated in the installation of Figure 5.8 are equally valid for the installation shown in Figure 5.9. In Figure 5.9, the flow is restricted by an orifice plate. The fluid forms its own high-velocity, small-diameter flow section after it has passed through the hole in the plate. No converging pipe walls guide it there. Nevertheless, the general principles relating to pressure changes and velocity changes are the same for Figure 5.9 as for Figure 5.8.

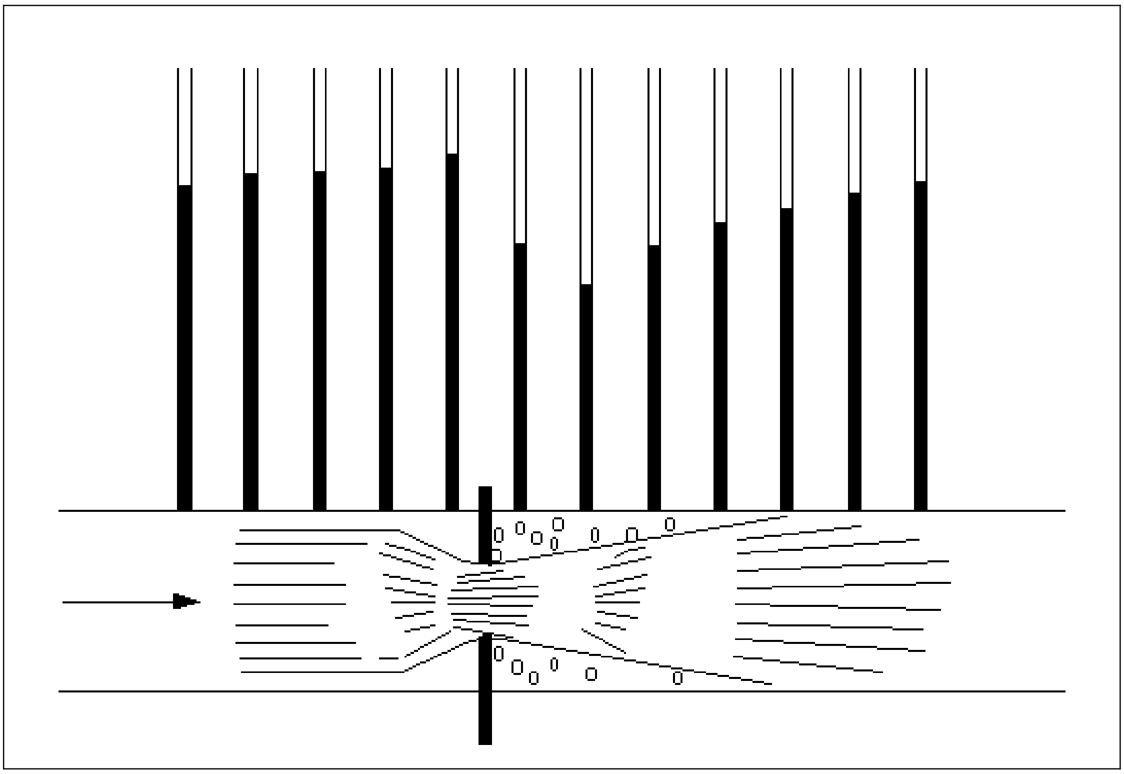


Figure 5.9 Orifice Plate in Flow Pipe

Figure 5.10 also illustrates an orifice plate flow installation. Instead of a series of piezometer tubes, there are only two static pressure connections into the side wall of the pipe. These connections, upstream and downstream from the orifice plate, are connected to a differential pressure manometer.

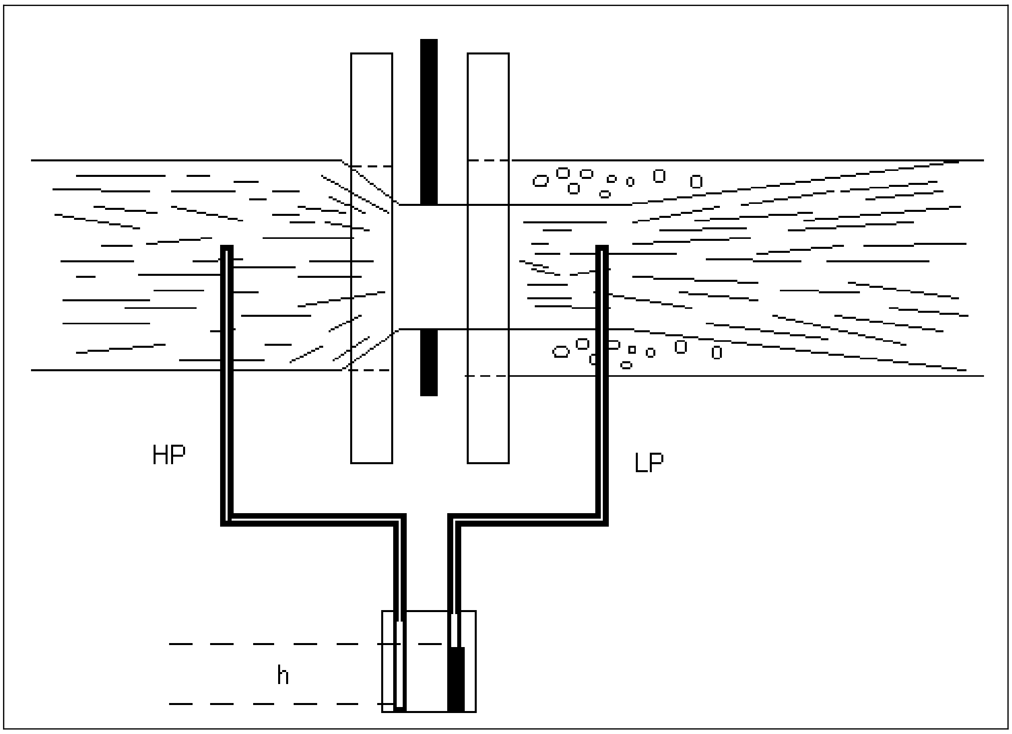


Figure 5.10 U Tube Manometer

Figure 5.10 may be said to show a typical differential flow meter installation.

The flow meter itself is the U-tube manometer.

Several significant points should be observed in this typical installation:

The point of smallest cross-sectional area of flow is not at the point where the flow passes through the hole in the orifice plate. The smallest area is actually located approximately half a pipe diameter downstream from the restriction. This point is known as the Vena Contracta.

In addition to being the spot where the smallest cross-section area of flow is located, the Vena Contracta is also the place where the velocity is the highest, and static pressure lowest.

Actually, of course, the fluid being measured completely surrounds the jet shaped steam downstream from the restriction. In fact, for any differential type flow meter to be able to measure flow, the fluid, which is being measured must completely fill the pipe. Furthermore, it must be homogenous - all gas, all vapor or all liquid. Another significant point to be observed in Figure 5.9 is that if the downstream pressure tap is at the location of the Vena Contracta, the maximum differential available is being used.

It will be noted in Figure 5.9 that after the flow has passed the location of the Vena Contracta, it starts diverging. Approximately 4 or 5 pipe diameters after the orifice plate, normal full pipe flow characteristics have been resumed.

A closer inspection of the piezometer tubes in Figure 5.9 discloses that after the flow has resumed full pipe characteristics, the static pressure is lower than it was upstream from the orifice plate. This loss, never regained, is the Permanent Pressure Loss. It is the result of the friction and turbulence developed in the fluid in passing through the restriction.

The amount of Permanent Pressure Loss depends on the type of flow restriction used. It also depends on the ratio of the diameter of the restriction to the inside diameter of the pipe. It also depends on the magnitude of the differential pressure developed.

Because Permanent Pressure Loss is generally quite small in relation to line pressures, it usually creates no problem. However, in installations where line pressures are relatively low, it can assume considerable importance. Its value can be definitely established by existing graphs. It can also be determined by calculation.

Components of a Flow Meter Installation

A typical industrial type flow meter installation is shown schematically in the block diagram of Figure 5.11.

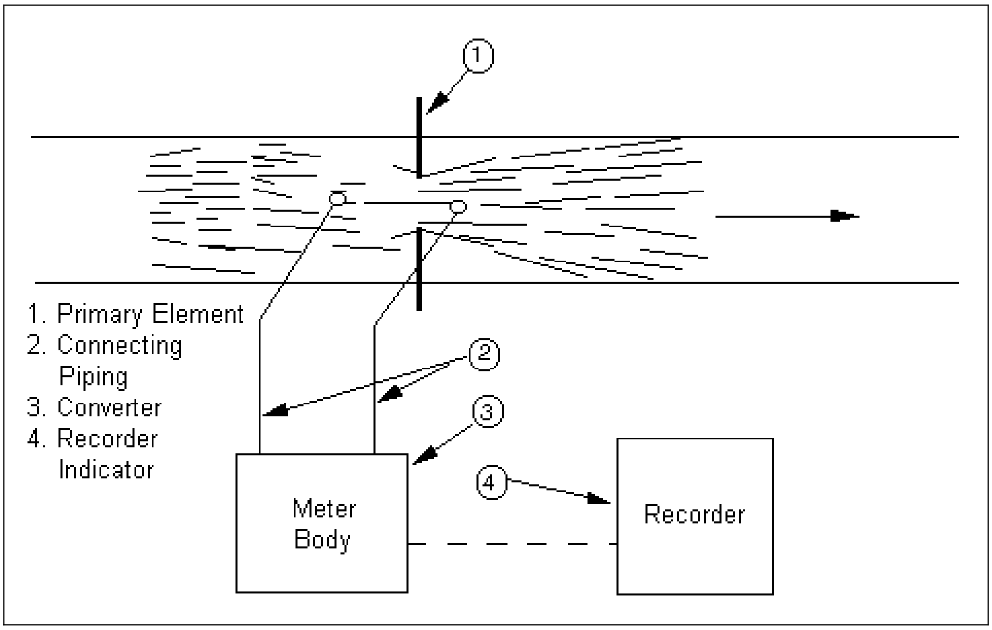


Figure 5.11 Differential Pressure Transmitter

The components of any typical flow meter installation are generally considered to be the following:

The Primary Element

This element provides the means by which some of the static pressure head is converted into increased velocity head for the purpose of creating measurable differential pressure.

The Connecting Piping

The connecting piping is an extremely vital component of a flow meter installation. Its function is to accurately transmit the differential pressure from the primary element to the meter body. The differential pressure usually must be read to an accuracy of a few tenths of an inch of water while the line pressure may be as high as thousands of psi. This means that there must be an uninterrupted column of process fluid (or seal fluid) between the process line and the meter body. It is preferred practice to lay out the connecting piping mainly in vertical runs; where a horizontal run is necessary it should have a slope of at least 1” to the foot. For liquid service, the meter body should be below the primary element and the piping should slope downward toward the meter body to prevent gases or vapor from accumulating; any that form should be self-venting up into the process line. For gas service, the meter body should be mounted above the primary element so that liquids will drain down into the process line and not accumulate in the connecting piping. For steam service, the connecting piping is filled with water and must be treated as a liquid installation.

The connecting lines should be run close together to maintain equal temperatures in them. The pipes must be supported to prevent sagging which might result in high points in liquid filled lines or low points in gas filled lines which may interfere with proper operation.

Shut off valves facilitate removal of the meter body or its isolation during blowdown of the connecting lines. An equalizing valve, in a line connecting the high and low pressure lines near the meter body, permits admitting the same pressure to both sides of the meter body, allowing the zero setting of the meter to be checked.

Settling chambers are sometimes located at low points in the connecting lines. Condensation and moisture (gas filled system) and sediment or foreign material (liquid filled system) are collected, helping to avoid blockages which could affect the measurement. Drip legs and sediment traps should be blown down periodically to prevent obstruction of the connecting piping.

Sometimes, especially with corrosive or overly viscous liquids, it is desirable to keep the measured fluid out of the pipes and meter body. A sealing chamber, located in the pipe near the process line, with an immiscible inert liquid in the connecting lines and meter body, serves the function.

Alternatively, the process liquid may be excluded from the connecting piping by introducing a purge (a small flow of clean liquid) into the connecting piping which would flow back into the process line. The purge flow must not be large enough to affect the magnitude of the pressure sensed at the meter body.

The Meter Body

This converts the differential pressure it feels into mechanical motion or an electrical signal.

The Recorder, Indicator, or Controller

This component presents the information. In some instruments, the meter body and the recorder may be integrally mounted to one another. In plants where processes are operated from central control rooms, this component will frequently be some miniature type of receiving instrument.

Recognition of the fact that there are four components in a flow installation is important in insuring a satisfactorily operating loop, from an installation and design viewpoint, and from a maintenance and troubleshooting viewpoint.

Primary Elements for Differential Flow Metering

The most frequently used primary elements are orifice plates, Venturi tubes, and flow nozzles. Each of these has it's own set of advantages and disadvantages, which will influence its choice for a particular application.

Orifice Plate

The orifice plate is the most widely used primary element in industrial flow metering. The principal reasons for this are:

- It is inexpensive and easily fabricated
- It is readily installed or replaced
- Accurate measurements are possible because of extensive, reliable performance data accumulated over a long period

Orifice plates are comparatively thin plates with a flat upstream face. Each one has a precisely machined hole in it. The size of the hole is carefully calculated for each specific flow meter installation. Many factors enter into the calculation, among which are quantity of flow, pressure, temperature, and the amount of differential pressure to be developed across the plate to actuate the instrument.

The three principal types of orifice plates are illustrated in Figure 5.12.

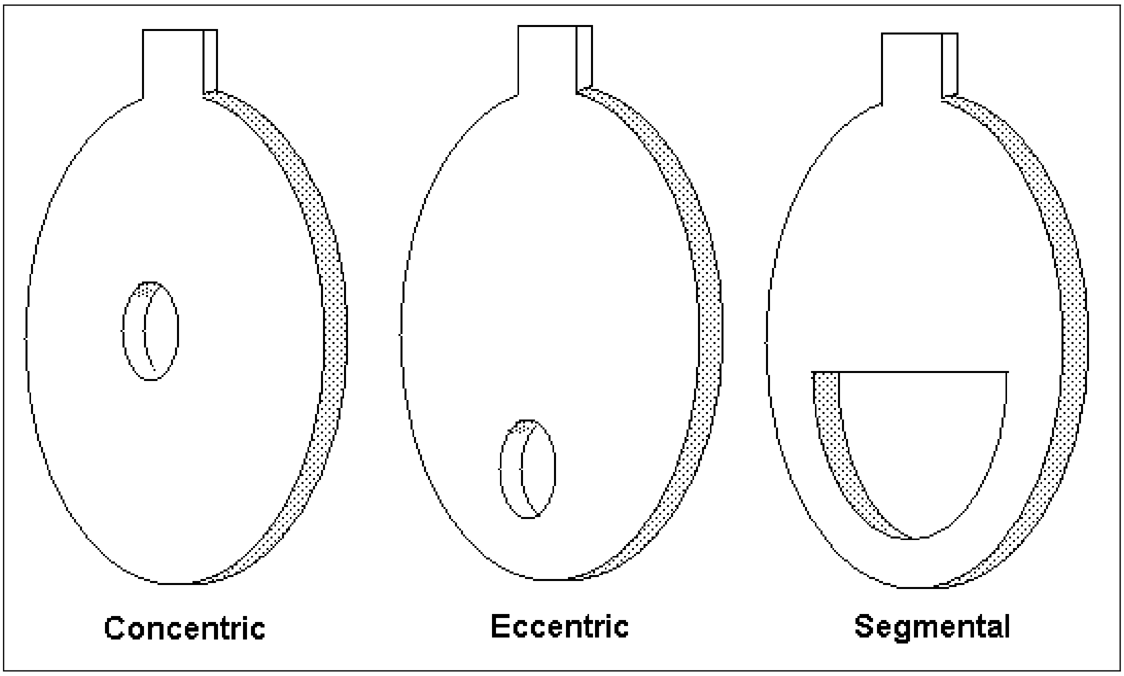


Figure 5.12 Typical Orifice Plate Types

Concentric

The most widely used is the Concentric Orifice Plate. In this type the hole is centered with the axis of the pipe. In almost all plates, there is also a small auxiliary hole. It may be located either at the top or bottom of the plate. When it is at the top, it is a vent hole and serves the purpose of passing entrained air or vapor in liquid flows. Otherwise trapped air could accumulate on the upstream side of the orifice plate. When it is at the bottom, it is a Drain' hole and its function is to pass any condensate in gas flows which would otherwise accumulate upstream of the orifice plate. In either case, the auxiliary hole is quite small, usually about 1/16-inch diameter.

The thickness of an orifice plate depends on the size of the pipe it will be installed in. The larger the pipe, the thicker the plate must be to eliminate the possibility of buckling or deforming. Customarily, the thickness is 1/16-inch for pipes up to 3-inch size (inclusive) and 118-inch thick from 4 to 12-inch pipe sizes.

If the orifice plate thickness is more than 1/16-inch, the downstream edge of the hole is beveled to a 45-clegree angle, so that the edge of the hole is 1/16-inch wide.

Most orifice plates have an orifice tab. The tab provides an excellent handle at the time the plate is being installed between flanges. However, the orifice tab also has several other functions. It furnishes information about the plate where it can be seen readily without the necessity of removing the plate after it has been installed. Into the tab itself are stamped I.D. of hole, instrument number, orifice calculation number, etc.

It is evident that because of the bevel and the auxiliary hole, the correct orientation of the orifice plate in the pipe is most important. If the plate in the pipe is most important and if the plate is not correctly positioned the Drain hole (or Vent hole) and the bevel will be unable to perform their respective functions. Correct orientation is assured if conventional recognized practice is observed when the plate is placed in the pipe.

The conventional practice is:

- The orifice tab should always be pointed upward. This assures correct positioning of the auxiliary hole.
- The lettering stamped on the orifice tab should always face upstream. This assures that the bevel, if any, is facing in the correct direction.

Although concentric orifice plates are by far the most widely used type, certain kinds of flow can be more satisfactorily handled by either Eccentric Orifice Plates or Segmental Orifice Plates. (Figure 5.12).

Eccentric

With Eccentric Orifice Plates, the hole is not located in the center of the plate — it is higher or lower. When the plate is installed in the pipeline, the edge of the hole will be almost tangent to the top inside of the pipe (or the bottom). One application where this arrangement is advantageous is in liquid flows with certain quantities of solids, perhaps in suspension, carried in the main flow. In this application, the opening is located in the lower part of the plate. A second application is in flows of gas or vapor carrying reasonably large amounts of liquid or condensate. In this case, the hole is located in the lower part of the plate.

A third application is in the flow of liquids, which carry fairly large quantities of gas or air. In this case, the hole is located in the top part of the plate. With eccentric orifice plates, the differential pressure connections through the pipe-wall or flange must be located either 90° or 180° from the tangency point.

Segmental

Segmental Orifice Plates have openings shaped in the form of a circular segment. The opening is comparable to that of a partially opened gate valve. The straight-line portion of the cutout is known as the dam. The differential pressure connections must be located through the side of the pipe where the dam is, in a direct line with the midpoint of the dam.

Segmental orifice plates are principally used in applications involving the flow of liquids or gases carrying impurities heavier than the flowing fluid. Liquid slurries or exceptionally dirty gases are examples.

It is obvious that proper orientation of both segmental and eccentric orifice plates in the pipeline is of particular importance.

High Hat

High Hat Orifice Plates (Figure 5.13) are used for the purpose of extending the orifice upstream or downstream from a flange, an elbow, or some other fitting. The flat plate, which fits in the bolt circle of a pair of flanges, has welded to it a cylinder of thin metal whose diameter is sized to fit the inside of the pipe. The length of the cylinder is determined by the distance required to locate the orifice plate, which is welded in the extremity of the cylinder, at the required distance from the flanges. High hat orifices eliminate piping changes when there are existing flanges in the pipe in almost the right location.

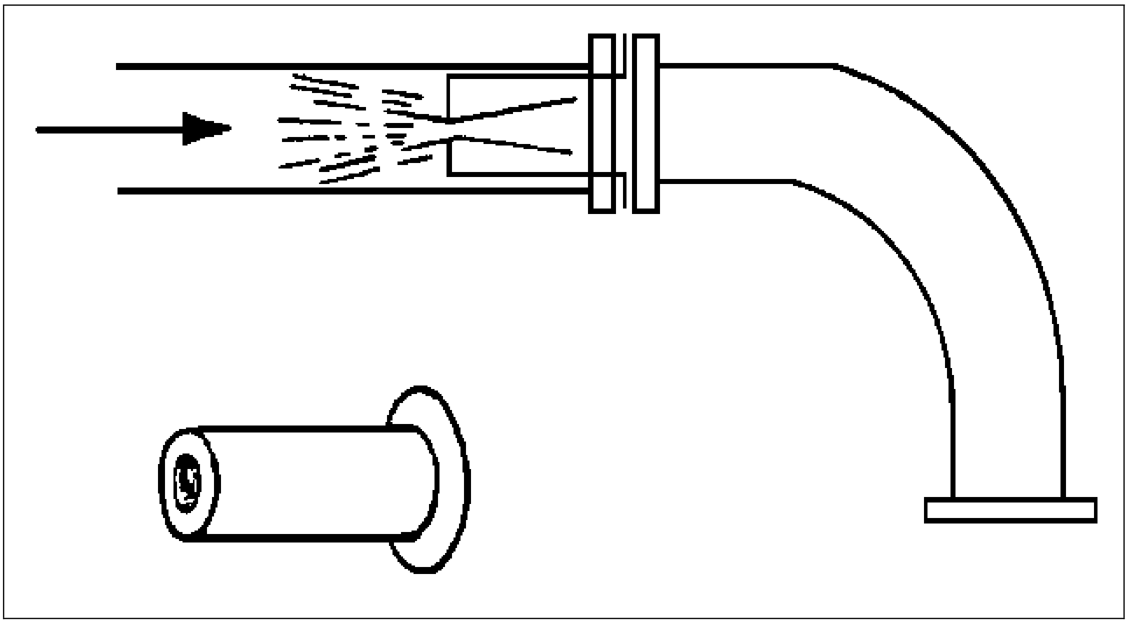


Figure 5.13 High Hat Orifice

There are three standard locations for the pipe taps that connect into the process line to feed the pressures on either side of the orifice plate to the flow meter body.

Flange taps are the most common, and are located in the flanges between which the orifice plate is clamped (Figure 5.14). They are drilled on a centerline 1" from the surface of the flange against which the orifice plate is clamped. With a 1/8" thick orifice plate these taps are 2-1/8" apart. Most modern flow meter bodies are designed with connections 2-1/8" apart to facilitate direct connection to flange taps. Much data is available for these tap locations.

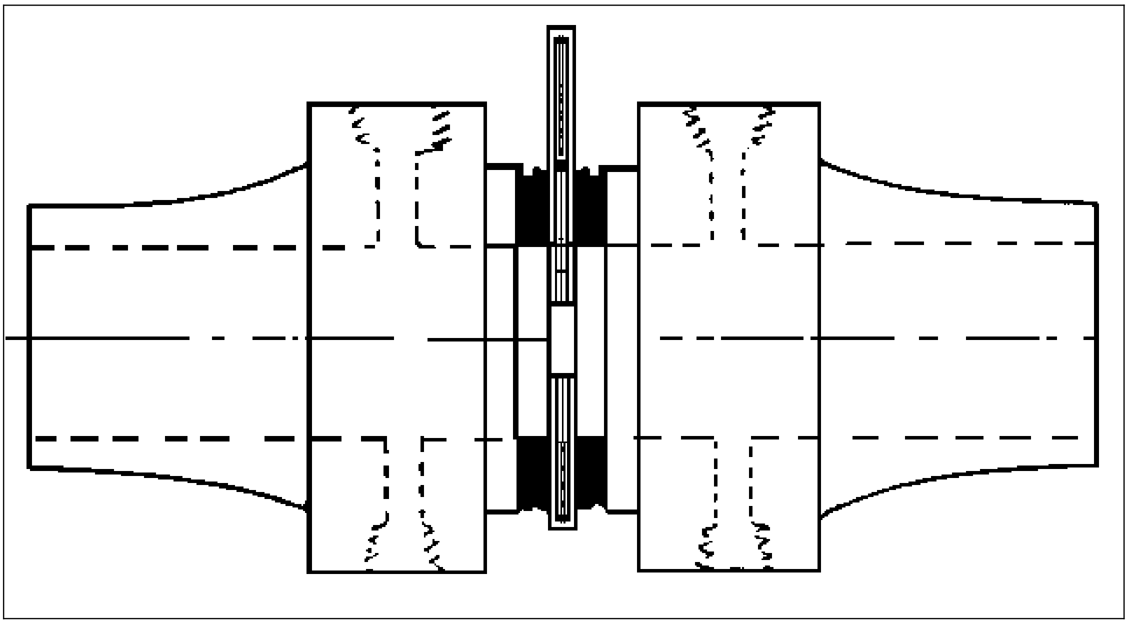


Figure 5.14 Flange Tap

Vena Contracta taps are located so that the upstream tap is one pipe diameter upstream and the downstream tap is at the Vena Contracta, which is about a half pipe diameter downstream from the orifice plate. This location provides the largest differential pressure for a given flow, but the location of the downstream tap is critical.

Pipe taps are located 2-1/2 pipe diameters upstream and 8 pipe diameters downstream. The differential pressure measured is the permanent pressure loss caused by the orifice plate. This is the lowest differential pressure for a given flow. These taps are used often on large flows.

Venturi Tubes

Venturi tubes have several advantages over orifice plates:

- They can satisfactorily measure the flow of fluids with large amounts of solids, such as wood pulp or crystals in liquor
- They have a considerably lower permanent pressure loss than either orifice plates or flow nozzles
- They can measure 60% more flow, for the same size pipe and the same differential than orifice plates
- They are, on the other hand, subject to the following limitations:
- They are usually large, heavy, and somewhat troublesome to install
- They are inflexible to changes of range
- They are relatively costly

Figure 5.15 shows a typical Venturi tube.

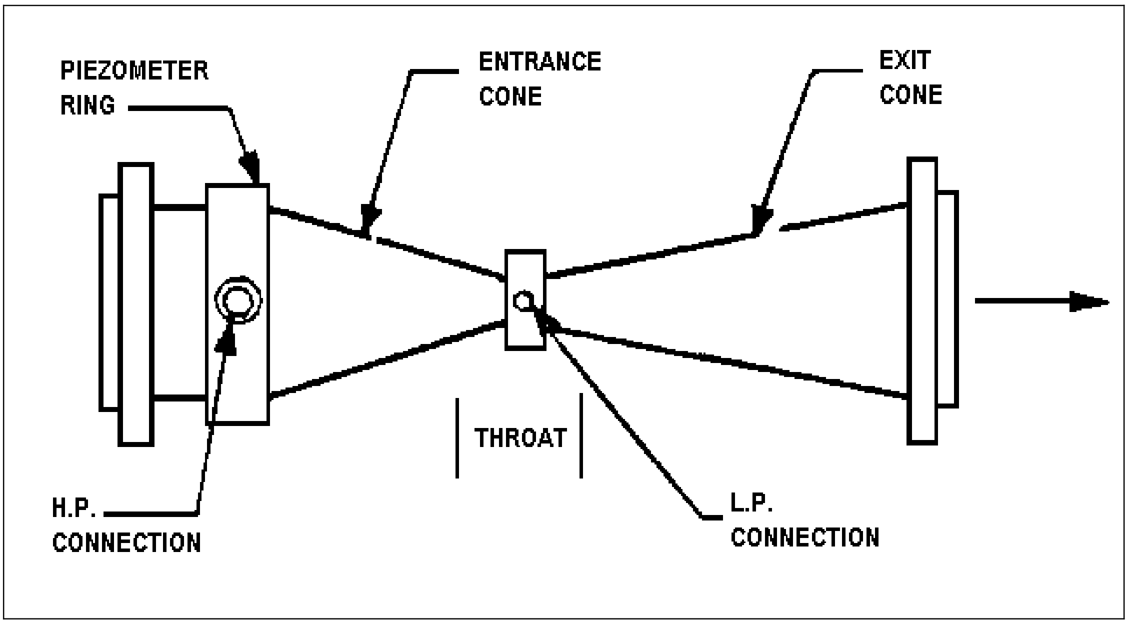


Figure 5.15 Venturi Tube

It consists of a flanged piping assembly with a converging entrance cone to guide the flow to the narrow neck and a diverging exit cone to guide it back to full pipe flow.

Flow Nozzles

Another type of primary element is the flow nozzle. One is shown diagrammatically in Figure 5.16. It consists of an entrance cone and throat, but no exit cone. The high-pressure connection is made through the pipe wall approximately one pipe diameter from the entrance. The low-pressure connection is located at the point of smallest jet area.

They are used in applications where the fluid carries entrained solids. Their cost is greater than an orifice plate, although not as great as that of a Venturi tube.

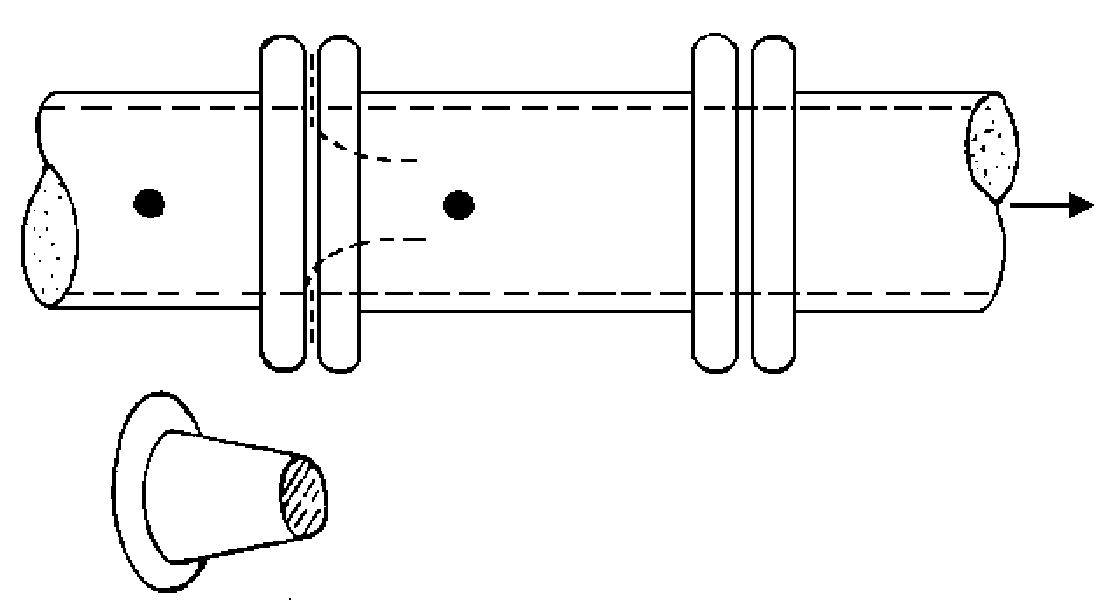


Figure 5.16 Flow Nozzle

Flow nozzles also will handle 60% greater flow than an orifice plate under the same conditions. This gives rise to one of their principal uses: namely, in installations where high operating pressures and greater capacities must be measured through lines reduced to minimum size to save piping.

Calculation of Flow From Differential Pressure

Where a differential pressure meter is used to measure flow, the reading from the meter in differential pressure must be translated into units of flow. This is not, however, a linear relationship. At zero differential pressure, the flow is, of course, zero and at maximum differential pressure, the flow is maximum, or 100%. At any differential pressure, the % of full flow may be found using the following formula:

$$\% \text{ FLOW} = \sqrt{\Delta P \text{ measured} \div \Delta P \text{ maximum}}$$

As an example, on a certain application, a Venturi with a ΔP of 200" H_20 at the maximum flow of 17 million gallons, is measuring raw sewage. Clear plastic tubing attached to the high and low pressure taps allows the pressures at these points to be indicated by the height to which water rises in them. If the difference between the height of water in the tubing is seen to be 66.67 inches, and since the liquid in the tubing is water, the ΔP is 66.67" H_2O. Using the formula given above, the % of full flow can be found.

$$\% \text{ FLOW} = \sqrt{66.67 \div 200} = 57.4\%$$

57.4% of 17 million gallons = 9.758 million gallons.

A reference chart of the square root relationship between % differential and % flow is provided in Table 5.1.

Table 5.1 Percent of Differential Pressure vs. Percent of Flow Rate

% Input	% Out	% Input	% Out	% Input	% Out	% Input	% Out
0	0	25	50	50	70.7	75	86.6
1	10	26	50.9	51	71.4	76	87.1
2	14.1	27	51.9	52	72.1	77	87.1
3	17.3	28	52.9	53	72.8	78	88.3
4	20	29	53.8	54	73.5	79	88.9
5	22.4	30	54.8	55	74.2	80	89.4
6	24.5	31	55.7	56	74.8	81	90
7	26.4	32	56.6	57	75.5	82	90.5
8	28.4	33	57.4	58	76.1	83	91.1
9	30	34	58.3	59	76.8	84	91.6
10	31.6	35	59.2	60	77.4	85	92.2
11	33.2	36	60	61	78.1	86	92.7
12	34.6	37	60.8	62	78.7	87	93.3
13	36.1	38	61.6	63	79.4	88	93.8
14	37.4	39	62.4	64	80	89	94.3
15	38.7	40	63.2	65	80.6	90	94.9
16	40	41	64	66	81.3	91	95.4
17	41.2	42	64.8	67	81.9	92	95.9
18	42.4	43	65.6	68	82.5	93	96.4
19	43.6	44	66.3	69	83.1	94	96.9
20	44.7	45	67.1	70	83.7	95	97.5
21	45.8	46	67.8	71	84.3	96	97.9
22	46.9	47	68.6	72	84.9	97	98.5
23	47.9	48	69.3	73	85.4	98	98.9
24	48.9	49	70	74	86.0	99	99.5

Differential Pressure Flow Meters

Over the years, industry has used a large variety of flowmeters whose principles of operation range from the very primitive (e.g., mercury manometer devices) to the very sophisticated (e.g., ultrasonic methods). In the recent past flowmetering has been dominated by flow transmitters, both pneumatic and electric. Most of these operated on what is known as the force balance principle. Differential pressure enters a meter body where it creates a force by acting on the area of a bellows. This force is transferred into the beam system of the transmitter, causing motion, which is detected by an electronic detector. The detector is very sensitive and the motion involved is minute. But the detector is part of an electrical circuit through an amplifier, and as this minute motion is detected, the output from the amplifier is changed. The standard output is 4-20 mA, and is fed back into an electromagnet which also exerts a force on the beam system, but in opposition to the force exerted by the differential pressure. The output stabilizes at the value necessary to null out the differential pressure force, thus providing an output that is proportional to the differential pressure input to the meter body.

These devices are characterized by critical mechanical adjustments and alignments, parts, which are vulnerable to mishandling, and have relatively high manufacturing costs.

Recently, manufacturers have produced a variety of state-of-art flowmeters, which utilize a minimum of mechanical linkages, levers and pivots. These operate on one of several principles:

- a pressure varying an electrical capacitance
- a piezoelectric material such as quartz which when stressed creates an EMF
- a piezoresistive material which when stressed varies resistance

Diffused Silicon Differential Pressure Transmitters

Principles

This is an electrical device for measuring differential pressure and transmitting a proportional electrical signal. The measuring system of the transmitter is based on a unique strain gauge made by diffusing a Wheatstone bridge circuit into a single-crystal silicon chip, creating an integrated piezoresistive sensor with no measurable hysteresis. Pressure is transferred from the process to the sensor through sealed chambers filled with liquid silicone (see Meter Body Operation in next section). The direct conversion of pressure into an electrical signal is achieved by a minute deflection of the sensor, which changes the resistance of the bridge with the applied stress. The bridge unbalance caused by the stress is amplified and converted in a card mounted amplifier to a 4-20 mA dc signal for transmission to process control instrumentation. The sensor is shown in Figure 5.17.

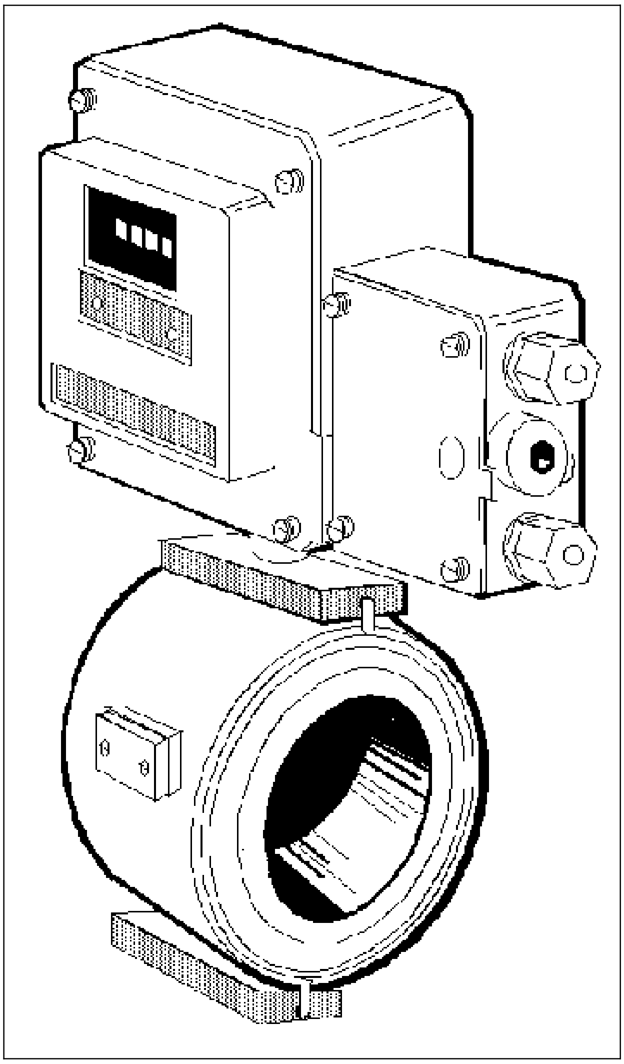


Figure 5.17 Magnew 3000 Sensor and Converter

Meter Body Operation

A cut away view of the meter body is shown in Figure 5.18.

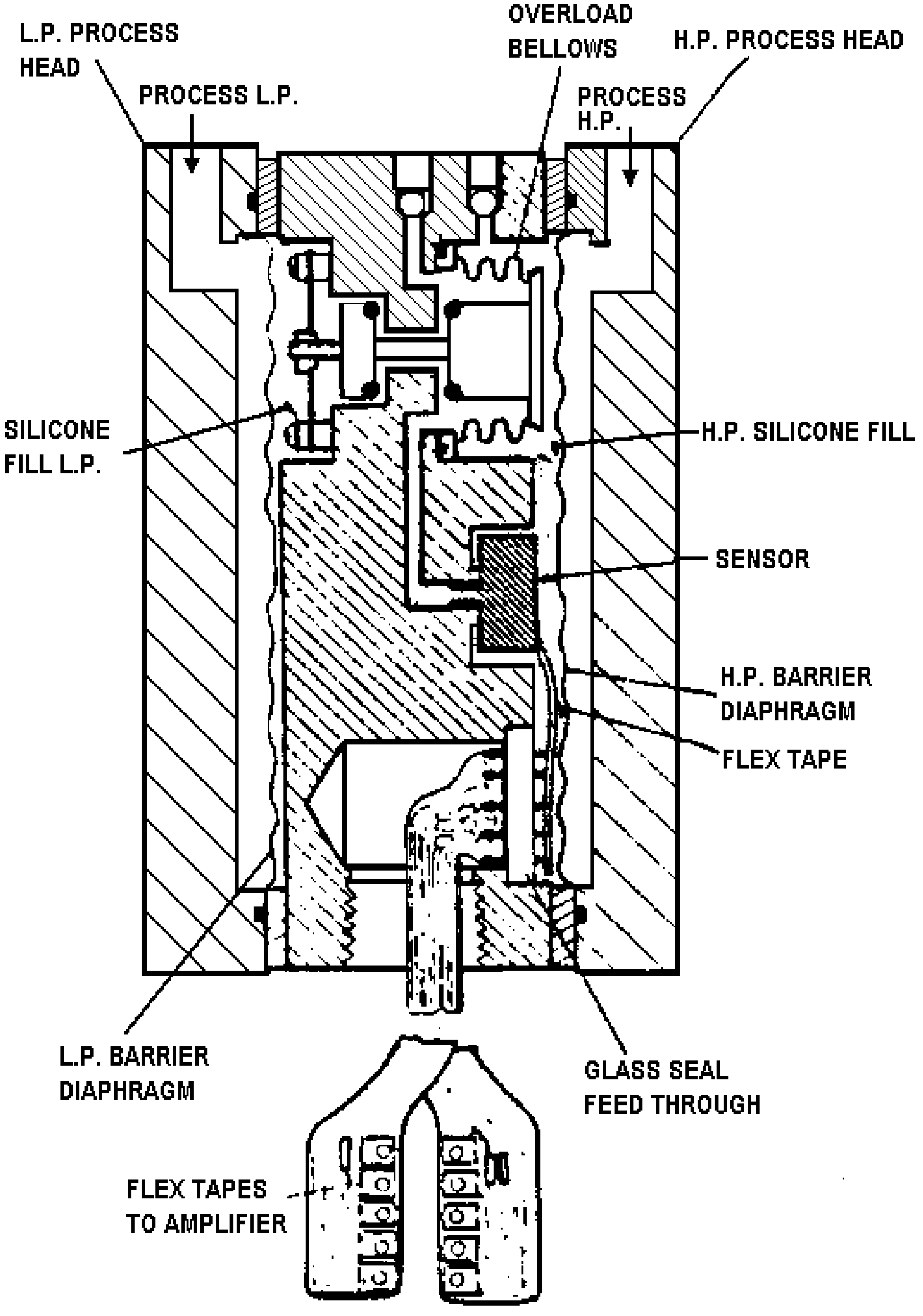


Figure 5.18 Meter Body

Process fluid enters the transmitter through high-(HP) and low-pressure (LP) connections, contacting only the two process heads, two barrier diaphragms and the gaskets.

The flexible, metallic barrier diaphragms, each electron beam welded to a back-plate, serve two basic functions: to seal-off the sensor from the process fluid and to transfer high and low pressure to the sensor. Pressure is transferred through an inert, incompressible silicone liquid fill. The diaphragms are simply transferring, not measuring, pressure. One of the diaphragms can be seen in Figure 5.19.

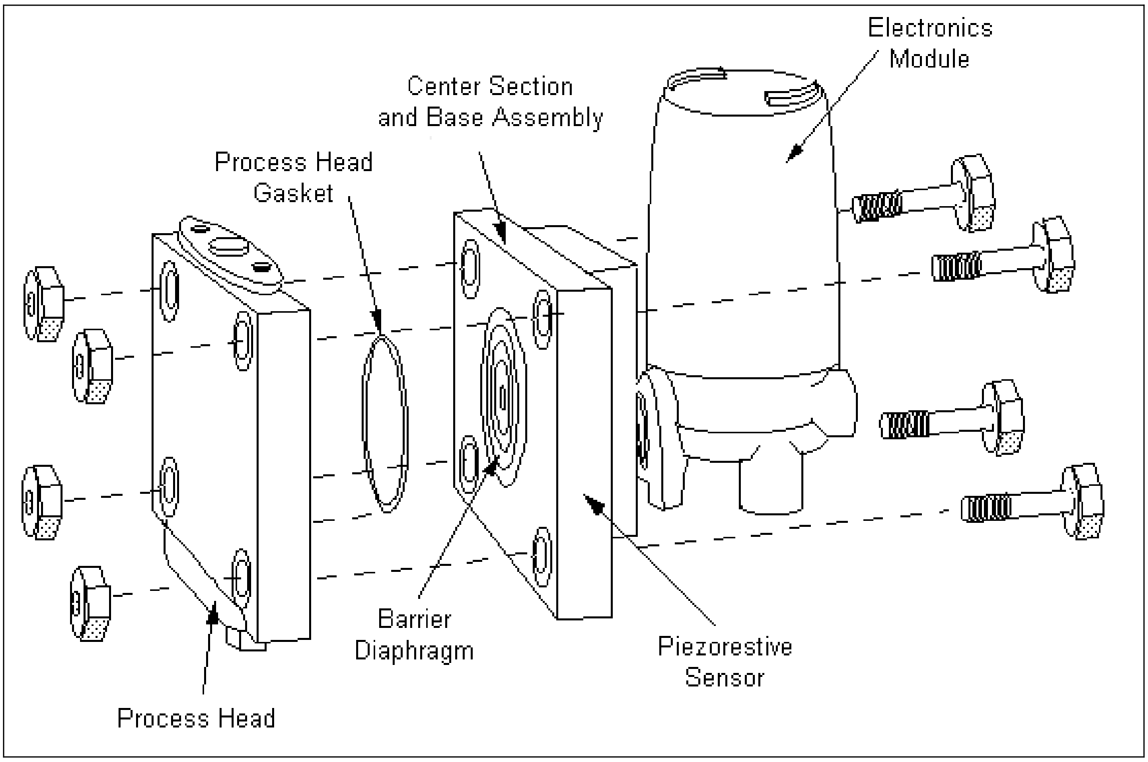


Figure 5.19 Pressure Measurement Transmitter

The diffused silicon sensor's active portion is a thin diaphragm that will deflect minutely as pressure is applied. The sensor is so mounted in the meter body that the high pressure fill is contacting one side of the diaphragm and the low pressure fill is on the other side. The deflection of the diaphragm is thus a function of the difference between the two pressures, and the resistance a change of the bridge will likewise be a function of the difference between the two pressures.

To protect the sensor from overload pressures up to the rated pressure of the meter body, there is an overload valve, as shown in the diagram in Figure 5.18. The overload bellows separates the high pressure fill from the low pressure fill. It also operates the overload valve. If the different pressure should exceed a preset value above the range of the sensor, the overload bellows will cause the overload valve to close. If the higher pressure is in the high pressure fill the closing of the valve will trap fill fluid inside the bellows and the sensor, protecting them. If the higher pressure is in the low pressure fill, the closing of the other valve will prevent the overload pressure from ever reaching the bellows or sensor.

Flextapes carry the electrical circuits from the sensor to the amplifier, passing through a glass seal feed-through which is pressure tight, holding the pressure within the meter body while allowing the electrical circuits to be made out of the meter body. When pressure changes cause the sensor bridge to be unbalanced, the output changes in proportion to the amount of unbalance. The output signal is then used to rebalance the bridge. In essence, the transmitter has a sensitive and accurate null balance measuring circuit.

Open Channel Flow Elements

Although most flow meter installations involve the flow of fluid through pipes, there are many cases where flow measurement must be made in open channels.

This type of flow measurement is generally made by causing the liquid to flow through an opening in a dam. The dam is known as a weir, and is designed with various shapes, some of which are shown in Figure 5.20.

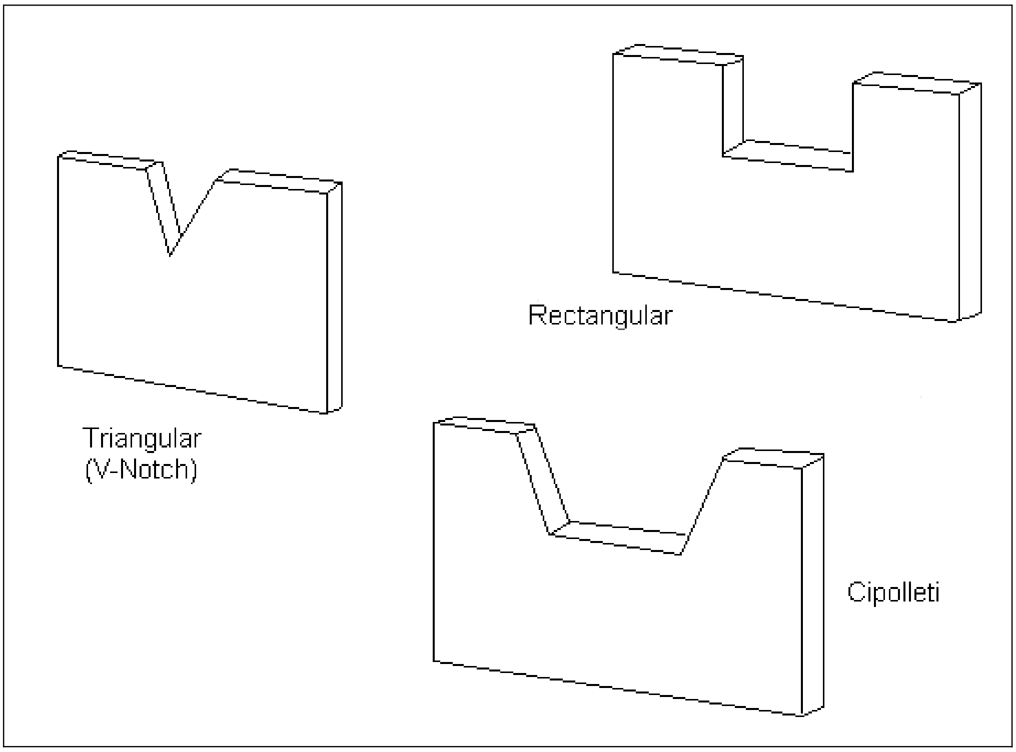


Figure 5.20 Open Channel Flow Sensing Elements

If the shape or cross-section area of the weir is known, and if the height of water level, h, flowing over it is also known, the flow can then be calculated. As the head, h, over the weir increases, the cross sectional area of the flow and the velocity increase. For this reason, weir meters are known as Head-Area meters.

The flow-measuring instrument continuously measures the head, h, going over the crest of the weir. It does this by means of a float that rides on the surface of the liquid at a point before it passes through the weir. Changes in level, reflecting changes in flow, cause changes in float position. The float actuates the pen of the flow recorder.

In applications where the flowing liquid carries excessive amounts of solids, or sediment, the element normally used is a Parschall flume. A plan view of one is shown in Figure 5.21. The narrowed section produces fast flow rates that aid in preventing build-up of solids in the region of measurement.

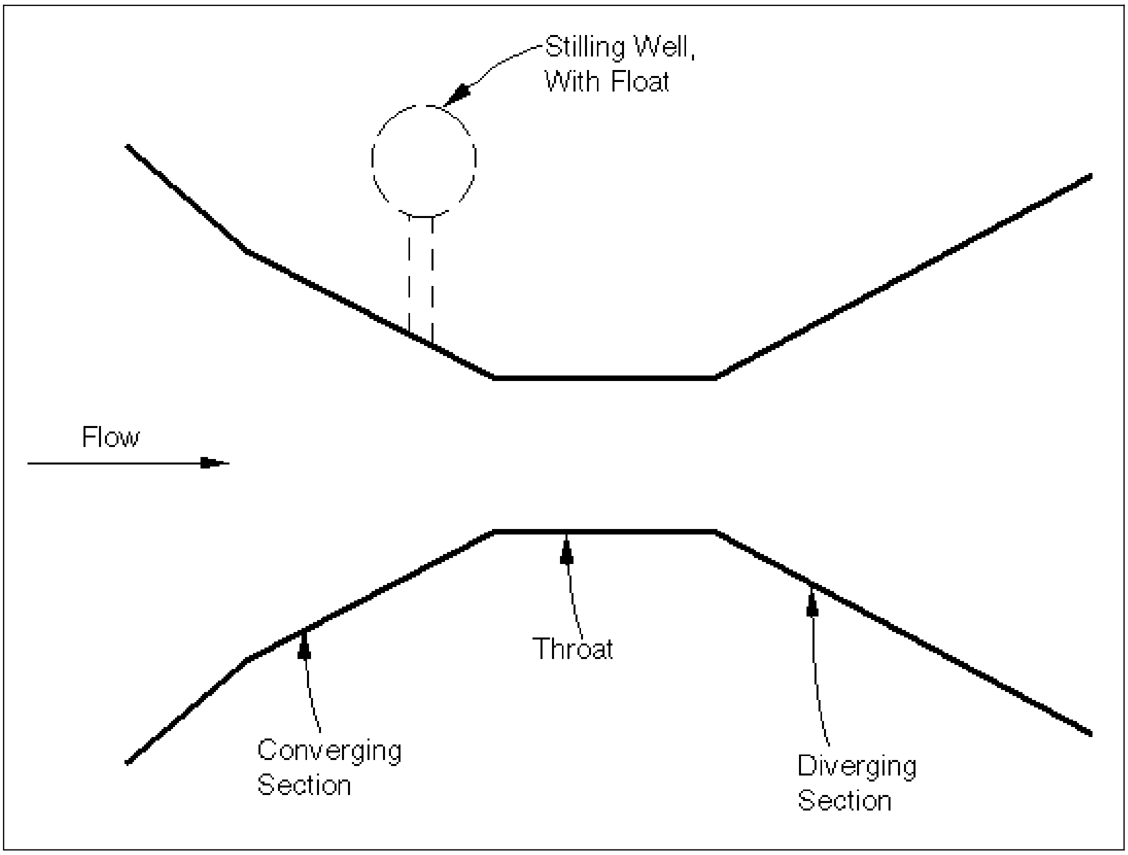


Figure 5.21 Parschall Flume

The float used to measure the head, h, over the weir or flume is installed in external stilling wells. The function of these is to eliminate the effect of turbulence, and other disturbances that may be in the channel.

Ultrasonic Flowmeters

Principles of Operation

For a number of years a great amount of effort has been expended to develop flowmeters that operate on the principle of measuring the velocity of sound as it passes through the fluid flowing in a pipe. The most common approach to this problem is described below and shown in Figure 5.22.

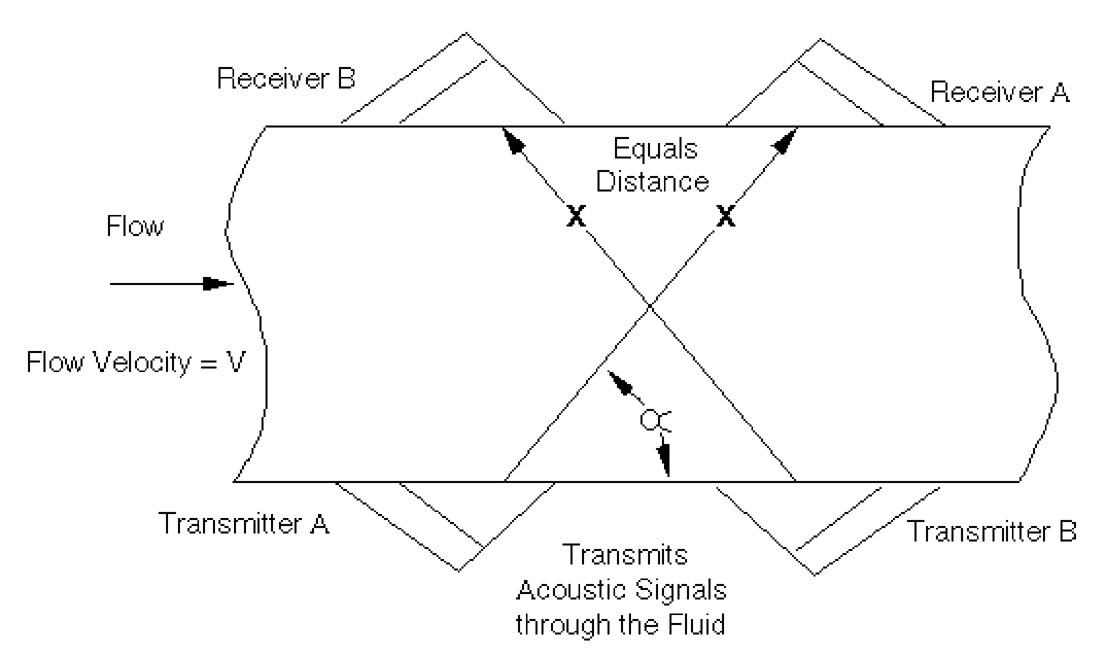


Figure 5.22 Ultrasonic Flowmeters

Piezoelectric crystals (barium titanate or lead zirconate-titanate) are used as transmitters to send acoustic signals through the fluid flowing through the pipe to receivers that are also piezoelectric crystals. The fluid flows through the pipe at a velocity V. The distance between each transmitter-receiver pair is X. The velocity of the sound through the fluid is Y. The path of the sound is at an angle a from the pipe wall. The velocity of sound from transmitter A to receiver A (increased by the fluid velocity) is Y + Vcosa, and its frequency is

$$fA = y + Vcisa \div X$$

The velocity of sound from transmitter B to receiver 6 (reduced by fluid velocity) is Y - Vcosa, and its frequency is

$$fB = y - Vcosa \div X$$

The beat or difference frequency Δf is

$$fA - fB \text{ or } \Delta = (2\ Vcosa) \div X$$

Since a and X are constant, the flow velocity can be obtained by measuring this beat frequency. Flow rate is then derived by multiplying the flow velocity by the pipe cross-sectional area.

The beat frequency is measured by the use of an electronic mixer. The purpose of the mixer is to translate the high frequencies to a lower frequency level where more efficient amplification and selectivity are possible. In general, the design of a mixer is similar to that of an RF amplifier with the addition of the injection of an oscillator frequency into the amplifier. The combination of two oscillators and mixer is referred to as a beat frequency oscillator (BFO).

Application Factors

The advantage of using an ultrasonic flowmeter will vary with the application. In general, there are seven main advantages:

- Relatively high accuracy (0.5% full scale), which is comparable to magnetic flowmeters and turbine flowmeters.
- Linear output over a wide range (up to 100 to 1). This is much higher than magnetic, flowmeters and turbine meters, which, in turn, have outputs that far exceed the linear ranges of differential pressure-based measuring devices such as orifice plates and Venturi tubes.
- High reliability, due to the fact that ultrasonic flowmeters do not contact the fluid medium with a part that can move (and, therefore, wear out). Deposits of material on the transducer faces will not affect accuracy.
- Obstructionless flowmetering, which means the flowmeter will not introduce a pressure drop like turbine meters and differential pressure measuring devices.
- Adaptability to a wide range of pipe diameters — from 1/4 inch to over 30 ft. — are possible. Sometimes relatively simple electronic adjustments in the electronic circuitry can adapt a single flowmeter to a wide range of pipe diameters.
- Flow monitoring is essentially independent of fluid temperature, density, viscosity and pressure.
- Low installation and operating costs.

There are disadvantages, of course. The main one is that Ultrasonic flowmeters tend to be initially more expensive than conventional meters in small-diameter pipe applications. In addition, ultrasonic flowmeters are sensitive to changes in the fluid composition (such as the percentage of particulates) and other variables that can distort the propagation of sound waves.

Conclusion

It should now be evident that the variety of methods of flowmetering available to industry is limited only by man's imagination; furthermore, the large variety of methods discussed in this section are quite indirect methods of measuring a variable which is often difficult to measure directly.

Lesson Summary

In this lesson you have learned the basics of flow measurement and instrumentation found in industrial plants.

In the next lesson you will learn about types of analytical measurement and instrumentation.

Lesson 6
Analytical Measurement

Lesson Objectives

At the completion of this lesson, you will be able to understand the basic principles and types of analytical measurement and instrumentation. This course will cover the basic types of analytical applications that most industrial plants measure and control.

pH Measurement

pH is the measure of the hydrogen ion concentration in a solution. It describes the degree of acidity or alkalinity (basicity) of a solution. The formal definition of pH is the negative logarithm (p) of the hydrogen ion activity (H): pH = - log [H+]. In layman's terms, that means the power of hydrogen ion activity. pH is used most often industrially with, but not limited to, aqueous (water-based) applications. The units of measure scale in most common applications ranges from 0 to 14 pH. 0 pH represents 1 (10^0) mole/liter of hydrogen, while 14 pH represents 0.00000000000001 (10^{-14}) moles/liter of hydrogen. There is a factor of ten difference between each pH unit.

H_2O (the water molecule) dissociates into the hydrogen ion [H+] and the hydroxyl ion [OH-]. In an aqueous solution, the hydrogen and hydroxyl ion concentrations are dependent on each other. If the H+ concentration is greater than the OH- concentration in an aqueous solution, the solution is acidic and the pH value is less than 7. Likewise, if the H+ concentration is less than the OH- concentration, the solution is basic and the pH value is greater than 7. If equal amounts of the ions are present, the solution is neutral and the pH is 7.

pH measurements can be most accurately made with a pH measurement “loop” consisting of a probe, a preamplifier, and an analyzer. The probe will have two or three modules - a measuring electrode, reference electrode, and a temperature compensator - which are required to make the measurement, as seen in Figure 6.1. In some cases, the temperature compensator may not be needed.

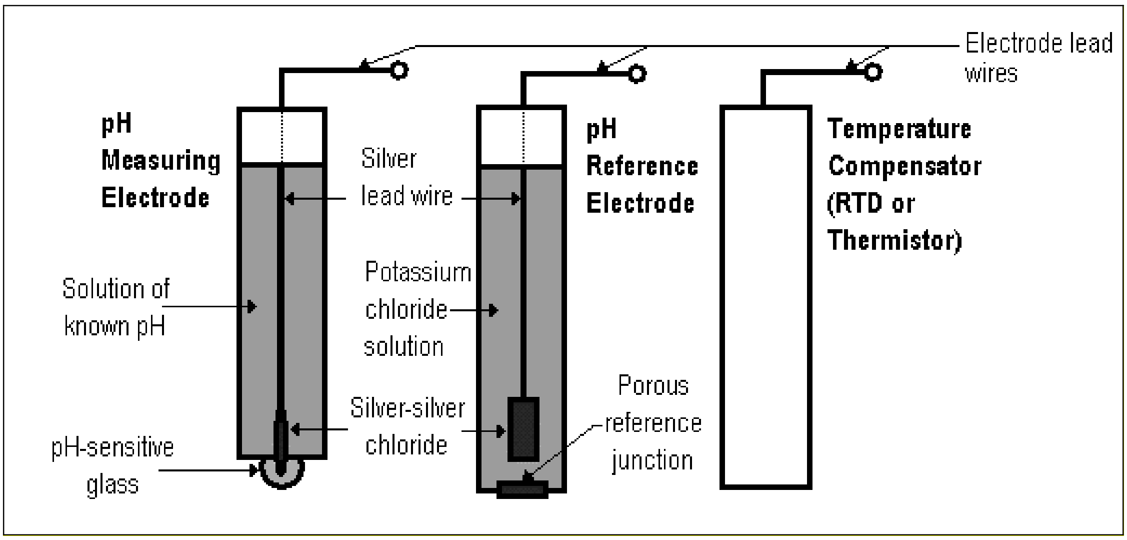


Figure 6.1 How pH Measurement Works

The pH measurement is, in effect, a battery. The negative terminal of the battery is the equivalent of the reference electrode, and the positive terminal is the equivalent of the measuring electrode. The measuring electrode, which is sensitive to hydrogen ions, develops a potential (voltage) directly related to the hydrogen ion concentration in the solution. The reference electrode contains a fill solution, which slowly flows out of the electrode through the reference junction. This fill solution makes contact with the solution and the measuring electrode, completing the circuit. Thus the voltage between the reference electrode, which should remain at a constant voltage, and the measuring electrode will change proportionally to the hydrogen ion concentration. However, just like a battery has a limited life span, the pH electrode’s lifetime is also finite. Due to inherent properties of the electrode, it will eventually have to be replaced even in the best environment.

The output of the measuring electrode will change with temperature (even though the process may remain at a constant pH), so a temperature compensator is sometimes necessary in most processes to automatically correct for this change. The preamplifier is necessary to change the high-impedance electrode signal into a low-impedance signal that the analyzer can work with, as well as strengthening the signal so no degradation takes place.

pH is measured to accomplish the following:

- Neutralize wastewater for reuse and to meet regulatory requirements.
- Protect from acid corrosion
- Control scaling
- Help diagnose demineralizer problems
- Reduce reagent costs
- Control chemical reactions

Oxidation Reduction Potential (ORP) Measurement

ORP (Oxidation-Reduction Potential), also called Redox, is a measurement of the activity of the oxidizing and reducing reactions which takes place in a solution. Electrons transfer from reducing agents to oxidizing agents. Oxidation and reduction are dependent on each other; one cannot take place without the other. ORP is a non-specific measurement, since it measures all oxidation and reduction which takes place in a solution. However, there is usually a dominating oxidation-reduction reaction, which provides most of the potential, so ORP can be used for specific applications. The units of measure with ORP are typically millivolts (mV).

A typical ORP measuring "loop" consists of a measuring electrode, a reference electrode, a preamplifier, and an analyzer. The preamplifier is not necessary for the ORP measurement as it is in specific ion measurements, but Honeywell's pH/ORP analyzers are designed to expect an input from a preamplifier. A temperature compensator is also not used with ORP measurements, since each ORP reaction would require different temperature compensation, and it would be nearly impossible to design an analyzer which could compensate for the immense numbers of possible ORP reactions which take place in a given process.

The ORP measuring system can be thought of as a voltmeter. The negative terminal of the voltmeter would be the equivalent of the reference electrode, and the positive terminal would be the equivalent of the measuring electrode (Figure 6.2). ORP measurements use a metal measuring electrode, usually made of gold or platinum. This electrode becomes charged by the electrons present (or absent) in the solution as a result of electron migration caused by one substance being oxidized and the other being reduced. Oxidizing agents, such as chlorine, raise ORP; reducing agents, such as sulfites, lower ORP. Typical applications will have a positive (0-1000) ORP reading, although it is possible to have a negative reading as well.

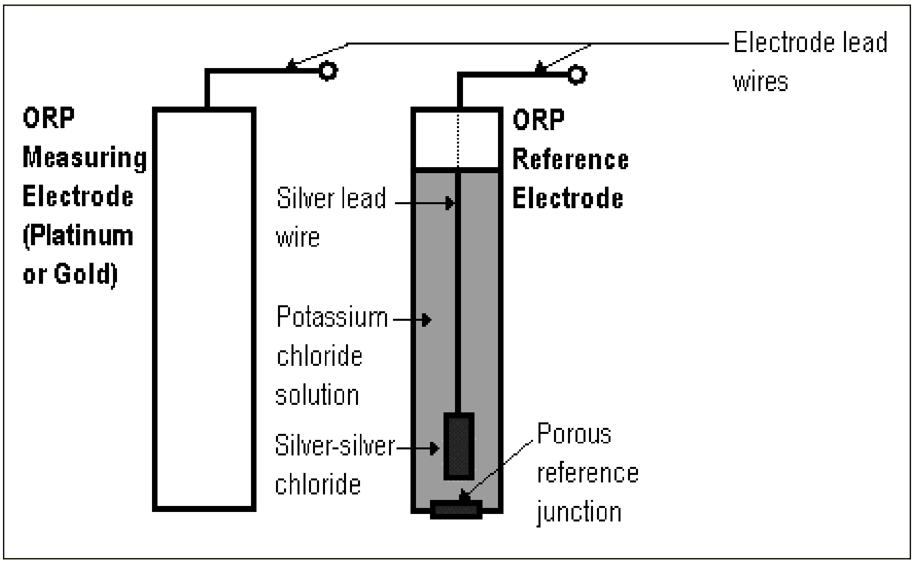


Figure 6.2 How ORP Measurement Works

Industrial equipment is used to empirically determine appropriate ORP values for a given process. Variations in temperature, dissolved oxygen content, pH, reagent purity, as well as unknown amounts of extraneous oxidizing and reducing ions eliminate the possibility of obtaining valid theoretical ORP estimates.

In water, analytical measurements relating to the composition of a particular component are usually given in units of concentration (ppm, ppb, g/l, etc.). Although ORP is used to control concentration levels, its unit of measurement is millivolts, a non-concentration unit. This tends to add confusion in understanding the usefulness of an ORP measurement. How do you accurately control the composition of a solution without directly measuring a component's quantity (concentration)? It is important to keep in mind that ORP measurements are really used in determining the "state" of a solution and not the solution's concentration. In this case, the word "state" refers to the solution's oxidation/reduction potential influenced by the addition of certain oxidizing and reducing reagents. By adding the appropriate type and amount of reagent, a solution's state of oxidation/reduction can be controlled.

A sensitive independent test for a critical material involved in the reaction is used to determine when just enough oxidant or reducing agent has been added and satisfactory treatment has been achieved. This kind of analysis can usually be performed using laboratory methods or portable colorimetric test kits. At the appropriate treatment point determined by the test, the ORP is measured, and this measurement can be used as the control set point. The ORP measurement permits consistent on-line control, assuring full oxidation or reduction while not wasting reagent.

Industries measure ORP to accomplish the following:

- Ensure control of and/or destruction of toxic chemicals
- Regulate effluent for conformance for regulatory requirements
- Regulate disinfection of water
- Protect processes from harmful chemicals

Specific Ion Measurement

Specific ion measurement, utilizing an ion-selective electrode *(ISE)*, is used for the analysis of specific ion concentrations in a solution. The most common type of ion-selective electrode *(ISE)* would be a pH electrode, which is sensitive (in most cases) only to the hydrogen ion in a solution. Other popular measurements include sodium, fluoride, and chloride ions. However, there are numerous other measurement types for which laboratory supply houses provide ISE's, such as nitrate, potassium, sulfate, water hardness, and calcium. Dissolved gases such as ammonia, nitrogen dioxide, and carbon dioxide may also be measured with ISE's. A careful assessment must be made by the user to determine if the electrode's limit of detection, selectivity, process interferences and possibilities of ion complexing will yield a meaningful electrode signal under the specific application conditions. Typical units of measure are parts-per-billion (ppb) and parts-per-million (ppm).

Specific ion measurements can be most accurately made with a specific ion measurement "loop" consisting of a probe, a preamplifier, and an analyzer. The probe will have two or three modules - a measuring electrode, reference electrode, and a temperature compensator -, that are required to make the measurement. The temperature compensator may not be required in some applications.

The specific ion measurement is, in effect, a battery. The negative terminal of the battery is the equivalent of the reference electrode, and the positive terminal is the equivalent of the measuring electrode. The measuring electrode, which is ion-selective, develops a potential (voltage) directly related to the specific ion concentration in the solution. The reference electrode contains a fill solution that slowly flows out of the electrode through the reference junction. This fill solution makes contact with the solution and the measuring electrode, completing the circuit. Thus the voltage between the reference electrode, which should remain at a constant voltage, and the measuring electrode will change proportionally to the specific ion concentration. However, just like a battery has a limited life span, the ion-selective electrode's lifetime is also finite. Due to inherent properties of the electrode, it will eventually have to be replaced even in the best environment.

Specific Ions are measured to accomplish the following:

- Measure sodium contamination

1. Sodium is pervasive throughout the environment, and its measurement at the low ppb level is representative of ionic contamination in general.
2. Sodium compounds are corrosive.
3. Sodium is the first ion to break through a spent cation bed and therefore the best indication for triggering regeneration.

- Measure concentrations of chloride ion

1. The concentration in plant effluent is restricted by environmental regulations.
2. Chloride is also corrosive in processes.

- Measure concentrations of fluoride ion

1. Measurements are used in potable water to verify levels of fluoridation.
2. Plant effluent is monitored, especially in glass etching & microelectronics.

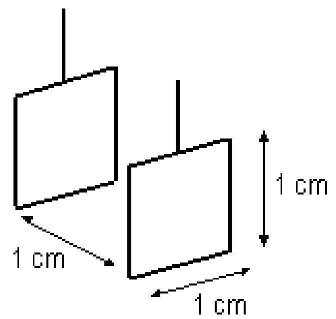
- Measure concentrations of sulfide ion

1. Sulfide is added to precipitate metal sulfides for removal in wastewater treatment.
2. Sulfite is measured in wet scrubbers to assure its removal from gas streams.

Conductivity/Resistivity Measurements

Conductivity is the measurement of the ability of a solution to carry an electric current - the higher the conductivity, the higher the current. Conductivity is based on the number of dissolved ions present in a solution. The unit of measure is either Mhos/cm or Siemens/cm (1 Mho = 1 Siemen). The ranges that are typically measured are much lower than 1 Siemen/cm, usually around 1 microSiemen/cm. The prefix "micro" (μ) means 0.000001, or 1 x 10^{-6}, so that 1 microSiemen/cm (μS/cm) would be 1,000,000 times smaller than 1 Siemen/cm. Resistivity is merely the inverse of conductivity, and its unit of measure is Ohms-cm (Ω-cm). Notice that the conductivity unit of measure, Mho, is really "Ohm" spelled backward. 10,000 Ohms-cm of resistivity represents 0.0001 Siemens/cm, or 100 μS/cm of conductivity.

The units of measurement used to describe conductivity and resistivity are quite fundamental and are frequently misused. A common question regarding conductivity and resistivity units involves the "cm" term. What does the "cm" term represent in the unit Ohm-cm for resistivity and Mhos/cm for conductivity? The basic unit of resistance is the Ohm. The basic unit of conductance, the inverse of resistance, is the mho or siemen. In discussions of bulk material, it is convenient to talk in terms of specific conductance (conductivity) or specific resistance (resistivity). This is the conductivity/resistivity as measured between two metal electrodes built into a conductivity/resistivity cell as seen in Figure 6.3). These electrodes have a fixed size and spacing that establishes the cell constant: the distance between the electrodes divided by the effective cross-sectional area of sample between them, measured in centimeters as seen in Figure 6.3. This geometry is critical to the accuracy of measurement.



$$\textbf{Conductivity Cell Constant} = \frac{\text{Length}}{\text{Area}} = \frac{1\ \text{cm}}{1\ \text{cm}^2} = \mathbf{1\ cm^{-1}}$$

Figure 6.3 Measuring Conductivity

As the dimensions of the cell are changed, the cell constant varies as the ratio of length to area. This practice of changing the cell constant has the effect of raising or lowering the conductance as read between the two plates and producing a value more easily handled by electronic circuitry. Probe manufacturers offer different cell constants to cover a variety of conductivity/resistivity ranges.

Although cells made in this manner are entirely usable, and most early data was collected with them, they rely on insulating walls to define the current path and are vulnerable to bending in shipping, rough handling or when subjected to high flowrate. Most modern cells use a coaxial cell design that is much more robust and can maintain a consistent cell constant over many years of operation. The coaxial design also provides an ideal location for the temperature compensator in its center electrode. This ensures that the temperature is measured at exactly the same point where the conductivity is measured.

Users of ultrapure water prefer to use resistivity units of Mohm-cm, because measurement in these units tends to spread the scale out in the range of interest. When measuring ultrapure water, a typical instrument reading out in resistivity units has 33 times the resolution of the same instrument's conductivity readout (18.18 Mohm-cm compared to 0.055 µS/cm).

A typical "loop" of conductivity consists of an analyzer and a cell. There are a few ways to make the conductivity measurement, but this explanation will be a typical application.

An AC voltage is applied across a conductivity cell, consisting of a pair of metal plates of known dimensions and placed a defined distance apart as seen in Figure 6.4. Since ions exist in the solution, a current will flow through the solution from one plate to the other. The solution acts as a resistor, allowing a certain amount of current to flow, which is dependent upon the dimensions of the plates, the distance between them, and the amount and type of ions present in the solution. The resistance (inverse of the conductance) of the solution can then be calculated based on the amount of current which flows through the solution. An increasing number of ions in the solution will produce a higher conductivity (lower resistivity), while a decreasing number of ions in the solution will result in lower conductivity (higher resistivity). High purity water has very few ions present in the solution, and thus has very low conductivity.

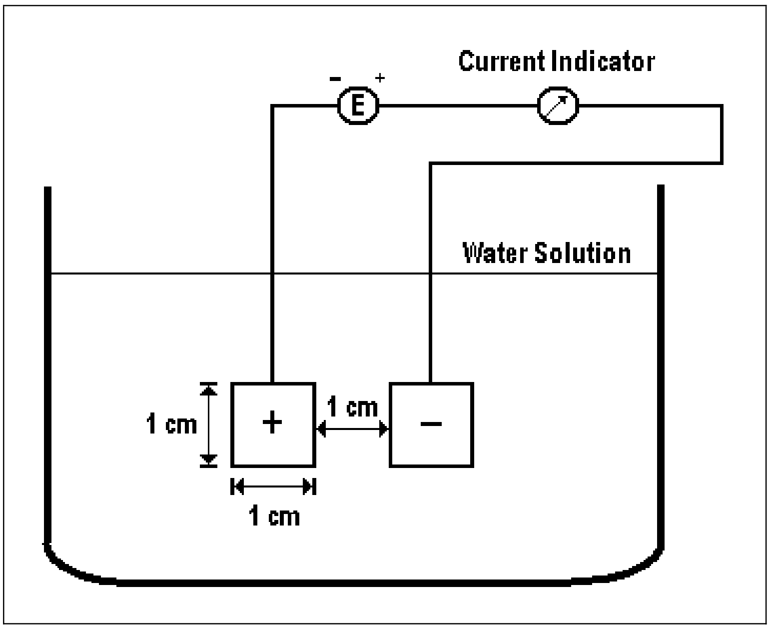


Figure 6.4 Loop Conductivity

A temperature compensator is very important when making the conductivity measurement. Whenever the temperature of a solution is increased, the ionic activity will increase, causing a higher conductivity measurement. Since the temperature of the solution would make comparisons between measurements difficult, conductivity measurement is usually referenced to the conductivity that a solution would have at 25 °C.

Types of Cells

Electrode Cells

The electrode cell operates by applying a fixed-amplitude, square wave voltage across two electrodes of known size and known separation immersed in the process liquid. If there are ions in the liquid allowing a current to flow, that current is measured and converted to the conductivity of the liquid at the time of the measurement. An alternating current is used to avoid "polarizing" the liquid, which involves complete ion migration to the two electrodes. This would make a reading impossible. All cells must be mounted so that they are in direct contact with the process liquid at all times. Each cell is connected to an indicator or transmitter by a 3- to 4-wire cable. The extra wires are used for temperature compensation. Figure 6.4 diagrams the operation of the electrode cell.

Inductive (Toroidal) Cells

The inductive magnetic field cell operates on a different principle than the electrode cell. This type of cell is also known as an electrodeless cell. The inductive cell is made up of two completely enclosed electrical coils as seen in Figure 6.5. During operation, the cell is entirely immersed in the process liquid. The cell is enclosed in a cell body. The instrument sends an alternating current of known value through one of the coils, the primary coil. This current creates a magnetic field and induces a current in the process liquid. This current, in turn, induces a current in the pickup coil. The induced current in the pickup coil is directly proportional to the conductivity of the liquid. No direct contact is necessary between the coils and the solution, thus eliminating potential maintenance problems. These probes are not recommended in low conductivity/high resistivity applications and are usually recommended in fouling environments. Like electrode cells, these devices must be completely immersed in the process flow to measure conductivity accurately. Each cell is connected to an indicator or transmitter by a 4- to 6-wire cable. Two pairs of the wires are connected to the coils. The remaining wires are used for temperature compensation.

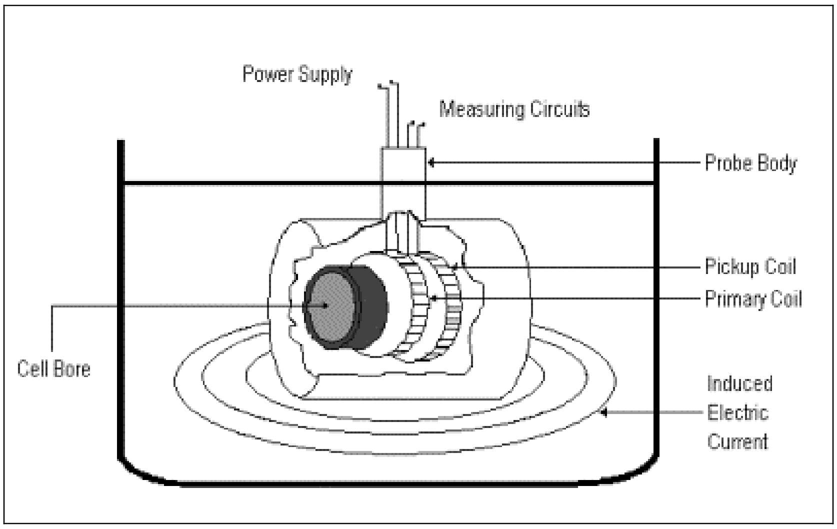


Figure 6.5 Inductive Probe

Conductivity is measured to accomplish the following:

- Reduce corrosion
- Reduce scaling
- Ensure purity of water in rinse operations
- Monitor contamination
- Control deionization re-generation concentrations
- Verify process chemical strength
- Sample conditioned conductivity

Dissolved Oxygen Measurement

Dissolved Oxygen is the term used for the measurement of oxygen gas dissolved in a unit volume of water. This measurement will indicate how appropriate a sample of water is for use in a particular application. The unit of measure is parts-per-million (ppm), parts-per-billion (ppb), mg/L (1 mg/L = 1 ppm) or % saturation.

The amount of oxygen that a given volume of water can have dissolved in it at any instant of time is a function of:

- The amount of other substances dissolved in the water
- The temperature of the water
- The pressure of the atmospheric air (and thus the atmospheric oxygen)

A typical D.O. "loop" consists of a dissolved oxygen probe and analyzer. The current Dissolved Oxygen probe technology involves a semi-permeable membrane, which separates cathode and anode electrodes and an electrolyte solution from the sample, in our case water. Only gases can penetrate this membrane. There are two D.O. measurement technologies that utilize this type of membrane, Diffusion and Equilibrium.

Diffusion-Type Sensor

As shown in Figure 6.6, a conventional diffusion-type sensor consists of a thin membrane, a metal anode and cathode, and an electrolyte. The membrane isolates the electrodes and electrolyte from the process and only allows oxygen gas to enter and react. Oxygen diffuses through the gas-permeable membrane, to the cathode, where it is reduced to H_2O as shown in equation 1. Concurrently, the anode is oxidized to complete the circuit as shown in equation 2. The diffusion rate of oxygen through the membrane is proportional to the partial pressure and thus proportional to the oxygen concentration in the sample.

Since oxygen is continuously reduced at the cathode, a continuous supply must pass through the membrane or a deficiency of oxygen results. If the sample flow is too slow to replace the depleted O_2, a low reading may be perceived. More oxygen must, therefore, diffuse from the sample solution through the membrane to the cell. This is why this type of probe is flow dependent. In addition, the depletion of oxygen extends into the area outside the membrane. There must be sufficient flow and turbulence to maintain a representative oxygen concentration at the surface of the membrane. Otherwise there would be a thin boundary layer of sample next to the membrane depleted of oxygen and yielding low readings. There is always a minimum flowrate specified for this type of sensor. Below that, the measurement becomes quite flow sensitive.

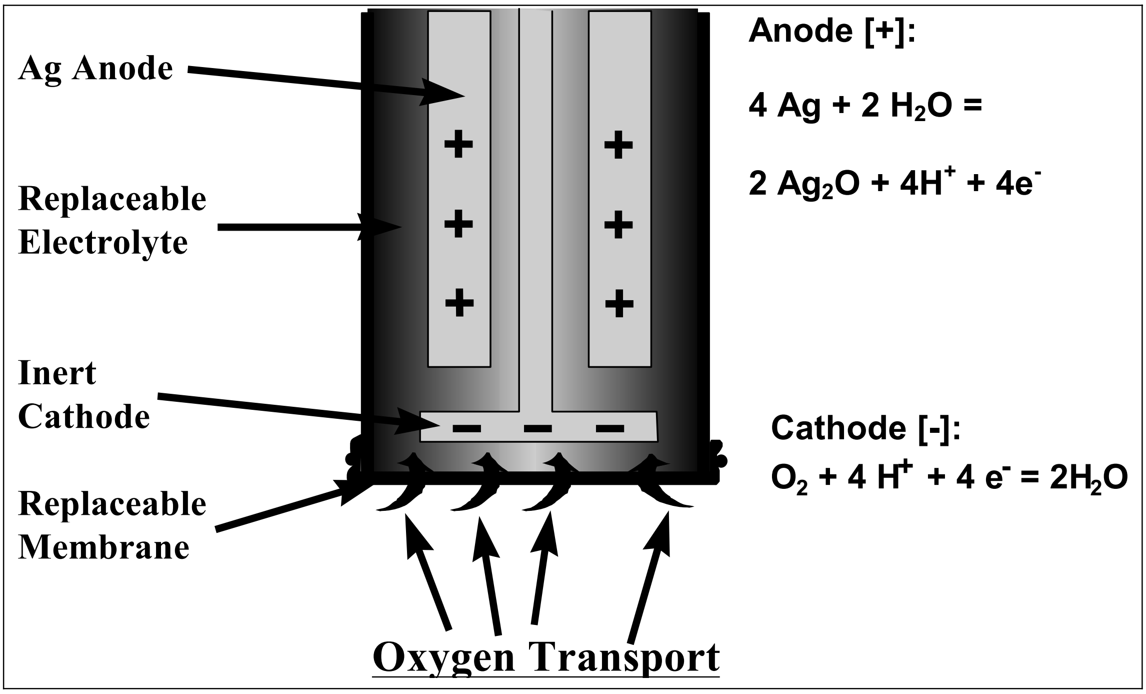


Figure 6.6 Typical Diffusion Type Dissolved Oxygen Sensor

The net reaction is that oxygen is consumed (reduced) at the cathode, producing a current proportional to the influx of oxygen through the membrane, while the active anode (usually lead or silver) is oxidized producing a metal oxide. Due to the formation of this by-product, the anode must eventually be cleaned or replaced. The membrane must be replaced during cleaning or replacement of the anode, or in the event of a punctured membrane. Anytime the membrane is replaced, the electrolyte must be refilled. Thus a substantial amount of internal maintenance is required with this type of sensor. Since a diffusion-type sensor is dependent on the rate of oxygen diffusion through the membrane, membranes must be thin to allow sufficient oxygen to diffuse through them to produce an adequate signal even at low ppb measurements. The rate of diffusion depends on the partial pressure of oxygen in the sample, as well as the thickness and permeability of the membrane. Any increase in membrane thickness (such as relaxation of a new membrane after it is installed and calibrated) slows the diffusion rate which directly affects the accuracy of measurement. Fouling or obstruction of the membrane will impede the influx of oxygen and, in turn, cause the analyzer to give perceived low readings. The only effective way to correct the low readings is to clean the membrane or recalibrate the instrument.

Galvanic and polarographic are two types of sensors that operate under the diffusion principal. In the case of Galvanic sensors, the spontaneous voltage of the dissimilar electrodes and electrolyte produces a current proportional to the amount of oxygen reaching the cathode where it is electrochemically reduced to water. Polarographic sensors apply a voltage between electrodes to more carefully control the reaction (a more stable method). Both of these diffusion-type sensors develop similar reduction reactions, resulting in a current proportional to the amount of oxygen reacted. The downfall of these sensors is that they experience all of the previously mentioned problems associated with diffusion-type sensors. In addition, Galvanic sensors, which are in essence batteries, loose their charge over time.

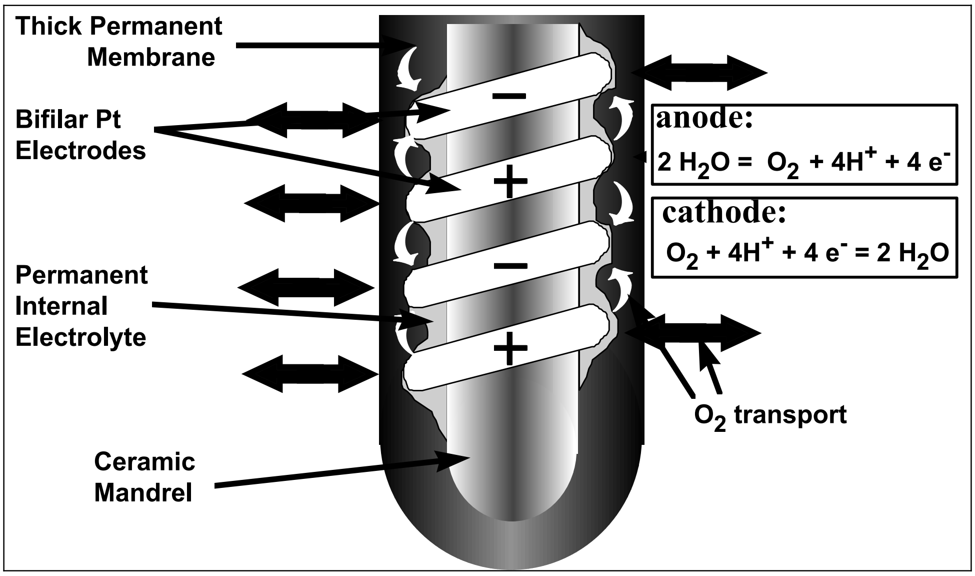


Figure 6.7 Sensor Cross Section

Industries measure dissolved Oxygen to accomplish the following:

- Determine the "health" of a sample of water for a particular application.
- Keep D.O. above a minimum value to support life in wastewater and aqua-culture applications.
- Keep D.O. below a maximum value to inhibit corrosion in power plant applications.
- Ensure that D.O. is kept within boundaries of operation in some power plants, which are using use a new oxygenated treatment (O.T.) water chemistry.
- Maintain low levels of D.O. for process control in semiconductor applications.

Thermal Conductivity Gas Measurement

All gases possess varying degrees of ability to conduct heat. In order to have a means of comparing the gases' abilities, a coefficient has been assigned to each gas according to its capacity to retain heat. These coefficients and a controlled environment provide a way to determine the amount of a particular type of gas present in a gas sample. The unit of measure is percentage concentration of gas.

A gas analyzer consists of two parts: a sensor assembly and a control unit. The sensor assembly contains two gas chambers, one for the measured gas and the other for the reference gas. The entire sensing assembly is temperature-controlled to ensure a constant temperature, and there is a thermistor in each of the chambers for sensing the temperature of the respective gases. By knowing the properties of the sensor assembly, the conductivity coefficients of each gas, and the temperature reading of each gas chamber, the concentration of the measured gas can be calculated and displayed on the control unit.

In most applications, the sample gas must be properly conditioned before entering the sensing unit's gas chamber. This conditioning usually consists of reducing and/or regulating the pressure of the sample, filtering the sample of various contaminants, and maintaining the temperature within a standard range. A sample panel, used for most applications, contains all the necessary filters, pumps, pressure and flow regulators, and valves for proper conditioning and ease of calibration and normal operation. The panel also provides the necessary piping for transporting the sample from the process to the analyzer, as well as for disposing of the analyzed sample by venting to atmosphere or returning it to the process.

The most common application where the thermal conductivity gas analyzer is used is in the utilities/power industry where a hydrogen-cooled generator is present. Other industries, such as pulp and paper, chemical, and food, also may provide their own power by means of their own hydrogen-cooled generator. Monitoring these gases with a thermal conductivity gas analyzer ensures enhanced safety (certain concentrations of hydrogen are explosive), lower maintenance, more efficient cooling (thus improving generator output), and constant monitoring.

Humidity Measurement

Measurement and control of moisture is an important consideration in many industrial processes. The moisture content of gas streams directly affects the overall profitability and/or quality of many industrial processes. Water vapor can shorten equipment life, affect product quality and significantly impact product cost. Thus, measuring and controlling moisture can help manufacturers cut fuel costs, optimize drying processes, produce consistently better product at a lower cost, and reduce capital expenditures and maintenance costs by prolonging equipment life.

Manufacturing processes are characterized by varying amounts of moisture. Many application areas such as natural gas, hydrocarbon gas streams, heat treating, instrument air require moisture levels be kept low and thus require the measurement of trace amounts of moisture. On the other hand, measurement of high moisture levels is called for in “wet” application, such as industrial drying in industries including food, paper, chemicals, building materials, textiles etc.

Humidity can be defined as the presence of water vapor in a gaseous sample. Consider the atmosphere for example. The atmosphere is made up of dry air, consisting of a variety of gases, and water vapor molecules. The amount of water vapor present in a gas affects process performance and product quality in a vast number of industrial processes. Engineers and technicians measure this moisture content using a variety of techniques, with results reported in a profusion of units. Although various charts (Physochometric) and tables are available to accomplish the seemingly complicated conversion from one moisture unit to another, frequently all that is required is a table of water vapor pressure as a function of temperature. A majority of process control applications express moisture content in one of two ways, dew point or relative humidity.

Dew point is defined as the temperature to which a gas must be cooled to observe liquid water condensation, or dew. If moisture content is already near saturation, the dew point will be only a little lower than the process temperature. If the gas is very dry, its temperature must be depressed greatly to observe condensation. Dew point, being an absolute measure of moisture in air, defines water vapor pressure. When condensation occurs below 0^oC, it is observed as frost and the temperature is called the frost point. Over the range of about -20^oC to 0^oC , either frost point or dew point may be reported and they can differ by more than 1^oC because the water vapor pressure over super-cooled liquid water differs from that of ice. Moisture sensing equipment can report either; so for highest accuracy it is important to discover which value an instrument is reporting. Dew point is a measurement that is independent of temperature, and therefore provides a desirable type of measurement for controlling the amount of moisture in a gas. The unit of measure is °Fahrenheit or °Celsius.

Relative humidity (RH) is defined as the amount of water vapor in the air divided by the maximum amount of water that could be present in the air at the existing temperature and pressure. Since the definition of RH is a ratio, "amount of water vapor" can be measured as mass, volume, or partial pressure compared with the maximum amount or "saturation value." However, measuring RH alone does not allow an accurate determination of the "amount of water vapor" present because the maximum amount that can be present is strongly temperature dependent. Therefore, temperature, if not stable, and pressure, if not assumed to be ambient, must be monitored as well.

Measurement Methods

There are two types of measurement methods. In the first, a portion of the air is cooled until a physical condition caused by the air's water vapor content is observed. The results are reported as temperatures such as dew point, frost point, and wet bulb temperatures. These may be considered primary measurements, as the only calibration required is that of the temperature sensor. The chilled mirror and wet bulb thermometer are examples of instruments that use this measurement technique.

Chilled Mirror

The dew or frost points are usually determined by thermoelectrically cooling a surface and optically observing the condensation as a change in reflectance as shown in Figure 6.8. Continuous results are achieved by continually cooling to the condensation point, heating to evaporate the condensation, cooling again, etc. These measurements are capable of very accurate results over wide ranges of both temperature and moisture content. They are, however, easily compromised by contamination or fouling. Thus, while they may be used in the control of some relatively clean processes, their major use is in calibrating other sensors.

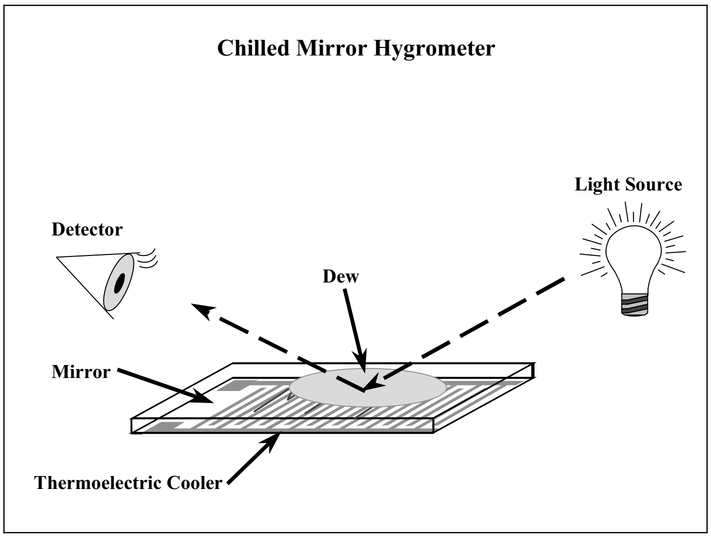


Figure 6.8 Chilled Mirror Hygrometer

Wet Bulb

When water evaporates, it takes heat from the surroundings, cooling them just as our bodies are cooled by the evaporating of sweat. This is also the principle of the wet bulb thermometer. A fluid thermometer "bulb" is wrapped with a wet wick such that water is continuously evaporating from the area surrounding the bulb, cooling the bulb as seen in Figure 6.9. The rate of evaporation and the temperature to which the bulb is cooled depend upon the drying power of the air, which depends on its moisture content and process temperature. If the air is dry, the cooling rate will be significant and the wet bulb will be many degrees cooler than a "dry" bulb measuring process temperature. If the air is nearly saturated with water vapor, the temperature depression for the wet bulb relative to the dry bulb will be small.

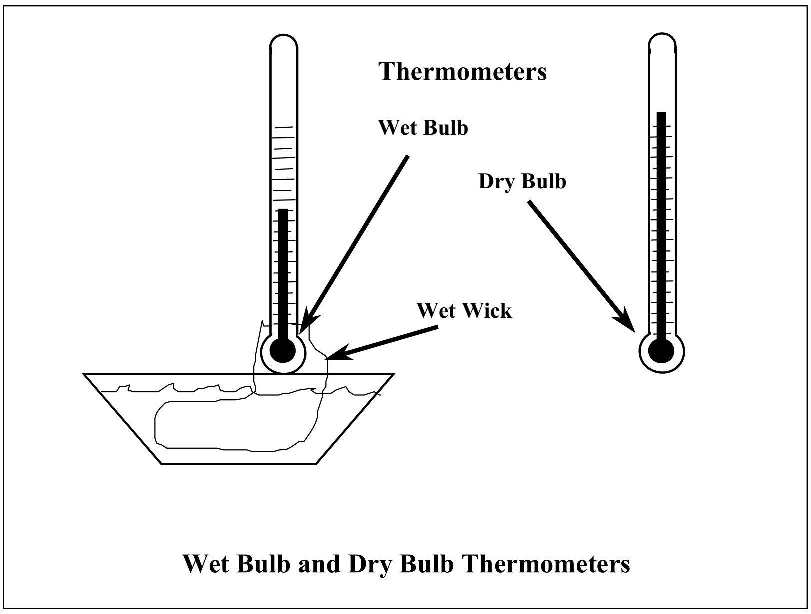


Figure 6.9 Wet Bulb Thermometer

If the air is 100% saturated, i.e., relative humidity is 100%, no net water evaporation will take place; there will be no cooling and the wet bulb temperature will equal the dry bulb temperature. In applications requiring continuous monitoring, both wet and dry "bulb" temperatures are determined with an electronic thermometer such as a thermocouple or resistance temperature detector (RTD). Although wet/dry bulb measurement is a primary method, there are several potential error inducing influences. All of the following result in erroneously high readings:

- Contamination decreases wetting water's vapor pressure at any given temperature, decreasing both its evaporation rate and wet bulb temperature depression.
- Fouling can alter water transport from the source to wick or wick to air and prevent full cooling.

- Insufficient airflow will create a thick saturated air layer around the bulb, slowing evaporation allowing more heat to flow down the thermometer to the bulb.

This will set up steady-state conditions with bulb temperature higher than it should be.

- Excessive airflow will inhibit formation of a still, saturated layer, so flowing process air will heat the bulb and prevent full depression to the true wet bulb temperature.
- If process air is too dry, then water vapor will diffuse into the air without forming a stagnant, saturated layer and process air will warm the bulb to a steady-state condition at a temperature above the true wet bulb temperature.
- Ice formation when wet bulb temperature is below $0^{o}C$ will inhibit water transport necessary for accurate wet bulb determinations.

In general, wet bulb measurements provide accurate and reliable results in clean, relatively moist applications where airflow is within an optimal range and the wet bulb temperature is above $0^{o}C$. Where these conditions are not met, more rugged and robust methods are required.

With the second measurement type, a material is allowed to equilibrate with the air sample, and some moisture-dependent property of the material is measured. Examples discussed in greater detail below include the salt cell and capacitive sensors. Other methods used less frequently in process control applications are: observation of condensation as a result of pressure changes, direct spectroscopic measurement of water molecule concentration, variation of oscillator frequency of a crystal coated with hygroscopic material, and reaction of water to form a subsequently measured chemical product.

Salt Cells

Usually, an air sample flows over bifilar windings of electrodes coated with a hygroscopic salt paste. Air moisture content is determined from the current resulting from applying a voltage to the electrodes (Figure 6.10).

The measurement is made in two different ways: continuously (amperemetric) and batch (coulemetric). With the amperemetric measurement, as salt absorbs or desorbs water to achieve equilibrium with the air sample flowing over it, its electrolytic conductivity changes, increasing with increases in moisture content. The conductivity is measured using alternating current to minimize electrode polarization**.** Since the current depends not only on air moisture content but also such variables of cell construction as electrode length and spacing, salt thickness, etc., this is not a primary measurement and requires calibration.

The coulemetric method does provide a primary measurement of air moisture content: a known volume of air is carried over the salt-coated electrodes by a carrier gas of constant, low moisture content. Confining flow to a narrow tube allows all water in the sample to diffuse into the salt paste and be electrolyzed. Shortly before the sample reaches the cell, a voltage sufficiently high to decompose water is applied to the electrodes. A "baseline" current resulting from moisture in the carrier gas is established.

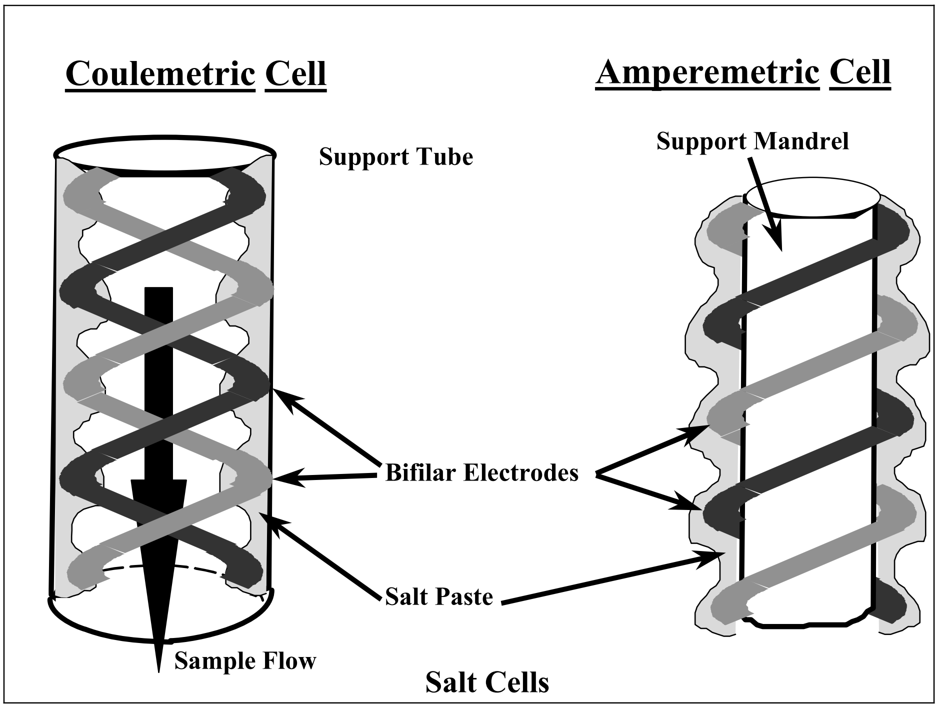


Figure 6.10 Salt Cells

When the sample reaches the cell, additional moisture content results in an increased current, which reaches a peak value and then diminishes back to baseline. The total charge, corresponding to the positive deviation from baseline current integrated over the time until baseline current is reestablished, is a direct, primary measurement of the total moisture content of the sample. Small variations in cell geometry, condition of electrodes, salt contamination, etc., do not affect the results provided. This salt cell method can provide more stable results than the amperemetric version.

Drawbacks include: continuous flow of dry carrier gas is required; direct current operation eventually produces a buildup of reaction products at the electrodes; and the inherent batch nature of the measurement means that updates to changes in moisture content occur only once every few minutes.

Both executions of the salt cell method suffer from plumbing clogging or gross contamination in dirty applications. Also, if the cells are exposed to very wet samples, dissolution of the salt can upset measurement or even destroy cells. The salt cell measurements are usually chosen for clean, relatively dry applications.

Capacitive Sensors

With all capacitive sensors, the dielectric material of a capacitor is a film whose dielectric constant depends on moisture content. The film is brought into equilibrium with the sample such that the water vapor partial pressure (fugacity) of the sample becomes equal to that in the film. The resulting capacitance depends on the concentration of water in the film. Because the capacitance depends on sensor geometry and characteristics of the dielectric material, capacitive sensors require calibration. They are the simplest and most rugged of moisture sensors.

The moisture-sensitive dielectric film is sandwiched between a lower electrode support and an upper electrode (Figure 6.11). The upper electrode must be porous to water vapor transport to allow the dielectric to achieve equilibrium with the sample. Aluminum oxide is fairly stable and can absorb a large concentration of water. This, in turn, produces a large change in dielectric constant and capacitance for moderate changes in water vapor pressure. The drawback is irreversible shifts in capacitance with exposure to condensing conditions or very high relative humidity. Polymer films have proven to be much more resistant to the effects of high relative humidity and some perform well at elevated temperatures as well. Sensors based on polymer films are used increasingly in process applications.

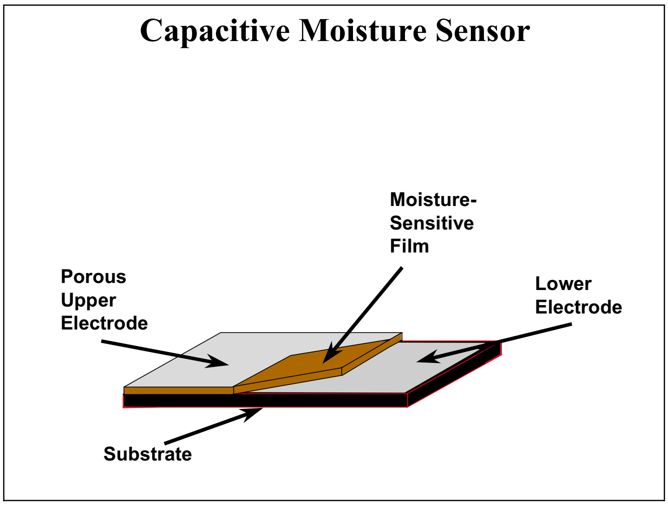


Figure 6.11 Moisture Sensor

Guarded Layer Moisture Sensor

The guarded-layer moisture sensor is a particularly useful capacitive sensor design for dirty environments (Figure 6.12). A pair of inter-digitated electrodes are deposited on an inert, non-conducting ceramic substrate and covered with a moisture-sensitive thin film. The moisture in the surrounding atmosphere comes into equilibrium with that in the film, resulting in a moisture-dependent capacitance between the inter-digitated electrodes. If the structure were complete at this point, a high-temperature moisture sensor would be the result. However, unless the film was very thick, it would be fouling dependent. Material adhering to the top surface of the film would alter the capacitance and, thus, the inferred moisture concentration. If the film were made thick enough to avoid this problem, the response of the sensor to changes in moisture content would be unacceptably slow. To avoid these limitations, a thin, porous platinum film is deposited on the moisture-sensitive film. This structure is equivalent to two capacitors in series - a first capacitance from the first inter-digitated electrode to the porous platinum film and a second capacitance from the film back to the second inter-digitated electrode. Finally, a second moisture-sensitive film is deposited onto the platinum film.

The purpose of this final layer is twofold. First, the moisture-sensitive material is a mechanically strong, chemically resistant polyimide serving to protect the platinum film. Second, a small portion of the electric field of the double capacitor extends beyond the second moisture-sensitive film. Were it not for this second layer, dirt or oil depositing on the platinum film could alter the capacitance providing a result that was dependent on sensor fouling. Thus, the second moisture-sensitive layer provides a capacitance independent of material depositing on the sensor, rendering the results independent of fouling.

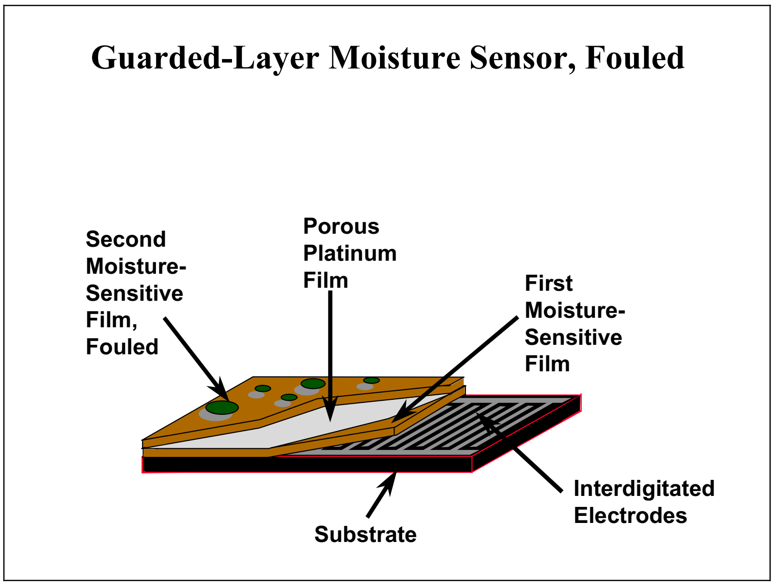


Figure 6.12 Guarded-Layer Moisture Sensor

Industries measure humidity and dewpoint to accomplish the following:

- To lower energy costs
- To reduce maintenance costs by improving equipment life
- To improve process control and product quality
- To eliminate need for sampling systems
- To accurately report emissions

Lesson Summary

In this lesson you have learned the different types of analytical measurement and instrumentation found in industrial plants.

In the next lesson you will learn about Final Control Elements.

Lesson 7
Final Control Elements

Lesson Objectives

At the completion of this lesson, you will be able to understand the basic principles and types of Final Control Elements.

General

Automatic control of a process depends ultimately on some sort of final control element to regulate the flow of energy to the process. The role of this element is therefore an important one. In many cases the selection, performance, and maintenance of the final control element will determine whether or not the control loop will perform satisfactorily.

There are many different types of final control elements. Some examples are metering pumps, variable pitch fans, dampers, silicon-controlled rectifiers, saturable core reactors, and magnetic amplifiers. The most widely used element of all, however, is the control valve.

Control Valves

Despite the importance and wide usage of control valves, they are probably the most neglected of all the elements in the control system. Actually the service conditions under which they often must operate can be more severe by far than those of any of the other elements in the control system. Extreme conditions of temperature, pressure, corrosion, and contamination must not interfere with the proper function of the control valve as it manipulates the flow of fluid, usually with a minimum amount of attention. Control valves are available in a wide variety of sizes, body styles, pressure ratings, materials actuators, and with a wide variety of accessories to meet the requirements of the broad scope of applications found in the process industries.

It will be useful to make a few statements to provide a working definition of a control valve. A control valve is:

- the operating end of the control system
- the muscle of automatic control
- a variable resistance in a flow system
- the link between the process instrumentation and the process
- a variable orifice

It will also be useful to consider the valve to be an assembly of four basic components:

- the body
- the actuator
- the bonnet
- the trim and guiding

The Valve Body

The valve body is that part having the inlet and outlet flow connections and housing the internal valve parts. Several common body arrangements are employed as follows:

Single seated having one port and one valve plug

Double seated having two ports and one valve plug

Two way having two flow connections, one inlet and one outlet

Three way, having three flow connections, two of which may be inlets, with one outlet (for mixing flows), or one inlet and two outlets (for diverting flows)

Valve Body Types

Globe style

This is the most common control valve body type. Its name derives from its globular shape. It is a general purpose valve (Figure 7.1). It is available single-seated or double-seated.

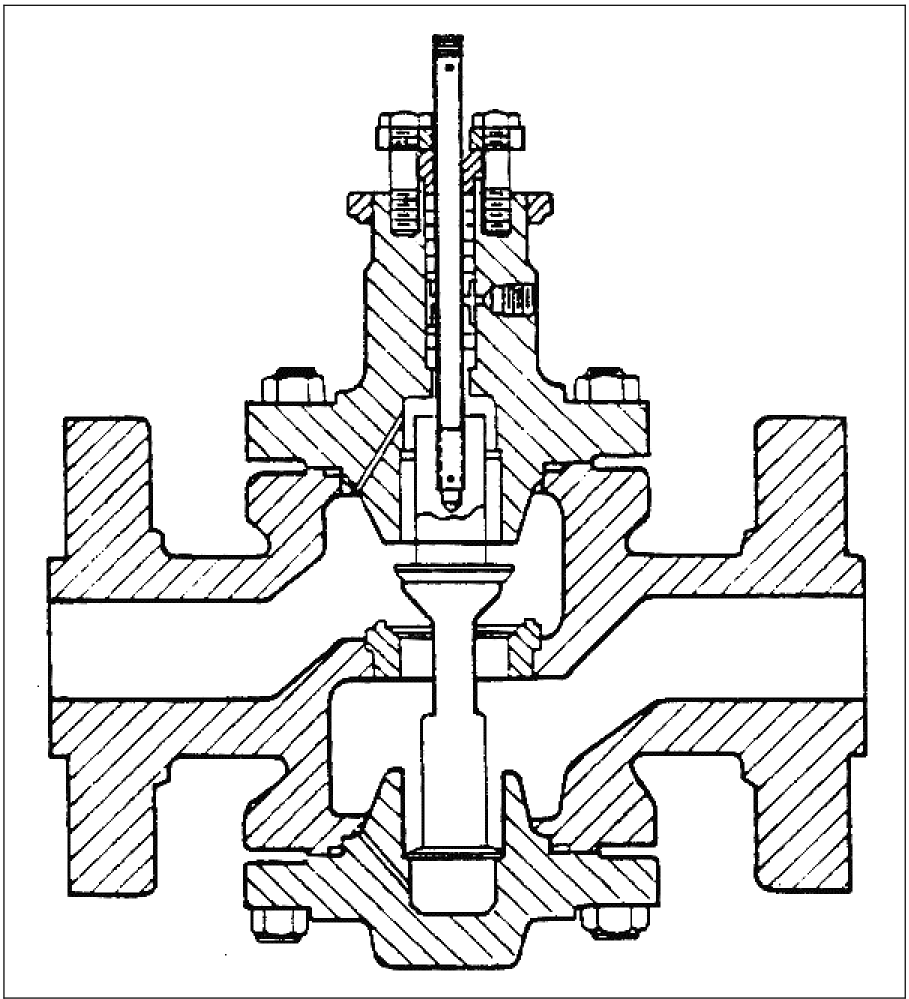


Figure 7.1 Globe Valve

Angle Valve

Angle valves have inlet and outlet connections at right angles to each other instead of inline as with most other valves. It is useful where a piping layout will benefit from this configuration. A typical angle valve is shown in Figure 7.2. It may also be used for handling certain erosive fluids. The streamlined flow pattern results in a relatively high-pressure recovery, which, in liquid flow with low or moderate pressure drops, may result in severe cavitation. Angle valves are self-draining, which is an asset in some installations.

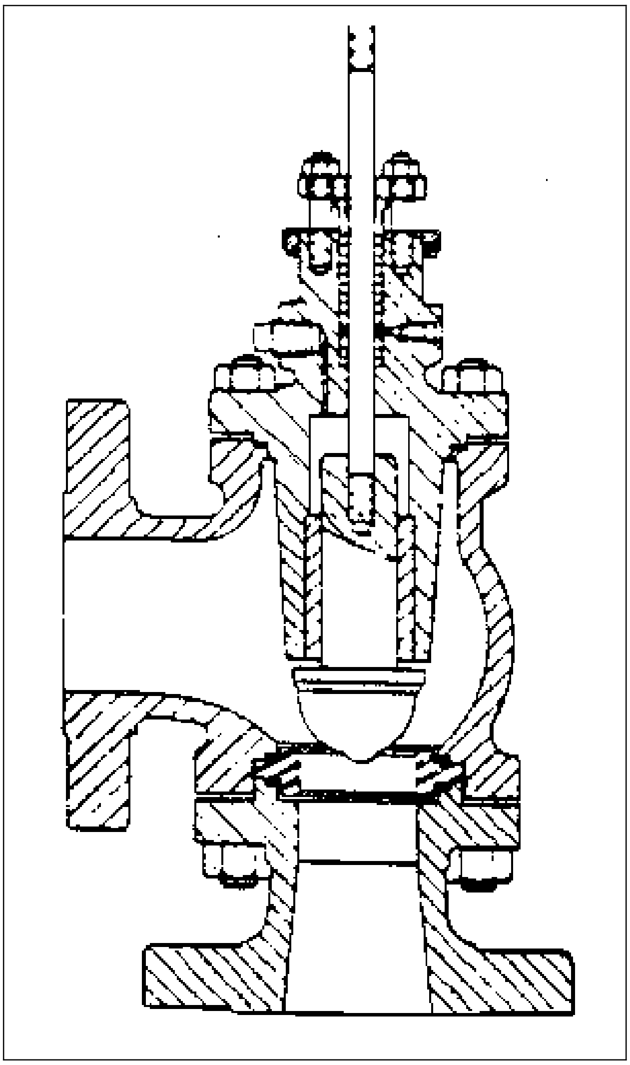


Figure 7.2 Angle Valve

Split-Body Valve

A split body valve has two parts, which are bolted together to clamp the seat. This allows relatively easy seat replacement, making this valve a good choice for service where frequent maintenance as necessary. It is reasonably free from collecting sediment.

Cage Valve

A cage valve is shown in Figure 7.3. A "cage" guides the plug. The fluid enters the bottom of the cage, passes up through it, then out through the ports. As the plug is raised, the ports are increasingly uncovered. The shape of the ports determines the valve flow characteristics. It is available either single-seated or double-seated. The cage is easily removed and replaced for maintenance purposes or for the purpose of changing the valve characteristics. Reduced port cages are also available for reducing the flow capacity of the valve where required.

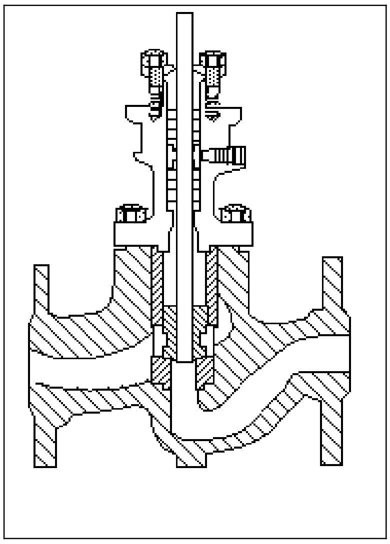


Figure 7.3 Cage Valve

Saunders Patent Valve

In this type of valve, shown in Figure 7.4, the body has a central raised weir against which a moveable diaphragm is pressed to provide shut off. The edge of the diaphragm is clamped between the body and the bonnet. The process fluid comes in contact only with the valve body and the diaphragm, so this valve is commonly used for the control of corrosive fluids, heavy liquids, or liquids having particles in suspension. The body is available with glass, plastic, lead, or teflon liners to provide extra corrosion resistance.

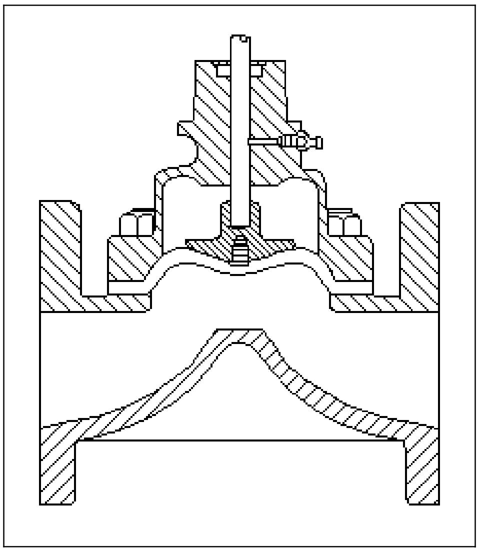


Figure 7.4 Saunders Valve

Butterfly Valve

The butterfly valve consists of a vane or disc mounted on a shaft through a flanged body. The shaft and vane are rotated by the actuator to open or close the valve. It is one member of a class of valves known as rotary valves. They are characterized by small pressure drops and large flow capacities. They will fit into a very small space.

Ball Valve

The ball valve has a spherical plug with a hole through it. The plug can be rotated through 90°. With the hole aligned with the flow the valve is open. With the hole at right angles to the flow, the valve is closed. Ball valves have the largest flow capacity of all control valves, since there is no restriction at all to the flow when the valve is open. The ball valve is a rotary valve. It gives creditable performance in controlling fibrous flows such as pulp stock or paper stock, and in the flow of slurries. Figure 7.5 illustrates the flow pattern through a ball valve.

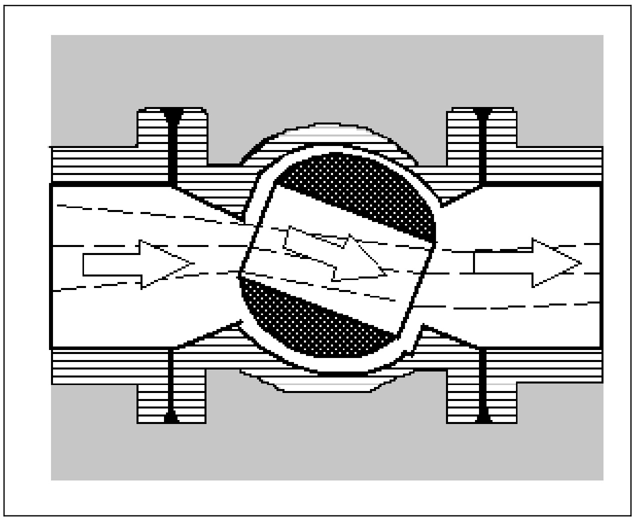


Figure 7.5 Flow Diagram of a Ball Valve

The Actuator

The actuator is the part of the control valve that, in response to the signal from the controller, moves the valve. It moves the valve either in a linear direction, as in a globe valve, or in a rotary direction, as in a butterfly valve. There is wide diversity among the commonly available actuators, and each type has some advantage that may influence its selection to meet particular conditions use. The actuators in widest use are classified as follows:

- Diaphragm actuators, pneumatically operated
- Piston actuators
- Electro-hydraulic actuators
- Electro-mechanical actuators
- Manual hand wheel actuators

Diaphragm Actuators

By far the most widely used of all is the pneumatically operated diaphragm actuator. Originally in favor because it operated directly from the pneumatic output of the common pneumatic controller. It has remained popular because it is safe, simple, reliable, and economical.

Diaphragm actuators usually have a circular flexible diaphragm clamped between two dished plates. At least one of the chambers formed between the diaphragm and plates is airtight. The valve stem is attached to the center of the diaphragm, and when air pressure is applied to one chamber and acts on the surface of the diaphragm, the resulting force will position the valve. Most commonly, a return spring is provided to return the valve stem when the air pressure is reduced, although some actuators provide for separate air pressures to be admitted to the two sides of the diaphragm, and have no return spring.

In a direct acting actuator, air is admitted above the diaphragm so that increasing air pressure forces the stem down into the valve body and the return spring brings it back out when the air pressure decreases. On a direct acting valve, the valve plug is pushed into the seat, closing the valve when the air pressure pushes the stem down, which results in a valve that is said to be air-to-close.

In a reverse acting actuator, air is admitted to the chamber under the diaphragm. Increasing air pressure moves the stem upward out of the valve body and the return spring pushes it back down when air pressure is decreased. On a direct acting valve, the valve plug is lifted out of the seat, opening the valve when the air pressure lifts the stem out of the valve body, which results in a valve that is said to be air-to-open.

The spring determines the fail-safe position of the actuator, since on loss of air pressure the spring will drive the valve stem to one end of its travel. In any particular installation the fail-safe position required should be determined by the needs of the process. For instance, on a thermal process that would be dangerous if too hot, with the valve on a steam line supplying heat to the process, the fail-safe position of the valve would be closed. The valve should be an air-to-open valve since on loss of air pressure the spring will close the valve. On the other hand, it the valve was on a cooling water line to the process, the fail-safe position would be open. The valve should be an air-to-close valve. Springless actuators have no fail-safe position perse.

Piston Actuators

Piston actuators are rugged in design and capable of handling high operating pressures. They provide rapid response and very large forces, and they are able to deliver very large movement when required.

Hydraulic Actuators

Hydraulic actuators do not enjoy the wide popularity associated with pneumatic or electrical systems. They are relatively expensive, and require operation of a hydraulic pump to supply the high-pressure hydraulic fluid needed. Electro-hydraulic actuators which combine a hydraulic actuator with an integral electric motor driven pump are used with great effectiveness for rapid operation of safety shut-off type valves.

Electro-Mechanical Actuators

These may be broadly classified as either:

- Solenoid operated, or
- Motor driven

Solenoid Operated Valves

In the many automatic control systems which can be satisfied by two-position or on-off control, the solenoid operated valve finds widespread use. They are as reliable as their source of power and are relatively inexpensive, but their use is limited to smaller sizes, up to six inches, and low pressures. Their operation is based on the well known principle that a coiled wire carrying current can be arranged to draw a metal core tube into the coil with considerable force.

Electric Motor Actuation

Electric control motors are used to operate valves, dampers, or other controlled devices in accordance with signals produced by electronic control instruments. This discussion will focus on motors as actuators on control valves.

The power of the electric motor actuator is usually 114 hp (about 200 watts) or less. One-tenth horsepower (75 watts) or less is even more common.

The selection criteria for motors are the following:

1. Control Action
2. Torque
3. Stroke
4. Timing
5. Voltage
6. Auxiliary Switches and Slidewires

Control Action

The motor can be activated by input signals from a variety of controllers. The variations or control actions are as follows:

Two Position Control

The control instrument uses a S.P.D.T. switch or relay. The switch contacts maintain one circuit to drive the motor clockwise and when switch action occurs, a second circuit to drive the motor counter-clockwise. Two-position control will produce cycling.

Floating Control

The control instrument uses two S. P. D. T. switches or relays to drive the motor. The switch positions are adjustable to provide a neutral or dead zone around the set point where the motor will not be driven. Floating control reduces cycling on fast changing processes.

Position Proportioning Control

The control instrument operates two relays to drive the motor. A proportional slidewire (135 or 1000 ohms) is supplied in the motor to provide a feedback signal to the controller. Position proportioning control provides precise motor position to maintain the process variable at the control set point.

Auxiliary Switches and Slidewires

Most motors have the capability of adding additional switches and slidewires for auxiliary control and position functions.

Bonnets

The bonnet joins the actuator to the body. The bonnet contains the packing box, through which the valve stem transmits motion from the actuator to the plug. This packing box, also called the “stuffing box”, must be able to seal in operating line pressure. It is made up of packing rings and packing follower. Good packing must not only prevent leaks, but must cause a minimum of friction so that the actuator can position the valve plug smoothly.

Teflon has become popular as a packing material, since it is inert to most chemicals, has a wide temperature range, and is self-lubricating. Valves with molded Teflon packing require careful maintenance, and procedures recommended by the valve manufacturer should be followed if difficulties are to be avoided.

Four types of bonnets are available to meet various operating temperatures and corrosive conditions:

- The Plain Bonnet is used for service between O°C and 232°C (33°F and 450°F) and up to 800°F with Gratoil packing.
- The Extension Column Bonnet is used for low temperature service between –101°C and O°C (-150°F and + 32°F). The extension bonnet keeps the packing material away from the sub-zero temperatures of the process fluid and prevents formation of frost on the stem that would tear up the packing.
- The Radiation Fin Bonnet is used for high temperature service above 232°C (450°F). The fins help to dissipate excess heat.
- The Bellows Seal Bonnet design provides a seal that limits leakage to a range where they can only be detected by the use of mass spectrometer-type leak testing. The bellows is either stainless steel or Monet for valves up to 6-inch size. The maximum temperature is 399°C (750°F).

Trim

While the actual components vary slightly depending upon the type of valve, the word “trim”' generally refers to the removable internal metal parts of a valve which come in contact with the flowing fluid. Trim for control valves generally consists of the stem, packing follower, lantern ring (when lubricated packing is used), packing retaining ring, stem lock pin, guide bushings, plug, and cage or seat ring. The type of trim to be used will depend almost entirely on two factors: (1) pressure drop across the valve and (2) the corrosive or erosive qualities of the fluid whose flow is controlled. The most common trim material is 316 stainless steel unless the flow will be corrosive to this material. In this case, the trim will be made from a compatible material such as Monet or Hastelloy. Hardened materials such as 17-7pH and Stellite are used for the trim parts when dictated by high-pressure drops or erosive flows.

The plug and seat are the components that most directly determine the flow characteristics of the valve. The primary function of the trim parts is to proportion the valve orifice area in such a manner that a prescribed relationship exists between valve plug lift and flow capacity. A secondary function may be to shut off tightly.

Valve Flow Characteristics

The flow characteristic of a valve is the relationship between the valve plug position and the flow rate through the valve. The “inherent”' flow characteristic is obtained with a constant pressure drop across the valve at all positions of plug travel. The “installed” characteristic is obtained when the pressure drop varies as dictated by the characteristics of the system where the valve is installed.

The shape of the ports or plug in a valve determines its inherent flow characteristic. The three most common flow characteristics are shown in Figure 7.6.

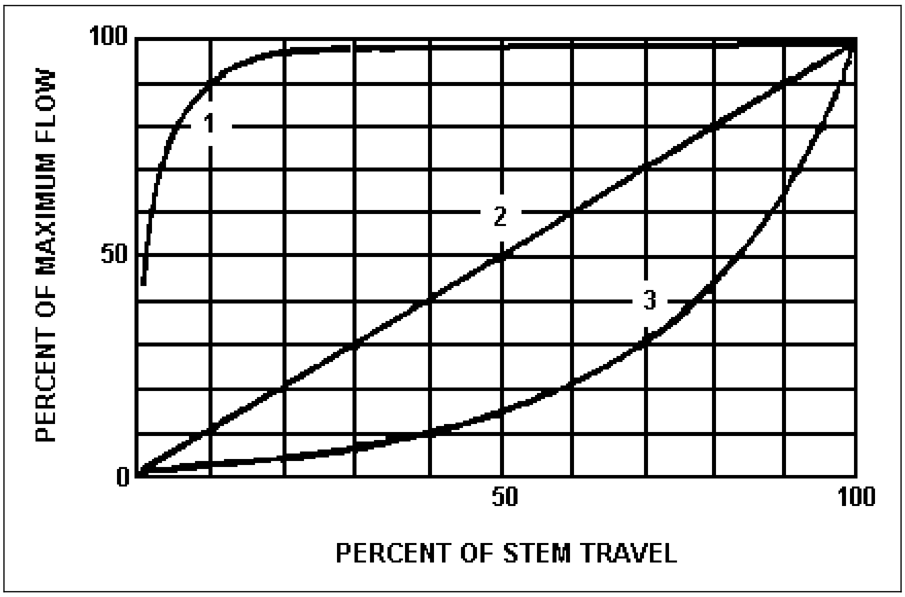


Figure 7.6 Characteristics of Quick Opening, Linear, and Equal % Valves

Curve 1 shows a quick-opening characteristic in which the largest increase in flow occurs as soon as the valve plug starts to move away from the seat. Curve 2 shows a linear characteristic, where equal increments of plug travel result in equal increments of flow rate. Curve 3 shows an equal percentage characteristic. Equal percentage is a characteristic in which each increment of plug travel produces a change in flow proportional to the amount flowing before the change. It is sometimes called slow-opening, since the increase in flow rate is very gradual as the valve plug starts to move away from the seat and then increases at a larger and larger rate as the plug continues to move. As an example of equal percentage, consider a valve with a 50 to 1 rangeability that passes 2.5 gpm at 10% plug travel. At 11% opening, the flow rate will be 4% greater, or 2.6 gpm. At 60% opening the flow rate will be 20 gpm and at 61% opening it will increase by 4% of 20 to 20.8 gpm.

The relationship of valve plug travel to flow rate in actual operation does not follow the inherent characteristic. The degree of distortion of the inherent characteristic to the installed characteristic depends on the ratio of the pressure drop across the valve to the total pressure drop in the system in which the valve is installed.

The valve characteristic is selected to provide stability in the control loop over the full range of operating conditions encountered. Matching a valve characteristic to a particular control system requires valve GAIN to change with valve travel to compensate for the GAIN changes of other elements in the control system.

GAIN = output ÷ input

Proper selection requires a complete dynamic analysis of the control system. Dynamic analysis varies greatly from system to system. In the absence of such an analysis, we generally recommend the use of equal percentage characteristics where:

1. The major portion of the control system pressure drop is not available through the valve.
2. Pressure drop at low flows is high and the pressure drop at high flows is low.
3. Limited data is available and possible oversizing could occur. With an equal percentage characteristic, the plug will operate further from the seat for given conditions than with a linear characteristic. This reduces the erosive effects of the flow.

The flow coefficient, Cv, is a means of measuring the capacity of a valve and is useful in selecting the correct size valve for a given application. It is defined as the number of U.S. gallons per minute of 60°F water that will flow through a valve with one psi pressure drop. The Cv of a valve is usually determined experimentally by the valve manufacturer, and is listed in the catalogues.

Single-Seated Valves

The term "single-seated" refers to the fact that a single path exists for passage of fluid through the valve. In single-seated valves, the process line pressure acts on the bottom area of the plug, creating an upward force on the valve stem. The diaphragm actuator must overcome this force in order to move or hold the stem downward. The larger the valve or the higher the line pressure, the greater the actuator force must be. The available actuator force limits the pressure against which a single seated valve will shut off. Single seated valves are capable of tight shut off, to ANSI 13-1,16, 104-1976, Class IV.

Double-Seated Valves

Double-seated valves have two flow paths, two plugs, and two seats. Differential pressure opposing the closing of the valve acts upward on one plug and downward on the other. The latter helps the actuator close the valve, and the actuator force required is less than with a single-seated valve. Double-seated valves are called balanced valves or semi-balanced valves because the two plug forces balance each other. Actually the lower plug is always smaller than the upper one, so there is always a net upward force which will keep the valve from "slamming" shut as it is being closed. Double-seated valves can handle greater shutoff pressures than single-seated valves, but both plugs cannot be seated tightly at the same time, so the leakage rate is larger. It is typically .5%, Cv. ANSI B-16, 104-1976, Class 11.

Valve Action

The "action" of a valve is generally defined as either air-to-close or air-to-open. These terms signify that an increase in air pressure acting over the effective area of the diaphragm will either close or open the valve depending upon the type of actuator used and the plug to seat-ring relationship. These are illustrated in Figure 7.7.

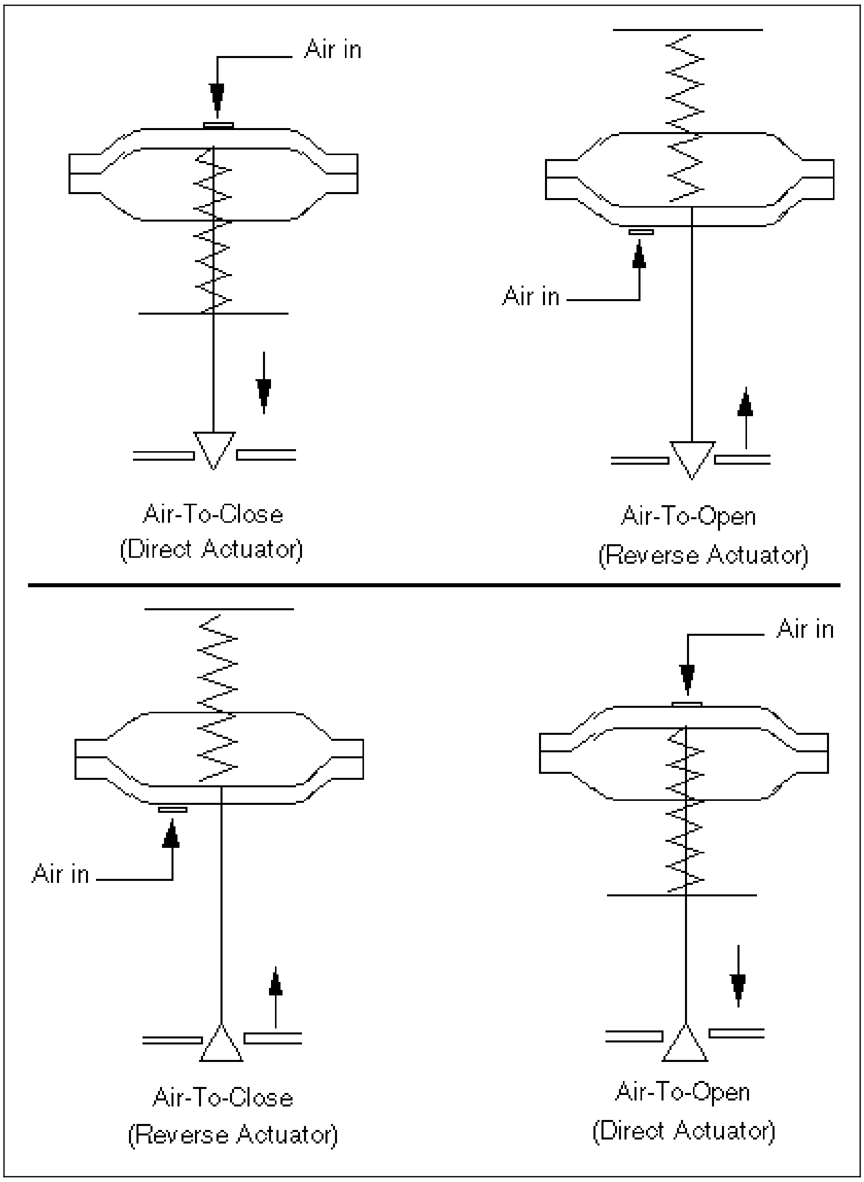


Figure 7.7 Valve Action

Whether air-to-close action or air-to-open action is chosen depends on the fail-safe position one wishes the valve to take upon failure of the air supply or pneumatic signal.

Three-Way Valves

Three-way valves are used for either of two types of service.

1. For mixing two inlet flows into one outlet flow.
2. For diverting one inlet flow to two outlet flows.

This same valve also can be used for diverting applications if the pressure drop is not too high. The flow into AB tends to move the plug toward either one of the seats depending on plug position and pressure drop. When the plug closes off one of the ports, the pressure downstream of the port can fall off to zero. This can result in an unstable condition with the flow tending to slam the plug toward' either seat.

Where pressure drops are high, or larger size valves are required in diverting service a diverting valve is used.

Here the flow enters through AB and between the seats. The pressure differential in this type tends to move the plug away from the seat. This arrangement adds materially to the stability of operation.

Valve Positioners

In pneumatically actuated valves, the actuator stem should assume any position within its limits of travel merely by adjusting the air pressure applied to the diaphragm. In theory, the movement should be a predictable function of the applied pressure, but in practice a number of factors arise which might cause difficulties. For example, the friction of guides and packing of the valve to which the actuator is attached, or the effects of flow through the valve can cause the stem to assume some position other than that dictated by the controller. In instances where these factors might be unacceptable, an auxiliary device is used with the actuator to ensure that the valve is positively positioned at the correct setting called for. This device is called a positioner.

A valve positioner is integrally mounted on the side or top of a control valve actuator. It is used to insure that the valve stem actually takes the precise position called for by the controller signal.

The following are some of the reasons for using a valve positioner:

1. To help overcome excessive friction in a valve due to coking, high-viscosity fluids, gumming or sedimentation
2. To reduce actuator deadband, about 1/2 of 1 percent compared to 1 or 2 percent for an actuator with no positioner
3. To provide for linear positioning of an actuator stem with the input signal from the controller when dynamic unbalances are present in a valve
4. To deliver added power in the form of higher air pressures to hold the stem position when high static unbalance forces are present in a fully-stroked valve with direct actuator.
5. To facilitate sequence or split-range valve operation
6. To gain added stroking speed and improve frequency response in the loop
7. To provide throttling control with a spring-less actuator

Silicon Controlled Rectifiers

In the introduction to final control elements, their role was established as devices that manipulate the flow of energy to the process. When the energy or material is a fluid, the appropriate device is some kind of valve. When the energy is in the form of electricity, what are the corresponding final control elements? The answer is the broad category of switches. The switches can take many forms that include mechanical, mercury-switches, relays, and solid state devices. Many of these devices are on-off by nature and are used in on-off applications. However, there are many applications where it is necessary to proportion the flow of electric power. Typical examples are:

a) welding

b) induction heating

c) electric furnaces and other heat process systems

d) lighting

e) electric motors

Although there are other ways of proportioning electric power, one of the most practical is a three-mode proportioning controller with current output in combination with a Silicon Controlled Rectifier (SCR) power manipulator.

The Basic Controller & The Power Manipulator

Before power can be proportioned automatically, there must be a signal that is a function of where the power level should be. The process controller provides this signal.

It has been established in the Modes of Control discussion that on-off control produces only two levels of power to the process, and that to a greater or lesser extent this always produces oscillation of the process variable. When processes can tolerate oscillation, this method of control is sufficient. But, where industry demands closer control, the power delivered to the load must be proportional (at less than line voltage) to the load requirement. With a closed control loop, any disturbance that occurs to the load will be corrected for by readjustment of the load power.

This power-proportioning is accomplished using one of several available gain devices: the saturable core reactor, and the silicon controlled rectifier. The function of these devices is to receive an input signal from the controller that is to serve as a trigger. The devices respond to the weaker controller signal by appropriately manipulating the supply power to the load.

Functions and Specifications of a Power Manipulator

The gain device or power manipulator receives the very weak signal from the control instrument and uses it to proportion the output power to the load. For fixed resistive loads, the power delivered is proportional to the RIVIS voltage squared.

The load may be only a few watts or many kilowatts and may have various line voltages, frequency, power factor and number of phases. All of these factors become a part of the specifications for the power proportioner.

The ideal characteristics for this proportioner would be:

- It should proportion the load power anywhere between the maximum available and zero in a linear relationship to the control signal
- It should have no power loss itself
- It should be unaffected by load resistance changes

One of the earlier devices that are still in use today is the saturable core reactor. Its method of delivering a proportioned power to a load is to let a small control current affect the degree of saturation of a magnetic core, which in turn affects the ability to pass larger currents through the load winding. The amount of ac power delivered to the load is determined by the inductance of the ac winding which is controlled by the amount of current in the dc control winding. The saturable core reactor has been the workhorse of industry. However, it is large and cumbersome and does not meet desired characteristics.

The thumb-sized silicon controlled rectifier has some distinct advantages over the saturable core reactor, and has gained popularity over it in industrial use. It is considered the heart of the complete power controller package. In common with all semiconductor devices, it is in a small enclosure and the critical parts operate at high current density.

Theory of Operation

The silicon controlled rectifier, or SCR is a PNPN type semiconductor device that belongs to the thyristor family of semiconductor components.

The operation of the silicon-controlled rectifier closely parallels that of a controllable rectifier. Since the device is a rectifier, it will conduct current in only one direction — the anode made positive with respect to the catriode, but a condition must be met. A gate terminal exists. This terminal must be given a positive potential to trigger conduction from anode to cathode. With a positive potential on the anode and a negative potential on the cathode, a positive gate pulse will turn the device on.

After the SCR has been turned on, it will remain in the conductive state, even after the gate potential has been removed. This turn-on' condition will only occur if a specific amount of current initially flows through the device when the gate potential is applied. This value of current is referred to as the device latching current.

Even after the SCR is latched into conduction, and the gate potential has been removed, the unit may prematurely turn off if the current falls below the holding current rating. Both latching and holding current values are SCR characteristics and properly designed circuits will stay well within these figures. If the gate potential is made negative with respect to the cathode of a conducting SCR, the device will remain conducting. To turn a conducting SCR off, it must be treated as a rectifier. Reverse potential (positive on the cathode and negative on the anode) or bringing the forward voltage to zero, will cease conduction. Both of these means of stopping the conduction of an SCR must exist for a specific period of time, to assure cut-off. The amount of time that the SCR must have zero or reverse potential applied to it is known as its turn off time. A typical turn off time may range between 10 and 300 microseconds. After the current has been at the zero level for an interval at least equaling the turn off time, forward voltage can be reapplied without it conducting . . . the positive gate potential is necessary to begin conduction again.

Because an SCR will turn off when a reverse bias is applied to the anode and cathode, it is quite simple to control the percent of output potential of an alternating current. To modulate the output, the triggering will occur somewhere within the AC cycle and the alternating potential will automatically turn the unit off. This method is known as phase angle firing. Phase angle fired units have two big advantages: they are simple to build, and rather inexpensive. Two disadvantages in using phase angle fired SCR units are the high level RF noise emission and possible power factor shifts occurring when many units are simultaneously firing. An example of a phase angle fired SCR circuit can be found in simple home light dimmers and some small electric drill speed controllers.

In using only one SCR, the output can never exceed 50% of the supplied power. By using two SCR's in a configuration, conduction can occur on either half cycle. Only one SCR will conduct at a given time.

An alternative to phase angle fired SCR units is the zero crossover or burst fire method. In this principle, the AC output delivered to the load is not interrupted within the cycle. The device allows the passing of a controlled number of complete cycles. For example, if an output of 50% were desired and the input frequency was 60HZ, the output could allow 30 cycles to pass for 1/2 second and not conduct for the remaining half, thus obtaining a regulated output without introducing RIF noise by continuously firing within the cycle. The power factor problem can also be eliminated because the units used are not firing in synchronization with the 60HZ line frequency. The disadvantage of using burst fire units is the circuit sophistication, which results in a more expensive device. Examples where burst fire SCR units may be used, are in modulating current to electric heaters and large motor speed controls for pumps, lathes, or drives in industry.

Many factors must be considered when large burst fire SCR units are used in industrial application. One problem that occurs in high power SCR drive circuits is the probability of false firing due to noise. Many transient protection circuits are utilized to prevent stray noise from accidentally gating an SCR on. These protection circuits can be as simple as zener diode clippers.

Lesson Summary

In this lesson you have learned the different types of Final Control Elements found in industrial plants.

In the next lesson you will be introduced to Process Characteristics.

Lesson 8
Process Characteristics

Lesson Objectives

At the completion of this lesson, you will be able to understand the effects that different process dynamics have on industrial plant control systems.

Process Characteristics

To the controller, everything surrounding it in the loop looks like the process. This embraces instrumentation external to the controller as well as the components of the process itself. The instrumentation is made up of the primary elements, measuring elements, and final control elements, etc. The process consists of piping, vessels, reactors, furnaces, distillation columns, etc.: in general, the equipment in which mass, heat, and energy transfer take place.

The instrumentation and its effect on the controller is predictable, and in some cases, adjustable. But the process is a different matter — each process being highly individualistic in its effect upon its control. These effects from the process are the dominant effects and in many cases impractical to change or adjust.

Every process exhibits two effects, which must be taken into consideration when automatic control equipment is being selected. These are:

1. Changes in the controlled variable due to altered conditions in the process, generally called *load changes*.
2. The delay in the time it takes the process variable to react to a change in the energy balance called *process lag*.

Load changes have been noted earlier just enough to define and categorize them according to their source, but here we will look at them in more detail. In order to discuss the subject further, however, we must first define just what process load is.

Process Load

Process Load is the total amount of control agent (energy) required by a process at any one time to maintain a balanced condition.

In a heat exchanger, for example, in which a flowing fluid is continuously heated with steam (the control agent), a certain quantity of steam is required to hold the temperature of the fluid at a given value when the fluid is flowing at a particular rate. This is the process load. Process load is directly related to the setting of the final control element.

Any change in process load requires a change in the position of the final control element in order to keep the controlled variable at the set point.

What changes the position of the final control element? The controller does.

The two prime properties of load changes, which need to be considered in the application of automatic controllers, are:

1. The size of the load change
2. The rate of the load change

Load changes in a process are not always easy to recognize. Some examples of process load changes are:

1. Greater or less demand for control agent by the controlled medium. In the heat exchanger cited above, a change in the rate of flow of the fluid to be heated, or a change in the temperature of the incoming fluid contribute load changes because a change in the quantity of steam is needed for either. Similarly, when a carload of bricks is added to a kiln, or where more new material is added to a cooking vessel, there is a load change.
2. A change in the quality of the control agent. If a gas-heated process is operating at a certain temperature and the BTU content of the fuel gas changes, then more or less gas must be burned to maintain the same temperature, even though nothing else changes. Changes in steam pressure also result in load changes.
3. Changes in ambient conditions. These are especially significant in outdoor installations where heat loss from radiation may be large.
4. If a chemical reaction will cause heat to be generated (exothermic) or absorbed (endothermic). This is also a load change because the position of the final control element must be adjusted to compensate for this generation or absorption of energy.
5. If the set point were changed, this would obviously require a change in the amount of energy input to the process.

It we could have it our way, any load change or disturbance would be met with an instantaneous response that would completely and immediately bring the process to its new equilibrium condition. This, however, is difficult, if not impossible, to achieve in any physical system. The response may start immediately, but it will require a certain amount of time to complete its effect. This delay is the *lag* of the system.

Suppose we have a valve in a pipe leading to a tank. It we want to raise the level in the tank to a new value, we will open the valve. But the level does not immediately change to the higher value. It may start to rise immediately, but it will not reach the new value until some time later, a time dependent upon the size and shape of the tank and the flow through the valve, among other things.

Process Lags

Process Lags are primarily the result of three process characteristics:

1. Capacitance
2. Resistance
3. Dead Time

Capacitance

The *Capacitance* of a process is a measure of its ability to hold energy with respect to a unit quantity of some reference variable.

It is related to capacity, but it is not the same thing — two processes with the same capacity might have very different capacitances. Some illustrations will serve to explain this concept.

First, look at the two tanks in Figure 8.1.

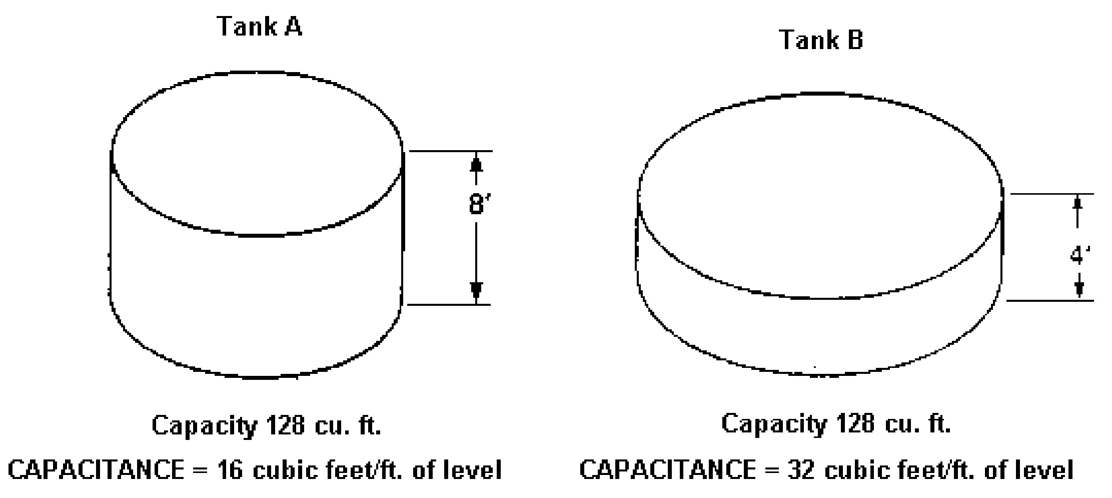


Figure 8.1 Capacity vs. Capacitance

Although both tanks have the same liquid volume capacity (128 cu.ft,), they do not have the same capacitance with respect to liquid level. Tank B has twice the liquid volume capacitance with respect to liquid level that Tank A has; 32 cubic feet per foot vs. 16 cubic feet per foot.

On the other hand, if Tank A is filled with a liquid requiring 200 BTU to raise its temperature one degree F, and the liquid in Tank B needs only 100 BTU, the thermal capacitance per degree F of 8 would be half that of Tank A. It is necessary to specify capacitance very precisely.

Capacitance may be likened to *Inertia*; in other words it acts like a flywheel.

Two principles emerge relating capacitance to control in the face of load changes.

1. Large Capacitance tends to keep the controlled variable constant despite load changes.
2. Large Capacitance tends to make it difficult to change the variable to a new value.

The overall effect of large capacitance on control is generally favorable, but it does introduce a time lag between control action and result.

When a liquid is heated in a vessel, it takes some time for the liquid to reach a higher temperature after the heat supply is increased. How much time it takes depends primarily on the thermal capacitance of the liquid relative to the heat supply. Capacitance does influence the corrective action required of an automatic controller, and so is a major factor in the analysis of any process and control loop.

As another example look at the two heaters in Figure 8.2.

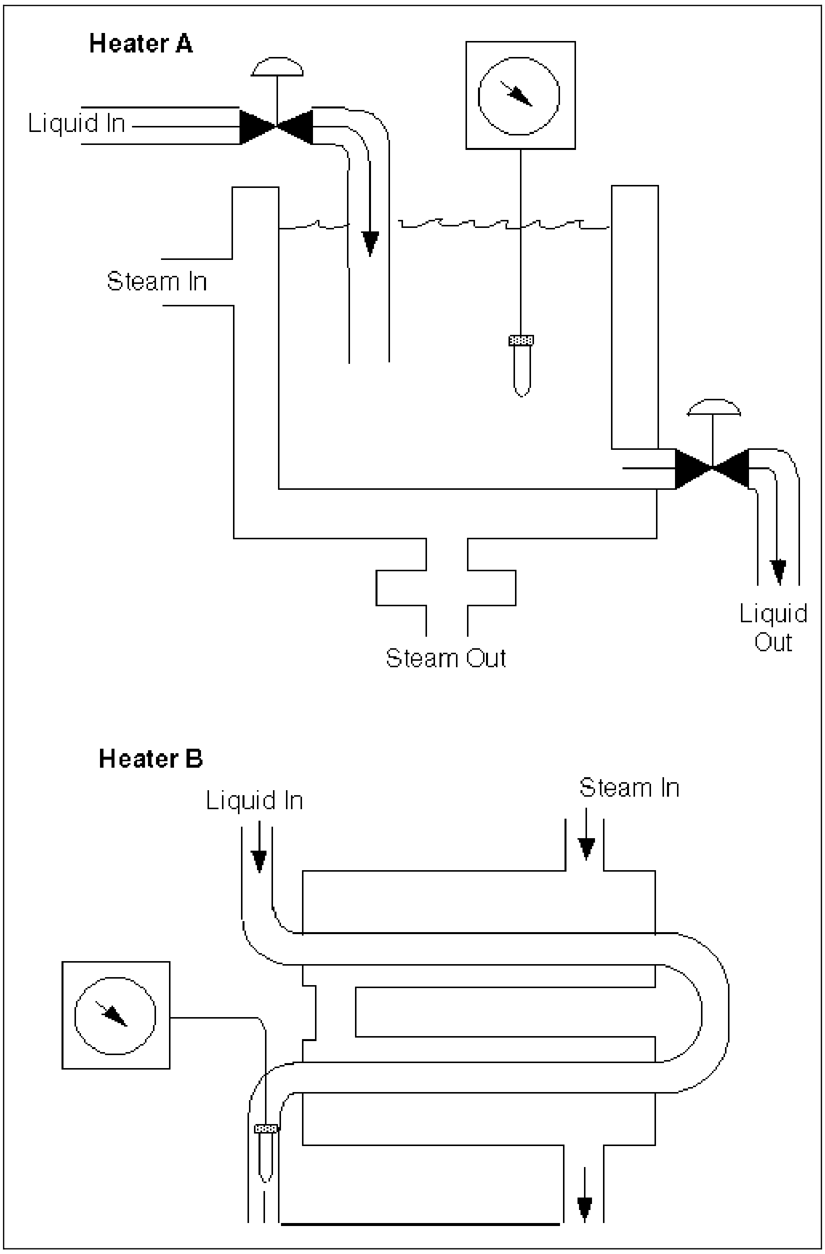


Figure 8.2 Process Heaters

Both of these heaters are used to raise the temperature of the liquid coming in. In Heater A, heat is applied to a jacketed vessel containing a considerable amount of liquid. The relatively large mass of the liquid exercises a stabilizing influence, and resists changes in temperature which might be caused by variation in the rate of flow, minor variations in heat input, or sudden changes in ambient temperature.

Heater B illustrates a high velocity heat exchanger. The rate of flow through this heater may be identical with that of Heater A. but a comparatively small volume is flowing in the heater at any one time. Unlike Heater A, the mass of liquid is small, so there is less stabilizing influence. The total volume of liquid in the heater is small in comparison to the rate of throughput, the heat transfer area, and the heat supply. Slight variations in the rate of feed or the rate of heat supply will be reflected almost immediately in the temperature of the liquid leaving the heater.

If Heater B were manually regulated, its small capacitance would keep an operator quite busy in a perhaps impossible attempt to keep the temperature constant.

On the other hand, if a change in temperature of the liquid output were desired, which heater would give the most rapid change?

Heater B would give the most rapid change if the set point were changed.

Listed below are dimensional units for capacitance as they relate to control applications:

Type of Process	Dimensional Unit
Thermal	BTU/deg
Volume	Cu Ft./Ft.
Weight	Lb/Ft.
Electrical	Coulomb/Volt (or Farad)

Resistance

The second process characteristic, *Resistance* is best defined as opposition to flow.

It is measured in units of the potential that is required to produce a unit change in flow. Examples are the differential pressure required to cause a quantity of flow through a pipe or valve, or the BTU /sec required to cause a change in temperature through the wall of a heat exchanger.

Resistance enters the picture whenever energy is transferred from one capacity to another. In the case of a heat exchanger there is a transfer of heat from the steam line to the fluid line. The transfer is never instantaneous, it is always resisted to some extent by components of the system.

If a material is being heated in a process with high thermal resistance, it will take a larger amount of control agent (energy) to change the temperature of the material than in a process with low thermal resistance. Since it is up to the controller to see that this amount of control agent is provided, the thermal resistance of a process will exert a strong influence on the selection of the proper controller.

Listed below are dimensional units for resistance as they relate to control applications:

Type of Resistance	Dimensional Unit
Thermal	Deg/BTU/Sec
Fluid	PSI/Cu. Ft./Sec.
Electrical	Volts/Coulombs/Sec. (OHMS)

Dead Time

A third type of process characteristic is, *Dead Time*, and is caused when there is a time interval between the initiation of some action and the detection of that action. This is also known as *Lag*, because often the time delay is present as a result of having to transport material that has been acted upon to a new location where the results of the action can be measured.

Mixing processes are often subject to dead time because the mixture takes a while to become homogeneous. Suppose, for example, we are concerned with the pH of water from a plant being put into a local stream, shown in Figure 8.3.

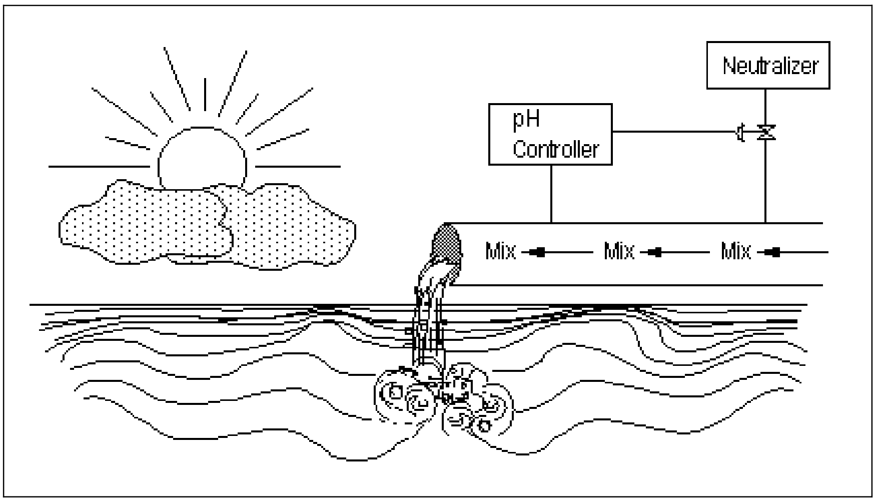


Figure 8.3 Mixing Process Illustrating Dead Time

Acid or base is added to neutralize the flow as shown. Because of the mixing required before a representative measurement of pH can be taken, there is a time delay. Control action cannot take place during this delay. The controller is helpless during that time.

Dead Time introduces more difficulties in automatic control than any of the other process characteristics, and every effort should be made to keep it to a minimum. Sometimes it may be possible to measure closer to the point where the process is in action. For example, a thermometer located 50 feet downstream of the outlet from a heat exchanger may have been placed there out of convenience and could be moved closer. In the mixing example above, however, it might be necessary to determine what in the incoming flow is causing the need for neutralizer to vary and keying from that with a more complex multi-element control loop system.

Process Reaction Curve

How does a given process respond to a change, with all these lags involved? This is an important consideration in the application of a control system for optimum results. Although process hardware may vary considerably from process to process, it turns out that there is a limited number of ways in which signal timing is affected. These can be realized by looking at the process output change that results from a sudden change (step change) in energy input to the process. If the energy input is suddenly increased, the output temperature will undoubtedly be raised in time. In Figure 8.4, is shown the simplest response encountered, one called a *First Order Lag.*

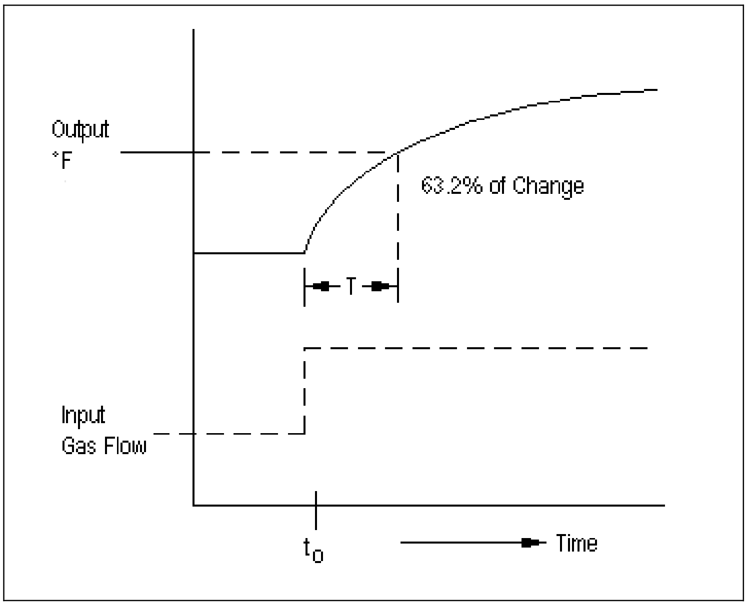


Figure 8.4 First Order Lag

This type of response can result from liquid level in a single tank or a bare thermocouple, examples of First Order systems. A First Order system is characterized by being able to store energy in only one place. All First Order responses are basically similar in shape but they can vary in size of output change and in the length of time required to make the change. The size comparison between input and output is called the *Gain*.

The length of time is basically defined by the *Time Constant*, which is the time required for the variable to reach 63.2% of the distance to the final value. Also, 98% of the distance is reached in four (4) time constants.

Figure 8.5 show *Second Order Lags*, which are the response of a system with two places to store energy. A thermocouple in a well is an example. In Second Order Lags, there is much less uniformity in the shape of the reaction curve from process to process. There are now two time constants combining to influence the curve shape in regard to time and a new concept, the damping factor (see below), which influences the curves characteristic shape. Second Order systems are capable of oscillation. This ability to oscillate is defined by two terms, which characterize Second Order systems, the natural frequency, which is the frequency at which the system will oscillate, and the damping factor, which describes how quickly the oscillations will die out.

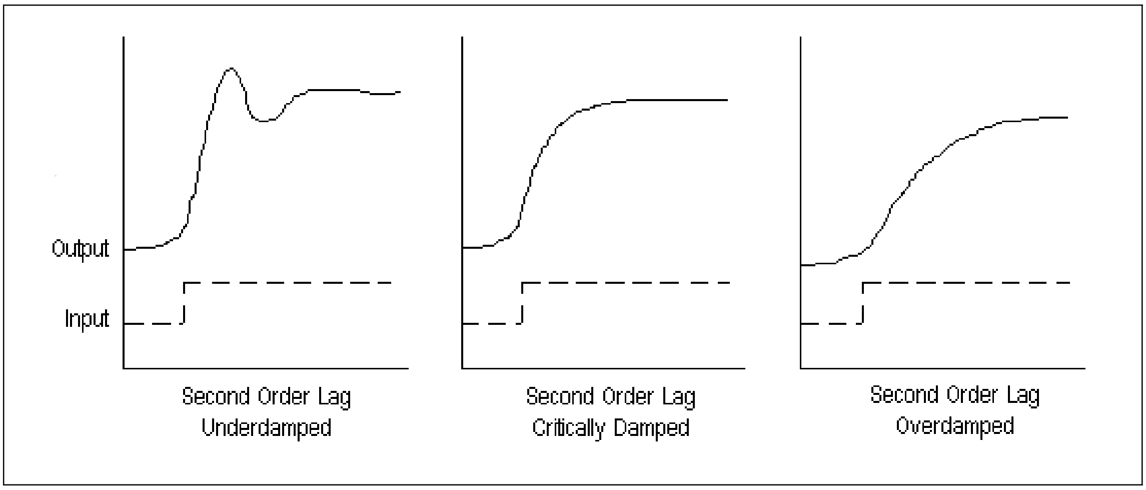


Figure 8.5 Second Order Process Lags

The under-damped curve shows a rapid change to the new value, but then overshooting the final value and temporary oscillation. The critically damped curve shows the fastest rise without overshooting. The over-damped curve shows a relatively slow rise - most processes respond this way. In all cases the start of the curve is gradual.

Because dead time is a condition of no response at all for a given time interval, it shows up on the reaction curve as a straight line delaying whatever other lags are present. Figure 8.6 shows a response incorporating dead time and a first order lag.

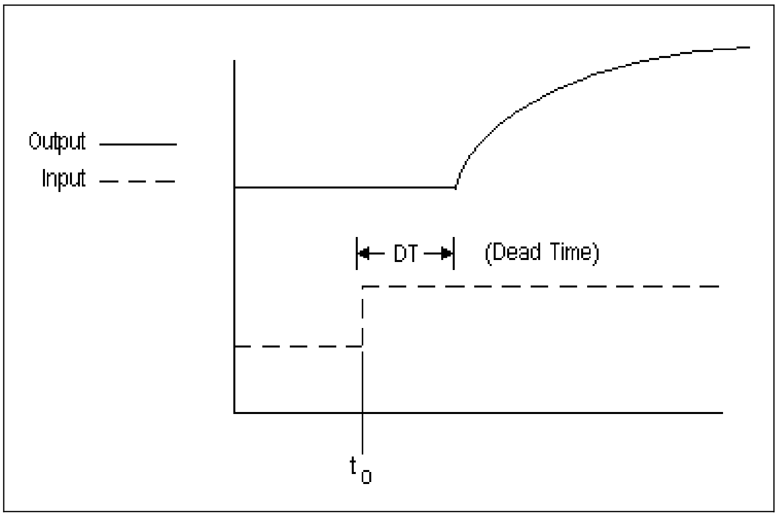


Figure 8.6 Dead Time

Lesson Summary

In this lesson you have learned the different types of Process Characteristics found in control systems.

In the next lesson you will learn the different types of Process Controllers and how they are applied.

Lesson 9
Types of Process Controllers

Lesson Objectives

At the completion of this lesson, you will be able to understand the different types of process controllers and how they are applied to control an industrial plant process.

Feedback Control Loop

In the process industries, control systems were put to practical use long before the theory of their operation or methods of analyzing their performance were available. Processes and control systems were determined by intuition and accumulated experience. This approach, unscientific as it was, was successful.

Tolerance for the intuitive approach is diminishing today, but it is still a valid way to obtain knowledge of the basics of the subject, so we'll start by considering a simple process and the way a human operator might handle its control.

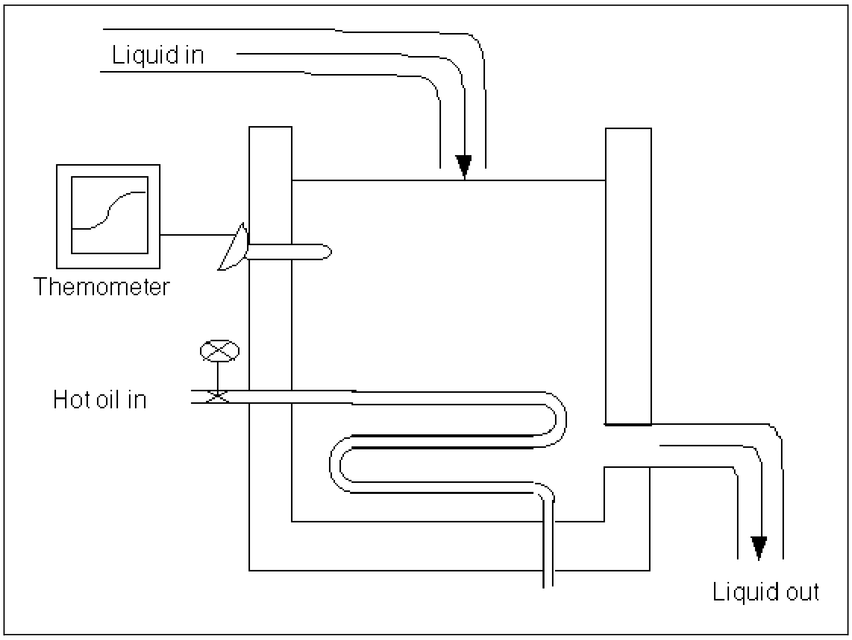


Figure 9.1 Process Heater Example

Suppose there is a process such as shown in Figure 9.1. A source of liquid flows into the tank at a varying flow rate. There is a need to heat this liquid to a certain temperature. To do this there is available hot oil from another part of the plant that flows through coils in the tank to heat the liquid. By controlling the flow of hot oil we can obtain the desired temperature. The temperature in the tank is measured and read out on a recording thermometer mounted within view of the valve on the hot oil line.

The operator has been told to keep the temperature at a DESIRED VALUE, or set point of 300°. He compares the reading on the thermometer with this mental target and decides what he must do with the valve to try to bring the temperature of the liquid to the desired value. In reading the actual value of the temperature and mentally comparing it with the desired value the operator is providing feedback.

If we draw a block diagram of this system, including the operator which shows the flow of information between components, it looks like this:

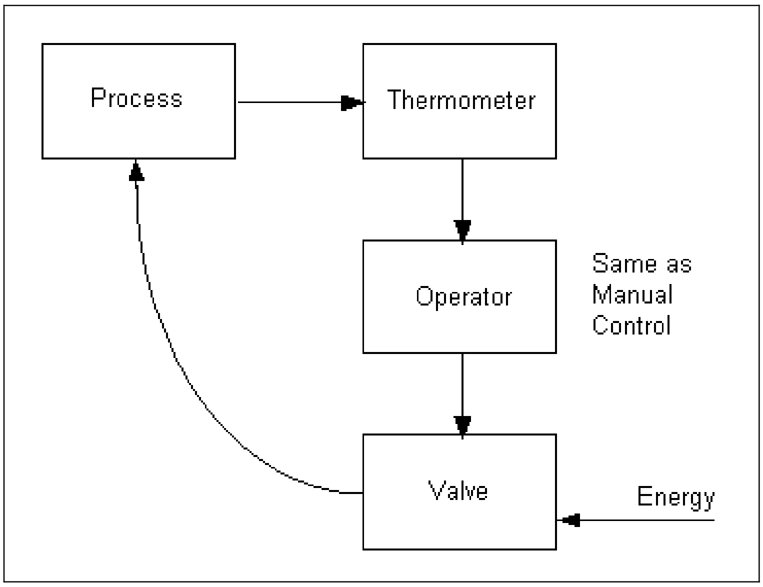


Figure 9.2 Diagram of System with Operator

This is not a very detailed block diagram, but we can see here an interesting feature of this type of control -information flows in a loop. The operator, to be sure, is a part of the loop, so it is not automatic control, but it is closed loop control, or feedback control, because the results are measured, compared to the desired results, and the valve is manipulated accordingly.

If we wish to supplant the operator with an automatic system, we will need a device that will compare the measured variable with the desired value, or SET POINT, and initiate control action according to what this comparison shows. A control loop with such a device is shown in Figure 9.3.

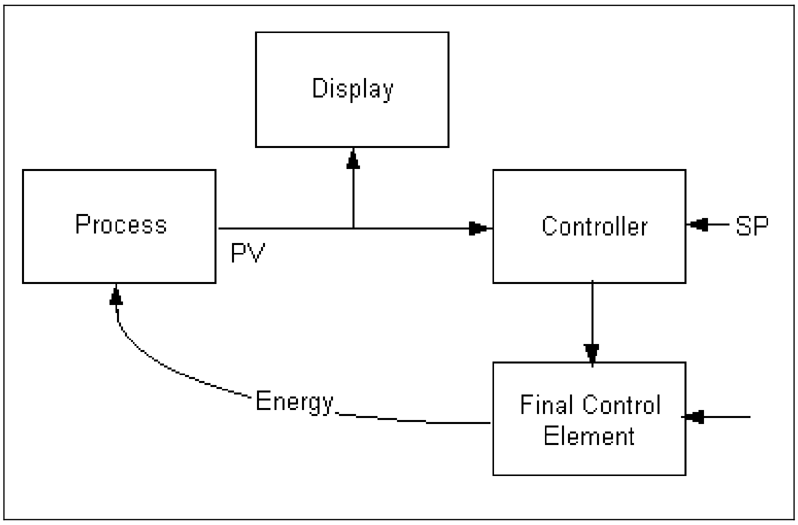


Figure 9.3 Diagram of System with Automatic Controller

Every new technical field starts out with a language barrier of sorts. Words perfectly familiar in one field suddenly take on a new meaning in another. So it becomes necessary from time to time to undertake the somewhat boring task of establishing definitions. We'll start by analyzing the components of the control loop in Figure 9.4, which is a more hardware-oriented version of Figure 9.3.

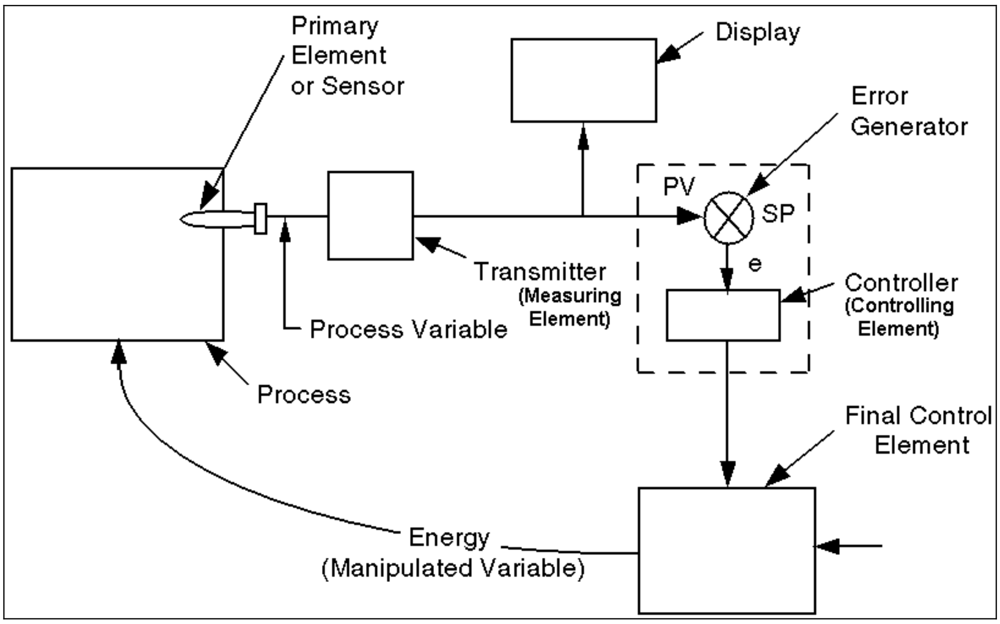


Figure 9.4 Feedback Control Loop

1. **Error Generator** - detects the difference between SET POINT AND PROCESS VARIABLE. Can be mechanical, pneumatic or electric. In the loop shown the set point value is entered manually.
   (Note: In the actual hardware sometimes the error generator is incorporated as part of the controller and sometimes it is a separate unit.) The difference between set point and process variable is called the ERROR or DEVIATION.

2. **Controller** - basically a logic machine that changes its output in accordance with the error signal it receives from the error generator. The manner in which it changes its output is built into it through a system of logic called its modes of control information the controller needs from the error generator:

   a) Polarity (sign) of the error

   b) Size of the error

   c) Rate of change of the error

3. **Final Control Element** – the element which directly changes the value of the manipulated variable.

   Examples:

   a) Pneumatic diaphragm value

   b) Motorized valve

   c) Contactor

   d) Silicon Controlled Rectifier (SCR)

   e) Rheostat

4. **Process** - the manipulation of raw materials to derive a more valuable product.

5. **Primary Element or Sensor** – a device that converts the process variable energy into a measurable form.

   (PROCESS VARIABLE = The variable being measured and controlled.)

Examples:

   a) bourdon tube

   b) orifice plate

   c) thermocouple

   d) float

   e) Filled thermal system

6. **Display (optional)** - shows value of process variable and set point, or sometimes set point and deviation.
7. **Transmitter (optional)** - changes value of process variable into a standard signal for transmitting over distances.

The notion of FEEDBACK is crucial to automatic control. Unless the results of the control manipulations can be compared against objectives, there is no way to arrive at a logical control strategy. When feedback exists, the system is said to be operating in a CLOSED LOOP fashion.

(Sometimes, however, control systems operate on information not directly obtained from the process variable. For example, if the liquid level in a tank were to be controlled it would be feasible to do so just by adjusting the output flow in proportion to the inlet flow. There is no closed loop with respect to liquid level: just a relationship between a flow and a valve position which indirectly, but not infallibly, establishes a level. When a quantity is being controlled indirectly in this fashion, it is considered to be OPEN LOOP control.)

Characteristics of Controllers

Mode of Control

In our section covering the feedback control loop we defined a controller as a logic machine that changes its output in accordance with the error signal it receives from the error generator. The change in output from the controller repositions the final control element, which, finally, adjusts the flow of energy into the process.

The manner in which the energy flow is adjusted in response to the error signal has been built into the controller through a system of logic called its *Mode of Control*.

ON-OFF Control

The simplest mode of control is ON-OFF, in which the final control element has but two positions: fully open (ON) and fully closed (OFF). If the process in Figure 9.5, in which a liquid is being heated by hot oil flowing through coils, drops below the *Set Point* of 300°F, ON-OFF control would open the valve all the way. This admits hot oil faster than is necessary to keep the liquid at 300°F. and as a result the liquid temperature will rise above 300°F. When it does. ON-OFF control will close the valve all the way and stop the flow of hot oil. With no oil flowing, the temperature of the liquid will drop, and when it drops below 300°F the control will open the valve and the cycle will be repeated. This cycling is an ever present feature of ON-OFF control, because the only two energy input levels are too much and too little.

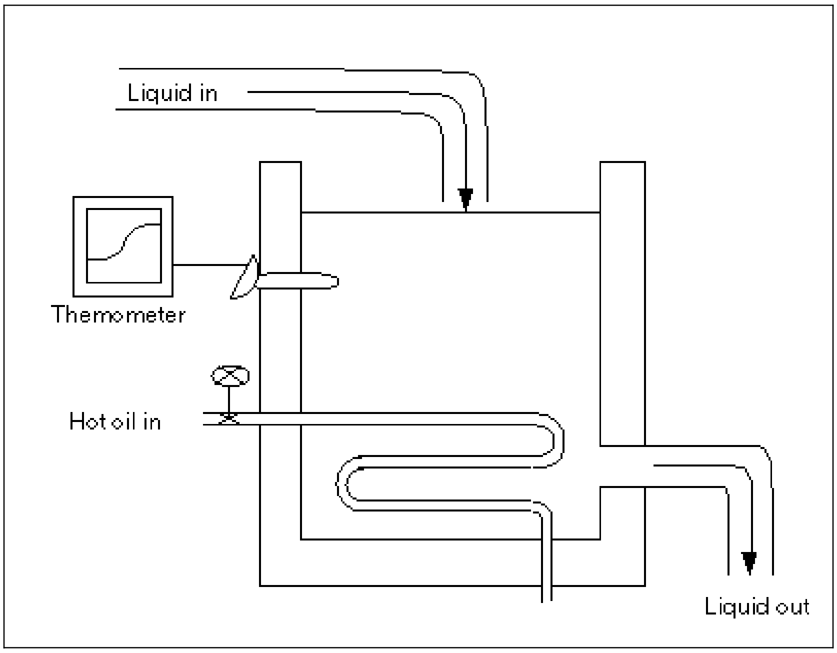


Figure 9.5 Process Heater

The appeal of ON-OFF control lies in its simplicity. A vast amount of ON-OFF control is in use. Its principle limitation is the inevitable cycling it causes in the process.

Graphically, ON-OFF control can be illustrated by Figure 9.6. Sometimes, as shown, there is a neutral zone around the set point. This is often intentional, to keep the components from wearing due to opening and closing too often.

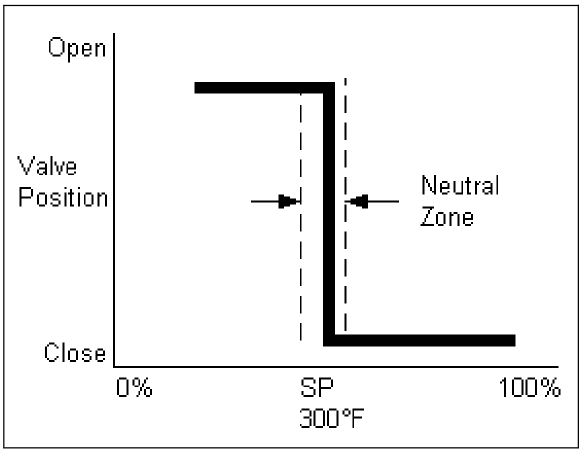


Figure 9.6 On-Off Control Action

Proportional Control

Since the cycling found in processes using ON-OFF control is due to the rather violent excursions between All and Nothing, could we not eliminate the cycling by maintaining a steady flow of hot oil that was just sufficient to hold the temperature of the liquid at 300°F? For each rate of flow of liquid in and out of the tank there must be some ideal amount of hot oil flow that will accomplish this. This suggests two modifications in our control mode.

We must:

1. Establish some steady flow value for the hot oil that will tend to hold the temperature at the set point, and
2. Once this flow value has been established, let any error that develops cause an increase or decrease in hot oil flow.

This establishes the concept of *Proportional Control*. Corrective action is now proportional to the amount of deviation between process variable and set point.

But now we need a different kind of control valve on our process. It must be capable of being positioned to any degree of opening from fully closed to fully open. This will generally be either a pneumatic diaphragm or electric motor operated valve.

Graphically, proportional control can be illustrated by Figure 9.7. The amount of control action (valve change) for a given error can be quite variable, but in Figure 9.7 it is shown as one to one. The valve would move 1% of its travel for a 1% change in error.

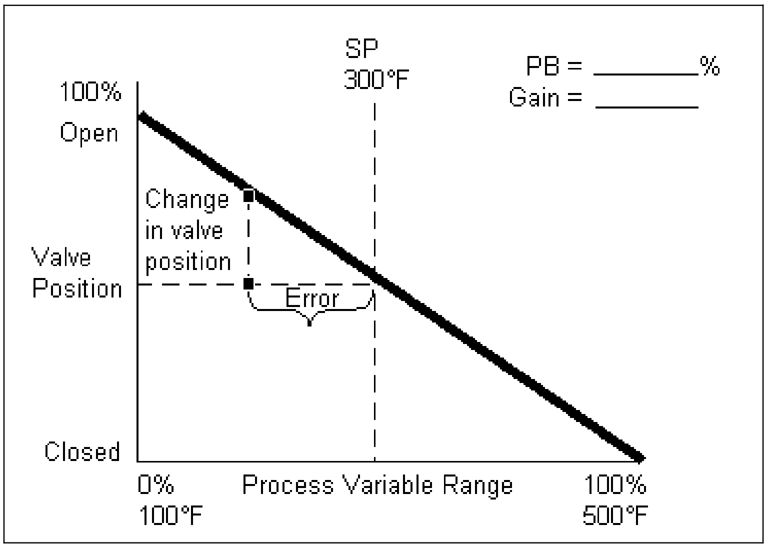


Figure 9.7 Proportional Control Action

This would be described mathematically as follows:

$V = K(E) + M$

where

E = error

K = proportional gain

M = a constant which is the position of the valve when the error is zero

The proportional gain, or just GAIN, is a measure of how sensitive the valve change will be to a given error. Historically, this proportionality between error and valve action has gone under various names, such as throttling range and gain, but mostly it has been called *Proportional Band*, or just PB, which is the expression stating the percent change in error required to move the valve full travel.

On the basis of the previous definition, look at the graphs, Figure 9.7, Figure 9.8, Figure 9.9, and determine the proportional band in each.

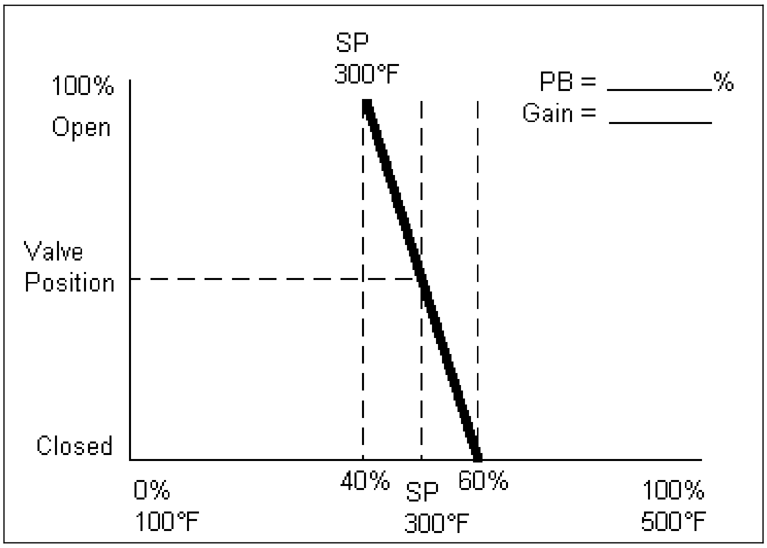


Figure 9.8 Narrow Proportional Band

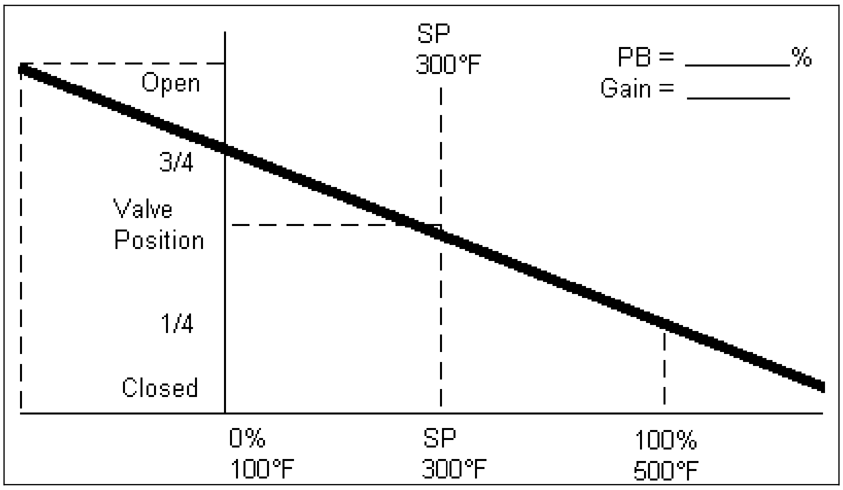


Figure 9.9 Wide Proportional Band

Proportional Band can be related to Gain as follows:

Gain, K = 100% ÷ PB

Using this relationship, compute the Gains in Figure 9.8 and Figure 9.9.

The more modern way of looking at this mode of control is to think in terms of gain (K), but in the field you will still hear it called proportional band (PB).

The M factor has to be that valve position which supplies just the right flow of hot oil to keep the temperature at the set point. It is often called the manual reset term.

A controller designed to provide proportional control must have two adjustments, one for the K and one for the M (manual reset).

There is, however, a rather serious limitation to proportional control. If there are frequent load changes to the process, it will hardly ever keep the process variable at the set point. The reason is that there is only one valve position for each value of the process variable. But if there are load changes like a change in flow rate of liquid such that more hot oil than before is needed to maintain the 300°F, this controller has no way of providing it except through the manual reset adjustment.

Proportional Plus Integral Control

A proportional controller does not change the position of the valve enough to keep the process variable at the set point when a load change occurs, as has been explained above.

Integral (sometimes called *Reset*) action will sense that an error, or offset is present after proportional action has taken place and continue to change the valve position further in an attempt to eliminate the error completely. Controllers with integral action will move the valve at a speed proportional to the size of the error present.

The Proportional plus Integral modes are illustrated in Figure 9.10. Assume a step change in Set Point at a point in time, as shown. First, there is an immediate change in valve position equal to K(E) due to the Proportional Mode. At the same time, the Integral Mode, sensing there is an error, begins to move the valve at a rate proportional to the size of that error.

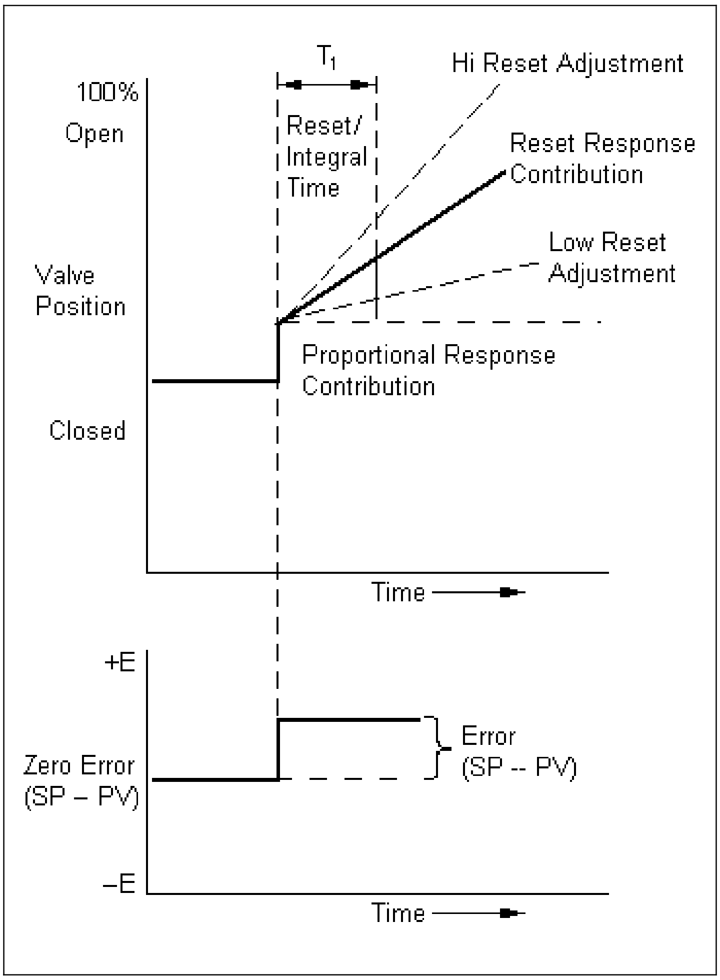


Figure 9.10 Proportional Plus Integral Control Action

Since the illustration pictures a constant error, the valve rate will be constant. It will be seen that after an interval of time. T_1, a change in valve position equal to the original proportional change has taken place. T, is called the Integral Time. An adjustment that is made to an integral controller determines the slope of the integral response portion of the graph. The dotted lines show other settings of the integral adjustment. When time is used to express integral action it is called the *Integral Time*. This Integral Time is expressed in *Minutes per Repeat,* abbreviated *MPR*. This term refers to the number of "M*inutes per Repeat*" that the integral action is repeating the valve change produced by the proportional control alone. The larger the number the slower the integral action and the smaller the number the faster the integral action.

Quite commonly you may hear, its reciprocal used, which is called *Reset.* Reset is expressed in "*Repeats per Minute*" abbreviated *RPM*. This term refers to the number of times per minute that the reset action is repeating the valve change produced by proportional control alone.

Proportional Plus Derivative Control

It seems reasonable that a process with a rapidly changing error would benefit from additional control action. The derivative (sometimes called rate), mode of control does just that. The movement of the valve is proportional to the rate of change of error or process variable. This additional correction exists only while the error is changing. It disappears when the error stops changing even though the error is not zero.

Graphically, this action is illustrated in Figure 9.11.

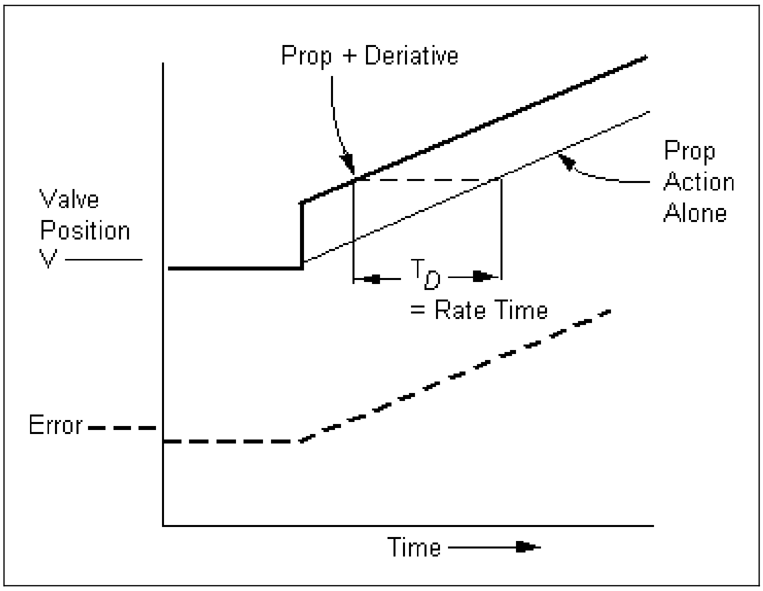


Figure 9.11 Proportional Plus Rate Control Action

It can be seen on this graph that the valve position change with derivative action exceeds that which it would have been with proportional action alone. It can also be seen that on a ramping error, the valve reaches any given position at an earlier time than it would have with proportional action alone. This difference in time is the *Rate Time*, or *Derivative Time*, Tp.

Controllers with this mode of control are designed with an adjustment on the amount of derivative action. This adjustment is made in terms of rate time. Longer rate times increase the amount of rate action.

It is also of interest to consider derivative action in response to a step change in error, as is illustrated in Figure 9.12.

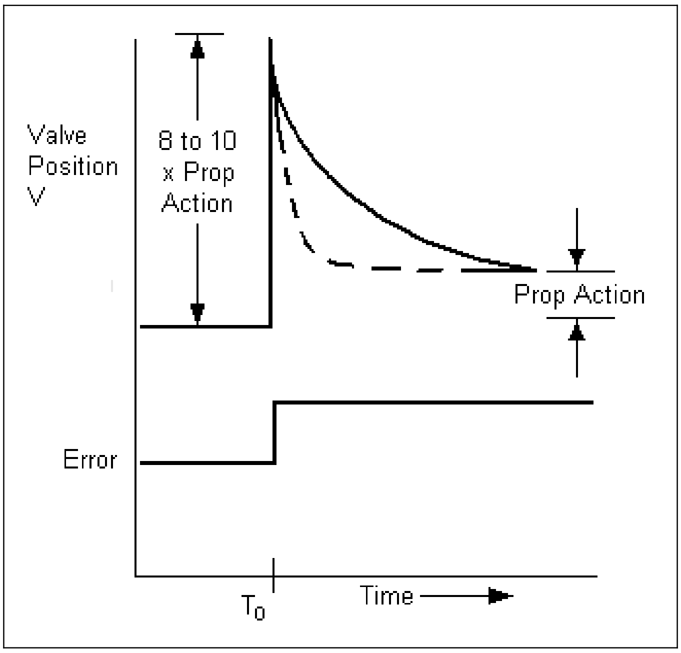


Figure 9.12 Rate Action Response to a Step Change

Changes in rate time here show up in the length of time for the decay of the valve position to the position it would have assumed with proportional action alone.

Proportional Plus Integral Plus Derivative

Finally, the full three-mode controller is achieved by combining the three modes simultaneously, Thus the valve position will be determined by adding the effects of the three modes.

The graph in Figure 9.14 illustrates how an increase in the flow of the liquid to be heated will be responded to by the various control modes in terms of the process variable, and liquid output temperature.

Graphically, its response to a step change in error is:

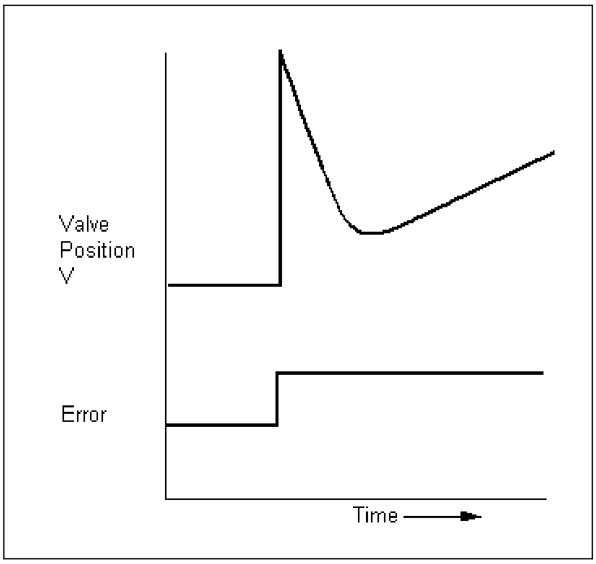


Figure 9.13 Three Mode Control Action

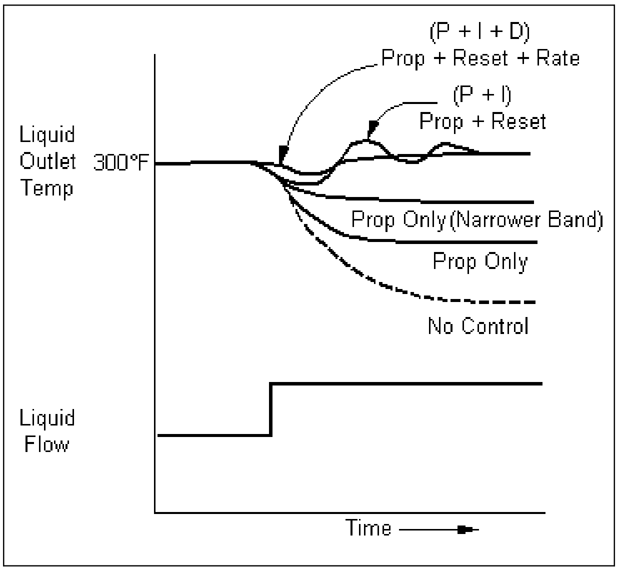


Figure 9.14 Response to Increase in Liquid Flow

Controller Selection

The selection of the proper modes of control to use on a particular process is a complex matter, but there are a few general statements that can be made for guidance.

ON-OFF

On-Off is popular because of its simplicity. In general it functions satisfactorily if the process has a large capacitance and minimum dead time. It will accommodate load changes to some extent, but such changes should not be rapid or large. Cycling at the new load will have a different average value depending on the direction of the load change.

In industry, ON-OFF control is ideally suited, for example, to the control of temperature in a cooking kettle where the only load changes are due to changes in ambient temperature. The capacitance is large and the load changes are small.

Proportional

Proportional control reduces cycling below that of ON-OFF control. It does a particularly good job when process capacitance is large and dead time small. These characteristics promote stability and allow the use of a narrow proportional band, which gives faster corrective action and less offset.

When the process has these favorable characteristics, proportional control can even make moderate load changes tolerable. When the proportional band must be made wider, however, even a small load change leads to offset.

Proportional Plus Integral (P+I)

The primary advantage of proportional plus integral is that it will eliminate offset with load changes. It can be used even when process capacitance is small and load changes are large. The main limitation of a proportional-plus-integral controller is its inability to prevent overshoots due to integral accumulation. When integral action responds to a large enough error, or one that exists for a long time, by putting the valve into saturation (either fully open or fully closed), it is subsequently unable to change the direction of the valve motion until the error changes sign, that is, until the process variable crosses the set point. This is usually too late to prevent overshooting of the process variable. It is a problem found particularly in the start up of processes, but any large or rapid load change may cause it.

Proportional Plus Integral Plus Derivative (PID)

Derivative action can be very useful in minimizing overshooting of the process variable when the controller is trying to compensate for large or rapid load changes. It is also useful in preventing overshoot of the process variable in the start-up of batch processes.

On very slow moving processes derivative will have minimal affect. On noisy processes, such as flow, derivative will amplify the noise and result in continual over correction. It has been most widely used for temperature control, and least on pressure or flow applications. In recent years, however, its use has been more widespread across all control applications.

Each mode of control is applicable to processes having certain combinations of characteristics. The simplest mode of control that will do the job is the best to use. Table 9.1 summarizes the guidelines for selection of control modes from various combinations of process characteristics.

Table 9.1 Control Mode Selection Guidelines

Mode of Control	Process Reaction Rate	Dead Time	Load Changes
On-Off	Slow	Slight	Small and slow
Proportional	Slow or moderate	Small or moderate	Small, infrequent
Proportional + Integral	Slow or moderate	Moderate	Small, faster
Proportional + Derivative	Fast	Small or moderate	Slow, but any size, frequent
Proportional + Integral + Derivative	Fast	Fast	Fast

Controller Tuning

Correct controller tuning is essential to good control. Tuning a controller means finding the optimum settings for gain, integral, and derivative. Good control may have different meanings for different processes.

At the outset we should realize that no corrective action is ever possible unless some deviation or error exists. The feedback principle establishes this generalization. Since it is not possible to achieve zero deviation control, can we state how closely we have approached it? Many criteria have been advanced in an attempt to judge control performance. It is impossible to say that any one of them is the absolute standard. Each process will have its particular requirements.

Essentially, however, most criteria strive to arrive at a compromise with three basic goals:

- Minimum deviation following a disturbance.
- Minimum time interval before return to the set point.
- Minimum offset due to changes in operating conditions.

There are also diverse methods for finding the controller settings that will satisfy these goals. Some are more precise than others, but all result in approximations that provide a good starting point from which fine-tuning can be done. We will consider here two different methods. The two require different amounts of information about the process. As you would suspect, the more process information that can be incorporated, the more precise will be the results. Both of these methods are based on conducting a few simple tests in the field. They can be validated against theory.

Lesson Summary

In this lesson you have learned the different types of basic Process Controllers found in control systems.

In the next lesson you will learn the different types of Multi-Loop Controllers and how they are applied.

Lesson 10
Multi-Loop Controllers

Lesson Objectives

At the completion of this lesson, you will be able to understand the different types of multi-loop controllers and how they are applied to control an industrial plant process.

Introduction to Multi-loop Systems

A simple feedback control loop consists of one measuring element, one controller, and a single final control element. In many cases, the loop will be capable of maintaining the process variable at the desired set point. However, in the event of certain process disturbances, the simple loop will not always be capable of good control. Even with optimum controller adjustments, frequent process disturbances can create undesirable deviations from the set point. This condition takes place because the controller cannot react fast enough to prevent the deviation. The controller only responds when an error becomes evident and by then, it can be too late.

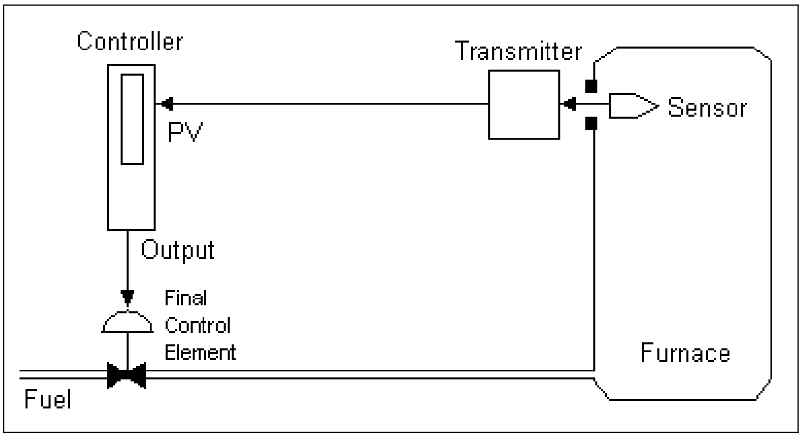


Figure 10.1 Simple Loop

To understand this problem, it is necessary to examine the action of a slow changing variable of a simple feedback control loop. The diagram in 5725014.02 219 illustrates a feedback loop used in controlling the product temperature in a gas-filled reheating furnace. The thermocouple within the furnace generates a signal representing the value of the process variable. This signal enters the controller either as a direct millivoltage or a standard output signal from a field-mounted transmitter. The local set point of the controller is adjusted to the desired value of the process variable and a sensitive device known as an error detector produces a signal representing the difference between these variables (PV & SP). In an effort to nullify the error signal, the three-mode controller produces a signal that will be a function of the polarity, magnitude, and rate of change of the deviation. This output is of sufficient power to manipulate the position of the control valve, which in turn manipulates the amount of fuel entering the furnace.

In a steady state condition (all uncontrolled variables remaining constant) this control scheme should function favorably, but true steady state conditions are not found. Process disturbances can enter the loop with a varying degree of impact. In applications of slow responding control variables (PV) and large disturbances, a multi-loop system may be required to minimize deviations.

The flow of fuel through a modulating control valve will be determined by valve position and other factors such as fuel pressure, temperature, specific gravity and so on. (For reasons of simplification, only valve position and fuel pressure will be examined at this time.) It the fuel pressure should rise, the increased differential pressure across the control valve will result in a rise in fuel flow. With an increase in fuel flow, there will be a greater release of heat energy into the furnace. When news of the rise in temperature reaches the controller through the sensor and transmitter, it will readjust the control valve position as if the original valve position had been incorrect. Time elapses before the deviation is of great enough size to command that the controller take corrective action. A small amount of time elapses before the controller produces the correct amount of output, and due to the thermal inertial and energy holding ability of the slow acting process, a significant amount of time passes before the process responds to the readjusted valve position and returns to the set point. The major problem in controlling the process variable during an unpredicted disturbance is the consumption of time. The controller will only change its output when an error has been detected . . . minutes after the disturbance has entered the process.

In this simple control loop, the system has been designed to control the process variable (temperature) by valve adjustment, although heat supply is actually the factor determining the temperature. A system that helps to overcome the serious time delays and poor control caused by fuel pressure and flow disturbances is called *cascade control*.

The Cascade Control Loop

The cascade loop is one of the most common multi-loop control systems in use today. The application of such a system can greatly decrease deviations of the primary variable and increase line out speed after a process disturbance has occurred.

Some of the common reasons for considering cascade control exist in the previously discussed case involving the control of temperature in a reheat furnace. In this example, fluctuations in fuel pressure created variations in the fuel flow. As the flow of fuel to the furnace changed, so did the amount of energy. The pressure fluctuations resulted in temporary deviations of the process variable, which could not be controlled adequately using only the simple feedback control loop. Avoiding the deviations was not possible because the disturbance entered the system without being detected, and once the error began developing, corrective action was initiated too late.

In the simple loop shown in 5725014.02 219, the output of the controller adjusted the final control element. A cascade control loop is shown in Figure 10.2. Note that the output of the temperature controller now adjusts the set point of a "secondary" controller, which in turn adjusts the position of the final control element. The cascade loop shown in Figure 10.2 uses the groundwork of the previously examined reheat furnace. The secondary variable used in this example is fuel flow.

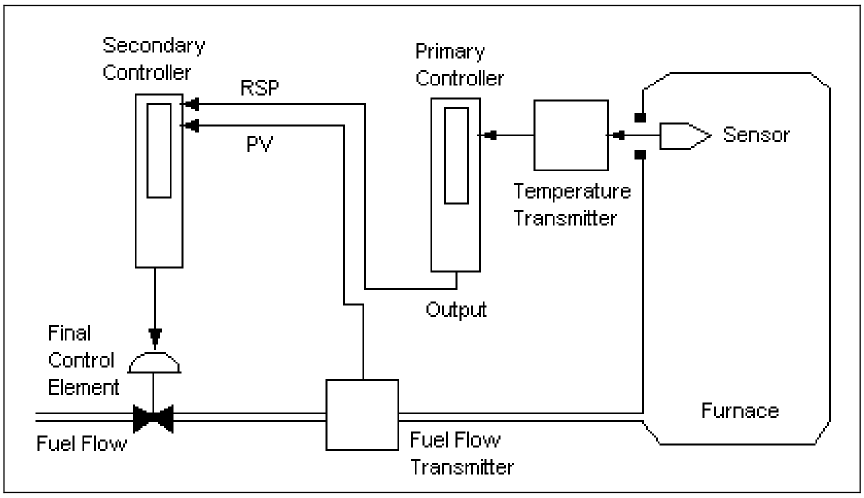


Figure 10.2 Cascade Control Loop

If the temperature of the product within the furnace is too high, the primary controller lowers its output, requesting a decrease in the fuel flow set point. If the temperature drops, the device raises the set point of the secondary controller, which in turn increases the fuel flow to match its new set point. In any case, the primary controller is controlling temperature by adjustments in the secondary controllers set point. Since the secondary controller is designed to measure and control fuel flow, the primary controller adjusts fuel flow, not valve position. Therefore, when a flow disturbance occurs, the fuel flow transmitter will notice it before it can adversely affect the process. The secondary controller will quickly readjust the valve position until flow once again matches the set point dictated by the primary.

The secondary control loop consists of a simple flow loop. This controller measures the flow of fuel and compares it to the value desired by the primary controller. The function of the controller is to maintain the flow at the remote set point it receives. Note that with this configuration, deviations due to fuel should increase, there will be a rise in fuel flow rate. Before this increased flow affects the temperature, it is detected by the secondary transmitter and the secondary controller. In an attempt to maintain a zero error between its PV and RSP (remote set point), the secondary controller quickly changes its output in a direction to reduce the fuel flow and reestablish a zero error. Because of the speed of response of this variable, as compared to that of the primary, the temperature changes very little.

The conditions existing in a simple feedback control loop that may warrant the consideration of cascade control are as follows:

1. Under control by the simple feedback control loop, the process variable is slow in responding to system disturbances and equally as slow in establishing a corrected output. This time consumption results in undesirably large deviations that optimum controller tuning cannot eliminate.
2. A change in the condition of the process causes serious upsets in the controlled variable.
3. The value of the variable other than the controlled one is being affected by the disturbance and there is a definite relationship between its value and the controlled variable.
4. The secondary variable is one that can be controlled. It responds swiftly to process disturbances and adjustments of the final control element. The value to which it is controlled must be dictated by the condition of the primary variable.

In addition to these conditions, some other points to consider about cascade control are:

1. In going to cascade control, at least two items of instrumentation must be added: A transmitter and sensor to measure the secondary variable and another controller.
2. The additional controller is a remote set point unit. This feature may call for a device that is slightly higher in cost as compared to a standard controller.
3. The secondary controller must be capable of controlling the secondary variable independently. In the previous example, the purpose of the secondary controller was to keep the flow at a desired level. Flow alone, as a major controlled variable cannot be used because its value would not respond to PV load changes or changes in the set point. The controlled variable (temperature) is still of primary concern: the secondary is important only because its value affects the primary.

In the cascade control loop previously introduced, it was noticed that the selection of fuel flow as a secondary variable was a good one. It should be obvious that to obtain the maximum benefits from a cascade control system, a wise choice of the secondary variable is a vital requirement. How does one choose the most appropriate secondary variables? Application engineers have developed some rules of thumb for choosing the optimum secondary variable.

To use these rules, begin by drawing a block diagram of the system to clarify its operation. A simple block diagram is shown in Figure 10.3. Identify the point(s) of disturbance in the system. It may be helpful to divide the final control element block into two blocks: actuator and body (if a valve). Next, draw a more detailed block diagram of the system in a cascade configuration, choosing one likely secondary variable, as shown in Figure 10.4. Figure 10.4 depicts a completed diagram including all blocks existing between the measurement of the primary variable and the positioning of the final control device.

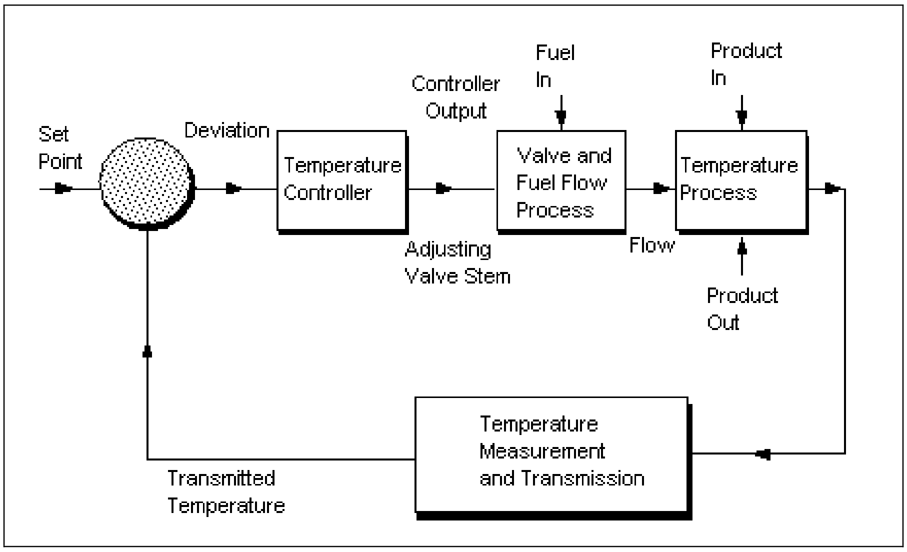


Figure 10.3 Block Diagram of a Simple Control Loop

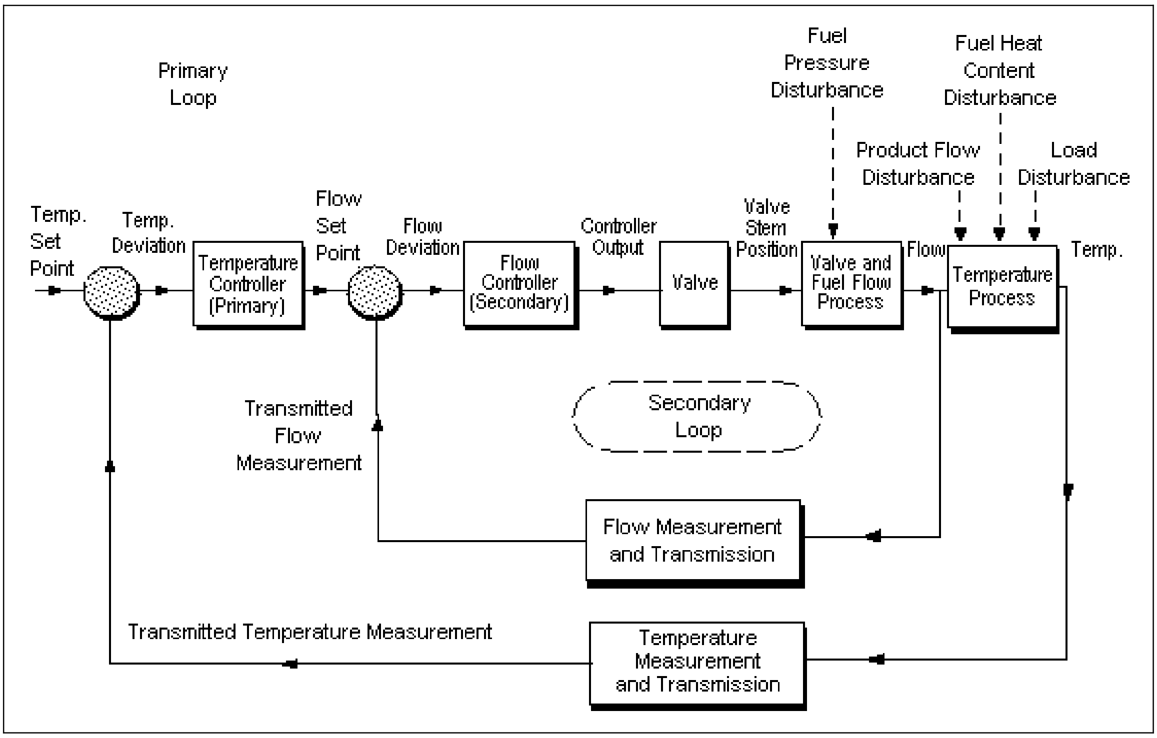


Figure 10.4 Cascade Control Loop

After the diagram has been made, plan possible alternates for the placement of the secondary measuring element and selection of the secondary variable, using these five rules.

1. Make the secondary loop include the input point of the most serious disturbances. It is the effect of these disturbances that the cascade loop must be most successful in controlling.
2. Make the secondary loop fast by including only minor lags. When comparing the speed of response of the primary variable (T_P) to that of a possible secondary variable (T_S), the ratio of T_P /T_S should preferably be at least 3. Ratios of 5 or 10 are even more desirable.
3. Use a secondary variable with set point values that are definitely related to the value of the primary variable. In undisturbed operation of the system, at line out, the relationship of the secondary set point to the primary variable should be represented by a single line. If the line is relatively straight rather than curved, this will simplify the tuning of the primary controller.
4. If the secondary loop can remain relatively fast, make it contain as many of the disturbance inputs as possible. The improvements in close control after a disturbance has entered a cascade control loop will be roughly related to the gain settings of both controllers.

Predictive Feedforward Control

In the previous section, cascade control systems were discussed. In these systems, the disturbance was noticed by the secondary sensor and controller and brought under control before it could adversely affect the primary variable. For cascade control to be a suitable option, the variable that is creating the disturbance (the secondary variable) must be controllable. For example, in the reheat furnace of the previous discussion, the changes in fuel flow were causing process upsets. In this example, fuel flow could be controlled. In other words, it can be sensed by the secondary transmitter and controlled in an on-going fashion by the secondary controller that manipulates the final control element. It is the disturbed variable's ability to be measured, compared to a remote set point, and continuously corrected by a final control element that makes it suited for cascade control.

In some applications, a disturbance takes place that cannot be controlled (although it can be measured). An example of such an application could be the disturbance in the feed rate of product through a heat exchanger. In this case, cascade control could not be used. However, a system called feed-forward can anticipate and compensate for the disturbance, although control of the disturbance is not possible.

The simple loop and the cascade loop are both types of feedback' control. There are several inherent limitations to feedback control, which the feedforward system improves upon:

- All feedback control systems obtain control by measuring the error and supplying a restoring output. The system depends on an error to generate a corrective signal. Without the error, the controller output is stable. When the error becomes evident, the controller must slowly integrate for correction. With a steady state error, gain and derivative cease to offer a contributing factor to the output.
- All feedback control systems obtain the correct output by trial and error. The system will never know the correct output necessary to solve the problem. The basic operation of the system is shown in Figure 10.5.

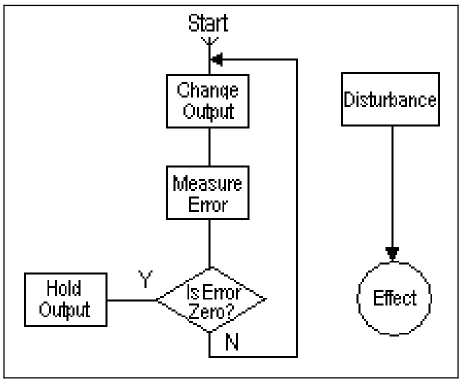


Figure 10.5 Trial and Error System

The simple flow diagram shown in this Figure 10.5 assumes that the controller output is changing in the correct direction.

Some degree of oscillation is common in any trial and error attempt at control.

To find methods of solving some of the problems existing with feedback control systems, one would begin by considering a different approach. The approach would be to measure the principle factors that affect the process, and calculate the correct output to meet current conditions.

If a disturbance should occur, information will be fed to the final control device before the system senses that a problem has arrived. A flow diagram depicting this concept might appear as shown in Figure 10.6.

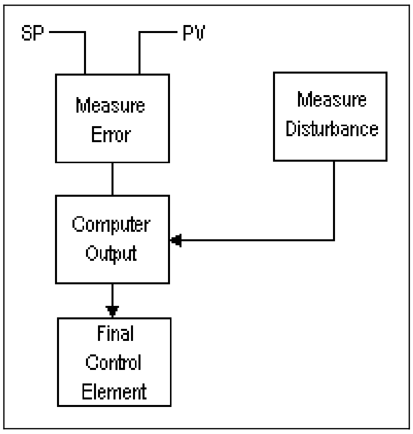


Figure 10.6 Feedforward Block Diagram

Note that in Figure 10.6, the system has no return of information. The correct output value is computed by changes in the set point, process variable, or fluctuations of external system disturbances. The process of feeding this information forward to compute the correct output value is known as *Feedforward*. The essential feature that distinguishes this system from feedback control loops is the forward flow of information. The feedforward scheme can produce tremendous improvements in control because in practice, it continuously balances the material or energy requirements of the process against the current demands of the load.

Figure 10.7 depicts a simple feedforward control system. The loop is of the continuous form, wherein liquid is fed through a heat exchanger and is heated to a desired value. The controller output feeds the final control element through a summation auxiliary. The auxiliary is an analog adder that sums the values of its inputs.

The feedforward transmitter measures inlet flow to the heat exchanger, and its Output is multiplied by the setting on the adjustable gain relay. The resulting feedforward signal becomes the second input to the summer.

If the influent feed rate should increase, the flow transmitter instantly feeds an increase signal to the summer. The magnitude of this signal will depend on the degree of feed flow increase and the gain set on the relay. The feedforward signal will increase the output from the summer and produce an immediate change in valve position. The increased fuel inlet can now prevent large deviations of the feed temperature from occurring.

Feedforward strategies that compute corrective output values in a manner independent of time are known as static systems. The computed output was instantaneous and is designed to anticipate current demand changes. Figure 10.7 is an example of a static system.

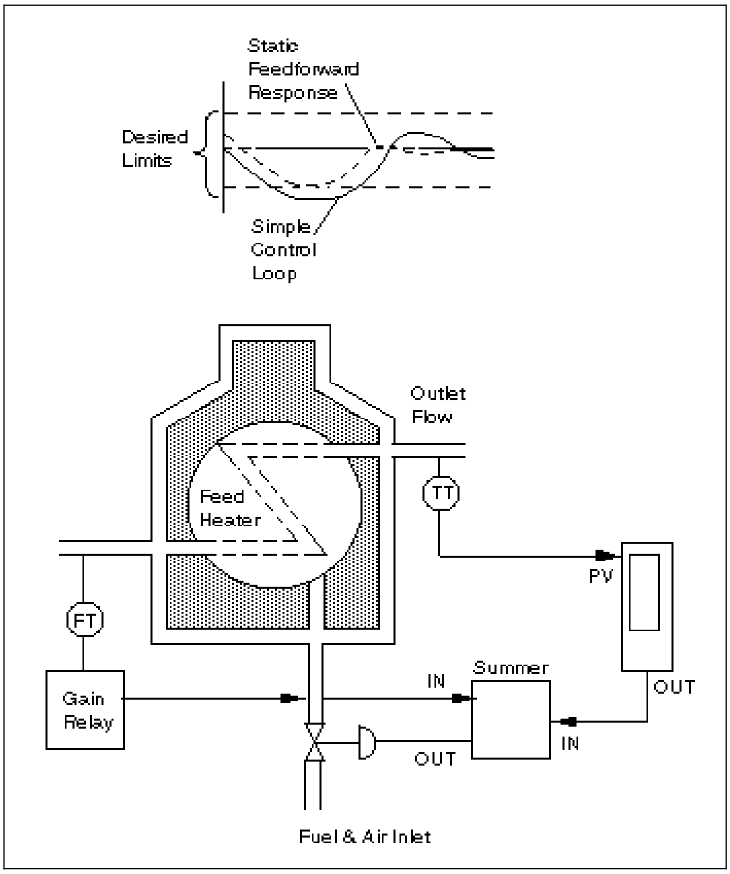


Figure 10.7 Static Feedforward System

Dynamic Feedforward Control

Applications often exist, as in previous example, where predictive feedforward strategies will offer a dramatic improvement in control of the process variable. Yet, even more improvement is sometimes obtainable by using Dynamic Feedforward. An application of this system is shown in Figure 10.8.

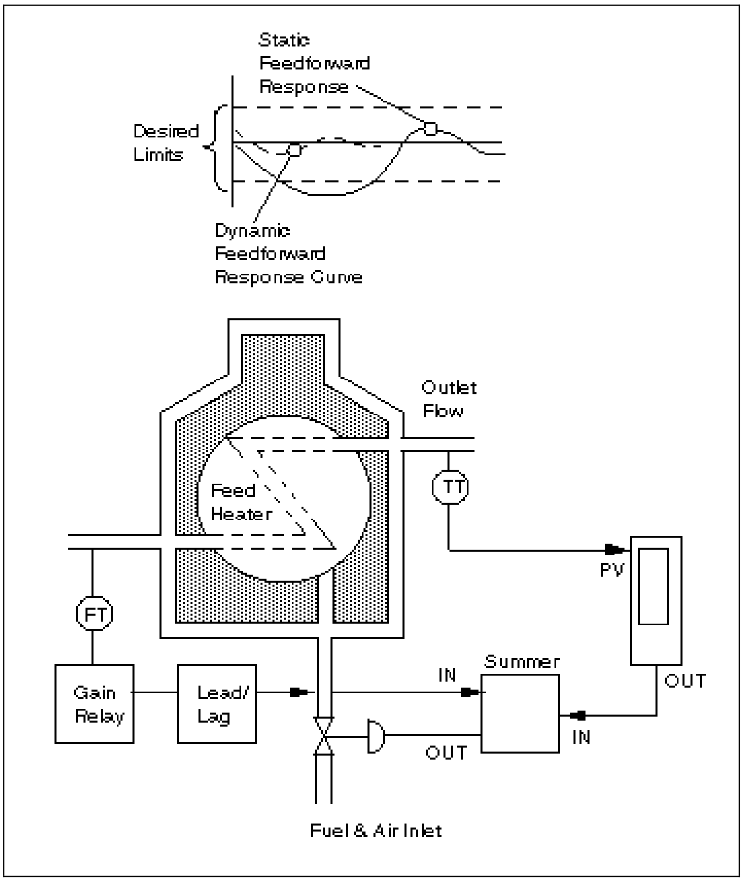


Figure 10.8 Dynamic Feedforward System

Assume that the increase of inlet feed had a much greater affect on product temperature. The alternative, in the static system, would be to increase the gain of the adjustable gain relay to cause a greater change in valve position. The stronger initial correction signal could create over correction — opening the valve too much, and causing a larger upset in the opposite direction. This deviation would have to be removed by the temperature controller.

The dynamic feedforward control system can provide more correction than the static system, yet not create the undesired over correction. With dynamic (or time variable) feedforward, the corrective signal will be momentarily large, then gradually cut back. By gradually cutting back the corrective signal, the process will not experience a large, sustained release of energy and over correction can be eliminated. The time dependent feedforward signal can be generated by another auxiliary device known as a Lead/Lag relay.

The Ratio Control Loop

In many control applications, there are two or more inputs to a process that must be varied and controlled to meet process demand. The value of these variables (most often two flows) must be kept in a prescribed ratio to achieve a particular end product. The system that maintains this ratio is known as a ratio control loop. Some examples of ratio applications could be blending a base product with a thinner, water and foaming agent, or air and fuel.

There are two ratio control configurations that are commonly used: Series and Parallel Configurations. There are definite advantages in choosing one over the other.

The series system uses a lead and follow approach. According to the demand of the process, a master controller will control one of the variables (the leader) to a particular value. The follower variable is then controlled by a remote set point controller to some predetermined ratio of the leader. This means that as the first input variable rises, so will the value of the second. If the leading variable falls to zero, so must the follower. This interaction is the primary characteristic of the series ratio system. These systems can be characterized by a definite interlock between the two controlled variables. This interlock can become a valuable safety feature.

Figure 10.9 illustrates the simplest method of accomplishing ratio control. The master controller, measuring the consistency of the final product blend, establishes the value of flow B. The flow is measured and its percentage equivalent becomes the set point of the flow A controller. Controller A is by necessity a remote set point controller, identical to the secondary controller of any cascade system. If flow B is 20%, then 20% becomes the set point for flow A.

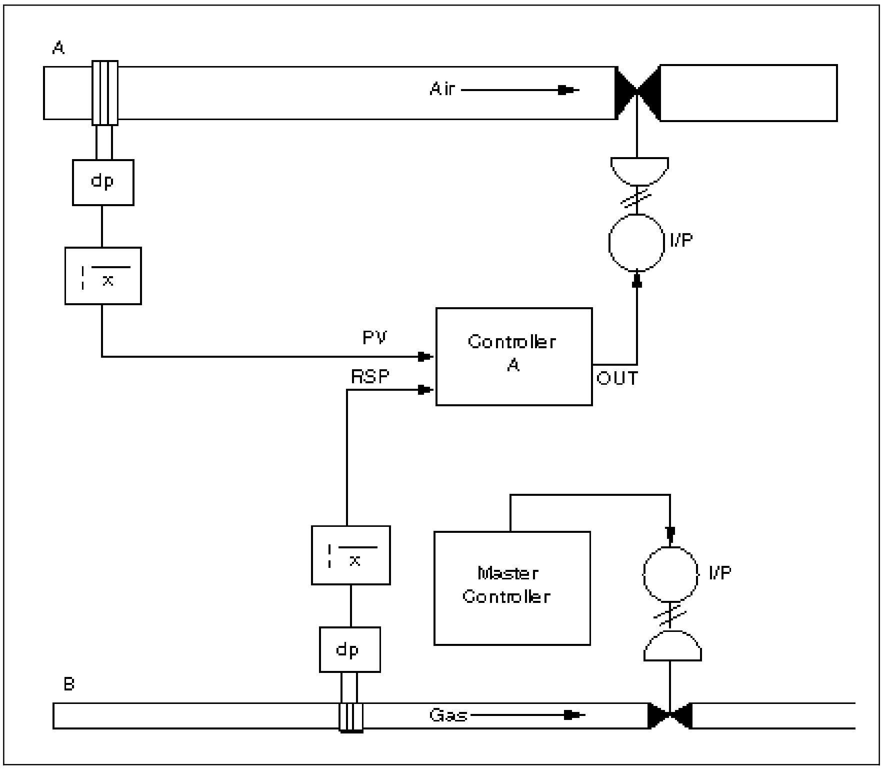


Figure 10.9 Basic Series Ratio Control System with Fixed Ratio

Notice that in Figure 10.9, the pipe for flow A is much larger than B. This will allow a pre-set ratio to be established. For example, if the range of operation of pipe A is 0 to 1000 cfh and pipe B is 0 to 500 cfh, the A:B ratio of maximum flow capacity would be 2:1. The 20% fluid flow in pipe B would be 100 cfh, but in pipe A the flow would be 200 cfh.

Since the value of A will be established by the value of B, the system is serial. The ratio of flow is fixed by the scale ranges of both variables and cannot be changed without a major change in system hardware. If pipe A and B were the same size, the system shown in Figure 10.9 would only be capable of maintaining a 1:1 ratio, since there is no device in the system to multiply or divide flow B by some gain factor before sending it as a remote set point to controller A. In the event that a ratio is desired other than the "pre-set" ratio established by the two pipe dimensions, another device must be added to the system. This device is called a ratio relay and is shown in system in Figure 10.10.

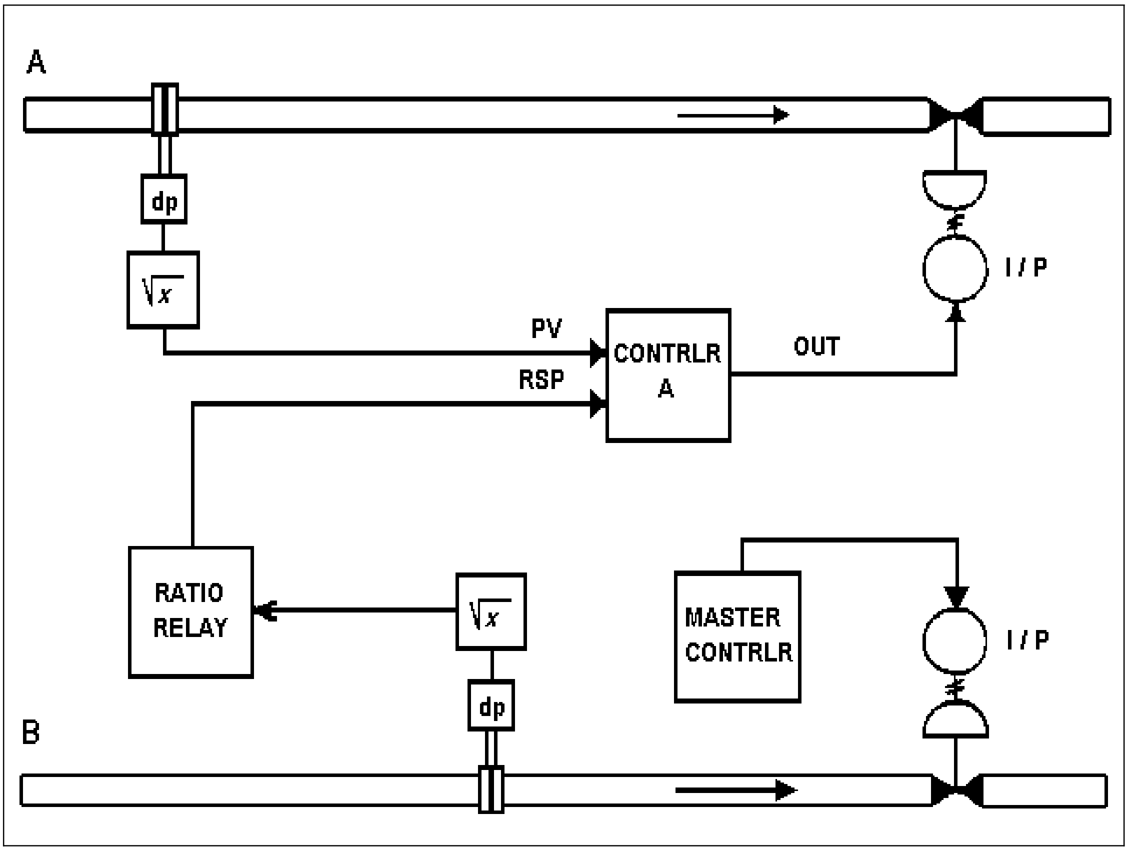


Figure 10.10 Ratio Control System with Ratio Relay

This system provides one major advantage over the previous example. By using a device known as a ratio relay between the flow in pipe B and the Flow A controller, the system will operate the same as example A, except that the ratio of the flows can be easily adjusted. The system remains serial because the value of flow B, although multiplied by the ratio, sets the value of Flow A. Any fluctuations in Flow B will be reflected in A. Note that the ratio, as well as pipe size, are now responsible for the actual ratio between the two flows. For example, if pipe A and pipe B are the same size, and the ratio relay is set at 2, then flow A will be twice as great as flow B. If pipe A is twice the size of pipe B, and the ratio relay is set at 2 then flow A will be four times as great as flow B. If pipe A is one-third (.33) as great as pipe B, and the ratio relay is set at .5 the flow A will be (.33 x .5) or .165 times flow B, or about one-sixth of B.

The parallel approach to ratio control allows the master controller to set the value of both variables. Instead of one control system leading and the second one following, the parallel concept ties both systems to the direct command of the master. As process demand changes, the master controller adjusts the values of both control systems simultaneously.

Since both systems receive their set points from the master controller, they will respond to a change at the same time. How well the two systems are kept together will depend upon the response characteristics of each.

One of the advantages of parallel ratio control is that any noise occurring in the leader variable will not be reflected in the follower. Without the interlock, both systems are independent of one another.

This configuration can lead to yet another advantage. The simultaneous updating of both systems could result in a smaller deviation from the desired ratio during changes in process demand. The obvious disadvantage is loss of interlock safety. If one variable of a parallel system drops to zero, the second will not.

A simple block diagram of a parallel ratio system is shown in Figure 10.11, and a complete parallel ratio system is shown in Figure 10.12.

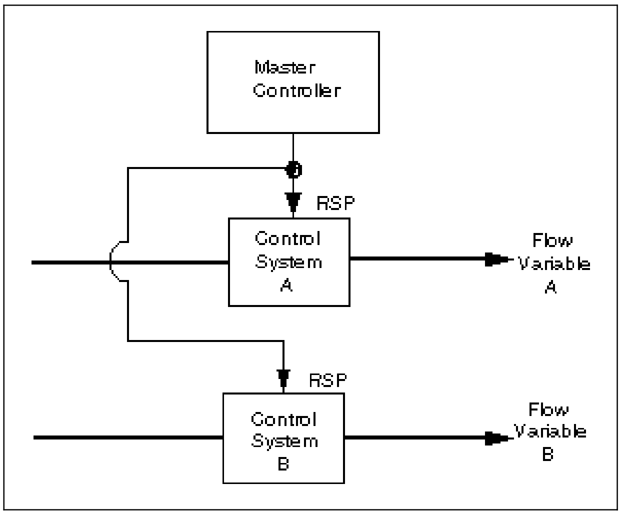


Figure 10.11 Parallel Ratio System Block Diagram

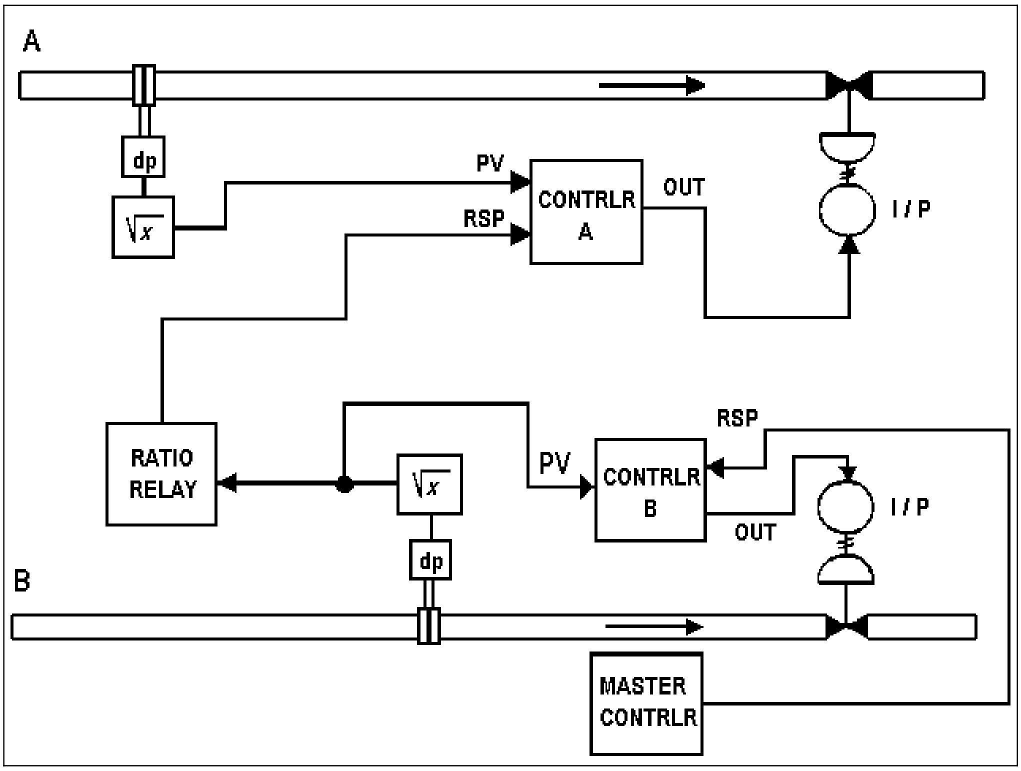


Figure 10.12 Parallel Ratio Control System

This ratio control system has been designed so that instead of the master controller setting the value of flow B only, the master controller sets the flow values of both controllers. Note that while in the series ratio system, the input to the ratio relay came from the flow B transmitter/square root extractor, in this system, the input to the ratio relay comes directly from the master controller. In the series ratio system, the RSP to controller A did not change until flow B actually changed, not when the Master Controller merely called for a change in flow B. In the parallel ratio system, the RSP to Controller A changes the moment the master controller calls for it.

The ratio of the two flows will be determined by the ratio relay adjustment. Since the master controller sends both set point commands in a parallel fashion to the flow controllers, both controllers will respond to a change at the same time. How well the flows track each other over changes in demand will again be determined by the two response characteristics.

The parallel system will, in most cases, result in a better ratio control as process load changes occur. The basic disadvantage is the lack of flow interlock. If Flow A should fall to zero in a fault condition, Flow B will not be affected. Note that if an application arises where process personnel would like to momentarily interrupt one of the flows without affecting the other, this non-interlocked parallel system would offer such a possibility.

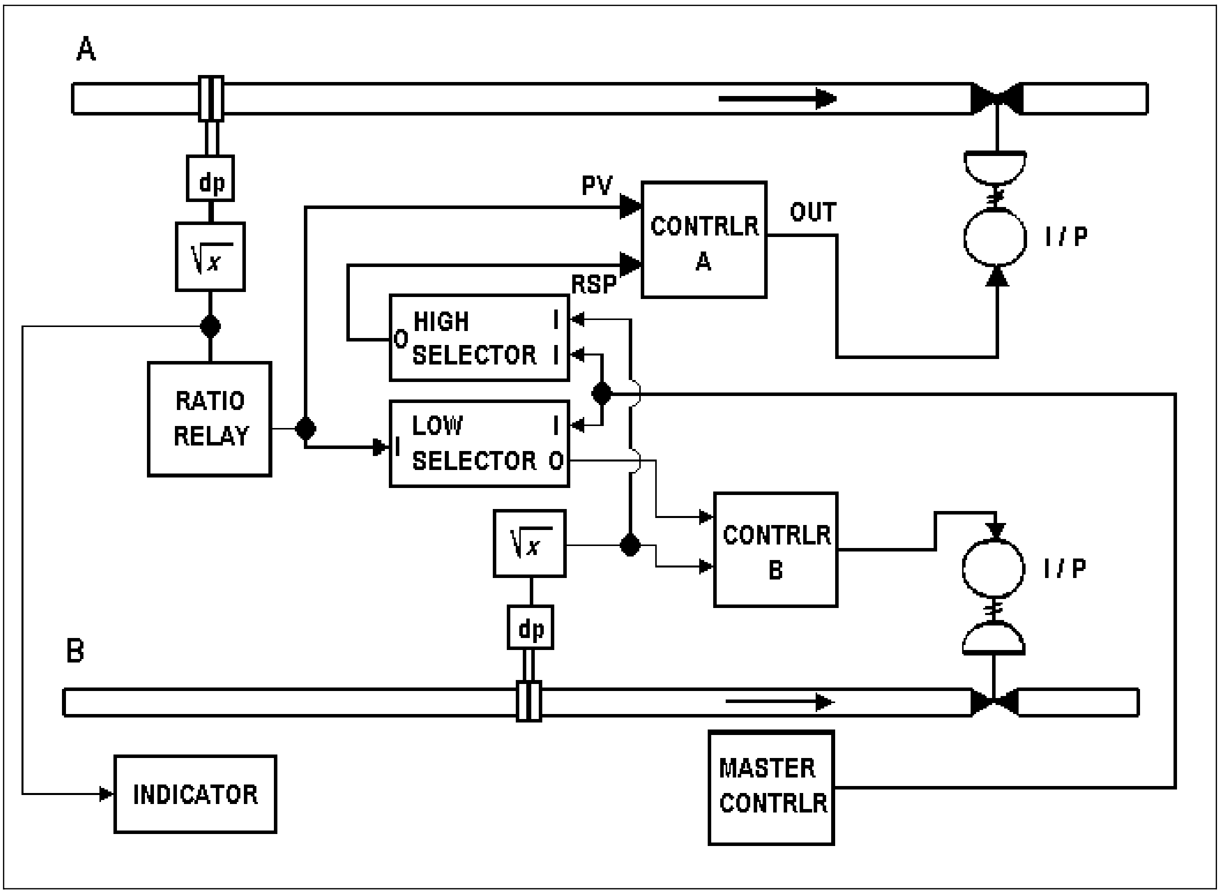


Figure 10.13 Ratio System with Interlock

Some applications require that the ratio between the two flows never exceed a set value in one direction, because the result may represent an uneconomical or unsafe condition. A typical example of this is the air/fuel mixture in a burner. To keep the mixture from ever being too rich in fuel, an interlock system is used. This system, shown in Figure 10.13, is capable of providing this form of interlock through the use of signal selectors. In this example, if we use X to represent the desired ratio and A & B to represent the actual flows, then the ratio of the actual flow must be equal to or greater than the desired ratio. This is how the system must perform:

$A \div B \geq X$

If the desired ratio has been met (A = X) then to satisfy the limits of the equation:

1)

Holding	A constant
	B cannot increase

AND

2)

Holding	B constant
	A cannot increase

If a change in demand requires more of both fluids, note that to satisfy the first rule, Flow B cannot increase unless Flow A increases first. Conversely, to satisfy the second rule, if a decrease in both fluids is necessary, Flow A cannot decrease unless Flow B does so first.

Because the response times of both systems may not be equal, it is important to note that we cannot simply state that "one variable must change first." We must ensure that one will lag the other, but accomplish this without the use of a time delay. (A time delay may result in an increased offset from the desired ratio during changes in demand. There may also be an unnecessary increase in system complexity.)

In Figure 10.13, the interaction and interlock between the two flows can be achieved by allowing the master controller to set the flows in a parallel fashion. The line between the Flow B controller and its set point input from the master controller is bridged by a low selector. The other input to the selector is the PV of the Flow A controller. In the line feeding the set point input of the Flow A controller, a high selector has been placed. The high selector has as a second input, the flow measurement of controller B. An adjustable ratio relay station has been placed in the PV input line to the Flow A controller. In this way, the relay multiplies the actual PV of Flow A times the ratio value. The controller then compares this value to its set point.

During a load change in the opposite direction, the converse will be true.

With a decrease in demand, Flow B must change first. After it has changed, Flow A may begin changing.

In this example, the signal selectors will provide the interlock between flows that is necessary to keep the ratio on the safe side of the desired value at all times. When the system comes to a point of balance, all signal selector inputs will be equal. To display the actual value of Flow A, an indicator has been added.

Analog Override Control Strategies

Override selectors are often used in applications that involve many controlled variables that are influenced by the value of a single manipulated variable. The function of the basic override selector will be to select either the highest or lowest of its input, and channel this value to its output. Non-selected inputs will be open.

Assume that there are two inputs to an override selector. These inputs represent two process variables that are both affected by the value of one manipulated variable. However, the two process variables are affected in opposite directions by the same manipulated variable. That is, as the manipulated variable is changed in one direction, one of the process variables will increase as the other decreases. A typical example of this would be the relationship between the position of a valve (manipulated variable), located on the discharge end of a compressor, and the suction (Process Variable 1) and discharge pressures (Process Variable 2) independently measured across the system. Figure 10.14 illustrates this example.

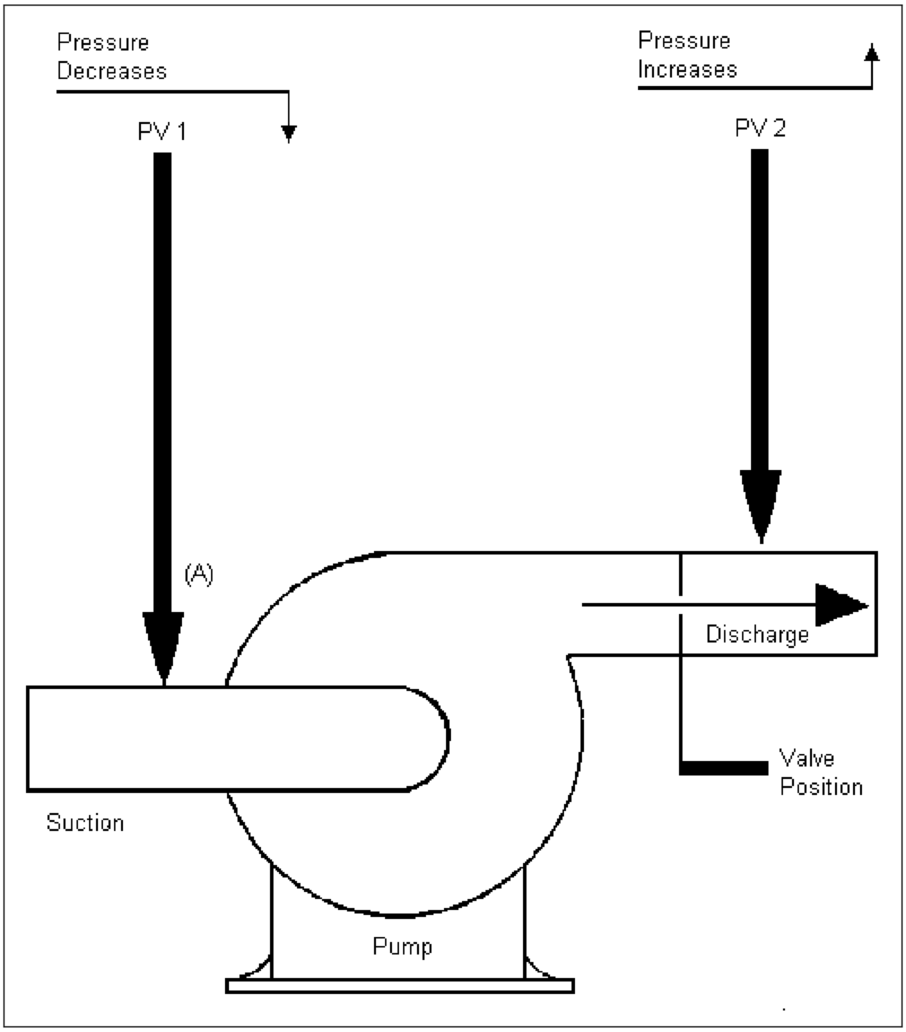


Figure 10.14 Compressor Application

With the pump running at a given speed, opening the valve would cause an increase in the suction measured at point A. If positive pressure is the measured variable, an increase in suction would be the same as a decreased pressure. Although the upstream pressure (Point A) decreases due to an opening of the control valve, note that the same change in valve position will cause an increase in downstream pressure (Point B). This relationship between controlled and manipulated variables is a major reason why override strategies are frequently used in compressor and pump station controls.

The objective of an override control system in compressor and pump control is as follows: Maintain a given discharge pressure, but do not attempt to do so at the expense of drawing a dangerously high suction at point A. A high suction could cause compressor damage and/or pipe cavitation.

Figure 10.15 shows the control system that meets this requirement, using two controllers. The controller that is used to measure downstream suction is direct acting, while the other is adjusted to be reverse acting. The outputs of both controllers feed the override selector, and it sends the signal of lowest value to the control valve. The valve is air-to-open, meaning that more output from the selector will open the valve more.

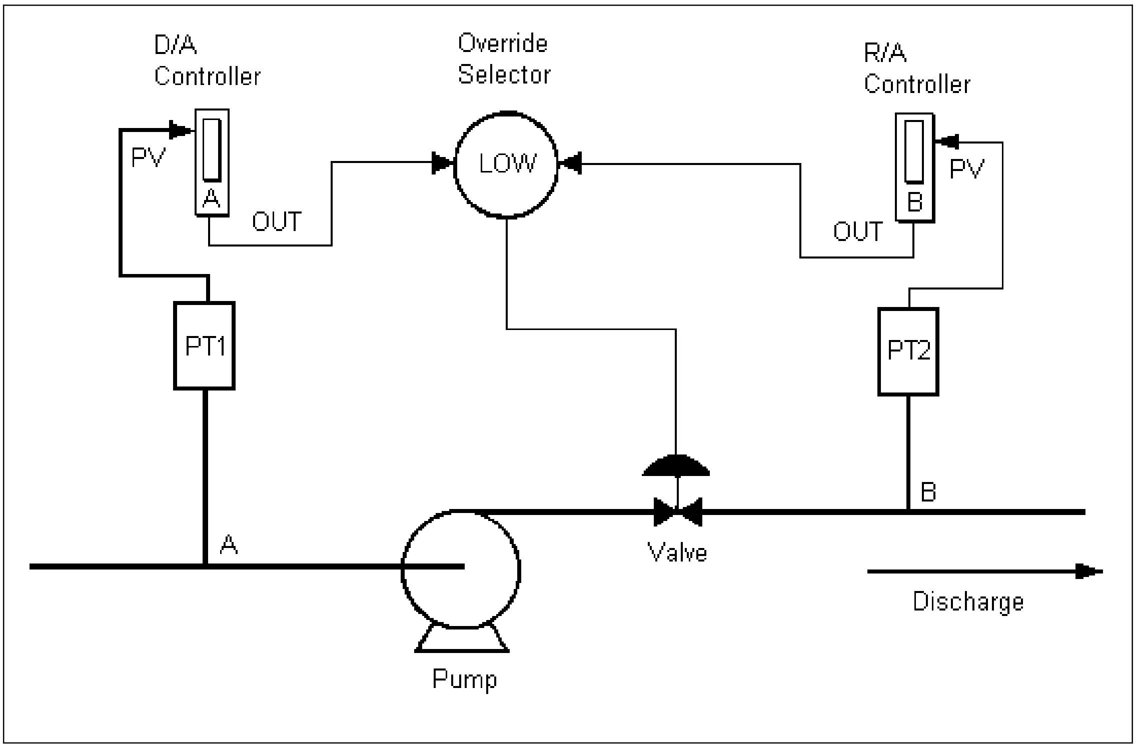


Figure 10.15 Analog Override System

A problem arises if either of the two controllers have the integral (automatic reset) mode of control. As mentioned earlier, non-selected inputs are opened. If the output of such a controller is not selected, integral wind-up will occur. To avoid this, one of two simple solutions can be used:

1. Both controllers can be proportional only, which would eliminate the problem.
2. Many override selectors are available with anti-windup protection on inputs designed for use with controllers having the integral mode of control.

The controlled variable of primary concern will be discharge pressure. A set point value representing the desired pressure will be set on this controller (controller B). The suction pressure controller (controller A) will be set to a minimum safe level of pressure. Unless the system experiences a fault condition, such as a shallow running supply or restricted line on the compressor inlet, the suction pressure should be well above the set point value of controller A. This variable is allowed to deviate from its set point, as long as the offset is in the acceptable direction. The system will be normally selecting the output of controller B. Since this controller is reverse acting, its output will decrease to close the valve if pressure B moves above the set point. Conversely, with the pressure dropping below the set point, the controller output increases to open the valve. The increasing and decreasing output of this controller must remain below the output of controller A. This ensures that it will be selected.

If the compressor supply runs shallow, controller B will open the valve in an attempt to maintain the discharge pressure at its set point. As the valve is opened to control the discharge pressure, the pump suction increases. This reduction in inlet pressure reduces the output of controller A because A is a direct acting controller. If the pressure at A reaches a dangerously low level, the override selector will select the low level output from controller A and send it to the valve. If the supply should begin running more shallow, note that the decreased pressure will cause controller A to close the valve. This action will decrease suction and maintain the inlet pressure at the minimum safe level. Once the supply has been replenished, the compressor suction will decrease naturally, driving the output of controller A up, and the override selector will select controller B for normal control.

Integrators

In applications involving flow measurement, the primary element will usually indicate rate of flow. There are flow meters that indicate total flow (positive displacement devices), but the more common methods will produce a signal that represents an instantaneous value. For example, if a flow meter was used to detect the rate of flow of a fluid, the output signal could be compared to taking a snapshot of the amount of flow for only an instant. Therefore, the flow rate which is indicated represents one instant in time, and the signal is a continuous measurement of the rate of flow of the process variable.

In many processes, an application may make it necessary to produce a history of the flow value over a period of time. For instance, a municipal water treatment plant must know the rate of influent sewage for controlling purposes. Along with controlling the purification of water, they must also report to the community the amount of water being treated each day. Such information can be obtained by integrating (totalizing) the flow signal over the one day period of time.

Integration, were it to be accomplished manually, could be rather involved and time consuming if the flow rate signal displayed on a chart is irregular (as it usually is). In an example where the flow is constant, a 50% rate of flow value on a 0-100.000 gallon /day chart, would yield a total daily flow of 50,000 gallons. In this case integration is simple.

The chart in Figure 10.16 shows a record of the rate of flow occurring in an application where the range of operation is from zero to one thousand gallons per hour. The chart is a twelve-hour history of the changes that occurred. To totalize the flow signal on the chart, a human operator or an electronic device must calculate the area that exists underneath the curve drawn by the recorder pen.

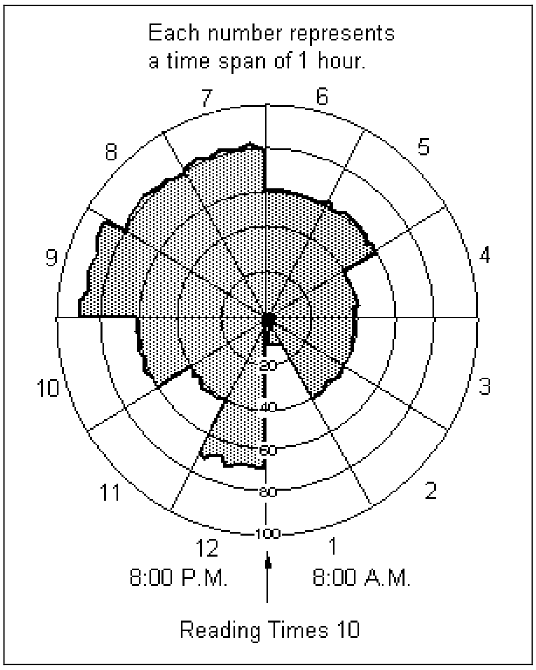


Figure 10.16 Integration Chart

To manually totalize the flow in this example, it is necessary to add the twelve one-hour flow rate values in order to yield the total flow between the hours of 8:00 A.M. and 8:00 P.M. Table 10.1 depicts this manual calculation and yields a total flow of 6,700 gallons.

Table 10.1 Computing Total from Rate of Flow

Chart Section	Time Span	Flow	Total Flow Per Time Span
#1	1 hour	100 gal	100 gal
#2, #3, and #4	3 hours	400 gal	1200 gal
#5 and #6	2 hours	600 gal	1200 gal
#7 and #8	2 hours	800 gal	1600 gal
#9	1hour	900 gal	900 gal
#10	1 hour	600 gal	600 gal
#11	1hour	400 gal	400 gal
#12	1 hour	700 gal	700 gal
Total	**12 hours**		**6700 gal**

Since most flow records will not be as clear-cut and easy to calculate manually as that in Table 10.1, an electronic auxiliary accomplishes integration. This calculation is achieved by producing a calibrated pulse train to a counter that continuously counts the total flow. As the flow rate decreases, so does the frequency of the output pulses. An electronic integrator might operate with a pulse rate output range from 0 to 50 ph to 0 to 50.000 cph. This means that a single unit will cover the desired span of most applications without a multiplication constant.

To calculate the amount of counts that an integrator should produce with a constant input, the range must be known. The integrator range is determined by dividing the maximum flow by the period of time involved.

Example: An integrator must be calibrated to indicate the total flow of water through a linear flow transmitter. Assume that the maximum amount of flow in the vessel was 20,000 liters per day. The desired period of time to which to calibrate the device is one hour. The relevant question becomes: how many counts should occur in 1 hour?

Maximum Count = maximum flow ÷ unit number in flow period

Maximum Count = 20.000 liters per day ÷ 24 hours per day

Maximum Count = 833.33 counts per hour

In one hour, with a 100% input signal, the integrator should count from zero to 833.3.

Since this device is a linear integrator, in 15 minutes, the counter should reach 1/4 of this value, or 208.33.

The range should be set so that with a 4ma input, the count rate is zero, and with 20 ma input, the count rate should be 833.3/hour. No multiplication need be used for this application.

Square Root Extractors

The square root extractor is an auxiliary whose primary function is in the linearization of a differential pressure signal in the calculation of flow. When a fluid passes through a restriction in a flow vessel, there will be a change in the differential pressure across the restriction. If impulse taps were placed both upstream and downstream of the restriction, and the difference in pressures of both taps was measured, the measurement would show that the relationship of flow rate to differential pressure would be exponential. The formula describing this relationship is as follows:

$$Q = K \sqrt{\Delta P}$$

Where:

Q = The quantity of flow

K = A calibration constant that depends on the size of the restriction when compared to the inner pipe diameter, the maximum flow rate, and other non-changing parameters.

ΔP = The differential pressure between the high pressure upstream side and the low pressure downstream side of the restriction.

The restriction can be any one of many primary elements. Depending on the application, the element could be an orifice plate, flow nozzle, venturi tube, dall tube, or flow tube.

In applications that involve the totalizing of flow signals, it is mandatory that the signals be linearized before the calculation is made. Linearization is also necessary when it is desirable to use linear scales and charts instead of square root indications in system receivers. Figure 10.17 shows a typical loop using a square root extractor and a linear integrator. The table shown below depicts the input and output percent values for a correctly calibrated square root extractor.

Table 10.2 Input and Output Values for Square Root Extractor

% Input	% Out	% Input	% Out	% Input	% Out	% Input	% Out
0	0	25	50	50	70.7	75	86.6
1	10	26	50.9	51	71.4	76	87.1
2	14.1	27	51.9	52	72.1	77	87.1
3	17.3	28	52.9	53	72.8	78	88.3
4	20	29	53.8	54	73.5	79	88.9
5	220.4	30	54.8	55	74.2	80	89.4
6	24.5	31	55.7	56	74.8	81	90
7	26.4	32	56.6	57	75.5	82	90.5
8	28.2	33	57.4	58	76.1	83	91.1
9	30	34	58.3	59	76.8	84	91.6
10	31.6	35	59.2	60	77.4	85	92.2
11	33.2	36	60	61	78.1	86	92.7
12	34.6	37	60.8	62	78.7	87	93.3
13	36.1	38	61.6	63	79.4	88	93.8
14	37.4	39	62.4	64	80	89	94.3
15	38.7	40	63.2	65	80.6	90	94.9
16	40	41	64	66	81.3	91	95.4
17	41.2	42	64 8	67	81.9	92	95.9
18	42.4	43	65.6	68	82.5	93	96.4
19	43.6	44	66.3	69	83.1	94	96.9
20	44.7	45	67.1	70	83.7	95	97.5
21	45.8	46	67.8	71	84.3	96	97 9
22	46.9	47	68.6	72	84.9	97	98.5
23	47.9	48	69.3	73	85.4	98	98.9
24	48.9	49	70	74	86.0	99	99.5
						100	100

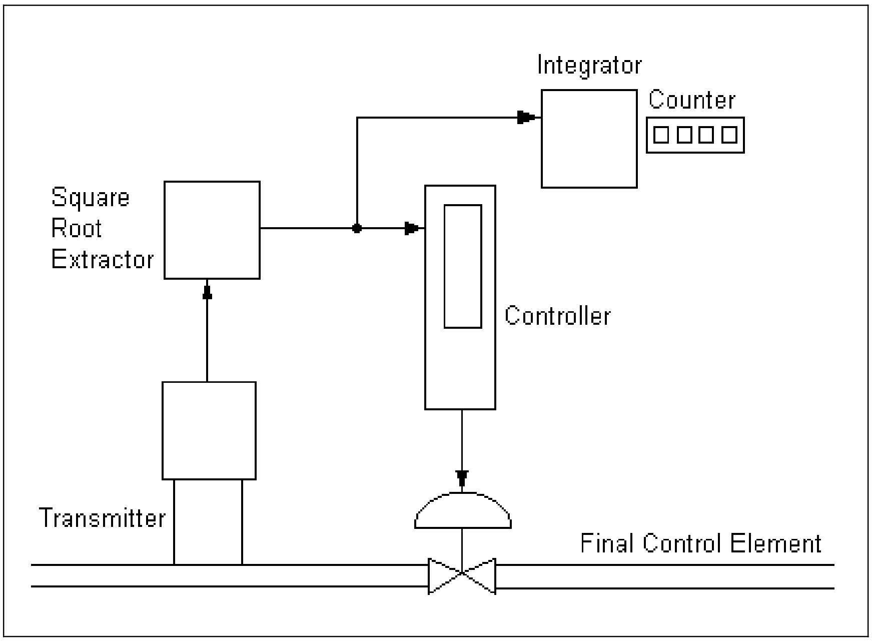


Figure 10.17 Square Root Extractor and Integrator

Multiplier/Dividers

A multiplier/divider is an analog computational auxiliary unit capable of performing one of seven mathematical operations. Each unit would typically be able to accept two or three 1-5 Vdc input signals and would compute a 1-5 Vdc output signal as a function of the program.

One of the most common applications of a multiplier/divider is in mass flow calculations. Mass flow is a type of flow measurement that is not only concerned with the differential pressure across a primary element, but also the temperature and static pressure of the fluid. By including pressure and temperature in the flow calculations the result will be a highly accurate measurement of flow.

If a gas is put into a confined area at a temperature and pressure equal to atmospheric conditions, the static pressure of the gas with reference to gage pressure will be zero.

The two conditions that could effect the static pressure of the gas would be a change in temperature, and a change in the volume of the container.

Increasing the temperature will cause the molecules of the gas to move more rapidly. As the molecular motion increases, so does the tendency for the moving molecules to bombard the inner walls of the container. This bombardment will result in a higher static pressure. Likewise, colder temperatures result in lower pressures. This effect is shown in Figure 10.18.

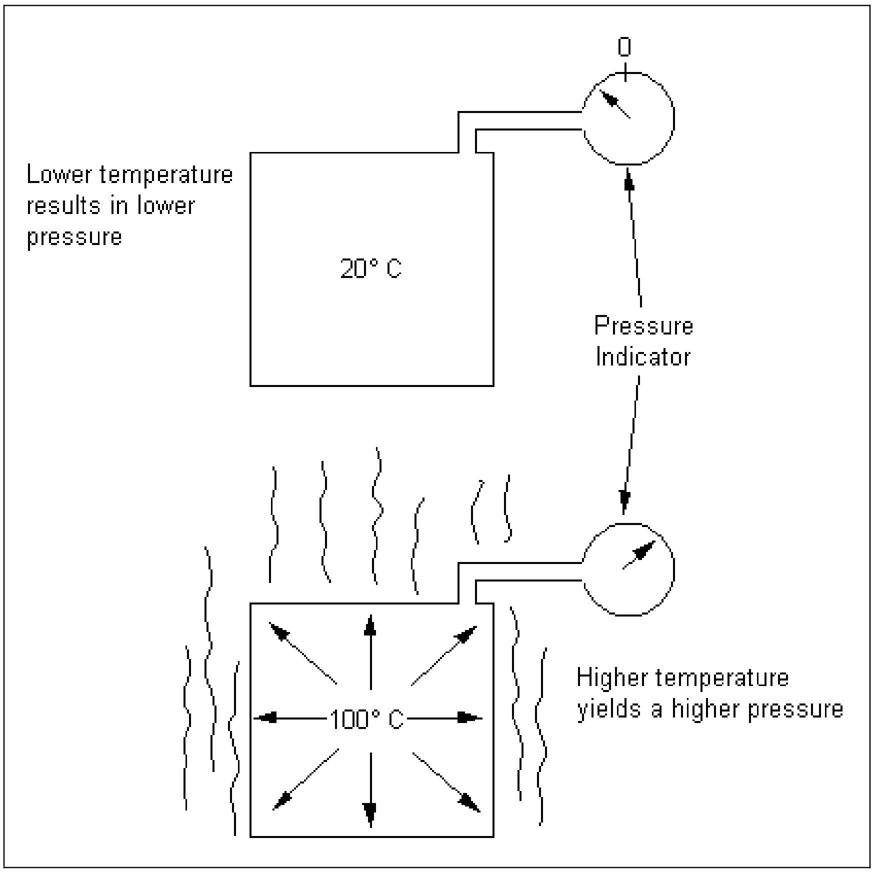


Figure 10.18 Effects of Temperature on BTU

If the volume of the container is decreased, there will be a compression of the molecules of the gas. The compression of the molecules will also increase the static pressure. This effect is shown in Figure 10.19.

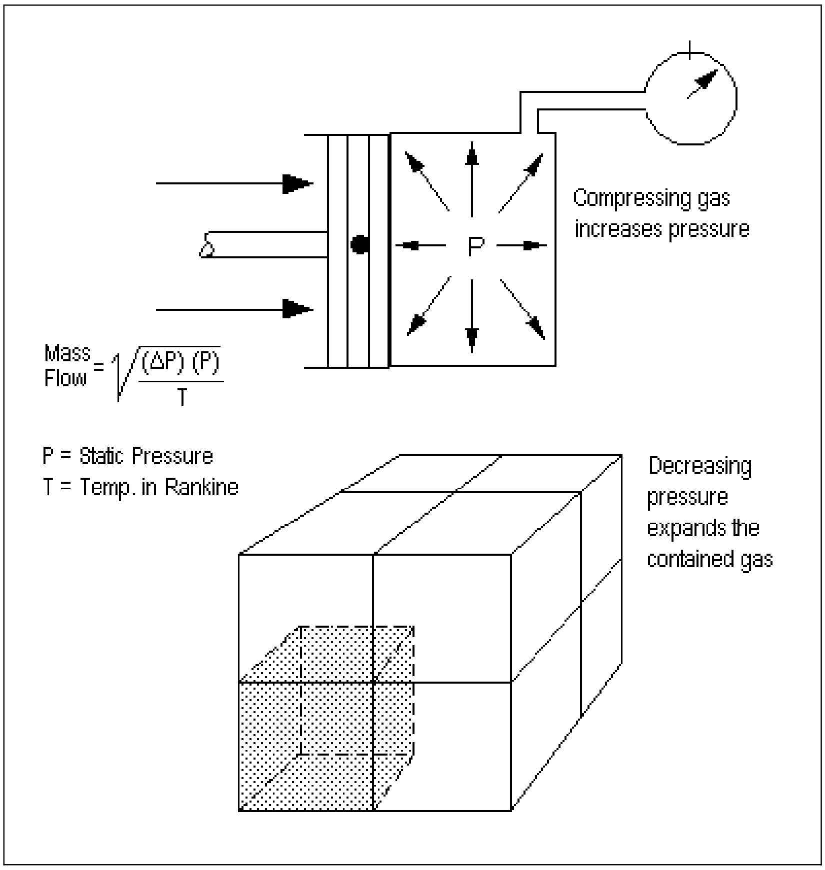


Figure 10.19 Effects of Pressure on BTU

In Mass Flow Measurement, the temperature and pressure of the flowing fluid can affect the flow by changing the volume of medium.

In Figure 10.19 the shaded area of the drawing represents one cubic foot of a methane gas. This volume of gas has the ability to do a specific amount of work. It can be assumed that it has the amount of energy equal to 1,000 BTU's. (The British Thermal Unit. or BTU, is the amount of energy required to raise the temperature of one pound of water, one degree Fahrenheit.) If the pressure of the gas decreases, or its temperature should increase enough to cause the volume of the gas to be eight times larger than the original cubic foot, the potential energy in one cubic foot will be much less then 1,000 BTU's. This condition has changed the total mass of one cubic foot of methane.

The definition of flow is the movement of a quantity of fluid past a given point in a particular interval of time. Examples of some units of flow could be gallons per hour, cubic feet per minute, or liters per hour. Using the same volumetric unit of measurement that was discussed previously, assume a fuel flow of 200 cubic feet per minute into a furnace. If one cubic foot of fuel has the potential energy of 1,000 BTU's, than a fuel flow of 200 cubic feet per minute will contain a specific amount of energy. The amount of energy being delivered to the furnace in any instant of time, depends on two variables: the rate of fuel flow and the mass of one cubic foot of fuel. In standard flow measurement, a controller can correct for changes in the fuel flow that the furnace will receive by correctly manipulating a control valve, but without knowing the mass, the amount of energy can fluctuate. If the temperature of the fuel increases, the mass of one cubic foot will decrease. A decrease in the amount of fuel in a cubic foot will decrease the BTU content. Maintaining a constant flow will not always assure a constant temperature. This is why mass flow calculation is necessary — especially in applications involving high consumption of steam or fuel. Mass flow measurement is a much more accurate means of measuring flow than simple rate of flow measuring devices.

The formula for mass flow calculation by differential pressure means is as follows:

$$\text{FLOW} = \sqrt{((\Delta P)\ (P))} \div T$$

Where:

ΔP = The differential pressure measured across the primary element.

P = The static pressure of the fluid in pounds per square inch absolute (psia).

T = The fluid temperature in degrees Rankine

NOTE:

1. The temperature in degrees Rankine is equal to the degrees Fahrenheit plus 460°. (°R = (°F + -460)
   Example: 120°F = (460° + 120°) R, so 120°F = 580°R
2. All variables must be zero-based absolute.
   Example: ΔP could be 0 — 100” H_2O, P could be 0 — 30 psia, T could be 0 — 660°R

By using scaling and biasing factors, each variable will be altered to create zero-based ranges.

Calculation of Scaling and Biasing Constants

As an example, assume that the following PV ranges exist:

ΔP = 0 — 20” $H_2$0
P = 0 — 50 PSIG
T = 0 — 150°F

On differential pressure measurement of flow, the low end of the range is always zero for a no flow condition. With the transmitter calibrated from zero to twenty inches of water, the multiplication factor (SCALE) will be 1 and the biasing will be zero. There is no need to condition the differential pressure signal.

SCALE = 1
BIAS = 0

In pressure measurement, the 0 to 50 PSIG must first be converted into absolute pressure. Using the approximate value of 14.7 psi as atmospheric pressure, add 14.7 to the high and low range values of the gage pressure reading. (Pressures in PSIA are approximately equal to the value in PSIG plus 14 7.) So, 0 to 50 psig equals 14.7 to 64 7 PSIA. Now the pressure value is in pounds per square inch absolute.

Next, the measurement must be zero-based. (14.7 to 64.7 PSIA must become 0 to 64.7 PSIA)

The formula for choosing the scaling factor is the span of the transmitter divided by the zero-based span. Notice that the calibration of the transmitter will be 14.7 to 64.7 PSIA (a span of 50), and the scaling and biasing constants will cause the auxiliary to see 0 to 64.7 PSIA.

K_{scale} = Transmitter Span ÷ Zero-Based Span

Using this formula, K_{scale} equals:

$$\frac{\text{Transmitter Span}}{\text{Zero Based Span}} \qquad \frac{(14.7 \text{ to } 64.7)}{(0 \text{ to } 64.7)}$$

or

50 ÷ 64.7 which equals .773

The Bias voltage can be calculated by the following formula:

K_{bias} =(LRV ÷ URV) x 4 volts

Where:

LRV = the Lower Range Value of the transmitter range in PSIA

URV = the Upper Range Value of the transmitter range in PSIA.

The transmitter range is 14.7 to 64.7 PSIA, so the LRV equals 14.7 and the URV equals 64.7. This formula produces a ratio times the 4 volt span (1 - 5 Vdc)

K_{bias} = (14.7 ÷ 64.7) x 4 volts or .91 volts

Therefore, the pressure scaling and biasing values are as follows:

SCALE = 773
BIAS = .91

In temperature measurement, the transmitter span is 0 to 150°F. First the Fahrenheit temperature must be converted into the Rankine scale.

°Rankine = 460 + °Fahrenheit

Using this formula, 0 to 150°F is equal to 460 to 610°R (a span of 150°). Making this value zero-based yields 0 to 610°R.

To compute K_{scale} and K_{bias}, use the same formulas that were introduced for pressure. In this example:

K_{scale} = Transmitter Span ÷ Zero-Based Span = (460 to 610) = 150 ÷(0 to 610)

or

K_{scale} = 246

K_{bias} = (LRV ÷ URV) x 4 = (460 ÷ 610) x 4

or

K_{bias} = 3.02 volts

Therefore, the temperature, scaling, and biasing factors are as follows:

SCALE = 246
BIAS = 3 02

Verification

The range of the transmitter is 0 to 50 psig. The function of the input conditioner of the multiplier/divider is to modify the transmitter signal so that it appears to be operating over a range of 0 to 64.7 PSIA.

The calculated constants were:

SCALE = .773
BIAS = .91

If the actual range of operation (0 to 50 psig) is graphically placed beside the desired zero-based range (0 to 64.7 psia), the result would appear as in Figure 10.20.

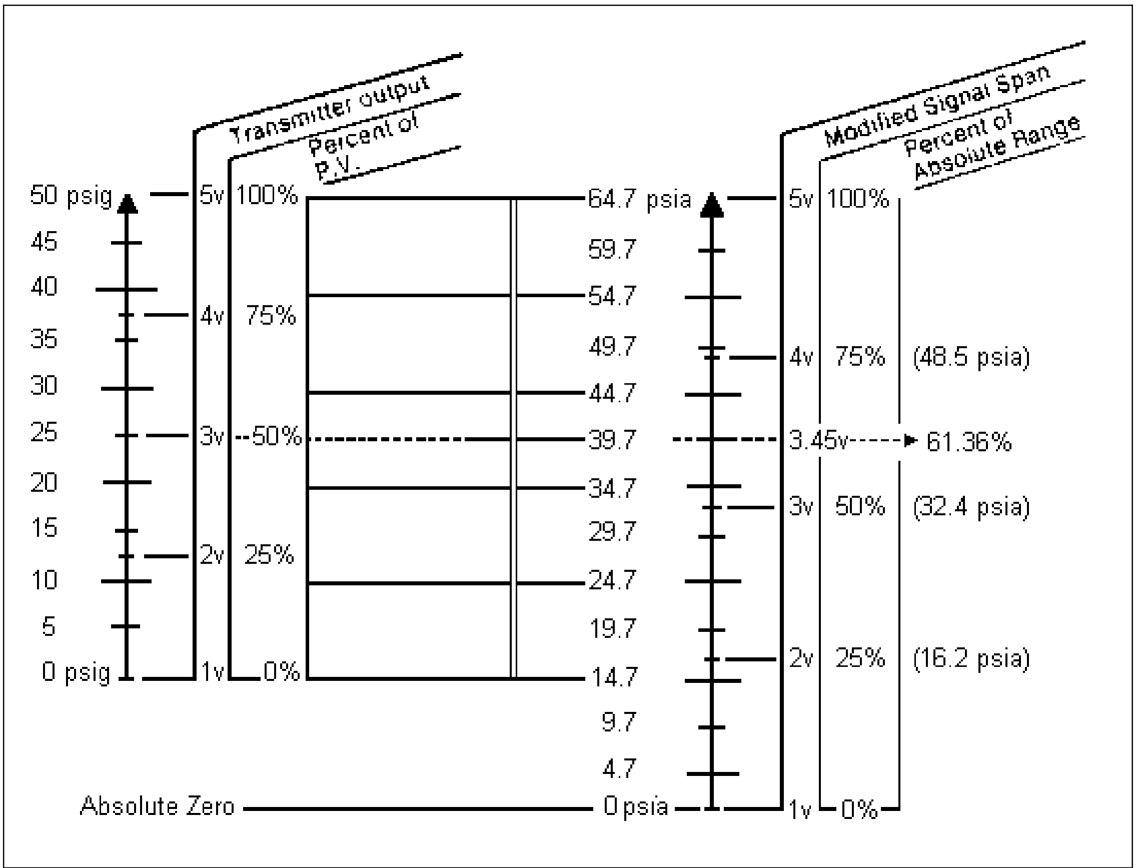


Figure 10.20 Transmitter Range

The zero percent end of the transmitter is 0 psig. The 50% and 100% values are 25 psig and 50 psig respectively. What the input signal conditioner must do is modify the voltage equivalent of this range (1 to 5 volts) so that it linearly represents the 14.7 to 64.7 psia span of the zero-based range (0 - 64.7 psia).

As an example, assume that the pressure existing is 25 psig. By adding 14.7 psi to the gauge pressure value, the approximate equivalent on the absolute scale will be obtained.

25.0 psig + 14.7 psi = 39.7 psia measured by the transmitter approximate atmospheric pressure.

The transmitter is measuring 39.7 psia. If it is calibrated correctly, its output will be 50% of 1 to 5 volts, or 3.0 Vdc.

The measured value of 39.7 psia does not represent 50% of the zero-based range. To calculate the actual percent of span that 39.7 psia represents, the measured value must be divided by the full scale span.

39.7 psia measured ÷ 64.7 psia scale span = 61.36%

The measurement of 25 psig (39.7 psia), which is 50% of the transmitter range, must be modified to become 61.36% of the zero-based range.

To check the operation of the input signal conditioner constants calculated earlier, calculate the desired voltage that should be obtained. With an input voltage of 3.0 Vdc (50%), the output from the input signal conditioner of the multiplier/divider must be 61.36% of 1 to 5 volts.

Removing the live zero of 1.0 volt, 61.36% of the full-scale span of 4.0 volts is 2.45 volts. After the percent of span figure has been calculated, adding the live zero of 1.0 volt yields 3.45 volts. This is the 25 psig equivalent signal on the zero-based absolute scale.

Using the calculated constants of:

SCALE = .773
BIAS = .91

the 3.0 volt signal is first zero stripped. In this way it becomes 2.0 Vdc. The zero stripped signal is multiplied by the input scaler of .773 to yield 1.546 volts. Adding the input bias value of .91 volts yields 2.456 volts. To check the validity of the signal conditioner, the +1 volt live zero must be summed with 2.456 volts. The result will be 3.456 volts.

This operation has modified the 50% (3.0 Vdc) transmission signal, representing 25 psig or 39.7 psia, to appear as its equivalent in an absolute range from 0 to 64.7 psia ... or 63.36% (3.45 volts). This exercise has proved both constants to be valid ones.

Note that the actual PV will not fall below approximately 23% of the modified signal span. This is the rough equivalent of a zero psig signal from the transmitter. This should not be viewed as a problem since the transmitter has been calibrated for a 0 to 50 psig range, so the actual PV should never fall into the vacuum range during normal operation.

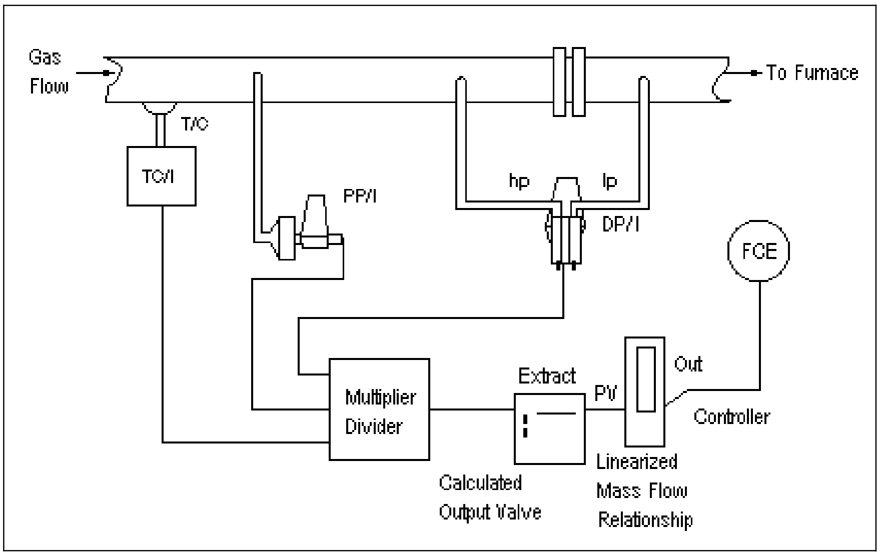


Figure 10.21 Mass Flow Calculation Control Loop

Using the previous example for scaling and biasing constants, assume that the A, B, and C inputs are ΔP, pressure, and temperature respectively. (See Figure 10.21.) In this case, the multiplier/divider will be programmed for:

(A x B) ÷ C

After the calculation has been made, square root extractor will linearize the signal.

For input A: K_{scale} = 1 and K_{bias} = 0

For input B: K_{scale} = .773 and K_{bias} = .91

For input C: K_{scale} = 246 and K_{bias} = 3.02

Adder/Subtractor

The adder/subtractor is an analog computational device capable of accepting up to four 1-5 Vdc input signals. The output is a 1-5 Vdc signal that is a function of the program.

One common application for the adder/subtractor is the addition of fuel flows to furnaces. One such application is shown in Figure 10.22.

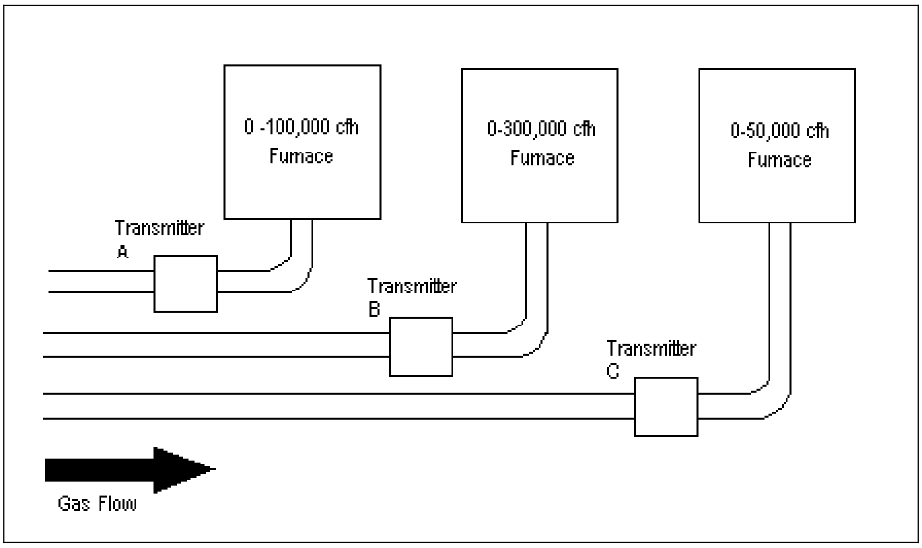


Figure 10.22 Multi-Loop Flow Application

The furnaces are labeled A, B, and C. The process variable in each control loop is the temperature of the raw materials being treated. This application requires a need for the total instantaneous fuel consumption. Knowing the total flow during periods of peak usage will prove to be a valuable economical aid in plant operation.

Furnace A operates in a range of 0 to 100,000 cubic feet of fuel per hour, Furnace B operates from 0 to 300.000 cfh and C operates from 0 to 50.000 cth. All transmitters are 4 to 20 milliamp units.

Figure 10.23 shows the role of the adder/subtractor in the loop.

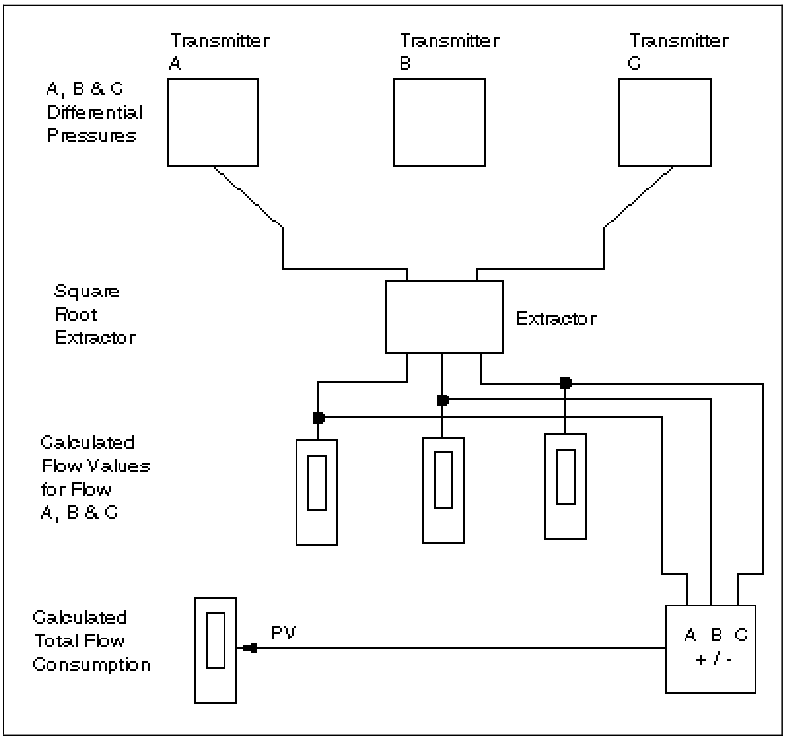


Figure 10.23 Multi-Loop Flow Totalization Application

To add the three ΔP/I differential pressure signals, they must first be linearized with respect to a linearly changing flow. The square root extractors accomplish this task by changing the exponential input change to a linear output. The linearized flow signals enter their respective controllers, where the final control elements regulate the amount of energy delivered to each furnace.

Each 1 to 5 volt PV flow signal will enter the adder/subtractor that will add the three signals. Notice that a 100% output signal from each will represent different flow values. In Transmitter A, 5 volts will represent 100.00 cubic feet per minute. In transmitters B and C, 100% output will represent 300,000 and 50,000 cfh respectively. Totaling the three 100% signals without input scaling and/or biasing would be like adding apples and oranges. The three signals must be placed on an equal basis. To do this, the adder/subtractor provides a scaling factor from 0 to 2.0 Vdc and a bias value of 0 to 8.0 Vdc.

Adder/Subtractor Calibration Coefficients

The formula necessary for performing flow totalization in the previous example is as follows:

Scale = Individual Max Flow ÷ Flow Total

Using the information provided on the previous page:

FLOW A = 100,000 cubic feet per hour
FLOW B = 300,000 cubic feet per hour
FLOW C = 50,000 cubic feet per hour

In a 100% condition, the TOTAL FLOW will equal 100.000 + 300.000 + 50.000. The TOTAL FLOW Value in this application is 450.000 cubic feet/hour

	Flow A	100,000
	Flow B	300,000
+	Flow C	50,000
	Total Flow	450,000

Using the flow signals for each input will yield the necessary scaling constants:

Scale for A

$$= \frac{\text{Max Flow A}}{\text{Flow Total}} = \frac{100{,}000}{450{,}000} = 22$$

Scale for B

$$= \frac{\text{Max Flow B}}{\text{Flow Total}} = \frac{300{,}000}{450{,}000} = 67$$

Scale for C

$$= \frac{\text{Max Flow C}}{\text{Flow Total}} = \frac{50{,}000}{450{,}000} = 11$$

Lesson Summary

In this lesson you have learned about the different types of Multi-Loop Controllers and how they are applied.

Glossary

Absolute humidity

The mass of water vapor in a given volume of air (i.e. density of water vapor in a given parcel, usually expressed in grams per cubic meter)

Absolute pressure

The pressure of a liquid or gas measured in relation to a complete vacuum (zero pressure).

Absolute zero

The temperature at which the molecular motion that constitutes heat ceases, and at which an ideal gas, kept at constant volume, would exert no pressure. This temperature (–273.15°C or –459.67°F) is theoretically the coldest temperature possible and is the 0° point on the absolute temperature scales.

Accuracy

The conformity of an indicated value to the true value, usually measured in terms of Inaccuracy, but expressed as Accuracy.

Actual vapor pressure

The partial vapor pressure exerted by the water vapor present in a parcel. Water in a gaseous state (i.e. water vapor) exerts a pressure just like the atmospheric air.

Ambient conditions

The conditions of temperature, pressure, humidity, etc., existing in the medium that surrounds a device. Ambient temperature refers to the temperature of the atmosphere under scrutiny.

Amplifier

A device whose output is an enlarged reproduction of the essential features of an input and which draws power from some external source.

Analog signal

A continuous signal such as voltage, pressure, or current that is mathematically proportional to the measured variable.

Atmospheric pressure

The pressure exerted on a body by the atmosphere, equal at sea level to about 14.7 pounds per square inch.

Automatic control

The process of using the differences between the actual value and desired vaiue of a variable to take corrective action without human intervention.

Automatic reset:

See "Integral"

Auxiliary

A device other than the controller which monitors, signal conditions or computes.

Batch process

A process which operates semi-continuously, processing raw material into finished product in a series of discrete quantities.

Bellows

A pressure-sensing element consisting of a convoluted metal cylinder closed at one end. Pressure difference between the outside and inside of the bellows causes it to expand or contract along its axis.

Bimetallic element

A device composed of two or more layers of metallic alloys having different coefficients of thermal expansion, and which will warp or bend as its temperature is changed.

Blackbody

The perfect absorber of all radiant energy striking it. It reflects none.

Bourdon tube

A pressure-sensing element consisting of a curved tube having a flattened elliptical cross-section closed at one end. A positive pressure difference between the inside and outside of the tube tends to straighten it.

British thermal unit

The amount of heat required to raise the temperature of one pound of water one degree Fahrenheit. It is abbreviated BTU.

Capacitance

The change in energy or material required to make a unit change in a measured variable, such as BTU per degree of temperature rise, or cubic feet of contents per foot of increase in level.

Capacity

Maximum quantity of energy or material which can be stored within the confines of a stated piece of equipment, such as volume of liquid a tank will hold when full. Different from "Capacitance".

Cascade control system

A control system where the output of one controller is used to adjust the setpoint of a second controller, and the second controller's output actually adjusts the control element.

Celsius scale

The SI temperature scale, an which the freezing point of water is 0° and the boiling point is 100°.

Cold junction

The point where the wires of a thermocouple connect to the measuring instrument. Also called the reference junction.

Condensation

The phase change of a gas to a liquid. In the atmosphere, the change of water vapors to liquid water.

Compensation

Provision of a supplemental device to counteract known sources of error.

Continuous process

A process in which raw material is treated by flowing continuously through a series of operations.

Control action

The kind of correction the controller makes for a deviation — proportional action, reset action, rate action. See also "Control Mode."

Control agent

The energy or material which is manipulated to hold the controlled medium at its desired value. In heating water with steam, the steam is the control agent. See 'Manipulated Variable".

Control mode

The way a controller acts to produce a control action.

Control valve

A final control element, through which a fluid passes, and which adjusts the size of the flow passage to modify the rate of flow of the fluid as directed by a signal from a controller.

Damping

The progressive reduction or suppression of oscillation in a device or system.

Dead band

The range through which the input can be varied without a change in output.

Dead time

A period of delay between two related actions such as the beginning of a change in an input signal and the beginning of a related change in output. Also called transportation lag.

Derivative control

A type of control in which the controller output is proportional to the rate of change of the error. Commonly referred to as Rate.

Desiccant

A moisture absorbing material used to create an atmosphere free of moisture (provided with Honeywell's calibration kits).

Deviation

The difference between the setpoint and the actual value of the measured variable, usually in percent of full-scale span of the variable. It is negative when the measured value is below the setpoint. See also "Error".

Dewpoint

The temperature to which a gas must be cooled to observe liquid water condensation, or dew. The dewpoint temperature assumes there is no change in air pressure or moisture content of the air.

Dewpoint depression

The mathematical difference between dry bulb and dew point (DB - DP).

Differential pressure

The difference in pressure between two pressure sources, measured relative to one another.

Digital signal

A signal In the form of digits which are a definite set of characters; discrete data as contrasted to continuous analog data.

Direct digital control

Control performed by a digital device that establishes the signal to the final controlling element.

Disturbance

A change in a condition outside the loop which affects the control signal.

Drift

An undesired change in the input-output relationship over a period of time.

Dry bulb

The actual temperature of the gaseous sample being analyzed.

Dynamic analysis

Study of control systern performance at time of disturbance in the controlled variable or in conditions that affect that variable.

Elevated zero range

A range in which the zero of measured variable is greater than the !ower range value.

Emissitivity

The rate at which a substance will radiate thermal energy.

Enthalpy

The measure of the energy content per unit mass. The enthalpy of a gas mixture equals the sum of the individual partial enthalpies of the components, in our case, dry air and water vapor.

Error

The difference between the actual value of the process variable and the desired value of the process variable. See also Deviation.

Evaporation

The phase change of liquid water into water vapor.

Fahrenheit scale

A temperature scale on which the freezing point of water is 32° and the boiling point is 212°F.

Feedback

Part of a closed loop system that provides information about a given condition for comparison with the desired condition.

Feedback control system

A control loop in which the measured variable is fed back and compared with a desired value, and the difference is used as the input to the controller.

Feedforward control

Control in which information concerning one or more conditions that can disturb the controlled variable is converted, outside of any feedback loop, into corrective action to minimize deviations of the controlled variable.

Final control element

Element of a control loop which directly changes the value of the manipulated variable.

First-order lag

A system whose dynamic behavior is described by a first order linear differential equation. Physically, a system with only one place to store energy.

Float

A level sensor for level management.

Flow nozzle

A primary element for flow measurement. A restriction with a bell shaped entrance for the flow stream.

Flow rate

The weight or volume of flow per unit of time.

Fouling

Refers to the contaminating of a sensor.

Freezing

The phase change of liquid water to ice.

Frost point

If measurements are made below the freezing point of water, that is if the indicated dew point is below the freezing point of water, then the equilibrium occurs at the vapor pressure of ice (not water), which is less than that of water. That is, the frost point is a bit higher than dew point.

Gage

A device or instrument containing the primary measuring elements applied to the point of measurement.

Gage pressure

The pressure of a liquid or gas measured relative to the ambient atmospheric pressure.

Gain

The ratio of change of output of part or all of a control system to its change in input.

Head

Pressure resulting from gravitational forces on liquids. Measured in terms of the depth below a free surface of the liquid which is the reference zero head.

Hot junction

The joined ends of a thermocouple. It is also called the measuring junction.

Humidity

The presence of water vapor in air or other carrier gas.

Humidity ratio

The mass of water vapor in a parcel divided by the mass of the dry air in the parcel (not including water vapor). Also referred to as mixing or mass ratio.

Hydrostatic pressure

The pressure at the bottom of a column of liquid caused by the weight of the liquid in the column.

Hysteresis

The maximum difference for the same input between upscale and downscale output values during a full range traverse in each direction.

Inclined tube manometer

A manometer with one arm at an angle, permitting the scale on that arm to be expanded for more precise readings of low pressure.

Instrument

Used broadly to connote a device incorporating measuring, indicating, recording, controlling, and/or operating abilities.

Integral action limiter

A device which limits the value of the output signal due to integral control action to a predetermined value.

Integral control

A type of control in which the controller output changes at a rate proportional to the size of the error. Commonly referred to as Reset.

Integral time

In reset action of a controller, the reciprocal of repeats per minute.

Integrator

A device which continually totalizes or adds up the value of a quantity over a given time period.

Intrinsically safe equipment and wiring

Equipment and wiring which are incapable of releasing sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of a specific hazardous atmospheric mixture in its most easily ignited concentration.

Isolated

Utterly cut-off from; refers to that condition where a conductor, circuit, or device is not only insulated from another (or others), but the two are mutually unable to engender current, emf, or magnetic flux in each other. As commonly used, insulation is associated predominantly with dc. whereas isolated implies additionally a bulwark against ac fields.

Kelvin temperature scale

A thermodynamic absolute Centigrade temperature scale, having as its zero the absolute zero of temperature (–273.15°C).

Lag

Refers to any delay from an instantaneous response to an input signal. Lag in a system is due to resistances and capacitances in the system.

Linear

The relationship between two quantities in which a change in one is proportional to the change in the other.

Linearity

The degree to which the calibration curve of a device matches a straight line. The linearity error is generally the greatest departure from the best straight line that can be drawn through the measured cafibration points.

Load

The conditions which determine the amount of energy or material which must be supplied to a process to maintain the variable at the desired level. A change in load results in use of a different amount of material or energy to produce the same value of the variable.

Magnetic field

The portion of space near a magnetic body or a current carrying body in which the forces due to the body or current can be detected.

Manipulated variable

That quantity or condition of the control agent which is varied by the automatic controller so as to affect the value of the measured (controlled) variable. In heating water with steam, the flow of steam is the manipulated variable.

Manual controller

A controller having all its basic functions performed by devices that are operated by hand.

Measured variable

See "Process Variable".

Measuring junction

The junction of the two wires of a thermocouple which is exposed to the temperature to be measured.

NIST

National Institute of Standards and Testing

Noise

Unwanted or extraneous disturbances in a variable which conveys no useful information.

Null-balance

A condition of zero difference between opposing quantities.

Offset

A steady-state deviation of the controlled variable from the setpoint, usually caused by a disturbance or load change in a system employing a proportional controller.

On-off control action

A special type two position control in which the manipulated variable has only one of two possible values: on or off.

Orifice plate

A thin, circular metal plate with an opening in it. It Is used for measuring flow rate.

Overshoot

The amount by which a changing process variable exceeds the desired value following a step change in input.

Partial pressure

The total pressure of a gas mixture is the sum of the partial pressures of the constituent gases, including moisture ($P = p_w + p_i$). The volume ratios of constituent gases are equal to the ratios of their partial pressures ($v_i/V = p_i/P$).

Peltier effect

Depending on the direction of current flow, heat is either absorbed or liberated at the junction of two dissimilar metal wires through which a current is passing.

Positive displacement flowmeter

A flowmeter which measures total flow by countinq known volumes.

Potentiometer

Measures by comparing the difference between known and unknown electrical potentials. In order to measure process control variables by means of a potentiometer, these variables, such as temperature, pressure, flow, and liquid level must first be translated into electrical signals that vary proportionally with changes in the variable.

Pressure

Force per unit area. Measured In pounds per square inch (psi), or by the height of a column of water or mercury that it will support (in feet, inches, centimeters or millimeters).

Pressure capsule

Two diaphragms, metallic or non-metallic, welded or otherwise joined together to form a sealed capsule which will deflect when subjected to pressure.

Pressure transducer

An instrument which converts a static or dynamic pressure input into a proportional electrical output.

Primary element

The portion of the measuring means which first either utilizes or transforms energy from the controlled medium to produce an effect in response to change in the value of the controlled variable. The effect produced by the primary element may be a change of pressure, force, position, electrical potential, or resistance, etc.

Process

The application of energy to raw materials to derive a more valuable end product.

Process reaction curve

A record of the reaction of a control system to a step change.

Process variable

The parameter whose measurement and control is indicative of the outcome of the product.

Program control

A control system in which the setpoint is automatically varied during definite time intervals in order to make the process variable vary according to some prescribed manner.

Proportional control

A type of control in which the control action is proportional to the size of the error.

Proportional band

The percent of instrument scale span through which the process variable must change in order to cause the output of a controller to change from minimum to maximum or maximum to minimum.

psia

Pounds per square inch absolute.

psig

Pounds per square Inch gage.

Psychrometry

The study of water vapor concentration in air as a function of temperature and pressure.

Purging

Elimination of an undesirable gas or material from an enc!osure by displacing the undesirable material with an acceptable gas or material.

Pyrometer

An instrument for measuring temperature. Usually refers to temperature measuring irstruments; used to measure flame temperature, temperatures above 1000°F.

Radiation

Emission and propagation of energy from a source.

Radiation pyrometer

A pyrometer in which the radiant power from the object or source to be measured is used in the measurement of its temperature. The radiant power within wide or narrow wavelength bands filling a definite solid angle impinges upon a suitable detector. The detector is usually a thermocouple or thermopile, a bolometer responsive to the heating affect of the radiant power, or a photo-sensitive device connected to a sensitive electrical instrument.

Range

A statement describing the upper and lower limits of measurement.

Rankine scale

Absolute Fahrenheit temperature scale, with the freezing point of water 491.69° and the boiling point 671.69°.

Rate action

See "Derivative Control".

Rate amplitude

The ratio of the maximum output of proportional-plus-rate action to the steady output of proportional action alone, after a step increase in deviation, both outputs being measured from the same baseline — the controller output before the step.

Rate time

The difference in time taken by proportional action alone and by proportional-plus-rate to produce the same controller-output for a ramp change in deviation.

Rate time constant

The time it takes 63.2% of the rate action to disappear after the deviation stops changing. Its value is Rate Time divided by Rate Amplitude.

Ratio control system

A control system that maintains two or more variables at a predetermined ratio by making the value of one variable (usually uncontrolled) adjust the controller setpoint for another variable.

Reference junction

The junction of a thermocouple whic is at a known or reference temperature.

Relative humidity

The amount of water vapor actually in the air divided by the amount of water vapor the air can hold.

Repeats per minute

The reset adjustment in "repeats per minute" — the number of times per minute that the proportional action is repeated by reset. It is the reciprocal of the integral time of the reset action.

Reproducibillity

The closeness of agreement among repeated measurements of the output for the same value of input made under the same operating conditions over a period of time, approaching from both directions.

Reset action

See Integral Control.

Resistance

Opposition to flow. It is a measure of the change in potential (energy level) caused by a change in flow of energy or material.

Resistance thermometer bulb (RTB)

See Resistance thermal device.

Resistance thermal device (RTD)

A temperature-sensitive unit whose electrical resistance changes with temperature, its supporting structure, and means for attaching conductors.

Resolution

The least interval between two adjacent discrete details which can be distinguished one from the other.

Response time

The amount of time it takes a sensor to signal a change in moisture content.

Reynolds number

The product of the density of the fluid, the flow velocity, and the internal diameter of the pipe, divided by the viscosity of the fluid.

RTD

Resistance Temperature Detector

Saturation

The condition under which the amount of water vapor in a air is the maximum possible at the existing temperature and pressure. Condensation or sublimation will begin if the temperature falls or water vapor is added to the air.

Saturation vapor pressure

The maximum partial pressure that water vapor molecules would exert if the air were saturated with vapor at a given temperature. Saturation vapor pressure is directly proportional to the temperature.

Second-order lag

A system whose dynamic behavior is described by a second order or greater differential equation. Physically, a system with more than one place to store energy.

Setpoint

The desired value of the variable which is being measured and controlled; the setting of the control index.

Signal transducer

A transducer that converts one standardized transmission signal to another.

Silicon controlled rectifier (SCR)

A solid state controlled rectifier consisting of an anode, a cathode, and the gate.

Slurry

A liquid containing suspended particulate matter.

Span

Is the distance between the upper and lower limits of measurement.

Specific humidity

The mass of water vapor in a parcel divided by the total mass of the air in the parcel (including water vapor).

Square root extraction

The process whereby the square root of a measurement is derived.

Suppressed zero range

A range in which the zero value of the measured variable is less than the lower range value. Zero does not appear on scale.

Temperature

The relative hotness or coldness of a body as determined by its ability to transfer heat to its surroundings. There is a temperature difference between two bodies if when they are placed in thermal contact heat is transferred from one body to the other. The body that loses heat is said to be at the higher temperature.

Thermistor

An electrical resistor whose resistance varies sharply with temperature.

Thermocouple

A pair of dissimilar conductors so joined that an electromotive force is developed by the thermoelectric effects when the two junctions are at different temperatures.

Thermocouple well

Device used for protecting thermocouples by eliminating direct contact of the thermocouple with possibly carrosive substances being measured.

Thermometer

A device for measuring temperature.

Thermopile

A group of thermocouples connected in series. This term is usually applied to a device measuring radiant energy or used as a source of electric energy.

Thomson effect

If there is a temperature gradient along a current carrying conductor, heat will be liberated or absorbed at any point where current and heat flow in the same direction, depending on the type of metal used as a conductor.

Time constant

Time required for the output of a First-Order Lag device to reach 63.2% of its final value for a step change in input. The output will reach 95 % in 3 time constants, 98 % in 4, and over 99 % in 5.

Time proportioning control

Control in which the output signal consists of periodic pulses whose duration is varied according to the actuating error signal.

Transducer

A transducer is an element or device which receives information in the form of one physical quantity and converts it to information in the form of the same or other physical quantity. Note: This is a general definition and applies to specific classes of devices such as primary element, signal transducer and transmitter.

Transfer function

An expression stating the relation between an input signal and a corresponding output signal, the relation involving both the size and the timing of the signal. (Sometimes defined as the ratio of Laplace Transforms of output and input signals.)

Transfer lag

Any lag except dead time.

Transmitter

A transducer which responds to a measured variable by means of a sensing element, and converts it to a standardized transmission signal which is a function only of the measured variable.

Transportation lag

See "Dead Time".

Ultimate period

The cycle time for deviation cycles shown when a proportional controller is adjusted for the ultimate proportional band. Also called the ultimate cycle. See also Ultimate Proportional Band.

Ultimate proportional band

The proportional band that produces a continuously cycling deviation of constant peak magnitude when the control action is proportional only and a small disturbance occurs.

V tube

A form of manometer used for pressure measurement.

Vana contracta

The smallest cross section of a fluid jet which issues from a freely discharging aperture or is formed within the body of a pipe owing to the presence of a constriction.

Venturi tube

A short tube of varying cross section is called a Venturi tube. The flow through the venturi tube causes a pressure drop in the smallest section, the amount of the drop being a function of the velocity of flow.

Volume ratio

The ratio of water vapor volume to dry air volume. Also referred to as mixing ratio by volume, or ppmv.

Weir

An obstruction placed across an open liquid stream to raise the level of the liquids. It is used for flow measurement.

Wet bulb temperature

The lowest temperature that can be obtained by evaporating water into the air at constant pressure is called wet bulb temperature. The name comes from the technique of putting a wet cloth over the bulb of a mercury thermometer and then blowing air over the cloth until the water evaporates. Since evaporation takes up heat, the thermometer will cool to a lower temperature than a thermometer with a dry bulb at the same time and place. Wet bulb temperatures can be used along with the dry bulb temperature to calculate dew point or relative humidity.

Index

H

I

L

M