

INSTRUMENTATION

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Alexandria Industrial Control



INSTRUMENTATION

Chapter 1: Basics & Introduction

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INDUSTRIAL CONTROL

1-1 Introduction to Industrial Instrumentation

Instrumentation is the science of automated measurement and control. Applications of this science abound in modern research, industry, and everyday living. From automobile engine control systems to home thermostats to aircraft autopilots to the manufacture of pharmaceutical drugs, automation surrounds us. This chapter explains some of the fundamental principles of industrial instrumentation.

The first step, naturally, is measurement. If we can't measure something, it is really pointless to try to control it. This "something" usually takes one of the following forms in industry:

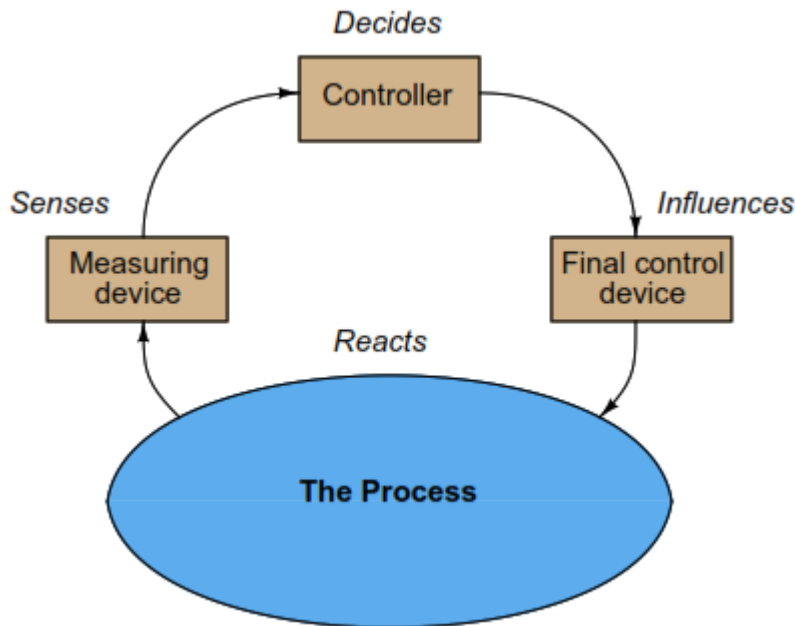
- Fluid pressure
- Fluid flow rate
- The temperature of an object
- Fluid volume stored in a vessel
- Chemical concentration
- Machine position, motion, or acceleration
- Physical dimension(s) of an object
- Count (inventory) of objects
- Electrical voltage, current, or resistance

Once we measure the quantity we are interested in, we usually transmit a signal representing this quantity to an indicating or computing device where either human or automated action then takes place. If the controlling action is automated, the computer sends a signal to a final controlling device which then influences the quantity being measured.

This final control device usually takes one of the following forms:

- Control valve (for throttling the flow rate of a fluid)
- Electric motor
- Electric heater

Both the measurement device and the final control device connect to some physical system which we call the process. To show this as a general block diagram



The common home thermostat is an example of a measurement and control system, with the home's internal air temperature being the "process" under control. In this example, the thermostat usually serves two functions: sensing and control, while the home's heater adds heat to the home to increase temperature, and/or the home's air conditioner extracts heat from the home to decrease temperature. The job of this control system is to maintain air temperature at some comfortable level, with the heater or air conditioner taking action to correct temperature if it strays too far from the desired value (called the setpoint).

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Industrial measurement and control systems have their own unique terms and standards, which is the primary focus of this lesson. Here are some common instrumentation terms and their definitions:

Process: The physical system we are attempting to control or measure. Examples: water filtration system, molten metal casting system, steam boiler, oil refinery unit, power generation unit.

Process Variable, or PV: The specific quantity we are measuring in a process. Examples: pressure, level, temperature, flow, electrical conductivity, pH, position, speed, vibration.

Setpoint, or SP: The value at which we desire the process variable to be maintained at. In other words, the “target” value of the process variable.

Primary Sensing Element, or PSE: A device that directly senses the process variable and translates that sensed quantity into an analog representation (electrical voltage, current, resistance; mechanical force, motion, etc.). Examples: thermocouple, thermistor, bourdon tube, microphone, potentiometer, electrochemical cell, accelerometer.

Transducer: A device that converts one standardized instrumentation signal into another standardized instrumentation signal, and/or performs some sort of processing on that signal. Often referred to as a converter and sometimes as a “relay.” Examples: I/P converter (converts 4-20 mA electric signal into 3-15 PSI pneumatic signal), P/I converter (converts 3-15 PSI pneumatic signal into 4-20 mA electric signal), square-root extractor (calculates the square root of the input signal).

Note: in general science parlance, a “transducer” is any device that converts one form of energy into another, such as a microphone or a thermocouple. In industrial instrumentation, however, we generally use “primary sensing element” to describe this concept and reserve the word “transducer” to specifically refer to a conversion device for standardized instrumentation signals.

Transmitter: A device that translates the signal produced by a primary sensing element (PSE) into a standardized instrumentation signal such as 3-15 PSI air pressure, 4-20 mA DC electric current, Fieldbus digital signal packet, etc., which may then be conveyed to an indicating device, a controlling device, or both.

Lower- and Upper-range values, abbreviated LRV and URV, respectively: the values of process measurement deemed to be 0% and 100% of a transmitter’s calibrated range. For example, if a temperature transmitter is calibrated to measure a range of temperature starting at 300 degrees Celsius and ending at 500 degrees Celsius, 300 degrees would be the LRV and 500 degrees would be the URV.

Zero and Span: alternative descriptions to LRV and URV for the 0% and 100% points of an instrument's calibrated range. "Zero" refers to the beginning-point of an instrument's range (equivalent to LRV), while "span" refers to the width of its range (URV – LRV). For example, if a temperature transmitter is calibrated to measure a range of temperature starting at 300 degrees Celsius and ending at 500 degrees Celsius, its zero would be 300 degrees and its span would be 200 degrees.

Controller: A device that receives a process variable (PV) signal from a primary sensing element (PSE) or transmitter, compares that signal to the desired value for that process variable (called the setpoint), and calculates an appropriate output signal value to be sent to a final control element (FCE) such as an electric motor or control valve.

Final Control Element, or FCE: A device that receives the signal from a controller to directly influence the process. Examples: variable-speed electric motor, control valve, electric heater.

Manipulated Variable, or MV: Another term to describe the output signal generated by a controller. This is the signal commanding ("manipulating") the final control element to influence the process.

1-2 Instrumentation Signal

There are three types of communication between instrument and controller:

- Discrete
- Analog
- Communication Protocol

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Chapter 2: Discrete process measurement

2- Discrete process measurement

The word “discrete” means individual or distinct. In engineering, a “discrete” variable or measurement refers to a true-or-false condition. Thus, a discrete sensor is one that is only able to indicate whether the measured variable is above or below a specified setpoint.

Discrete sensors typically take the form of switches, built to “trip” when the measured quantity either exceeds or falls below a specified value. These devices are less sophisticated than so-called continuous sensors capable of reporting an analog value, but they are quite useful in industry.

Many different types of discrete sensors exist, detecting variables such as position, fluid pressure, material level, temperature, and fluid flow rate. The output of a discrete sensor is typically electrical in nature, whether it be an active voltage signal or just resistive continuity between two terminals on the device.

2-1 “Normal” status of a switch

Perhaps the most confusing aspect of discrete sensors is the definition of a sensor’s normal status. Electrical switch contacts are typically classified as either normally-open or normally-closed, referring to the open or closed status of the contacts under “normal” conditions. But what exactly defines “normal” for a switch? The answer is not complex, but it is often misunderstood.

The “normal” status for a switch is the status its electrical contacts are in under a condition of minimum physical stimulus. For a momentary-contact pushbutton switch, this would be the status of the switch contact when it is not being pressed. The “normal” status of any switch is the way it is drawn in an electrical schematic. For instance, the following diagram shows a normally-open pushbutton switch controlling a lamp on a 120 volt AC circuit (the “hot” and “neutral” poles of the AC power source labeled L1 and L2, respectively):



We can tell this switch is a normally-open (NO) switch because it is drawn in an open position. The lamp will energize only if someone presses the switch, holding its normally-open contacts in the “closed” position. Normally-open switch contacts are sometimes referred to in the electrical industry as form-A contacts.

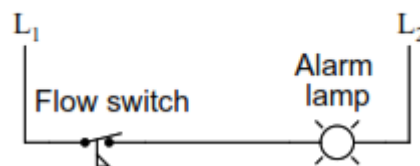
If we had used a normally-closed pushbutton switch instead, the behavior would be exactly opposite. The lamp would energize if the switch was left alone, but it would turn off if anyone pressed the switch. Normally-closed switch contacts are sometimes referred to in the electrical industry as form-B contacts. :



This seems rather simple, don't you think? What could possibly be confusing about the “normal” status of a switch? The confusion becomes evident, though, when you consider the case of a different kind of discrete sensor such as a flow switch.

A flow switch is built to detect fluid flow through a pipe. In a schematic diagram, the switch symbol appears to be a toggle switch with a “flag” hanging below. The schematic diagram, of course, only shows the circuitry and not the pipe where the switch is physically mounted:

A low coolant flow alarm circuit



This particular flow switch is used to trigger an alarm light if coolant flow through the pipe ever falls to a dangerously low level, and the contacts are normally-closed as evidenced by the closed status in the diagram. Here is where things get confusing: even though this switch is designated as “normally-closed,” it will spend most of its lifetime being held in the open status by the presence of adequate coolant flow through the pipe. Only when the flow through the pipe slows down enough will this switch return to its “normal” status (remember, the condition of minimum stimulus?) and conduct electrical power to the lamp. In other words, the “normal” status

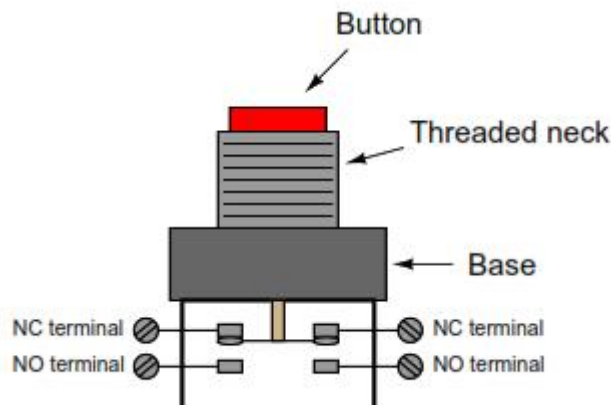
of this switch (closed) is actually an abnormal status for the process it is sensing (low flow)!

Here is a listing of “normal” definitions for various discrete sensor types:

- Hand switch: no one pressing the switch
- Limit switch: target not contacting the switch
- Proximity switch: target far away
- Pressure switch: low pressure (or even a vacuum)
- Level switch: low level (empty)
- Temperature switch: low temperature (cold)
- Flow switch: low flow rate (fluid stopped)

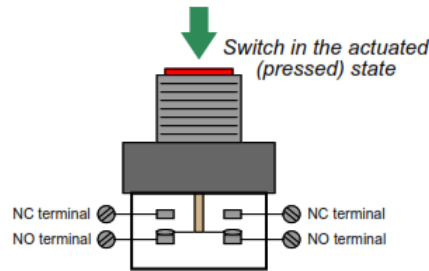
2-3 Hand switches

A hand switch is exactly what the name implies: an electrical switch actuated by a person’s hand motion. These may take the form of toggle, pushbutton, rotary, pull-chain, etc. A common form of industrial pushbutton switch looks something like this:



The threaded neck inserts through a hole cut into a metal or plastic panel, with a matching nut to hold it in place. Thus, the button faces the human operator(s) while the switch contacts reside on the other side of the panel.

When pressed, the downward motion of the actuator breaks the electrical bridge between the two NC contacts, forming a new bridge between the NO contacts:

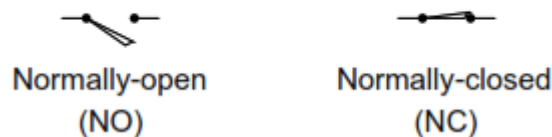


The schematic diagram symbol for this type of switch looks much like the real thing, with the normally-closed contact set on top and the normally-open contact set below:



2-4 Limit switches

Limit switch symbols

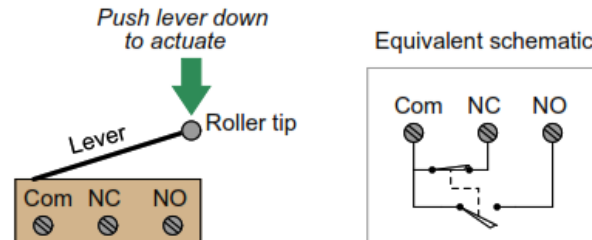


A limit switch detects the physical motion of an object by direct contact with that object. An example of a limit switch is the switch detecting the open position of an automobile door, automatically energizing the cabin light when the door opens.

Recall from page 368 that the “normal” status of a switch is the condition of minimum stimulus. A limit switch will be in its “normal” status when it is not in contact with anything (i.e. nothing touching the switch actuator mechanism).

Limit switches find many uses in industry, particular in robotic control and CNC (Computer Numerical Control) machine tool systems. In many motion-control systems, the moving elements have “home” positions where the computer assigns a position value of zero. For example, the axis controls on a CNC machine tool such as a lathe or mill all return to their “home” positions upon start-up, so the computer can know with confidence the starting locations of each piece. These home positions are detected by means of limit switches. The computer commands each servo motor to travel fully in one direction until a limit switch on each axis trips. The position counter for each axis resets to zero as soon as the respective limit switch detects that the home position has been reached.

A typical limit switch design uses a roller-tipped lever to make contact with the moving part. Screw terminals on the switch body provide connection points with the NC and NO contacts inside the switch. Most limit switches of this design share a “common” terminal between the NC and NO



This switch contact arrangement is sometimes referred to as a *form-C* contact set, since it incorporates both a form-A contact (normally-open) as well as a form-B contact (normally-closed).

2-5 Proximity switches

A proximity switch is one detecting the proximity (closeness) of some object. By definition, these switches are non-contact sensors, using magnetic, electric, or optical means to sense the proximity of objects.

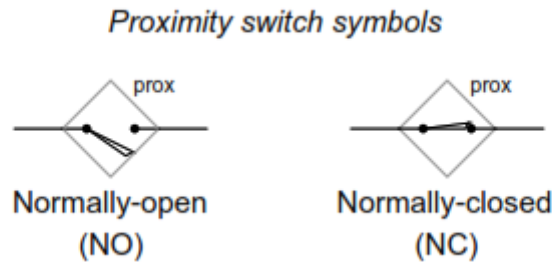
Being non-contact in nature, proximity switches are often used instead of direct-contact limit switches for the same purpose of detecting the position of a machine part, with the advantage of never wearing out over time due to repeated physical contact. However, the greater complexity (and cost) of a proximity switch over a mechanical limit switch relegates their use to applications where lack of physical contact yields tangible benefits.

There are three types of proximity sensors:

- Inductive proximity sensors are used in place of limit switches for non-contact sensing of metallic objects.
- Capacitive proximity switches can also detect non-metallic objects.
- Magnetic Both inductive and capacitive sensors are limit switches with ranges up to 100mm.
- Optical Sensor

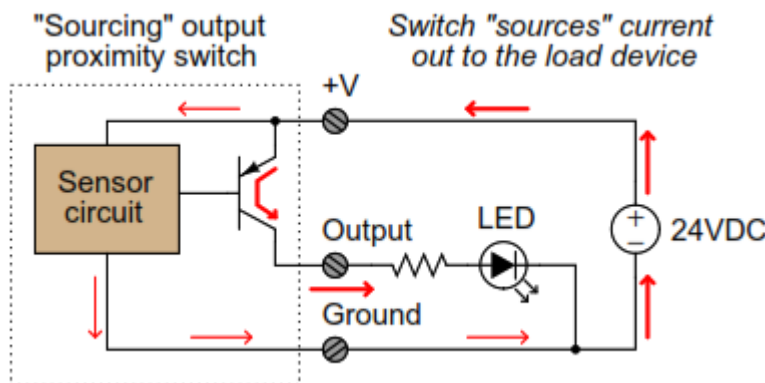
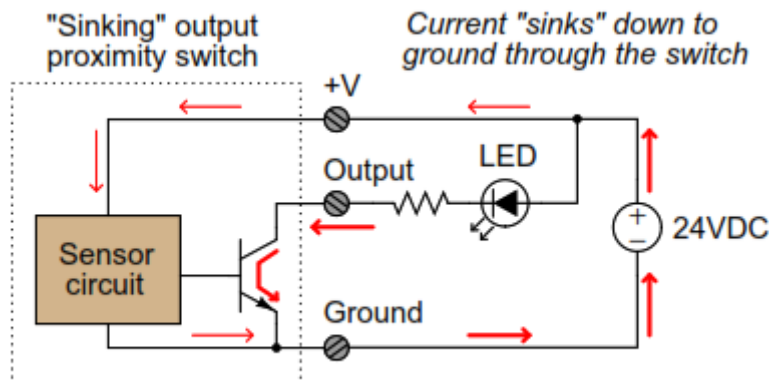
Most proximity switches are active in design. That is, they incorporate a powered electronic circuit to sense the proximity of an object. Inductive proximity switches sense the presence of metallic objects through the use of a high-frequency magnetic field. Capacitive proximity switches sense the presence of non-metallic objects through the use of a high-frequency electric field. Optical switches detect the interruption of a light beam by an object.

The schematic diagram symbol for a proximity switch with mechanical contacts is the same as for a mechanical limit switch, except the switch symbol is enclosed by a diamond shape, indicating a powered (active) device:

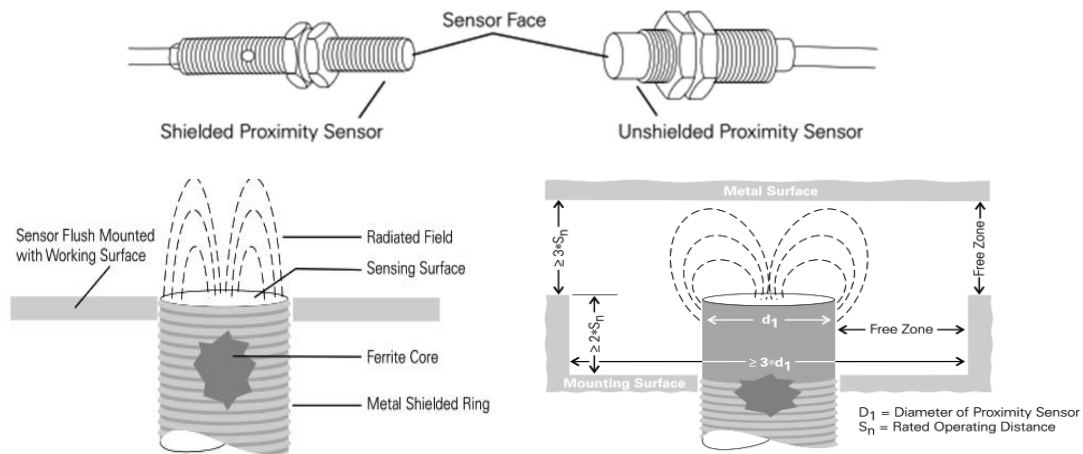


Many proximity switches, though, do not provide “dry contact” outputs. Instead, their output elements are transistors configured either to source current or sink current. The terms “sourcing” and “sinking” are best understood by visualizing electric current in the direction of conventional flow rather than electron flow.

The following schematic diagrams contrast the two modes of switch operation, using red arrows to show the direction of current (conventional flow notation). In both examples, the load being driven by each proximity switch is a light-emitting diode (LED):



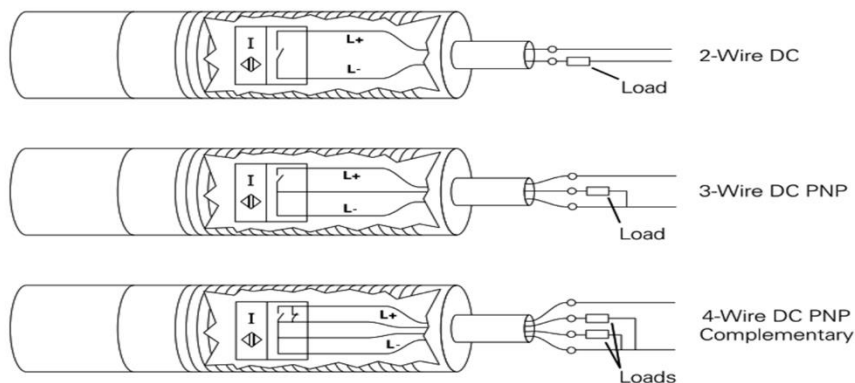
Proximity sensors contain coils that are wound in ferrite cores. They can be shielded or unshielded. Unshielded sensors usually have a greater sensing distance than shielded sensors.



2-5-1 Proximity Sensor Wiring

Operating Voltages

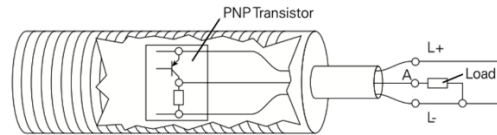
Inductive proximity sensors include AC, DC, and AC/ DC (universal voltage) models. The basic operating voltage ranges are from 10 to 30 VDC, 15 to 34 VDC, 10 to 65 VDC, 20 to 320 VDC, and 20 to 265 VAC.



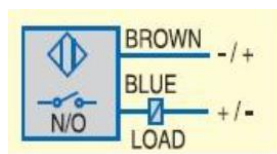
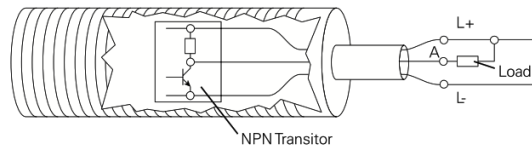
2-5-2 PNP - NPN

Three-wire, DC proximity sensor can either be PNP (sourcing) or NPN (sinking). This refers to the type of transistor used in the output switching of the transistor

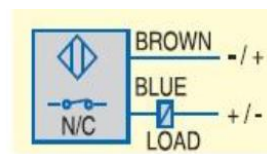
PNP sensor. The load is connected between the output (A) and the negative side of the power supply (L-). A PNP transistor switches the load to the positive side of the power supply (L+). When the transistor switches on



NPN sensor. The load is connected between the output (A) and the positive side of the power supply (L+). An NPN transistor switches the load to the negative side of the power supply (L-)



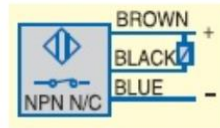
NO Case



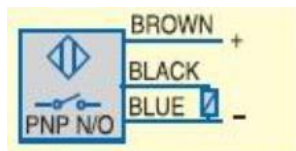
NC Case



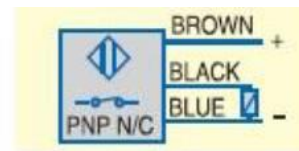
NO Case



NC Case



NO Case



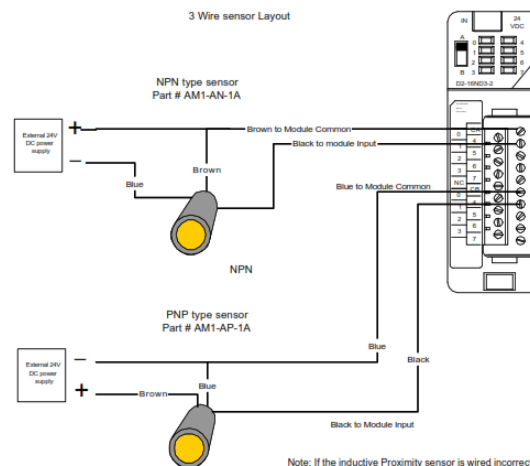
NC Case



NPN Case



PNP Case



Note: If the inductive Proximity sensor is wired incorrectly:
The sensor LED will stay ON and go OFF when activated.
(Normally Open sensor will work Normally Open)

2-5-3 Photoelectric Sensors

A photoelectric sensor is a semiconductor component that reacts to light or emits light. The light may be either in visible range or the invisible infrared range.

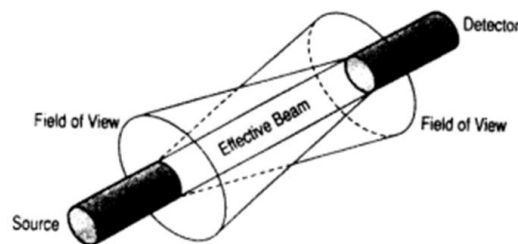
Infrared sensors may be active or passive. The active sensors send out an infrared beam and respond to the reflection of the beam against a target.

The distinct advantage of photoelectric sensors over inductive or capacitive sensors is their increased range.

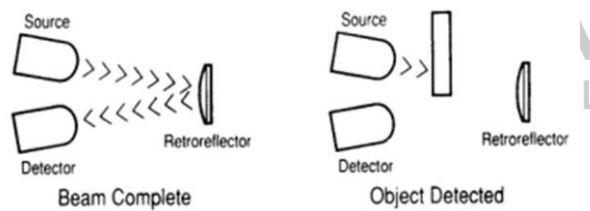
Dirty oil mist and other environmental factors will hinder operation of photoelectric sensors during manufacturing process.

There are three modes of detection used by photoelectric sensors:

- Through-beam detection method



- Reflex/retro-reflective detection method



- Proximity/Diffuse reflective detection method



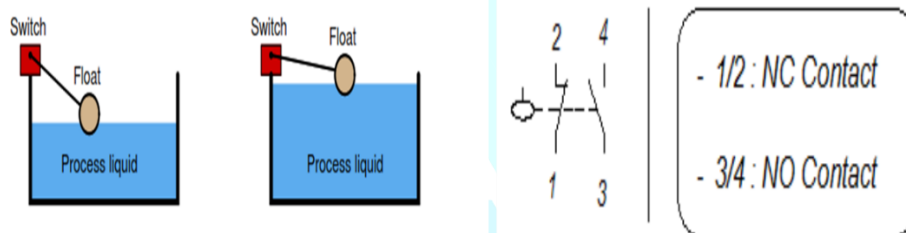
2-6 Pressure switches

A pressure switch is one detecting the presence of fluid pressure. Pressure switches often use diaphragms or bellows as the pressure-sensing element, the motion of which actuates one or more switch contacts.



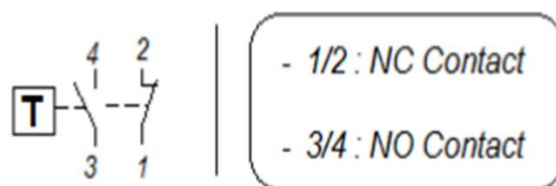
2-7 Level Switch

Level switch is one detecting the level of liquid or solid (granules or powder) in a vessel. Level switches often use floats as the level-sensing element, the motion of which actuates one or more switch contacts.



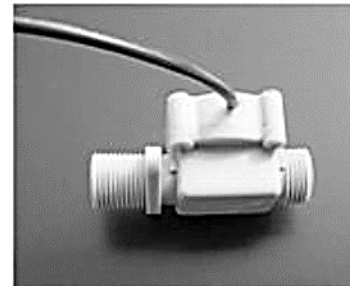
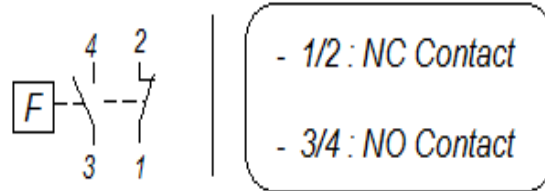
2-8 Temperature switches

A temperature switch is one detecting the temperature of some substance. Temperature switches often use bimetallic strips as the temperature-sensing element, the motion of which actuates one or more switch contacts. An alternative design uses a metal bulb filled with a fluid that expands with temperature, causing the switch mechanism to actuate based on the pressure this fluid exerts against a diaphragm or bellows. This latter temperature switch design is really a pressure switch, whose pressure is a direct function of process temperature by virtue of the physics of the entrapped fluid inside the sensing bulb.



2.9 FLOW SWITCHES

A flow switch is one detecting the flow of some fluid through a pipe.



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Chapter 3: Analog instrumentation

When selecting the sensor, there are a number of factors to keep in mind. Knowing these factors in advance, and the needs of the process, saves a buyer time and money. Before any of these factors can be considered, the intended use of the sensor must be known. Once that is established, several factors should be considered:

Type. Is there a transducer that measures your physical phenomenon?

Process Variables

- ▶ Pressure
- ▶ Level
- ▶ Flow
- ▶ Temperature
- ▶ Analyzer

Range. What are the maximum and minimum values expected to be measured?

Sensitivity. Is the ability to discriminate small changes in the measured quantity sensitive enough?

Accuracy. How close is the sensor to the actual value?

Repeatability. What is the ability of the sensor to reproduce an output given the same input?

Resolution. What is the smallest signal increment that can be detected?

Response Time. How fast (a value of time or frequency) can the sensor react to a stimulus?

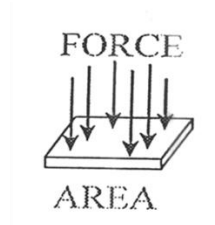
Special Needs. Are there special mounting requirements, hazardous environments, or other special needs?

3-1 PRESSURE MEASUREMENT

What is Pressure?

Pressure is the action of one force against another force. Pressure is force applied to, or distributed over a surface.

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



P = pressure

F = force

A = surface area exposed to the force

Production operations require operating pressures be regulated to specific pressures in order for the system(s) to work properly.

Types of pressure

In order to understand various types of pressure the following will be considered: Pressure Scale reference points, there are two reference points, the zero point of pressure which is assumed to a perfect vacuum, another point is atmospheric pressure which varies with altitude above sea level and with weather conditions.

Absolute pressure scale starts from a zero reference point representing the full vacuum and extends through atmospheric pressure to the highest limit of measurable pressure.

Gauge pressure scale starts zero reference point representing the local atmospheric pressure and extends to a chosen limit applicable to the specific process system.

Vacuum scale starts from the absolute zero reference point and extends to a maximum represented by atmospheric pressure.

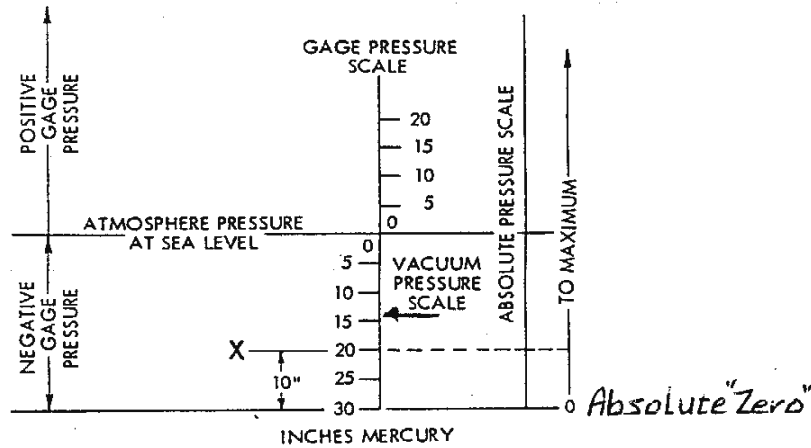
The above can be expressed as following:

Zero of absolute pressure = perfect vacuum

Absolute Pressure = Pressure above Absolute zero

Gauge Pressure = Absolute Pressure – Atmospheric pressure

Vacuum gauge Pressure = Atmospheric Pressure – Fluid Pressure



* The pressure at point X can be expressed as 10 inches of mercury absolute, or as 20 inches of mercury vacuum, or as -20 inches of mercury gage.

Pressure Units:

ADMA OPCO uses a variety of pressure units but the two main systems are the Imperial (British and American) units and the S.I. (System International).

As pressure can be expressed as FORCE divided AREA then the units of pressure can be expressed as the units of force divided by the units of area.

a) Imperial units

In the Imperial system the unit of force is pound force (lbf) and the unit of area is the inch square (in²). It follows that the unit of pressure in the Imperial system is the pound force divided by the inch square (lbf/Sq. in) (pounds per square inch). This is often abbreviated to PSI.

b) S.I. Unit

In the S.I. system the unit of force is the Newton (N) and the unit of area is the meter square (m²). Therefore the unit of force in the S.I. system is the Newton per square meter (N/m²). This is a very small unit of pressure and the S.I. unit that is more commonly used on the plant is bar. One bar is equal to 100000 N/m².

c) Liquid Column

Pressure can also be expressed in terms of liquid column height. The Imperial units are inches water column (in Wc) and the S.I. units are millimeters water column (mm Wc). Imperial units are inches Wc (or Hg) S.I. units are mm Wc (or Hg).

Pressure Conversions

The table below gives a few examples of different pressure:

IMPERIAL		S.I.	
Lbf/in ²	Inch Wc	bar	mm Wc
1	27.73	0.06895	703.1
0.03613	1	2.487x10 ⁻³	25.4
14.504	402.1	1	10.22x10 ³
1.422x10 ⁻³	0.03937	97.98x10 ⁻⁶	1

Conversion factors for pressure (either all gauge or all absolute)Note:

all conversion factors shown in bold type are exact, not approximations.

1 pounds per square inch (PSI) = 2.03602 inches of mercury at 0 o C (in. Hg) = 27.6799 inches of water at 4 o C (in. W.C.) = 6.894757 kilopascals (kPa) = 0.06894757 bar

1 bar = 100 kilopascals (kPa) = 14.504 pounds per square inch (PSI)

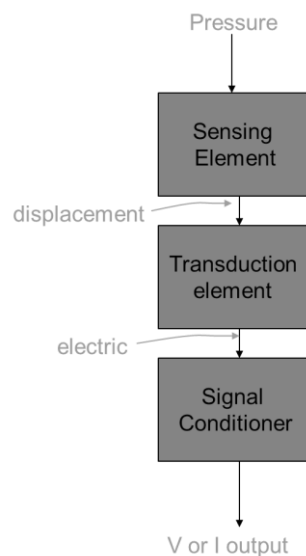
1 meter of water at 4 o C (m W.C.) = 9.80665 kilopascals (kPa)2.4.10

Conversion factors for pressure (absolute pressure units only)Note:

all conversion factors shown in bold type are exact, not approximations.

1 standard atmosphere (Atm) = 14.7 pounds per square inch absolute (PSIA) = 101.325 kilopascals absolute (kPaA) = 1.01325 bar absolute = 760 millimeters of mercury absolute (mmHgA) = 760 torr (torr)

Pressure Sensing



Pressure is sensed by mechanical elements such as plates, shells, and tubes that are designed and constructed to deflect when pressure is applied. This is the basic mechanism converting pressure to physical movement.

Next, this movement must be transduced to obtain an electrical or other output.

Finally, signal conditioning may be needed, depending on the type of sensor and the application.

Sensing Elements

- Bourdon tubes (C-type – Helical - Spiral bourdon)

- C-type bourdon

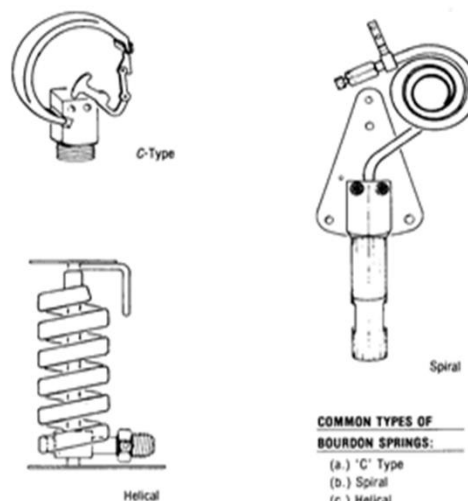
C-type bourdon tubes are used for ranges as low as 0 - 15 psig (0 - 100 kPa) and as high as 0 - 1500 psig (0 - 10,000 kPa). They are simple, accurate, and have good repeatability, but they are bulky and highly subject to damage from over-ranging. Most C-type bourdon tubes will tolerate only minimal overpressure.

- Helical bourdon

Helical bourdon tubes are used for ranges as low as 0 - 200 psig (0 - 1300 kPa) up to 0 - 6000 psig (0 - 40,000 kPa). Heavy-duty helical bourdons can sometimes tolerate as high as ten times the maximum range pressure.

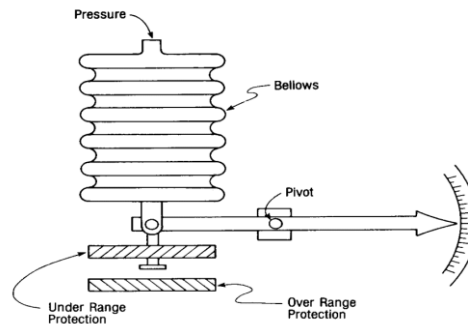
- Spiral bourdon

Spiral bourdon tubes are used for both very low ranges and very high ranges. Very sensitive units are manufactured to measure as low as 0 -10 psig (0 - 65 kPa). Heavy-duty units can measure up to 0 -100,000 psig (0 -700,000 kPa).



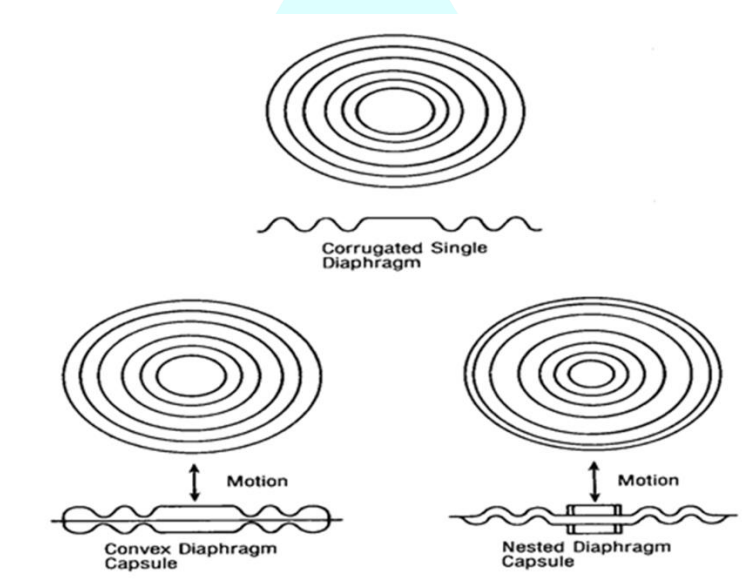
- **Bellows Sensors**

A bellows sensor is an axially flexible, cylindrical enclosure with folded sides. When pressure is applied through an opening, the closed end extends axially



- **Diaphragm Sensors**

A diaphragm is a thin, flexible, flat or corrugated disk, held in place so that it is axially flexible. When pressure is applied to one side of the diaphragm it will deflect.



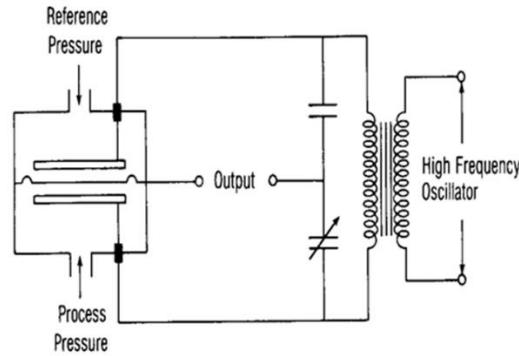
- **Strain-Gauge Sensors**

Strain-gauge pressure sensors are used in most brands of electronic pressure transmitters. When metallic conductors or semiconductors are subjected to mechanical strain, a change in resistance will occur. This resistance is then electrically converted into a 4-20 mA signal proportional to the pressure. Most of the strain elements in current use are semiconductor type.

- **Capacitance Pressure Sensors**

Capacitance pressure sensors are also used in electronic pressure transmitters. These devices operate on the principle that the change in capacitance resulting from the movement of an elastic element is proportional to the pressure applied to the elastic

element. The elastic element usually is a stainless steel diaphragm. Other materials are available if stainless steel is not suitable for the process fluid. As shown in figure the capacitor plates. A high-frequency oscillator is controlled by the sensing element. Changes in pressure deflect the diaphragm and the resultant change in capacitance changes the oscillator frequency. The variation in oscillator frequency is converted to a 4-20 mA signal proportional to the pressure.

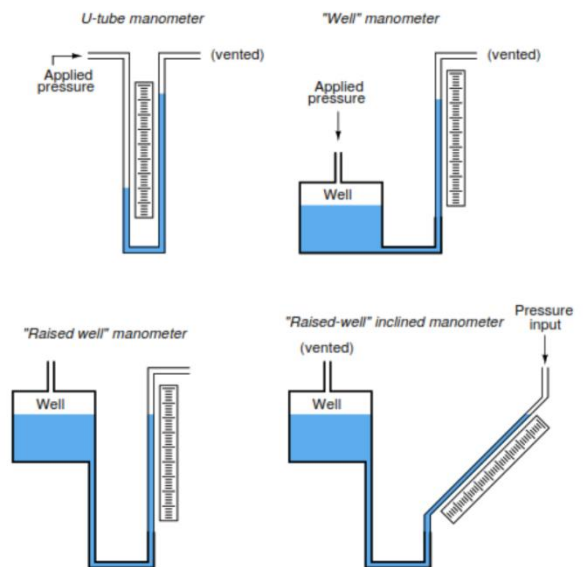


PRESSURE MEASUREMENT DEVICES

- **Manometers**

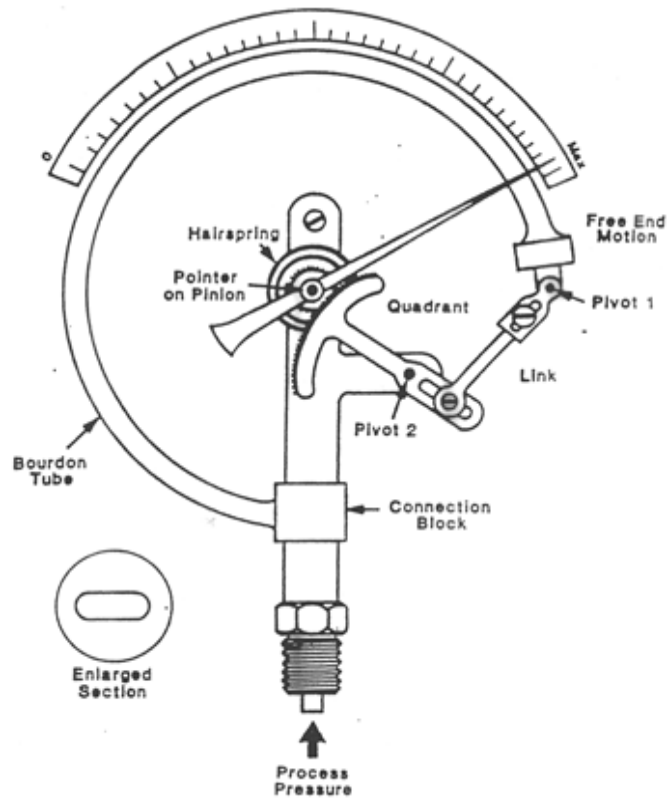
Manometers work on the principle of balancing an unknown pressure against a known pressure produced by a column of liquid in a vertical or inclined tube.

The typical pressure range covered by manometers is from absolute zero pressure to approximately 1.5 bar depending upon the length of the tube and the liquid used within the manometer.



- **Pressure Gauges**

A pressure gauge is a device, which senses pressure and provides a visual representation of that pressure. Most pressure gauges have bourdon tube sensors. Vacuum gauges and low-range gauges often use bellows sensors. Differential-pressure gauges can use piston or bellows sensors. The preferred manufacturer and the required range usually dictate the sensor type.

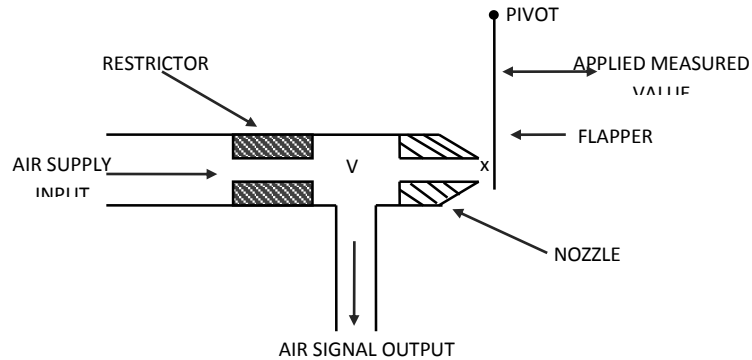


- **Pressure Transmitter**

Pressure transmitters are used when the controller, recorder, or indicator needs to be located in a control room or panel where it is undesirable to pipe the process fluid. They are also used when several devices are to be operated from a single measurement or when elevated zero is required. The output is usually 4-20, mA for electronic transmitters or 3-15 psig (20-100 kPa) for pneumatic transmitters. Other signals can be used if required by the receiver, but these are the most common and should be used if possible.

THE FLAPPER-NOZZLE

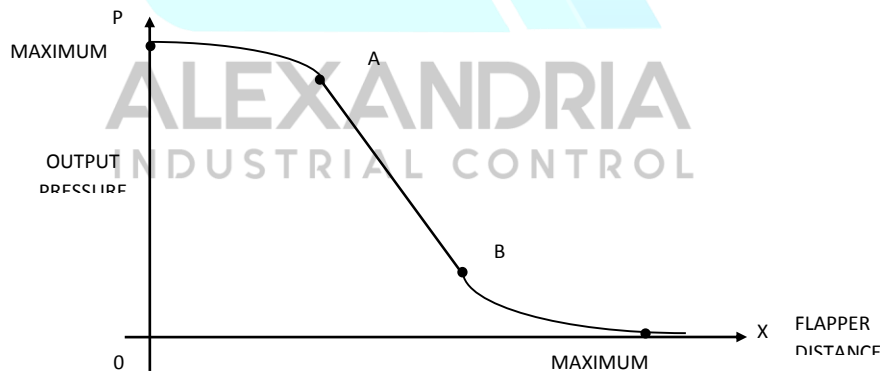
The flapper-nozzle is the primary device for all pneumatic instruments which convert a measurement to a pneumatic signal. Figure 3-1 shows the layout of the device.



The Flapper-Nozzle

Operation:

The air supply input (20 psi (1.4 bar)) passes through a restrictor (small hole). It then goes out of the nozzle or down the air signal output line. If the flapper is placed against the nozzle, no air can escape through it. So, the air signal output shows full pressure. If the flapper is pulled away from the nozzle, most of the air flows out of the nozzle, so the air signal output pressure is very small. The back pressure output signal depends on how near the flapper is to the nozzle. A simple graph of the output pressure (P) against flapper distance (X) is shown below.



The graph is linear (straight) over the distance A B. This reflects only a few millimetres of travel of the flapper. This part of the curve is used to convert a change in a measured value connected to the flapper into an output signal. The restrictor increases the speed of operation. The small volume (V) can change pressure quickly before the air supply can pass through the small hole in the restrictor.

The change in output pressure due to flapper movement is very small. It must be enlarged (amplified) using a device called a PNEUMATIC RELAY.

THE PNEUMATIC RELAY

Different manufacturers make pneumatic relays in different ways. However, they all work on the same principle. A simplified explanation of this device is given in Figure 3-2.

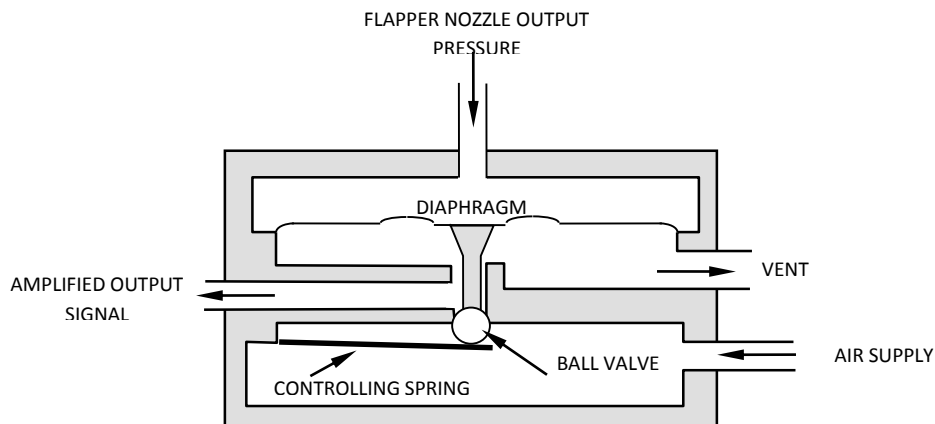


Figure 3-2 The Pneumatic Relay

Operation:

The output pressure from the flapper-nozzle goes to the top of the diaphragm. The diaphragm moves down against the controlling spring and opens the ball valve. The air supply now enters the area under the diaphragm and goes into the output.

At some point, the pressure from the air supply under the diaphragm will equal the pressure above. The diaphragm moves up and the ball valve closes and they hold momentarily at that pressure. If the flapper-nozzle pressure increases, the ball valve will open and hold momentarily at the new higher output pressure. If the pressure on the diaphragm decreases, the ball valve stays closed and the output signal falls as air escapes through the vent. When the output pressure has fallen enough the ball valve opens again to maintain the output at the new lower pressure. This kind of relay is called a continuous bleed device because it controls the output signal pressure by slowly venting the air supply all the time.

The standard amplified signal from the relay is:

- (a) 3 -15 psi imperial
- (b) 0.2 -1 bar ISO.

Remember that these standards are not the same. The control system can work on (a) or (b). It must never work on a mixture of the two standards.

THE PNEUMATIC TRANSMITTER

There are many different types of pneumatic pressure transmitters. However, they are not used much nowadays.

One of the few types still in use is the Foxboro type 11. This is shown below as an example of the pneumatic transmitter.

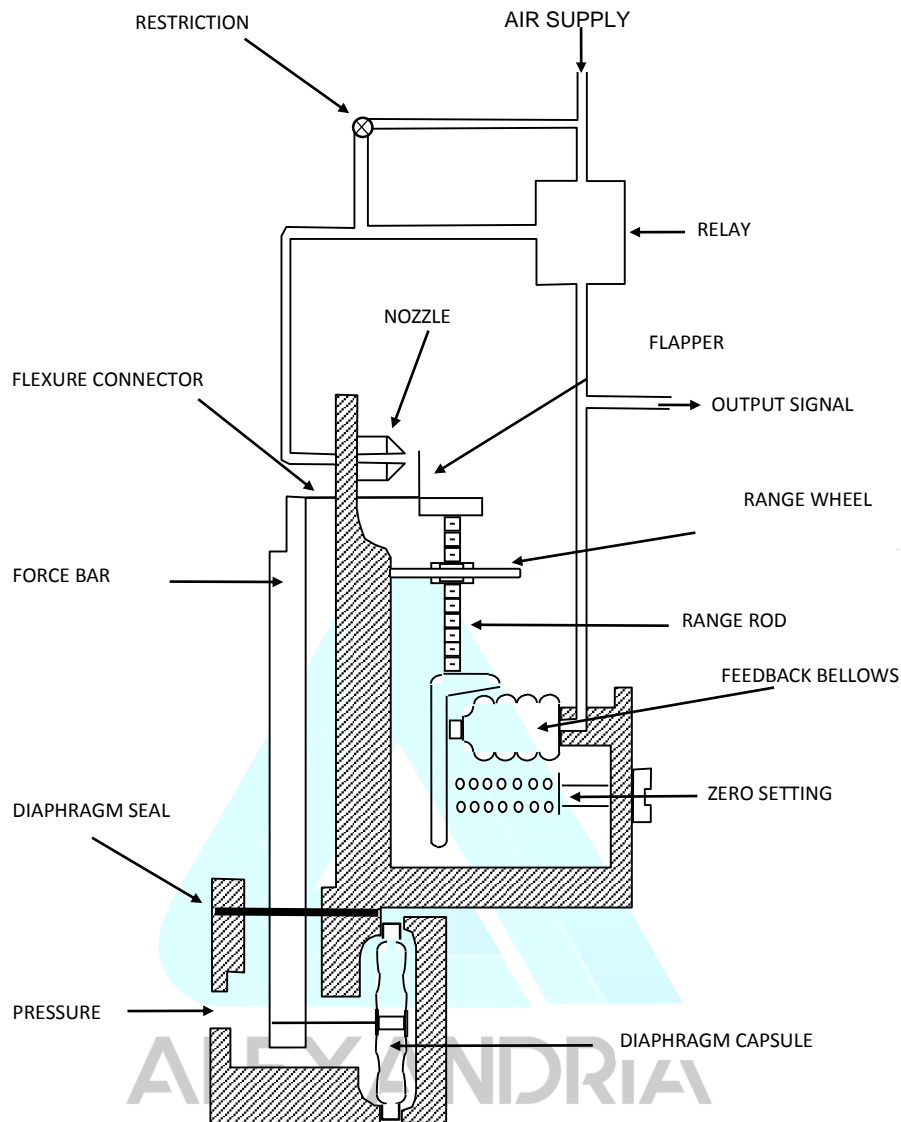


Figure 3-3 The Pneumatic Pressure Transmitter

Figure 3-3 shows the basic design of a Foxboro pressure transmitter.

Operation:

- The process pressure to be measured and transmitted as a standard signal is applied to a diaphragm capsule.
- The pressure moves the capsule. This movement is applied to one end of a force bar pivoted about the diaphragm seal.
- The force bar moves the flexible connector. The connector pulls the flapper to and from the nozzle.
- The back pressure from the nozzle is amplified by the relay. This gives the standard output signal.

The system is not stable. The flapper will go either full on or full off. So a feedback bellows is added. The output signal goes to the bellows. The bellows applies a force to the range rod in opposition to the force bar. The system balances to give an output signal which depends on the position of the range wheel.

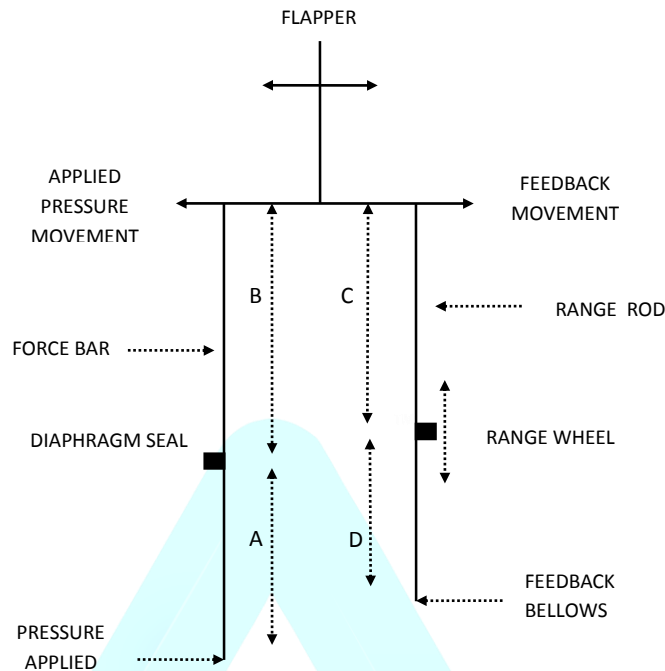


Figure 3-4 Balancing action

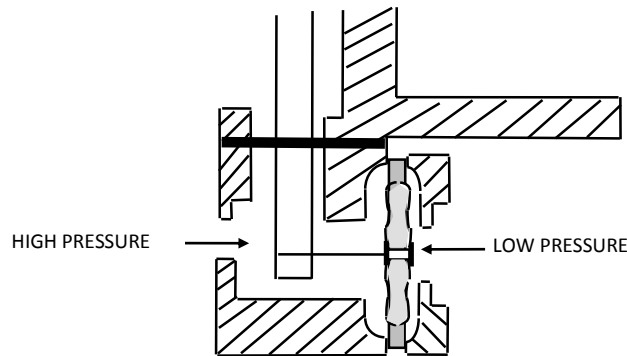
Figure 3-4 shows the balancing action of the transmitter. The movement of the flapper is the pressure applied times B over A ($B:A$). The feedback movement is the output pressure times the ratio $D:C$.

The ratio $B:A$ is fixed but $D:C$ can be changed by the range wheel. If the $D:C$ ratio is large the feedback is small. This makes the range larger.

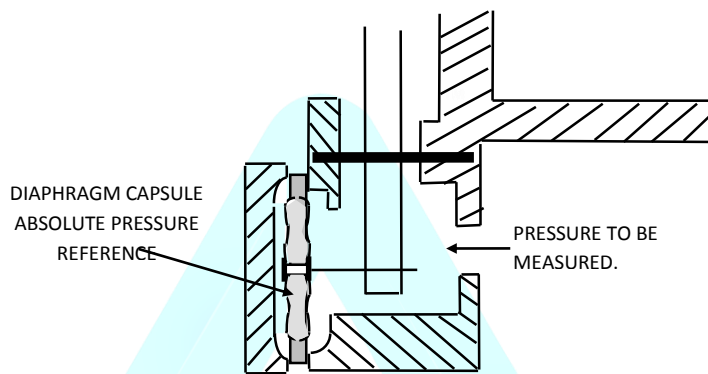
Calibration Adjustments

- When there is no pressure (zero gauge), the zero spring, which sets the force on the range rod, is adjusted for a 3 psi or 0.2 bar output signal.
- With the maximum pressure (range) applied, the range wheel is adjusted to give 15 psi or 1 bar output signal.

Note : Figure 3-3 shows a gauge pressure transmitter. This transmitter can easily be adapted to measure differential pressure. This is done by adding an extra input to the diaphragm capsule as shown below. The force bar now moves according to the differential pressure applied. Remember the device must be connected correctly to the high and low pressure connections. It will not read correctly if it is connected the wrong way round.



DIFFERENTIAL PRESSURE APPLIED TO THE CAPSULE



ABSOLUTE PRESSURE APPLIED TO THE CAPSULE

The pneumatic signal loop

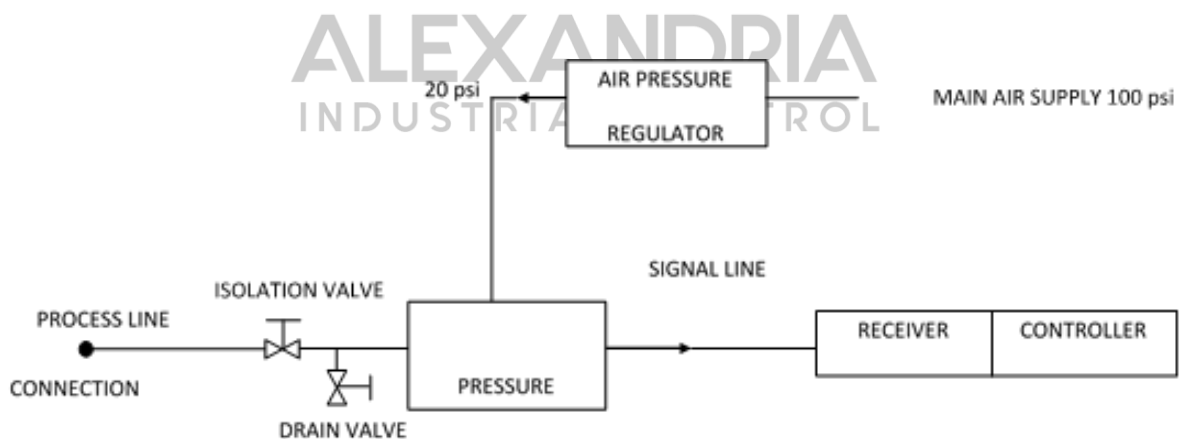


Figure 3-5 The Pneumatic Signal Loop

Figure 3-5 shows a block diagram of the pneumatic signal loop :-

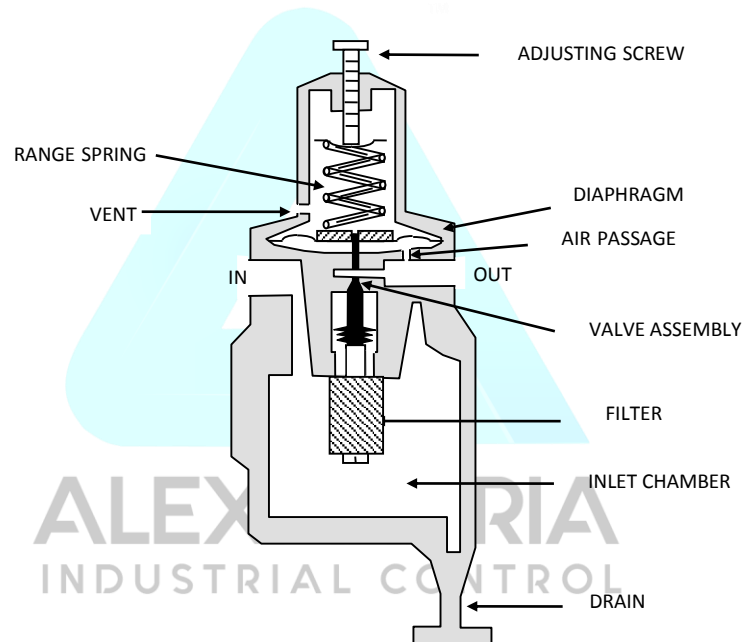
- The process line to the pressure transmitter (usually 3/8" or 1/4" stainless steel tubing) has an isolation valve and a drain valve so it can be disconnected.

- The pressure transmitter has an air supply set at 20 psi. This comes through the air pressure regulator from the main air supply (usually about 100 psi).
- There is a signal line (usually 1/4" stainless steel tubing) which transmits the signal (3-15 psi) to the receiver in the controller.

The air pressure regulator

The air pressure regulator is a simple device. It is used to lower the main instrument air supply of a plant to a pressure suitable for an air-operated instrument; eg, a transmitter, control valve, etc.

Normally, each air operated instrument has its own regulator. So an air regulator is one of the most common devices in the plant. There are various manufacturers of air regulators, eg, Masoneilan and Fisher. However, they all work in much the same way. The example given is manufactured by Fisher



The Air Pressure Regulator

Operation:

- The main air supply is connected to the IN port. Air passes into the inlet chamber at the bottom of the regulator.
- Air passes through the filter which removes dirt particles in the incoming air which may block nozzles etc. It then goes into the valve assembly.
- The valve assembly is moved by the range spring pressing on the diaphragm.

- The range spring will hold the valve assembly down until the output pressure is high enough to lift the diaphragm (via the air passage shown). At this point the small spring in the valve assembly closes the valve.
- Air is allowed to pass through a hole at the centre of the diaphragm and out of the vent. This maintains balanced pressure across the diaphragm.
- If the outlet pressure is above the pressure set by the range spring, the air will go out through the vent above the diaphragm. When the outlet pressure is correct, the valve assembly opens to set the correct pressure.
- If the outlet pressure is below the pressure set by the range spring the valve assembly will stay open until the set pressure is reached.

Note :-

- The drain valve should be opened regularly to drain any moisture in the inlet chamber.
- Range springs come in various sizes. The most common is from 5-35 psi (0.34-2.4 Bar). This is set to give an output of 20 psi for transmitters, etc.

The electrical pressure transmitter

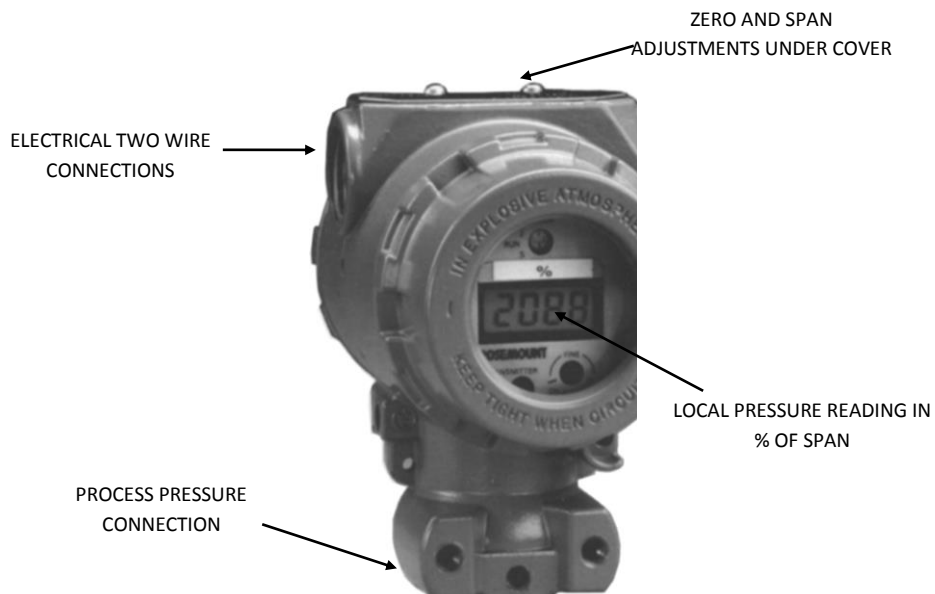
Electrical transmitters have replaced pneumatic transmitters in most petrochemical plants. This is because they are cheaper to install and maintain. The transmission of the signal is also cheaper and easier to install. This is because an electrical transmitter has one pair of wires instead of expensive stainless steel signal tubing and air supply lines.

There are three main types of transmitters. They use three kinds of capsules: capacitive (Rosemount), strain gauge (Honeywell) or vibrating wire (Foxboro). The output from the capsule is electronically converted to a STANDARD 4-20 mA SIGNAL for transmission to the control room.

An electrical transmitter is calibrated with an instrument screwdriver or push buttons. There are two adjustments, zero and span (range).

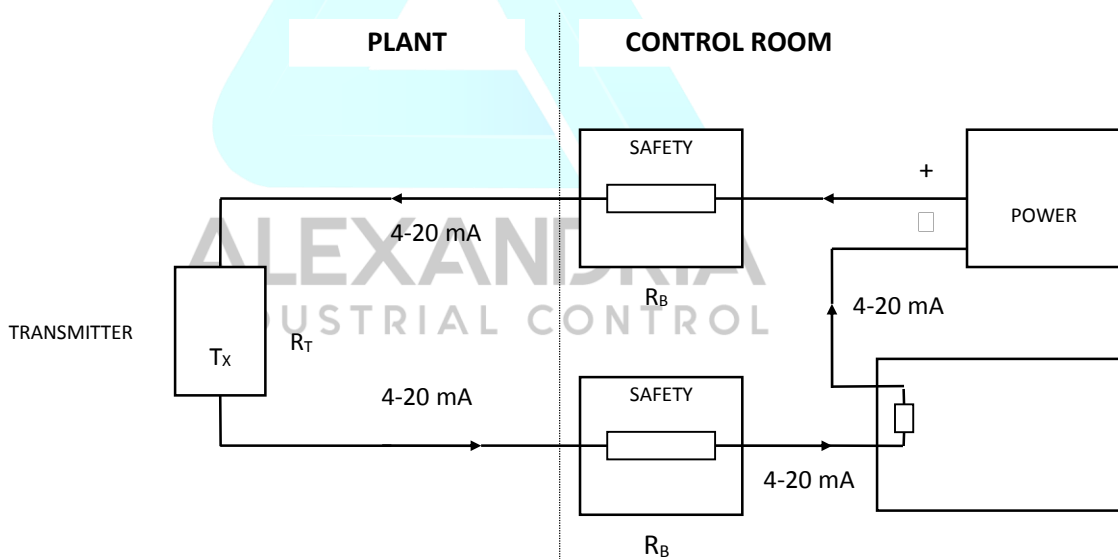
The calibration and servicing depends on the manufacturer. It must be carried out using the manual. Modern transmitters have become throw away items. If they cannot be calibrated they are not serviced. They are thrown away and replaced with a new transmitter.

Figure below shows, as an example, a Rosemount electrical transmitter.



The Rosemount Electrical Transmitter.

Any electrical transmitter uses an electrical series loop and it acts as a variable resistor. The basic diagram of the loop is shown in



The Electrical Series Loop

The power supply provides the EMF, around 24V d.c., to drive the series loop. This loop consists of:

- Two safety barriers(R_B) which protect the plant from dangerous voltages in the case of a fault.

- The transmitter, whose resistance (R_T) changes with the measured pressure changes.
- The controller with a resistance R_C . The voltage across the resistance provides the signal for the controller electronics.

The current around the circuit (I) will be

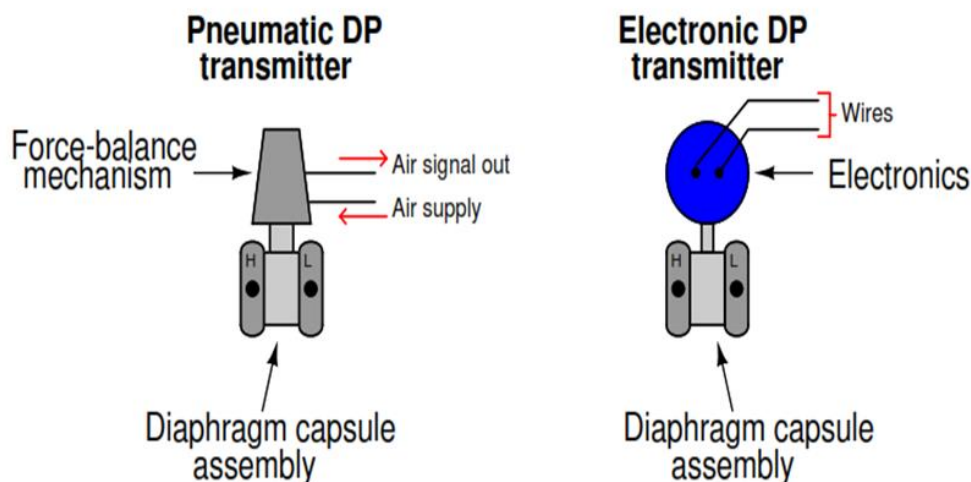
R_B and R_C are constant. So, the current changes as the resistance in the transmitter (R_T) changes.

The system is set so that with zero pressure, the current is 4 mA and 20 mA at the maximum value of the measured pressure.

Note : Both pneumatic and electrical transmitter signals have a **live zero**. This means that a broken circuit can easily be detected.

DP transmitter construction

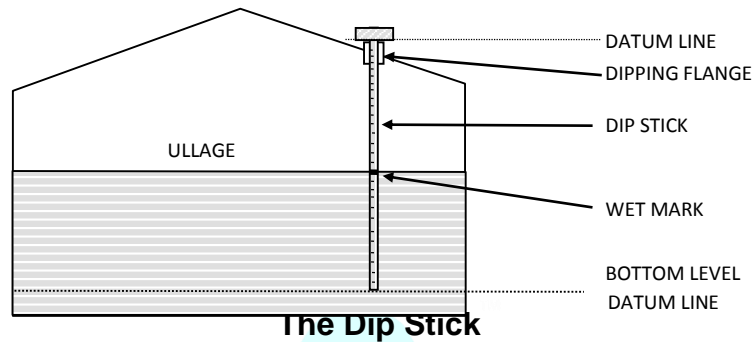
Differential pressure transmitters constructed for industrial measurement applications typically consist of a strong (forged metal) body housing the sensing element(s), topped by a compartment housing the mechanical and/or electronic components necessary to translate the sensed pressure into a standard instrumentation signal (e.g. 3-15 PSI, 4-20 mA, digital fieldbus codes):



3-2 Level MEASUREMENT

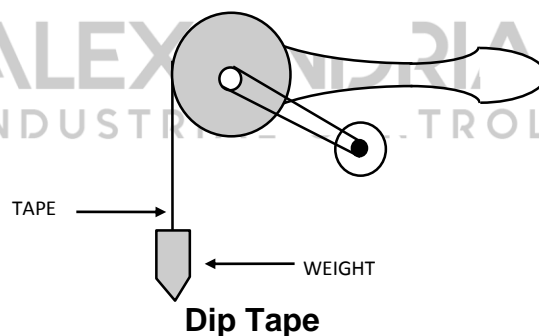
The dip stick

The dip stick shown in Figure is the only true measurement of level. It is still used by operators and ships' captains to check that the instrumentation which measures the level of a liquid in a tank is correct.



The dip stick is a long calibrated ruler. The depth of the liquid in the tank is indicated by a WET mark when the stick is removed. It's the same principle as checking the oil level of a car. Because there may be rubbish at the bottom of the tank the level may be taken from a bottom level datum line. A datum line is a base line from which things can be measured. There is also a top datum line which is used to measure the space above the liquid (the ullage).

The Dip Tape

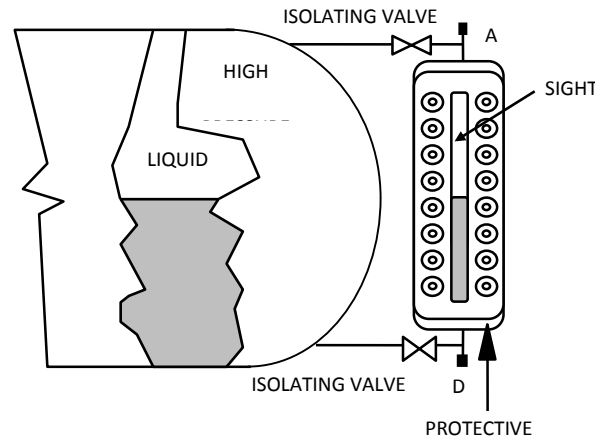


The dip tape shown in Figure is a development of the dip stick for finding the level in large tanks. The tape is run out until the weight touches the bottom of the tank. It's then pulled up. The wet mark on the tape indicates the depth of the liquid.

Note :- The dip stick / tape is no good if the liquid does not leave a WET mark. An example of this type of liquid is mercury.

The sight glass

This is the level indicator used by operators in the plant. The device is connected to the side of a vessel and the level is seen by looking through the glass. A high pressure sight glass is shown in Figure.



High Pressure Sight Glass

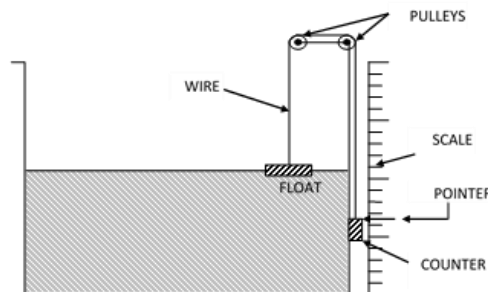
There are many different types of sight glasses. A single glass tube is strong enough for low pressures. For high pressures you need a reinforced glass tube with a steel case, as shown in Figure 5-3. Most industrial sight glasses can be cleaned on site by closing the isolating valves, draining the tube via valve D and rodding through valve A. Good sight glasses also have an automatic shut-off valve. This operates if the glass breaks. It stops all the liquid draining out of the vessel.

High pressure sight glasses have very specific instructions about how they are put together and taken apart. You must use the manufacturer's manual. A high pressure sight glass should never be used again because re-tensioning will make the glass break.



Floats

The Simple Float



Simple Float Indicator

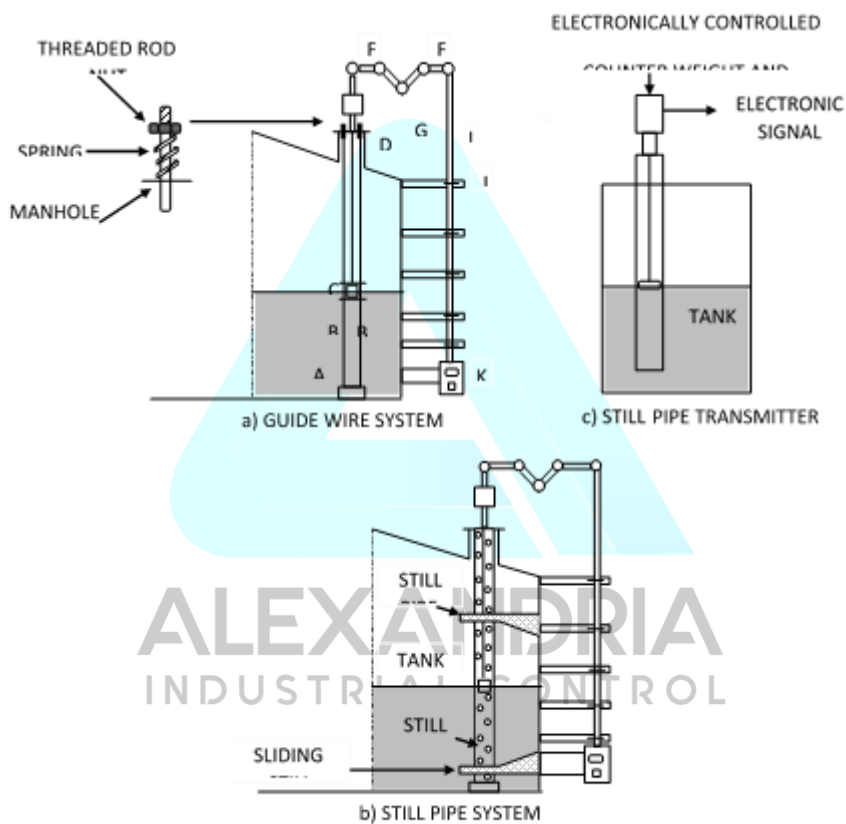
Figure shows a simple float level indicator. It is still used by water departments and on chemical tanks on older oil platforms. It is cheap to install and easy to operate.

Operation

The float and counter weight are connected together by a wire on pulleys. The system is in balance with the float on the surface of the liquid. If the level rises, the float rises and the counter weight falls to the new balance point. If the level falls the counter weight rises. The counter weight has a pointer which indicates the level on a scale on the outside of the tank. The scale shows "full" when the pointer is at the bottom and "empty" when it is at the top. The scale can be very large so that, for example, water tower levels can be seen from the ground.

Industrial Float Systems

The simple float is not very accurate and can be very difficult to read. If the surface of the liquid has waves then the float starts to swing. This problem is solved by fitting special devices inside the tank as shown in Figure.



Tank Constructions

Guide wire system (Figure a)

This is the cheapest system. The float; C, is held in place by wires; B. These are fixed to the bottom by a concrete block; A, and tightened by a spring; D.

The float is connected by a wire (to the indicating unit K) via a pulley system (FGF) and pipe (I) supported on brackets (J). The indicating unit is the counter-weight and the level is indicated by a mechanical counter.

Still pipe system (Figure b and c)

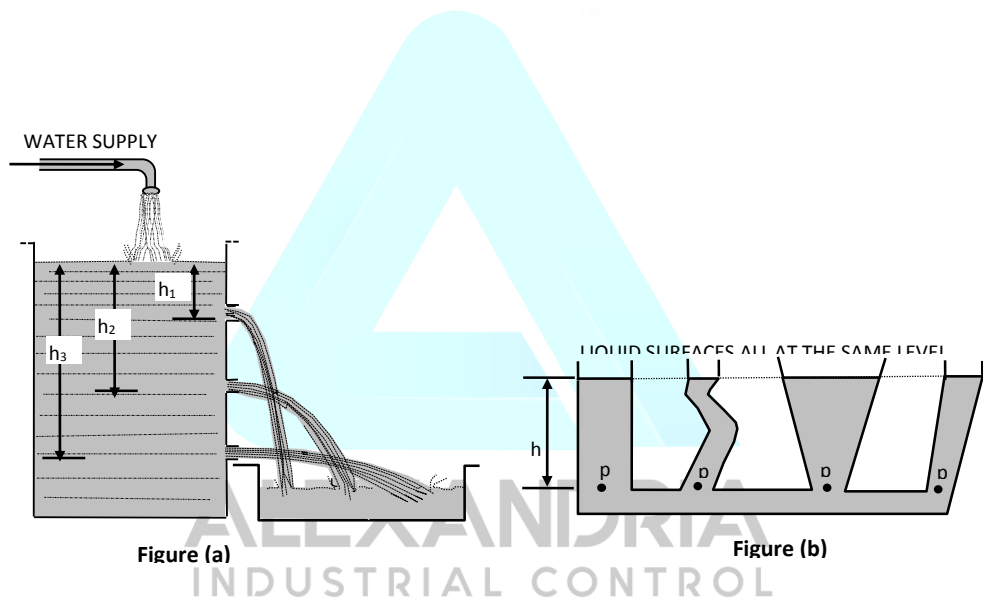
This is a more expensive method but it is more accurate. The float is contained inside a still pipe (a steel pipe with holes in it). The level inside the pipe doesn't move so it gives very accurate measurements of level. Figure b shows the older mechanical indication method. Figure c shows the modern method (Entis-Enraf). The system is electronically controlled and the level measurement is sent as an electronic signal to the control room.

Hydrostatic tank gauging (htg)

Introduction

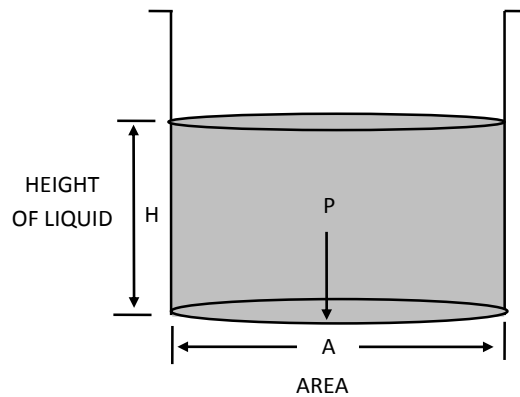
Many of the modern oil storage tank facilities (tank farms) use hydrostatic tank gauging to indicate the level in a tank. HTG is good because there is no equipment inside the tank. It is cheaper to install and maintain than float installations.

BASIC PRINCIPLE



The higher the level of a liquid in a tank, the higher the pressure on the bottom of the tank. The nearer the outlet is to the bottom of the tank, the greater the pressure and the further the flow stream will reach. Figure (a) shows this effect.

The pressure on the bottom of a tank only depends on the level of the liquid in the tank. Figure (b) shows this effect. No matter what the shape of the tank, the pressure (P) at the bottom of the tank is the same.



PRESSURE =

The force on the bottom of the tank is the weight of the liquid.

WEIGHT OF LIQUID = VOLUME x DENSITY x GRAVITY

but VOLUME = AREA (A) x HEIGHT (H)

Therefore

WEIGHT OF LIQUID =

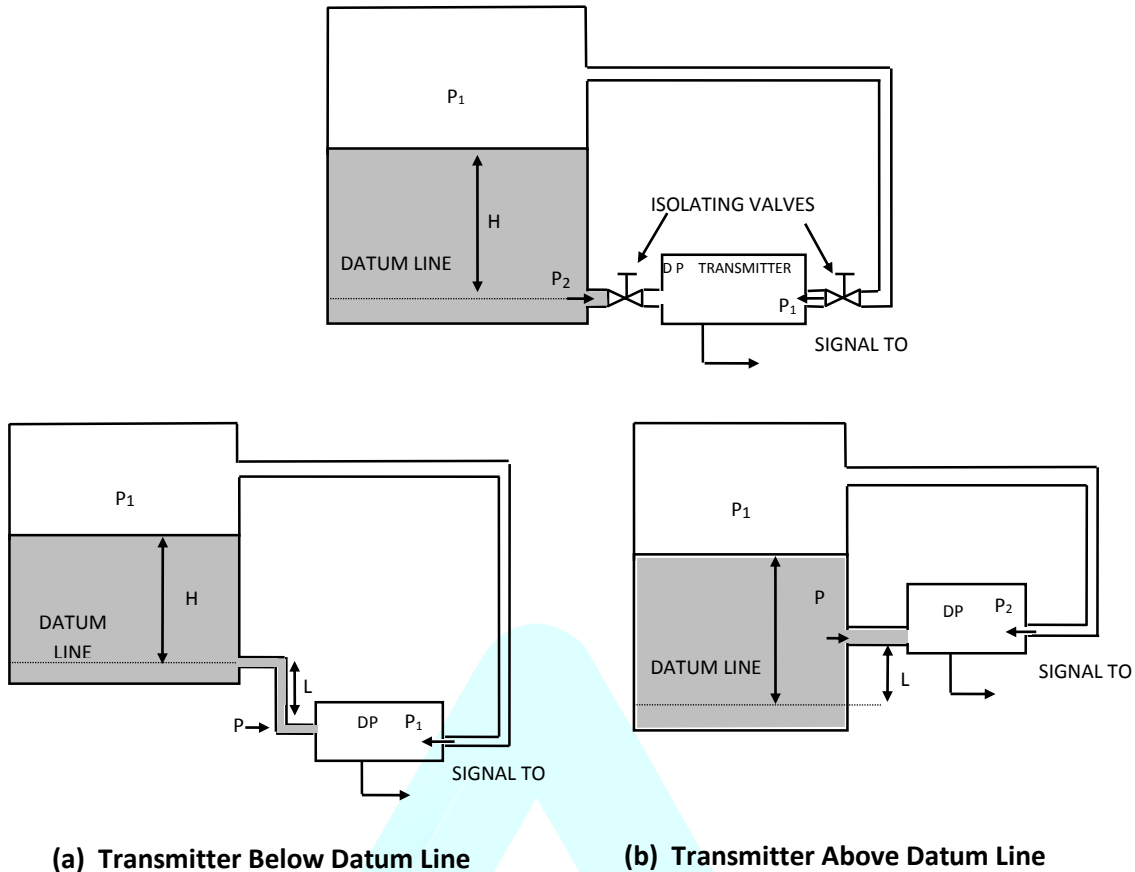
AREA (A) x HEIGHT (H) x DENSITY (ρ) x GRAVITY (g)

PRESSURE (P) = HEIGHT(H) x DENSITY (ρ) x GRAVITY (g)

$$P = \rho gH$$

This equation shows that the pressure at the bottom of a column (level) of liquid does not depend on the shape of the container.

Hydrostatic Tank Gauging (HTG) uses the pressure of a column of liquid to measure the level. The diagram below shows the basic layout of the system (see Figure 5-6)



Hydrostatic Tank Gauging

Theory

P_1 = Pressure above the liquid level

P_2 = Pressure at inlet to differential pressure transmitter

$P_2 = P_1 + \text{Pressure of liquid above the datum line.}$

The pressure of the column of liquid above the datum line is given by the formula:

$$P = \text{Density} \times \text{Gravity} \times \text{Height}$$

Gravity is a constant and providing the density of the liquid does not change then

$$P = KH \quad \text{where } K \text{ is a constant}$$

and
$$P_2 = P_1 + KH$$

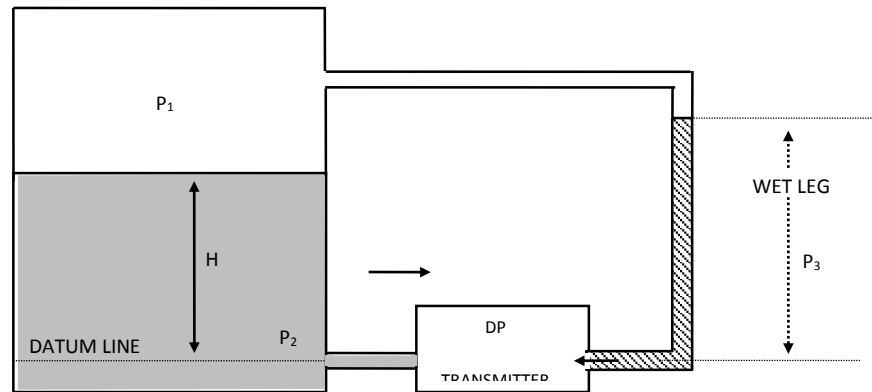
The differential pressure (DP) across the transmitter is

$$P_2 - P_1 = P_1 + KH - P_1$$

$$DP = KH$$

This means that the DP transmitter signal gives a direct indication of level.

Wet Legs

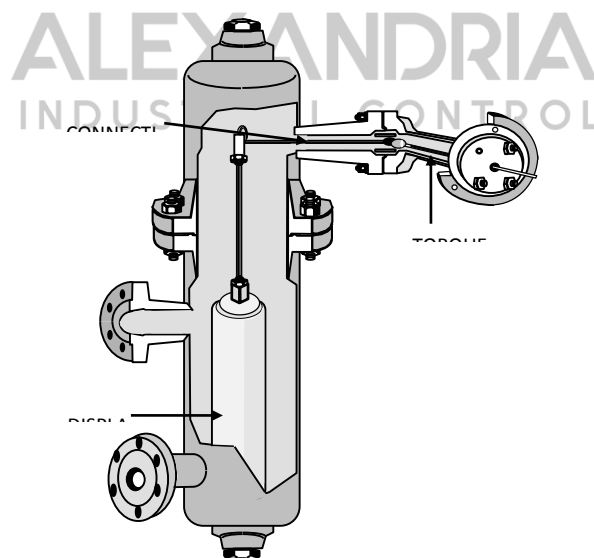


Wet Legs

Some liquids produce heavy vapours. These vapours may condense to liquid in the pipe between the differential pressure cell and the top of the tank. This condensate can cause the transmitter to give the wrong reading. To stop this, the pipe is filled with a known liquid (eg glycol). This is called the "Wet Leg". The differential pressure transmitter is adjusted using the elevation/depression units to offset the pressure caused by the height of the liquid in the wet leg (P_3).

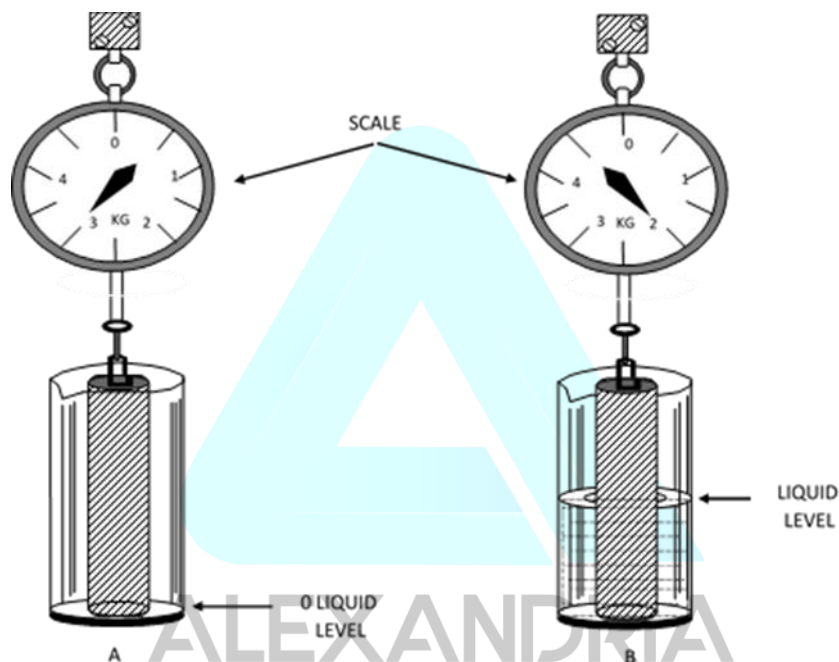
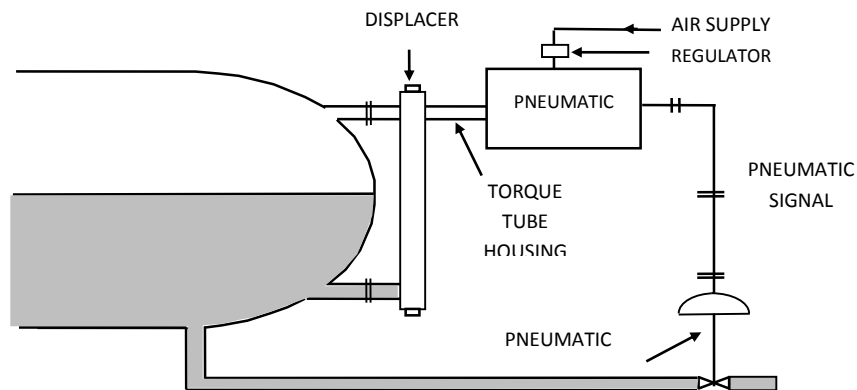
Displacers and local level control

The displacer is a locally mounted device which controls the level in a vessel. It is used on remote sites where it is too expensive to return signals to the control room. The most common types in use are manufactured by Fisher or Masoneilan. shows a Fisher device (The Level-Trol).



The Displacer

The displacer unit is connected to both the vessel and the control valve. This makes a self-contained local control loop as shown in Figure



Simple Example of Archimedes Principle

Shows a simple example of Archimedes' principle. In 'A', the scale shows 3 Kg weight. The displacer weighs 3 kg. In 'B' the displacer has displaced a volume of water which weighs 1 kg. So, the scale shows a weight of 2 kg i.e. 3 kg minus 1 kg for the liquid displaced.

The diameter of the container and displacer are kept constant. So, the weight loss on the displacer is directly proportional to the liquid level in the displacer housing. If the displacer weighs less then the torque tube is twisted less. The amount the torque tube twists depends on the level of liquid in the displacer housing.

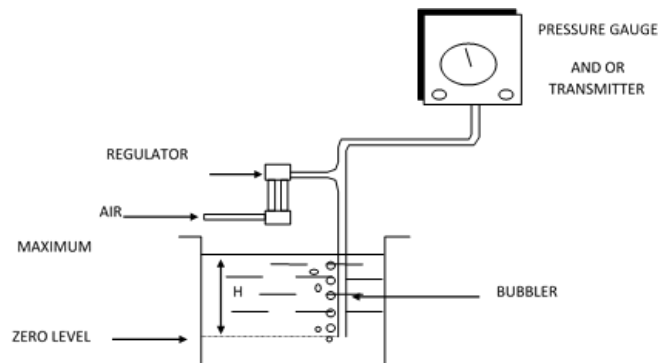
Note :- The weight of the liquid displaced is given by the formula

$$\text{Weight} = \text{Volume} \times \text{Gravity} \times \text{Density}$$

So, changing the density of the liquid in the vessel means the Level-Trol must be recalibrated.

Air bubble method

The air bubble method is one of the oldest and simplest methods used to indicate and or transmit a signal. The diagram below shows a simplified layout of the method



Liquid Level Measurement by Air Bubbler Method

Operation

- An inert gas (air or nitrogen) is passed down the bubbler tube. There is just enough gas pressure for the bubbles to appear when the liquid is at the maximum level in the vessel.
- When the vessel is full the pressure gauge or transmitter will read a maximum back pressure equal to the hydrostatic head (H), (the pressure of the liquid above the zero level).
- At the zero level the back pressure will be zero and the gauge or transmitter will read zero.
- The back pressure between zero and maximum levels is proportional to the liquid level in the vessel. The pressure gauge or transmitter can be calibrated to indicate the liquid level.
- The gas pressure is adjusted by the regulator to give a steady flow of gas down the bubbler tube. The gas flow is indicated on the Rotameter.
- This method can be very accurate. A modern differential pressure transmitter, open at one side, can easily be calibrated to give a span of 0-6" H₂O.

other methods of level measurement

In this unit we have introduced some common methods of measuring level used on most installations.

There are many other methods using various types of high technology. These will be special for only one or two installations. You will have to learn them on the job. A few examples are:

- (a) Radar, ultrasonic, gamma and infrared detectors.
- (b) Capacitive sensors.
- (c) Resistive sensors.

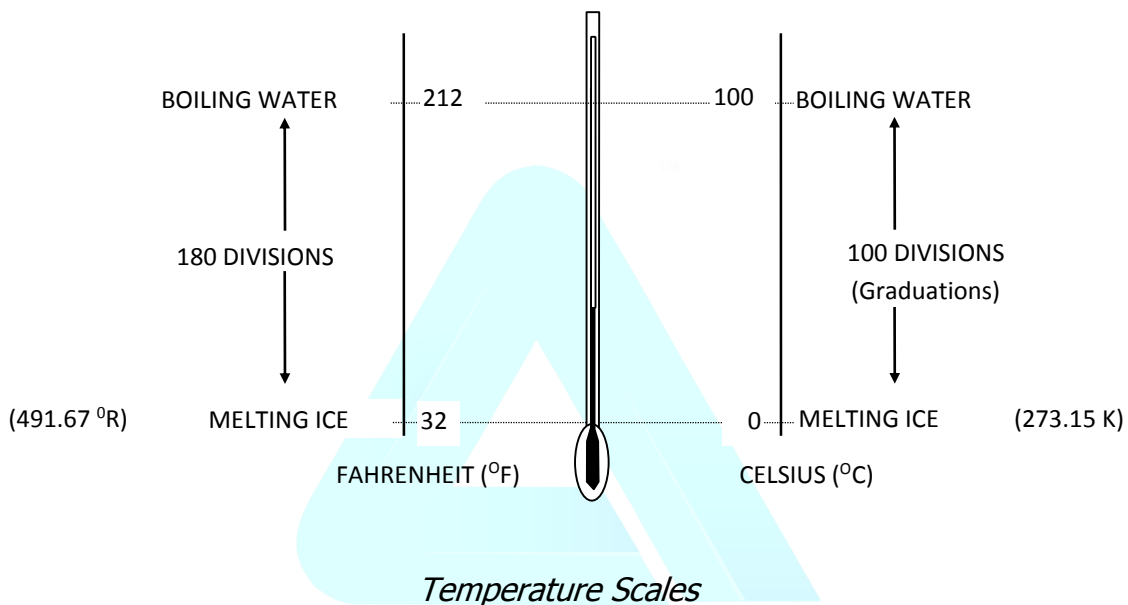


3-3 Temperature Measurement

INTRODUCTION

The aim of this unit is to introduce temperature measurement devices; both expansion types and modern electrical sensors.

Temperature scales



There are different scales for measuring temperatures. compares the two common temperature scales; Fahrenheit (Imperial) and Celsius (ISO). The fixed points for both scales are the temperature at which ice melts and water boils at standard pressure.

A temperature in Fahrenheit can easily be changed to Celsius and vice versa. The conversion equations depend on the number of divisions in each scale. Fahrenheit has 180 divisions between the freezing and boiling points of water but Celsius has only 100 divisions. Therefore, the ratio is 180/100 or 9:5. This gives:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) \quad \text{or} \quad ^{\circ}\text{F} = ^{\circ}\text{C} + 32$$

There are tables available for Fahrenheit-Celsius conversions. They are usually displayed in the instrument workshop.

The Absolute Scale

In instrumentation, many temperature measurements have to be made from ABSOLUTE ZERO. Absolute zero is the temperature at which no heat energy (atomic movement) exists. This temperature is impossible to reach. On the Celsius scale, absolute zero is around -273.15°C (-459.67°F). This figure is used as the standard for absolute zero. So 0 Kelvin (K) is the same as -273.15°C

Absolute temperature in ISO is called degrees KELVIN (K)

Absolute temperature in Imperial is called degrees RANKINE ($^{\circ}\text{R}$)

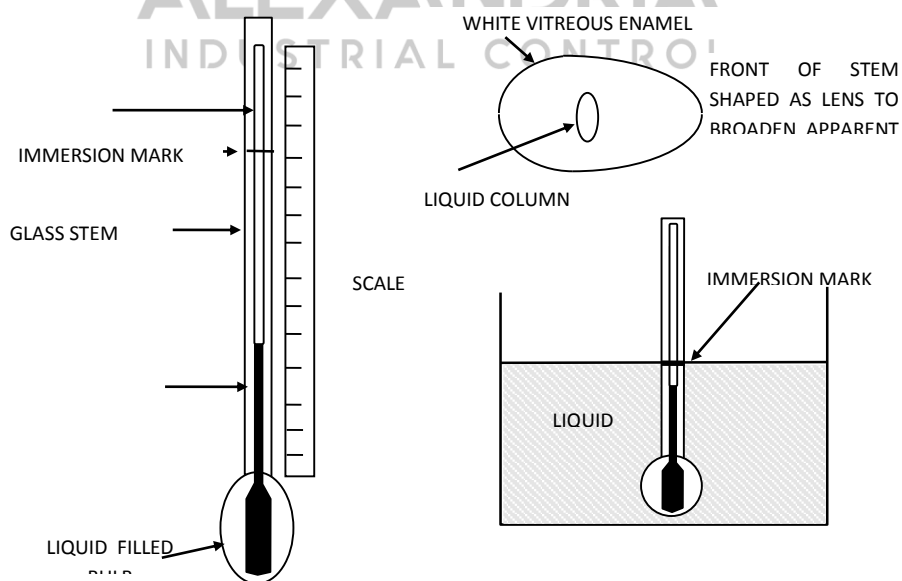
$$\text{KELVIN (K)} = ^{\circ}\text{C} + 273.15$$

$$\text{RANKINE (}^{\circ}\text{R)} = ^{\circ}\text{F} + 459.67$$

Expansion type thermometers

Most materials expand as they get hotter. An expansion type thermometer uses the expansion of a material to indicate temperature. There are several different types.

Liquid in Glass Thermometers



The "liquid in glass" thermometer is the most common of all thermometers. It has industrial, domestic and medical uses.

The instrument workshop uses these devices as a basic standard for calibration purposes. A good quality device is accurate to 0.1°C.

The thermometer, consists of a glass tube (the stem) which has a very small but uniform bore (hole). At the bottom of this stem there is a thin, walled glass bulb. The bulb holds much more liquid than the stem. The bore in the stem is sealed under a vacuum so that there is no air in the system. The system works by differential expansion. The liquid expands over 20 times more than the glass when the bulb is heated.

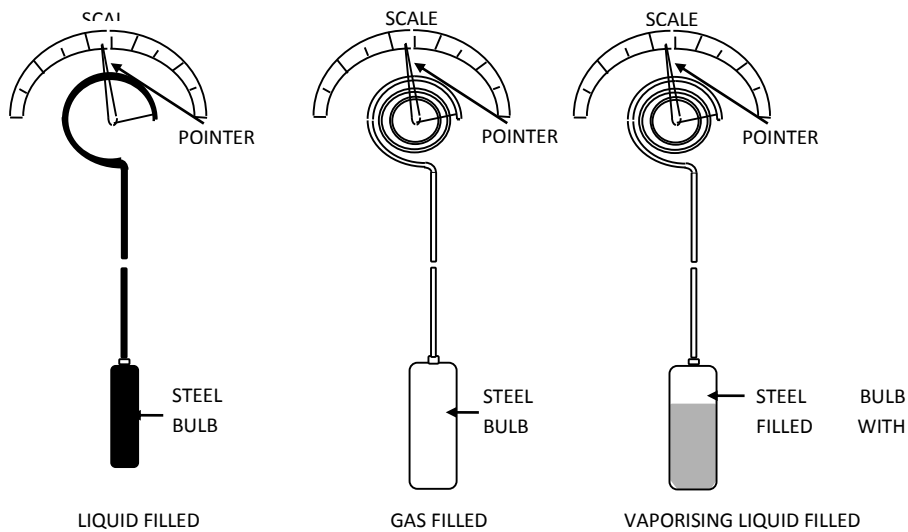
As the liquid expands it rises up the stem. The temperature is shown on a calibrated scale on the glass. A good workshop thermometer will have an immersion mark. The thermometer must be placed in the liquid up to this mark for accurate temperature readings.

Typical liquids in use are:

Liquid	Range (°C)
Mercury	□35 To +510
Alcohol	■80 To +70
Pentane	□200 To +30

Filled Systems

Liquid in glass thermometers are not strong enough for plant use so in industry the bulb and stem are made of steel. The bulb and stem are completely filled with the expansion liquid under pressure. The indicator is a spiral Bourdon tube, or a pressure cell (strain gauge) which gives an electronic signal. Figure 1-3 show the three basic systems.

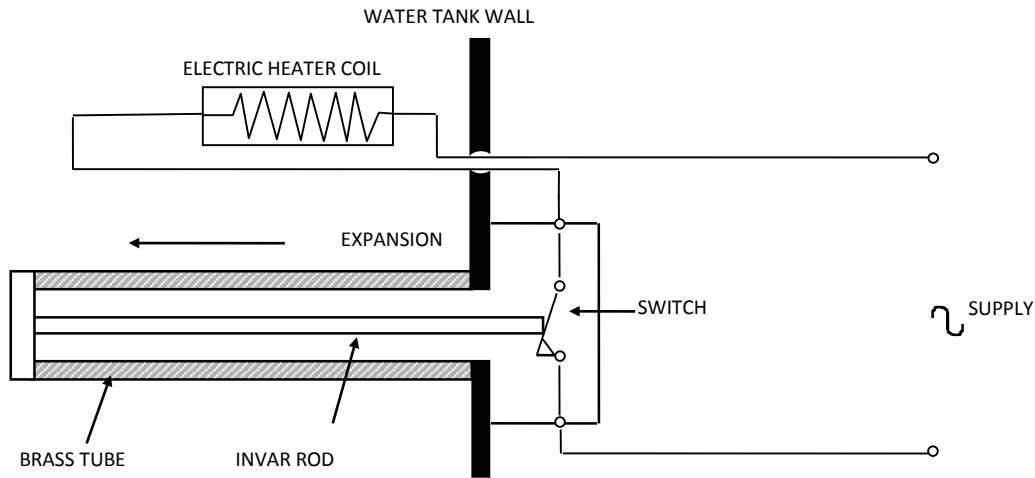


Filled Systems

The steel bulb, stem and indicator (Bourdon tube) are completely filled under pressure with either; a liquid, eg. mercury, a gas, eg. freon or a vaporising liquid, eg. methyl chloride. Each system works in the same way. The system is totally filled to provide a constant volume. Expansion of the fluid in the tube is converted to a pressure. This pressure expands the Bourdon tube which moves the pointer on the scale.

Note: The capillary (the stem) can be many meters long so that the indicator can be placed in a control room away from the fluid temperature being measured.

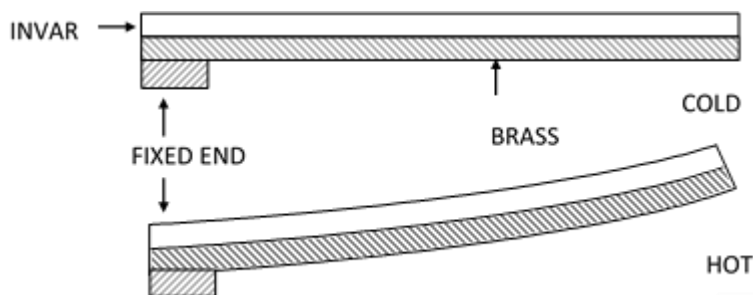
Thermostats



The Simple Rod Thermostat

shows a simple rod thermostat. The brass tube expands a lot as it gets hotter but invar expands very little . When the liquid is cool the brass does not expand so the switch is closed and the electric heater heats the water. When the water reaches the set temperature the brass tube has expanded enough to pull the invar rod away from the switch. This opens the switch and breaks the circuit. The electric heater will stay disconnected until the brass tube contracts enough to close the switch again. Normally the thermostat and heater are together in one unit. The temperature at which the switch is opened can be adjusted by changing the tension of the spring which closes the switch. Thermostats are not very accurate($\pm 3^{\circ}\text{C}$) but they are long lasting and cheap.

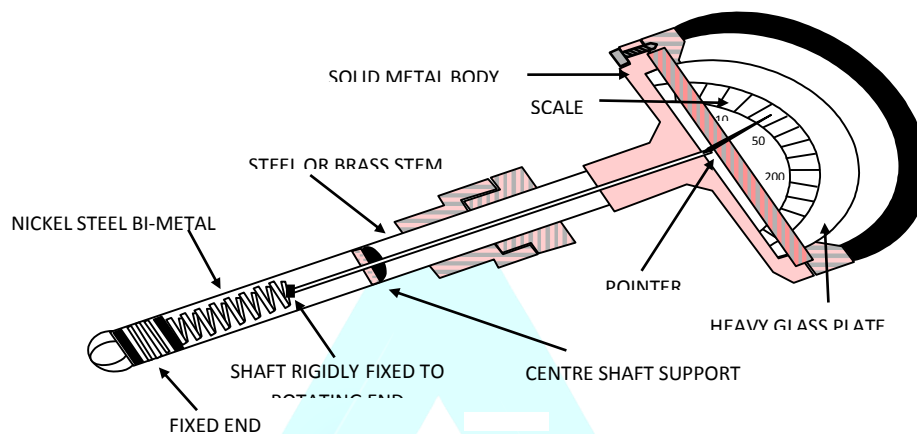
Bi-metal Strip Thermometers



Action of a Bi-metal Strip

Another kind of solid expansion thermometer is the bi-metal strip. Figure shows the action of a bi-metal strip. Two strips of metal, brass and invar, are tightly bonded together and fixed at one end. When the strip is heated the brass expands much more than the invar and the strip bends as shown.

This action is used to make a dial thermometer as shown in Figure 1-7. The most common type is the Rototherm.



Dial Thermometer (Rotometer)

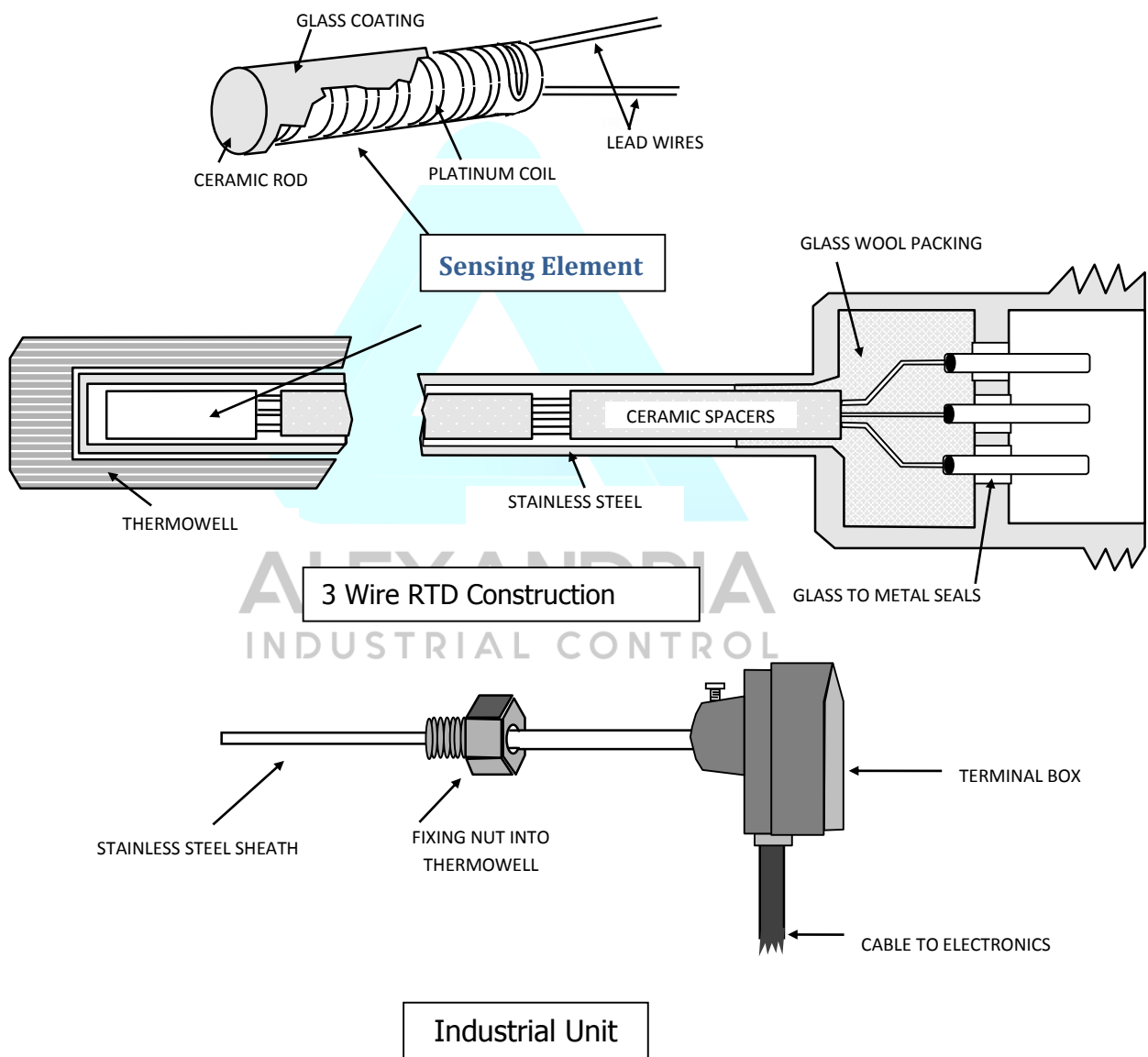
Operation:

The bi-metal strip is shaped into a helix. The helix is fixed at one end. The other end of the helix is free to rotate the shaft which is fixed to it. The heat applied to the bi-metal strip at the fixed end causes the helix to unwind and turn the pointer on the scale. Rototherm supplies these dial thermometers in ranges up to 560°C.

Electrical methods of temperature measurement

The Resistance Temperature Detector (RTD)

The Resistance Temperature Detector (RTD) is the international standard thermometer for measuring temperatures from -258°C to 727°C . It is accurate to 0.00001°C although in industry 0.1°C is usually good enough. Figure shows the RTD together with a typical industrial unit (Kent Instruments).



Basic Construction of the RTD

Construction:

This device indicates temperature by measuring the change in the electrical resistance of a metal. The sensing element has a platinum coil of about 100Ω at 0°C (the Pt 100) see Figure 1-9. The sensing element is connected to the terminal box by three wires. The ceramic spacers stop heat moving through the casing (the sheath). The terminal pins have glass to metal seals held in place with glass wool packing. The output cable connects the sensing head to the electronics unit. This converts the changes in resistance into temperature readings.

Theory of Operation

When metals get hotter their resistance increases. This increase in resistance is almost linear. When it's measured it gives an accurate indication of temperature. The sensor is usually platinum because it is stable over a large temperature range and does not corrode. The normal platinum RTD is 100Ω at 0°C and rises to 138.5Ω at 100°C . The resistance of a Pt 100 at a particular temperature is given in a standard table. These tables must be used when calibrating this device. There is a Pt 100 table on the next page.

Note: Cheaper RTD metals (e.g. nickel and copper) are used where the temperature range is small.

Nickel is used in water heaters and air conditioners.

Copper is used in oil product tank temperature sensing.

Manufacturers provide tables for the calibration of these RTD's.

TEMPERATURE RESISTANCE VALUES FOR A Pt 100.

°C										
	0	-10	-20	-30	-40	-50	-60	-70	-80	-90
-200	18.61									
-100	60.24	56.18	52.10	48.00	43.88	39.73	35.54	31.33	27.10	22.85
0	100.00	96.08	92.15	88.21	84.26	80.29	76.31	72.32	68.31	64.28
	0	+10	+20	+30	+40	+50	+60	+70	+80	+90
0	100.00	103.90	107.79	111.67	115.54	119.40	123.24	127.07	130.89	134.70
100	138.50	142.29	146.06	149.82	153.57	157.31	161.04	164.76	168.46	172.15
200	175.84	179.51	183.16	186.81	190.45	194.07	197.69	201.29	204.88	208.46
300	212.03	215.58	219.13	222.66	226.19	229.70	233.20	236.68	240.16	243.63
400	247.08	250.52	253.95	257.37	260.78	264.18	267.56	270.93	274.30	277.65
500	280.98	284.31	287.62	290.93	294.22	297.50	300.77	304.02	307.26	310.50
600	313.72	316.92	320.12	323.30	326.47	329.63	332.78	335.92	339.04	342.15
700	345.25	348.33	351.40	354.47	357.51	360.55				

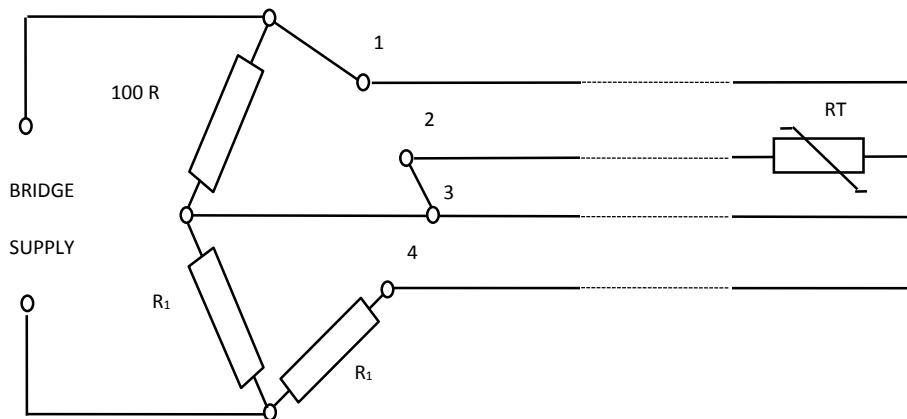
Examples of table use.

1) The resistance at 200°C = 175.84Ω

2) The resistance at □150°C = 39.73Ω

3) The resistance at 560°C = 300.77Ω

The RTD Detector: The electrical circuit

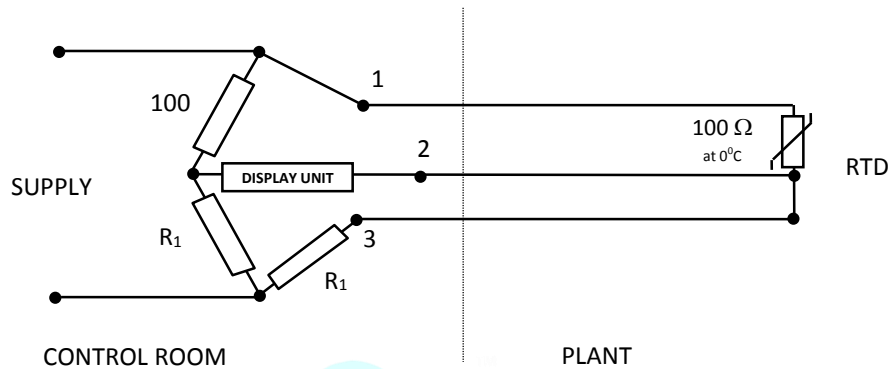


Simple RTD Detector

The basic circuit for detecting the resistance of a 3 wire RTD is the unbalanced Wheatstone bridge. When the RTD is at 0°C (100Ω) the bridge is balanced so that the display unit reads 0°C . As the temperature of the RTD changes the unbalanced current through the display unit is converted to give the temperature. The system is calibrated with a decade box (variable resistance unit) and the Pt 100 tables. For example; place a 335.92Ω resistance value across 1 and 2 when 2 and 3 are joined together and the display unit should read 670°C .

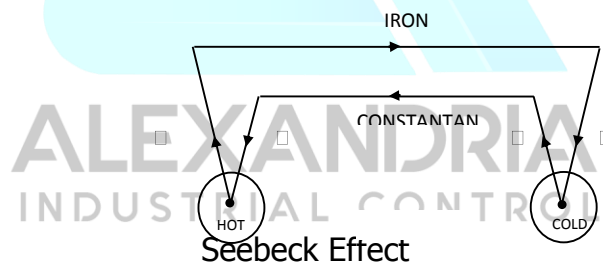
The 3 wire system is used to cancel out unwanted changes in resistance. These can be caused by temperature changes in the air around the connecting leads. This is called ambient temperature compensation. The leads to 1 and 3 are on opposite sides of the bridge so that any changes in resistance because of ambient temperature changes cancel each other out.

For greater accuracy, a 4 wire system of ambient temperature compensation is sometimes used. This is shown below . Changes in the resistance of leads 1 and 2 are cancelled by changes in the resistance of leads 3 and 4.



The 4 Wire System

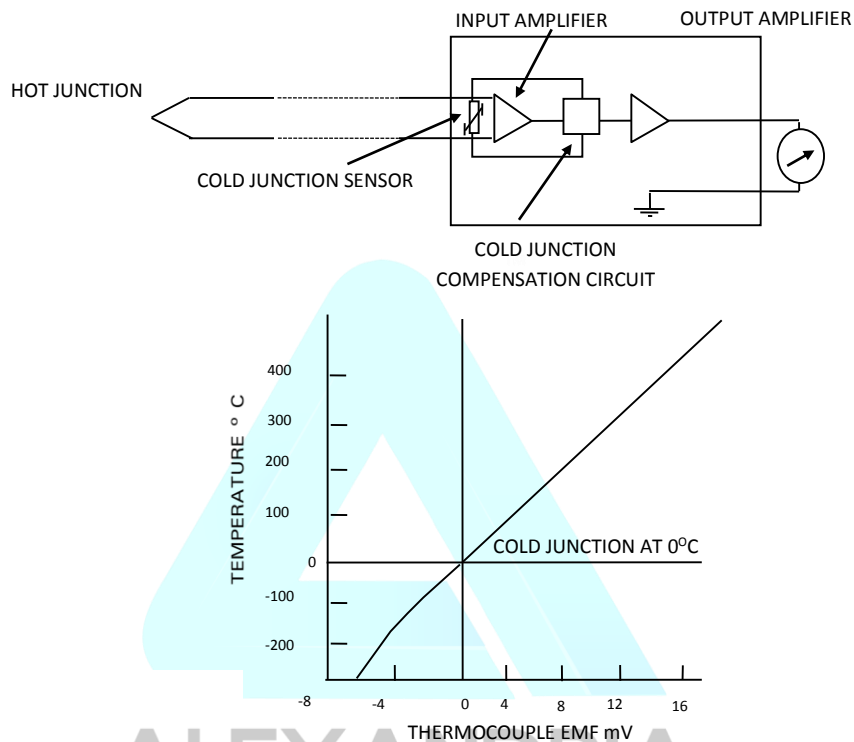
The Thermocouple



The thermocouple uses thermoelectric EMF produced by the difference in temperature between two ends of a metal wire. This is an effect discovered by Seebeck, see Figure. Two different metals are joined to make two different junctions which are held at two different temperatures. The difference between the metals and the difference in temperature between the hot and cold junctions makes a current flow around the circuit. To use this effect you need standard tables which give the EMF produced by the temperature difference in various metal combinations. The EMF is picked up by an electronic amplifier. The indicator is pre-calibrated to show the

temperature. The voltage can be checked against the tables, to make sure the indicator is correct.

Figure shows a typical thermocouple temperature measuring system, with a typical EMF/temperature curve.



The Thermocouple Thermometer

There are many different thermocouples in use. They are classified by letter. Most modern thermocouple detecting instruments can use any standard thermocouple pair. However, they must be connected to the correct letter position.

STANDARD THERMOCOUPLES IN USE

TYPE	CONDUCTORS (Positive conductor first)	ACCURACY	OUTPUT FOR INDICATED TEMPERATURE Cold Junction At 0°C	SERVICE TEMPERATURE
B	Platinum : 30% Rhodium Platinum : 6 % Rhodium	0 to 1100°C ± 3°C 1100 to 1550°C ± 4°C	1.241 mV at 500°C	0 to 1500°C Better life expectancy at high temperature than types R & S.
E	Nickel: Chromium /Constantan (Chromel/Constantan)	0 to 400°C ± 3°C	6.317 mV at 100°C	-200 to 850°C Resistant to oxidising atmosphere.
J	Iron / Constantan	0 to 300°C ± 3°C 300 to 850°C ± 1%	5.268 mV at 100°C	-200 to 850°C. Low cost, suitable for general use.
K	Nickel : Chromium / Nickel : Aluminium (Cromel/Alumel)	0 to 400°C ± 3°C 400 to 1100°C ± 0.75%	4.095 mV at 100°C	-200 to 1100°C Good general purpose, best in oxidising atmosphere.
N	Nickel : Chromium : Silicon:/Nickel Silicon	-230°C to 1230°C ± 0.75%		New high Tech. replacement for Type K
R	Platinum : 13% Rhodium / Platinum	0 to 1100 ± 1°C 1100 to 1400°C ± 2°C	4.471 mV at 500°C	0 to 1500°C. High temperature corrosion resistant.
S	Platinum : 10% Rhodium/Platinum	1400°C ± 3°C	4.234 mV at 500°C	0 to 1500°C. High temperature corrosion resistant.
T	Copper/Constantan: (Cu/Con)	0 to 100°C ± 1°C 100 to 400°C ± 1%	4.277 mV at 100°C	-250°C to 400°C. High resistance to corrosion by water.

The cold junction (inside the amplifier) must be kept at a constant temperature. This is done electronically using a cold junction sensor (a thermistor)

Compensating Leads

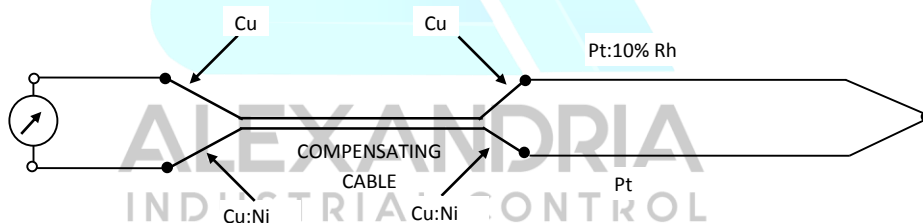
It is important for the thermocouple wires to be made of the same material all the way through even if there is a large distance between the hot and cold junctions. However, this is not always possible for various reasons.

Sometimes the high resistance of the wire reduces current flow. Sometimes the material is too expensive; (platinum - rhodium).

In these cases you can still get on accurate measurement by using compensating leads of similar thermo-electrical properties. The standard compensating leads are

TYPE	COMPOSITION	FOR USE WITH TYPE	AMBIENT TEMPERATURE RANGE
U	Copper/ Copper-Nickel	R and S	0 - 50°C
V _x	Copper/ Constantan	K and N	0 - 80°C

Figure 1-13 shows a typical arrangement of a thermocouple with compensating leads.



The Practical Thermocouple.

An industrial thermocouple sensing unit looks nearly the same as an industrial RTD sensing unit. Unfortunately some manufacturers (USA standard) mark the negative connection with a RED DOT or RED WIRE. The manual must be used when connecting or checking these devices.

All thermocouple systems can be calibrated by checking the EMF generated. This requires standard tables such as the table for a type T thermocouple given below.

MILLIVOLTS (mV) VERSES TEMPERATURE TYPE 'T' THERMOCOUPLE

°C										
	0	-10	-20	-30	-40	-50	-60	-70	-80	-90
-100	-3.378									
0	0	-0.383	-0.757	-1.121	-1.475	-1.819	-2.152	-2.475	-2.788	-3.089
	0	+10	+20	+30	+40	+50	+60	+70	+80	+90
0	0.000	0.391	0.789	1.196	1.611	2.035	2.467	2.908	3.357	3.813
100	4.277	4.749	5.227	5.712	6.204	6.702	7.207	7.718	8.235	8.757
200	9.286	9.820	10.360	10.905	11.456	12.011	12.572	13.137	13.707	14.281
300	14.860	15.443	16.030	16.621	17.217	17.816	18.420	19.027	19.638	20.252
400	20.869									

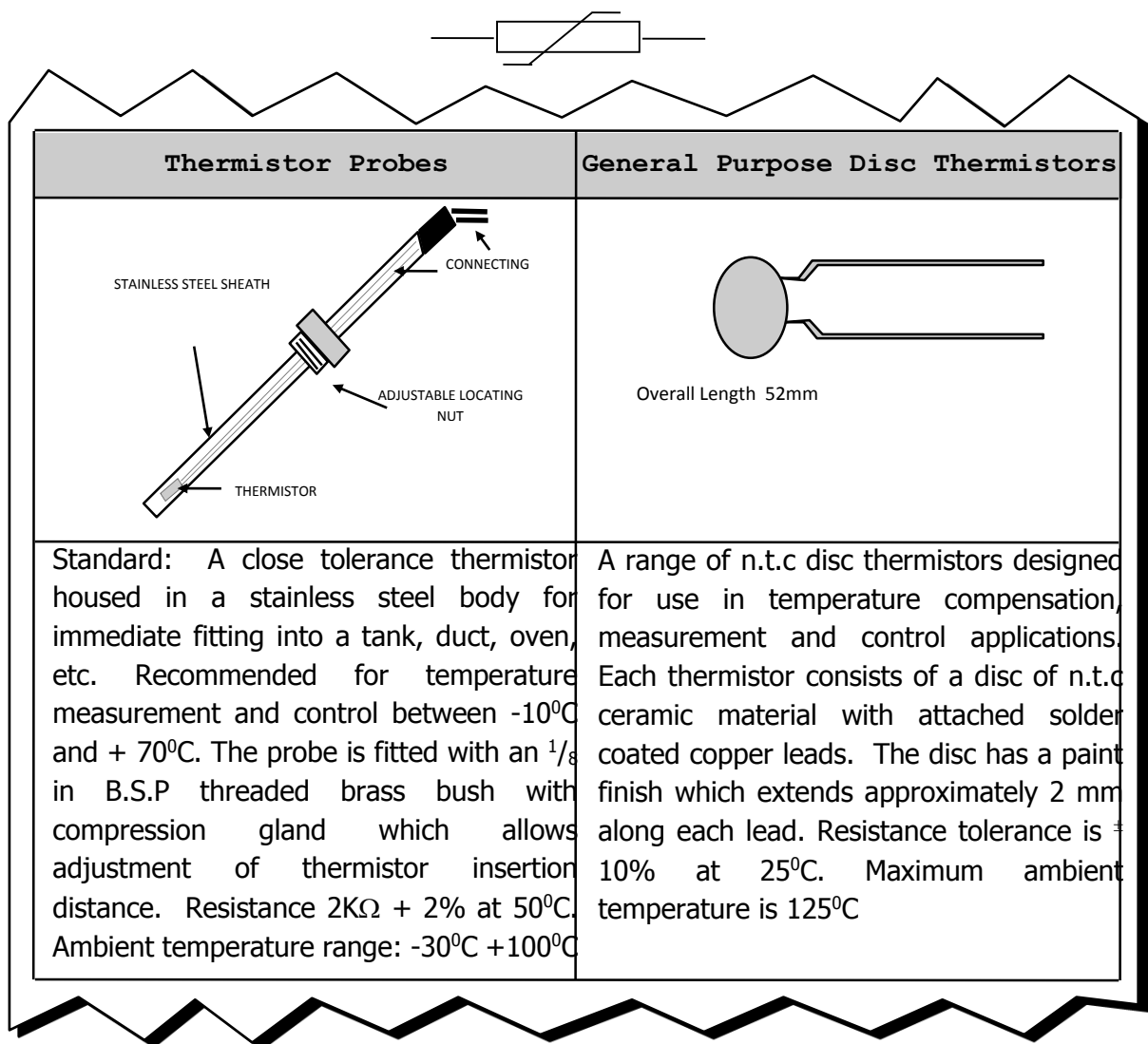
Cold junction at 0°C

Example:

- 1) A hot junction temperature of 350°C will give an output of 17.816 mV
- 2) A voltage output of 7.718 mV will indicate a temperature of 170°C

The Thermistor

A thermistor is a semiconductor made of metal oxides. The thermistor's resistance increases or decreases with temperature. Thermistors are not very accurate but they are small. They are often used for ambient temperature compensation. Some of the cheaper hand-held devices use a thermistor as a sensor but indicate the temperature using the same system as an RTD. The symbol for the thermistor is the same as an RTD.

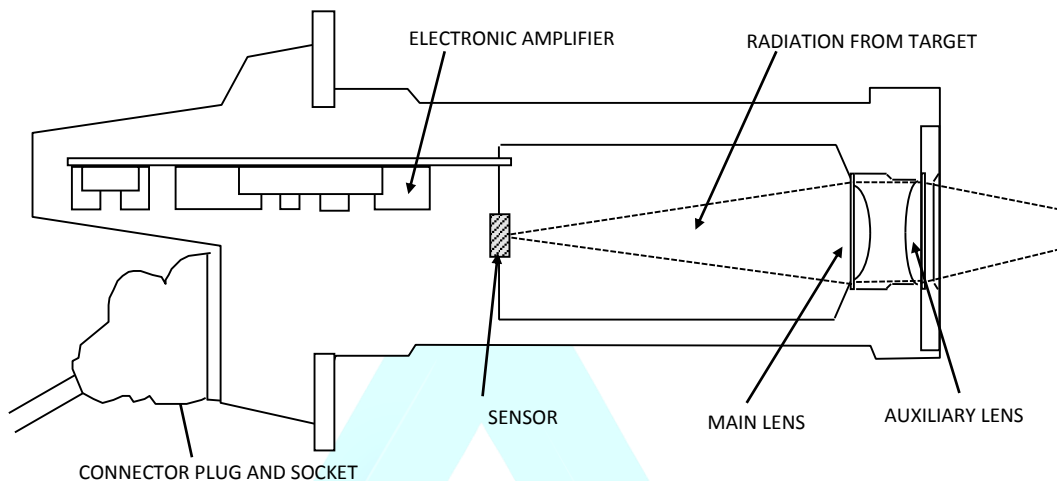


Typical Industrial Thermistors

shows two typical industrial thermistors. Both use negative temperature coefficient materials (n.t.c). This means that their resistance goes down as the temperature rises.

Radiation Temperature Detectors (Pyrometers)

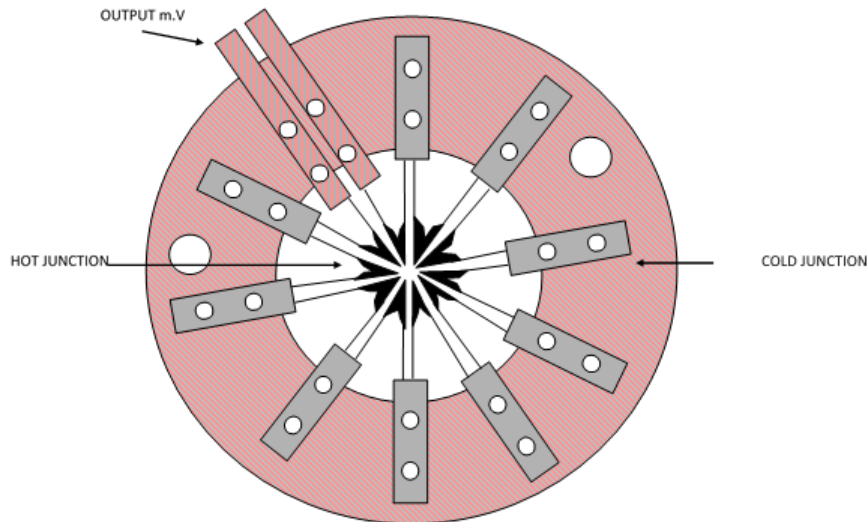
Radiation temperature detectors (Pyrometers) are non contact devices. They are used to measure the temperature of something which is difficult to reach by other means, (eg. gas turbine combustion chambers). They are also the only way to measure very high temperatures (above about 1500°C) as all other devices melt. Figure shows a typical radiation thermometer.



Typical Radiation Thermometer

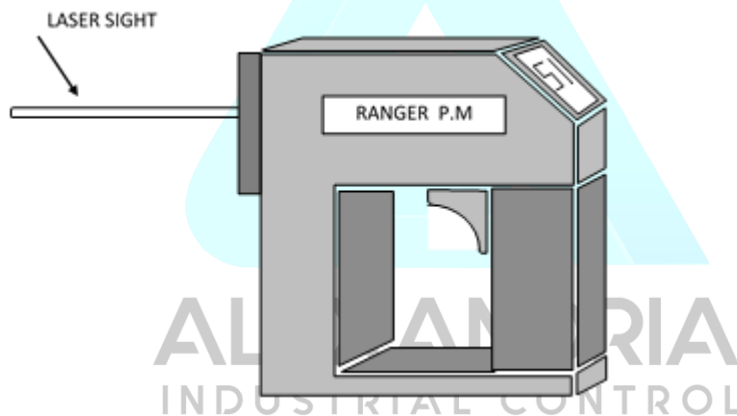
The heat from the object is focused by lenses onto a sensor. The output from the sensor is electronically processed by the amplifier to give a reading in degrees. This device can also transmit a signal to the control room if required.

The sensor is usually a thermopile. A thermopile is a collection of thermocouples connected in series to produce a larger millivolt output. A typical thermopile is shown in Figure 1-16. The radiation is focused onto the black painted centre and the output connected to an electronic amplifier.



Thermopile for use in a Radiation Pyrometer

Using modern electronics these devices are now very common. One of the newest radiation Pyrometers is shown

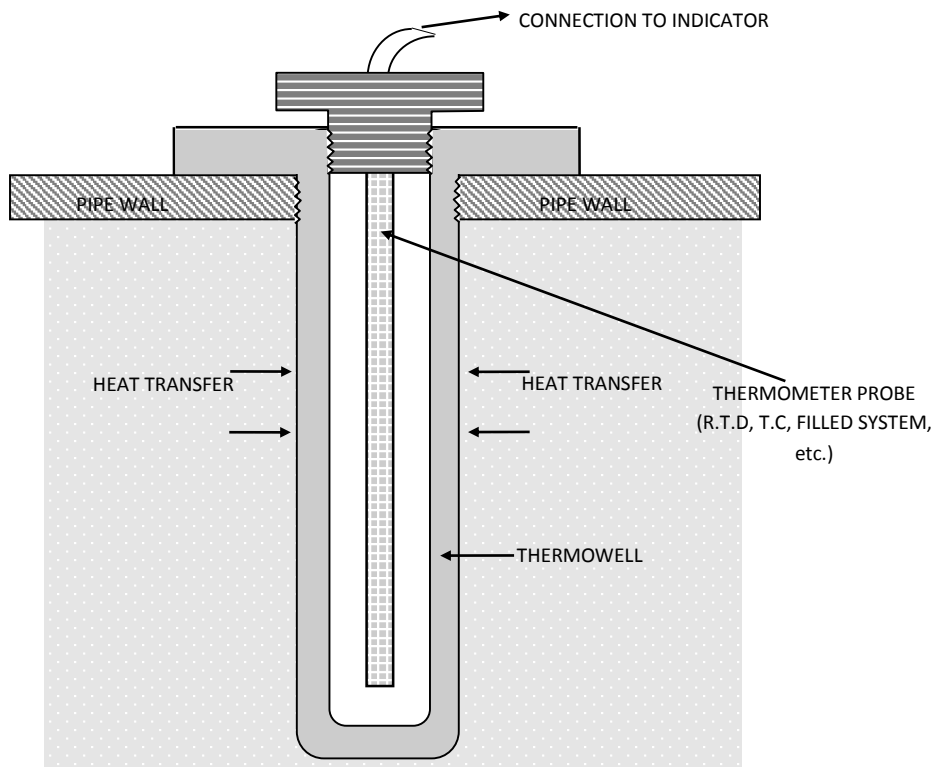


Pistol Grip Type Radiation Thermometer

This device (Calex/Rayteal) is a pistol grip non-contact infrared thermometer. It has a laser sight for pin point accuracy and other advanced features. The instrument has a measuring temperature range of -18°C to $+540^{\circ}\text{C}$ (0° to 1000°F). There is no need to focus or calibrate it and the operator does not need special training. A microprocessor makes the device accurate for repeated measurements on very small objects, (less than 25mm diameter). It gives current and maximum readings and it recalls the last reading. It's very good for measuring temperatures of hazardous materials or materials which are hard to reach or moving. The laser sight allows the operator to pinpoint small targets at a distance, even in the dark. It has an accuracy of $\pm 1\%$.

Thermowell

A thermowell is a device fitted in to a flow line so that the temperature of a fluid can be measured without shutting down the process. A Thermowell is placed in a flow line when the line is built. The thermometer is fitted into the thermowell. A typical thermowell installation is shown .

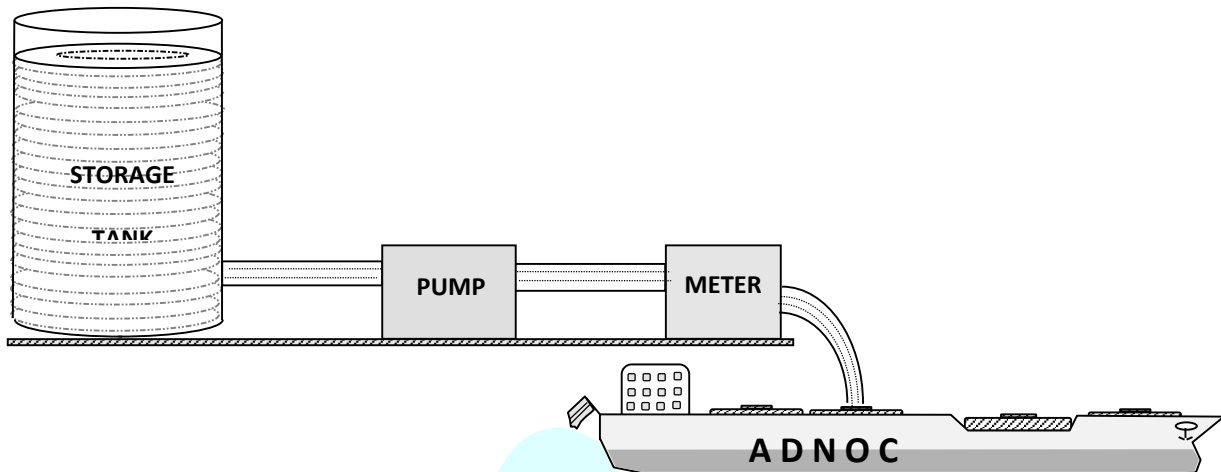


Thermowell Installation

The heat in a fluid takes longer to transfer through a thermowell, so changes in temperature take longer to show. Different methods are used to speed up heat transfer. Sometimes the space between the probe and the thermowell is filled with a liquid which conducts heat well. Sometimes the probe is placed in a corrugated aluminium cover to give a direct metal contact between the probe and the thermowell. When you change the probe in a thermowell you must replace the new probe in the same way as the original.

3-4 Flow Measurement

Units of flow



Flow Measurements

Figure shows a tanker being loaded from a storage tank. The amount of oil loaded must be accurately measured to know how much it costs (fiscal purposes). The total flow (quantity) of oil into the tanker can be measured in two ways:

- by volume, in barrels or cubic meters.
- by mass, in metric or imperial tons (the international standard for oil/gas transfer).

For control purposes the rate of flow (how fast the ship is loaded) is also measured. Rate of flow units can also be given in either volumetric or mass units.

For example

- Rate of flow by volume (volumetric)
 - Barrels / Hour
 - Cubic Feet / Min.
 - Cubic Meters / Sec.
- Rate of flow by mass
 - Tons / Hour
 - Kilograms / Sec.
 - Pounds / Min.

The petrochemical industry uses many different units and there is no common standard. The following list gives some of the units and their conversion.

VOLUME	
Barrel (bbl)	= 42 US gallons = 34.97 Imperial gallons = 163 litres.
Cubic foot (ft ³)	= 0.0929 m ³
Cubic meters (m ³)	= 10.76 ft ³
Cubic meter (m ³)	= 1000 litres
1 Litre	= 1000 cubic centimetres (millilitres).
MASS	
Pound (lb.)	= 0.454 kg
Kilogram (kg)	= 2.2 lb.
Imperial ton	= 2240 lb. (long ton)
Metric tonne	= 1000 kg
American ton	= 2000 lb. (short ton)
Long ton	= 1.016 Metric tonne
Metric tonne	= 0.984 long ton

VELOCITY			
ft/sec	ft/min	metre/sec	metre/min
1	60	0.3048	18.29
0.01667	1	0.005080	0.3048
0.03281	1.9685	0.01	0.600
3.281	196.85	1	60
0.0547	3.281	0.01667	1

ABBREVIATIONS	
Bopd	= Barrels oil per day
Blpd	= Barrels liquid per day
Bcpd	= Barrels condensate per day
Scfpd	= Standard cubic feet per day
MScfpd	= Thousand standard cubic feet per day
MMScfpd	= Million standard cubic feet per day
Nm ³ pd	= Normalised meters cubed per day
l/m or Lit/m	= Litres per minute
500 ml/s	= 500 millilitres per second.

Note : Sometimes the p (per) is omitted in the abbreviation. Standard and normalised refer to a standard temperature and pressure. This is normally fixed between buyer and seller. Common standards are:

14.7 psi at 68°F and 1.013 Bar at 15°C.

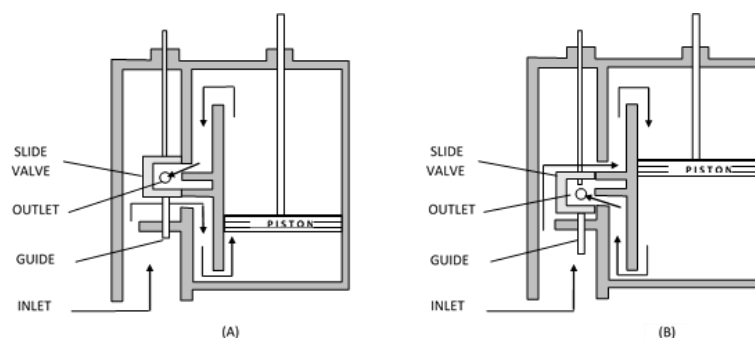
Quantity meters

There are two basic methods used to measure quantity (total flow)

- (a) Positive displacement.
- (b) Velocity meters (semi-positive displacement)

- **Positive Displacement**

The simplest form of positive displacement meter is the gasoline (petrol) pump. It will release an exact amount of gasoline in either imperial gallons or litres. A simple diagram to show its operation is shown in Figure 4-1.

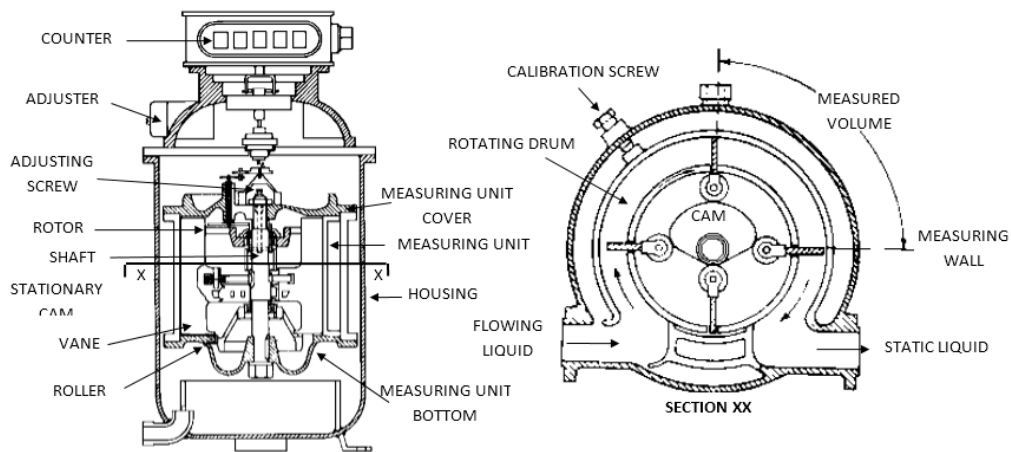


Reciprocating Piston Meter

Operation:

When the piston is at the bottom of its stroke (see Figure (A)) the slide valve opens the inlet vent to the bottom of the cylinder. The liquid (petrol) flows into the cylinder below the piston and pushes the piston upwards. As the piston rises the liquid in the top half of the cylinder is pushed through the outlet vent into the outlet pipe. When the piston is at the top of its stroke the slide valve closes the outlet at the top of the cylinder and opens the inlet vent. At the same time the slide valve opens the outlet vent at the bottom of the cylinder and closes the inlet (see Figure (B)). The pressure of the liquid coming into the top of the cylinder pushes the liquid at the bottom of the cylinder into the outlet pipe. The amount of liquid coming out of the cylinder during each stroke is measured. Each time the piston makes a stroke a meter connected to the top of the piston indicates how much liquid has been delivered.

The oil industry's positive displacement meter is the sliding vane meter. It can be used for measuring large quantities of liquid flow; eg, oil being loaded onto a tanker. A typical example is shown in Figure



ALEXANDRIA
INDUSTRIAL CONTROL
The Sliding Vane Meter

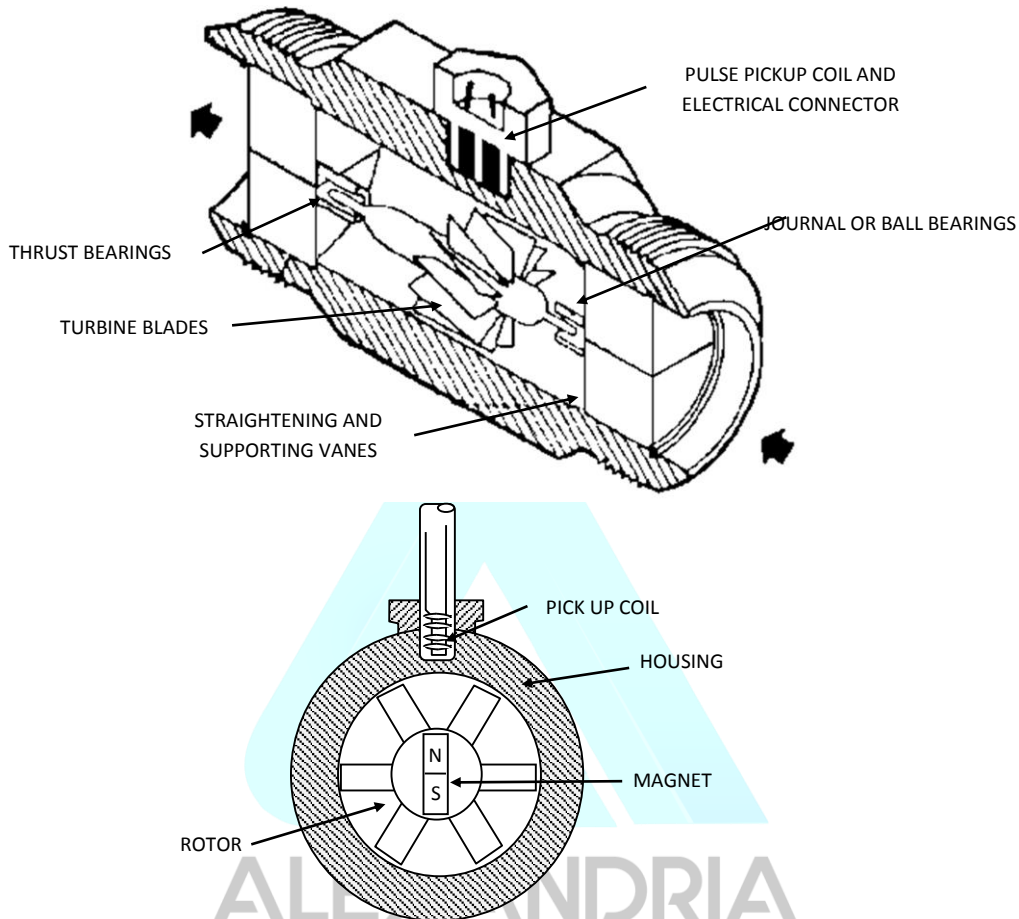
Operation:

This meter consists of a rotating drum with four sliding vanes (long blades) set inside it. The vanes move around a cam which is fixed in the centre of the drum. The liquid flowing through the meter pushes the vanes round with the drum. As the vanes rotate with the drum the cam pushes them in and out against the measuring wall. As the vanes are pushed against the measuring wall, they trap a measured volume of liquid between the drum and the measuring wall. Each revolution of the drum will measure 4 lots of the measured volume. The number of revolutions of the drum is counted and displayed. This gives the total flow passing through the meter. The calibration nut is used to adjust the side of the measurement chamber so that the volume of liquid passing through the meter can be measured exactly.

Note: A static liquid chamber is added so that there is no differential pressure across the measurement wall.

Velocity Meters (semi-positive displacement)

The sliding-vane type meter is not used much nowadays because it is slow. Most loading meters for shipping are now of the velocity type. The velocity meter measures the speed of the flow and works out the volume of flow using calibration figures.



The Turbine Meter

Operation:

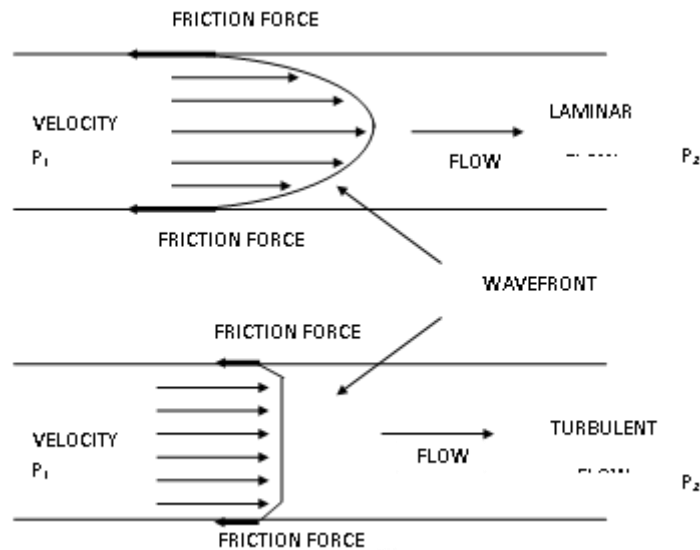
The velocity (speed) at which the rotor turns depends on the flow rate. The pick-up coil gets a pulse induced for every rotation. The number of pulses is counted by an electronics unit. This unit displays the total quantity of flow.

Note :- In the oil/gas industry these two quantity meters are only for liquid measurements.

Rate of flow measurement

The previous two quantity meters are used to calculate how much oil the customer pays for, so they must be extremely accurate. A modern turbine meter will measure to within $\pm 0.1\%$ of the true reading. Devices for measuring the rate of flow do not need to be so accurate. They are used mainly to give a flow signal to a controller.

Flow Basics



Flow in a Pipe

Figure shows the flow of a fluid (gas or liquid) down a pipe. The flow is produced by the differential pressure across the ends of the pipe ($P_1 - P_2$). The walls of a pipe are not perfectly smooth. The frictional force at the walls will cause the fluid to go slower at the edge than at the centre.

This leads to two different types of flow.

- **LAMINAR FLOW**

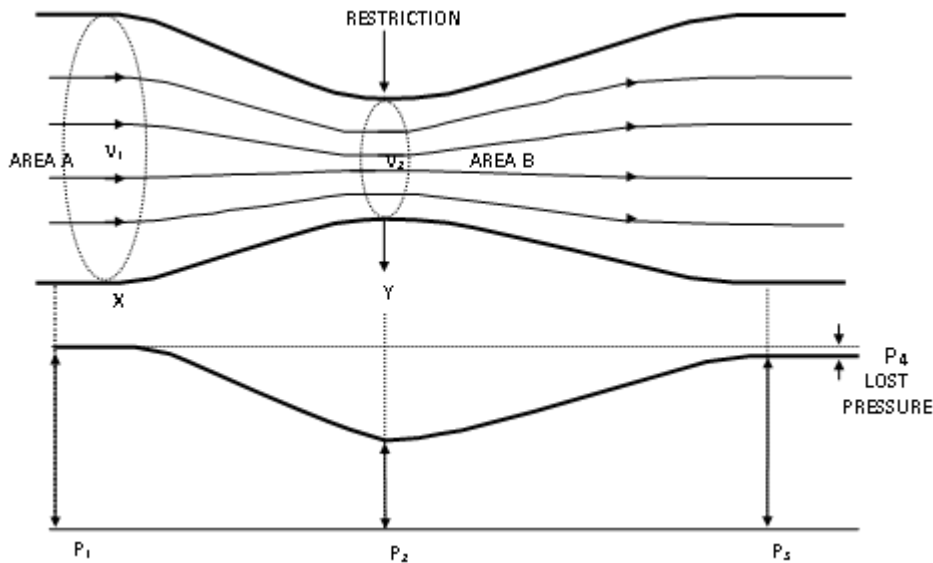
The fluid flow rate is slow and the velocity of the wavefront down the pipe is much higher in the centre of the pipe than at the edges.

- **TURBULENT FLOW**

The fluid flow rate is high and the velocity of the wavefront is the same across the pipe. However, the flow is a little slower at the edges against the wall.

The velocity lines on the diagram are called **STREAMLINES**. Engineers assume the streamlines are straight and parallel to each other.

Flow Measurement by Differential Pressure



Flow through a Restriction

Figure shows the flow of a fluid through a closed pipe full of liquid or gas. It has a restriction in the pipe.

Because there is a restriction, there is a difference between the pressure at the centre of the restriction (position Y) and the pressure in the normal pipeline (position X)

The difference in pressure between the centre of the restriction and the normal pipeline pressure ($P_1 - P_2$) is proportional to the square root of the flow rate (Q) given as an equation.

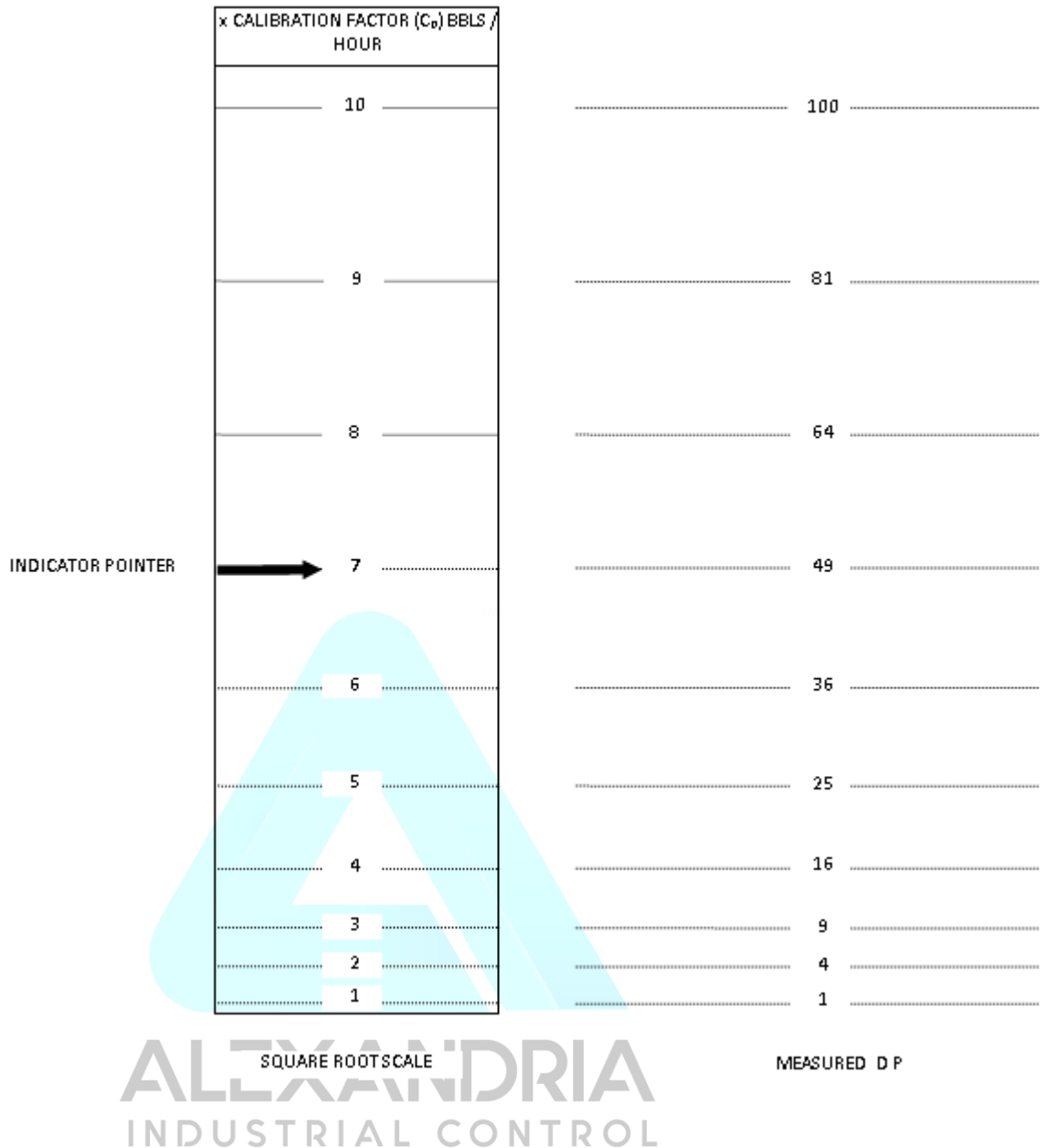
$$Q \propto \sqrt{P_1 - P_2}$$

or $Q = C_D \sqrt{P_1 - P_2}$

C_D is called the "coefficient of discharge". We can get this from tables. It depends on what is used to make the restriction.

Note :- $P_1 - P_2$ is often written as DP (Differential Pressure) or (ΔP).

The above equation means that the measured DP has to be square rooted before the flow rate can be calculated. Modern electronic transmitters do this automatically and a linear 4-20 mA signal for flow rate is produced. The older pneumatic systems produce a flow rate indication by using a square root scale or chart. A typical square root scale is shown below.



Theory

The equation $Q \propto \sqrt{D P}$ comes from Bernoulli's theory.

Bernoulli said "The sum of the kinetic energy (velocity energy) and pressure energy at any point in a closed pipe is a constant", i.e. the sum of these two types of energy is always the same.

This is true if the pipe is horizontal and the temperature of the fluid does not change.

$$\text{Kinetic Energy} = \frac{1}{2}mv^2$$

where m = Mass of fluid

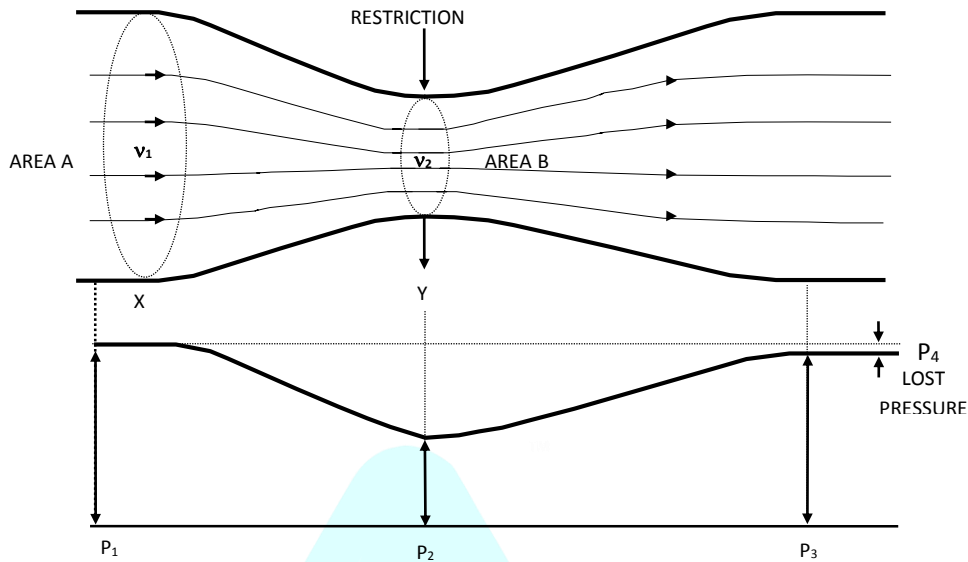
v = Velocity of the fluid

$$\text{Pressure Energy} = P m / \rho$$

P = Pressure of fluid

ρ = Density of fluid

As the fluid flows through the restriction, it gets faster (the velocity increases). This is because $\text{FLOW} = \text{VELOCITY} \times \text{AREA}$. If the area is smaller, the velocity is bigger. So, the pressure must fall and from the diagram;



Energy at point A = Energy at point B

$$\frac{1}{2}mv_1^2 + P_1 = \frac{1}{2}mv_2^2 + P_2$$

$$\text{or } P_1 - P_2 = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2$$

In this equation m can be cancelled, so that

$$P_1 - P_2 = \frac{1}{2}(v_2^2 - v_1^2)$$

The flow is constant so that

$$Q = AV_1 = BV_2$$

$$V_2 = V_1$$

$$P_1 - P_2 = \frac{1}{2} ((V_1)^2 - V_1^2)$$

$$P_1 - P_2 = \frac{1}{2} (V_1)^2 (-1)$$

This equation means that the velocity at the restriction is given by;

$$V_1 \propto \sqrt{P_1 - P_2}$$

The flow rate will be V_1 multiplied by the area B to give the equation;

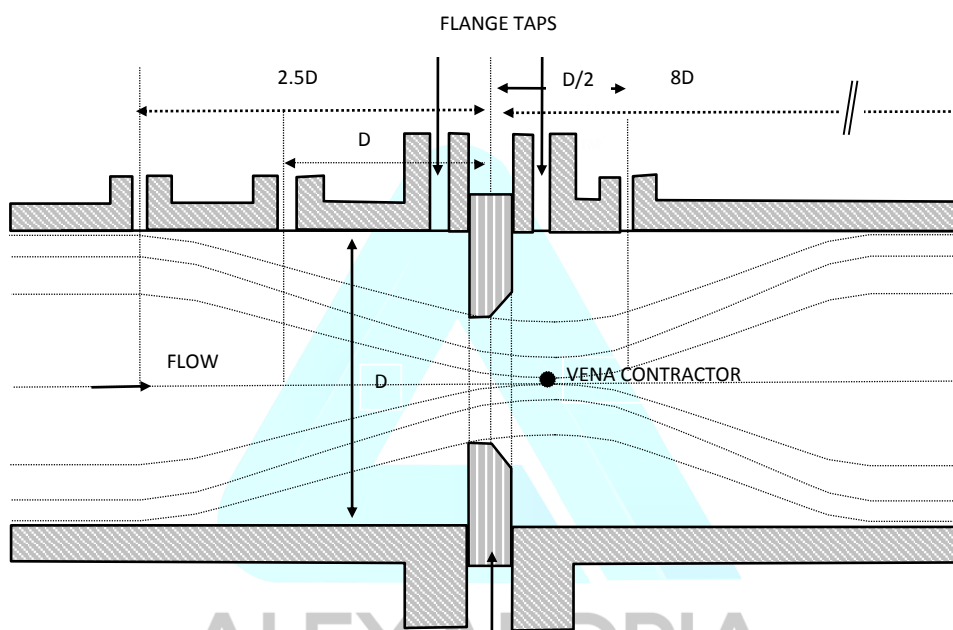
$$Q = C_D A \sqrt{P_1 - P_2}$$

C_D is called the "coefficient of discharge". We can get this from tables. It depends on what is used to make the restriction.

Differential Pressure Devices

There are many devices used to make a restriction in a pipeline so that rate of flow can be measured. The design of each device is fixed by either ISO or ISA (Instrument Society of America) standards. There are standard tables which are used to calculate flow. In the petroleum industry engineers assume the flow is turbulent. However, you can get tables for laminar flow if you need them. A field technician will only need to calibrate the differential pressure transmitter. An engineer will give a technician the figures he needs to do this. Some of the more common devices are given below together with their uses.

- The Orifice Plate



The Orifice Plate and Tappings

Figure shows an orifice plate fitted into a pipeline to make a differential pressure. The orifice plate is a flat disc with a hole in it shaped as shown. The front edge is sharp and the back edge is chamfered. The fluid is squeezed as it passes through the hole and has a maximum velocity at a point called the VENA CONTRACTOR.

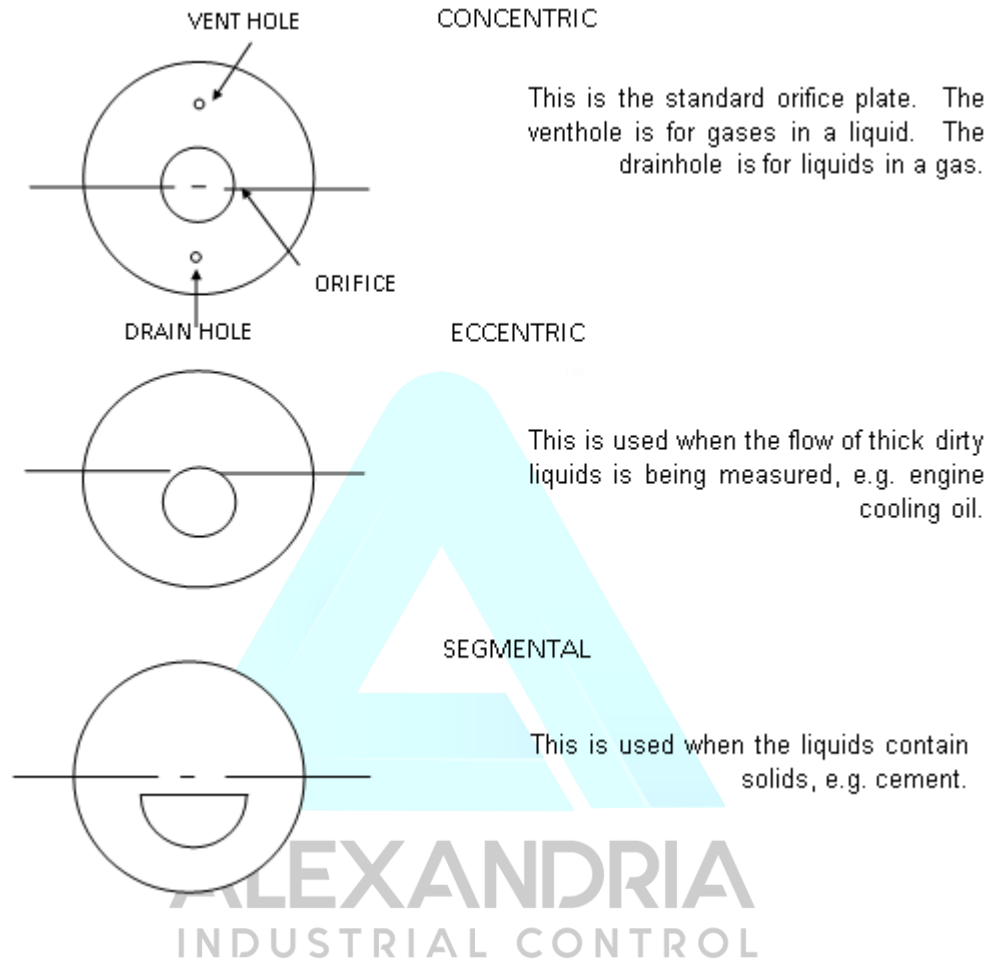
Taps (holes) are drilled into the pipeline and a differential pressure transmitter connected across the orifice plate. The differential pressure is measured. The square root of the differential is used to produce a flow signal which is proportional to the flow.

Standard tables are produced for the tapping places as shown.

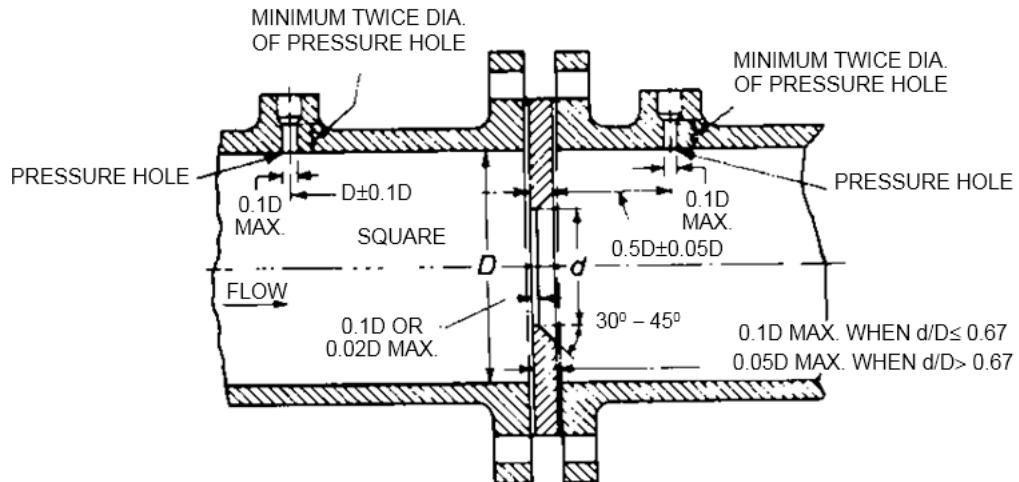
D & D/2	For maximum dp
Flange Taps	The most common tapping place. It produces a high D.P. These can be drilled accurately in the workshop. The taps can be vertical as shown on the diagram or they can be at an angle of 45° (corner taps).

2.5D & 8D	Not much used nowadays. This is because it is difficult to place them exactly on the pipeline. They measure the pressure loss across the plate.
-----------	---

The position of the hole in the plate depends on the fluid being measured. The diagram below shows typical plates and their uses.



All orifice plates must be made to an exact standard to fit the reference tables. A typical example is given below for a D and D/2 tap fitting.



Dimensions for a D and D/2 orifice plate fitting

The advantages and disadvantages of an orifice plate.

Advantages

1. Simple in operation
2. No moving parts
3. Reliable for a long time
4. Not expensive

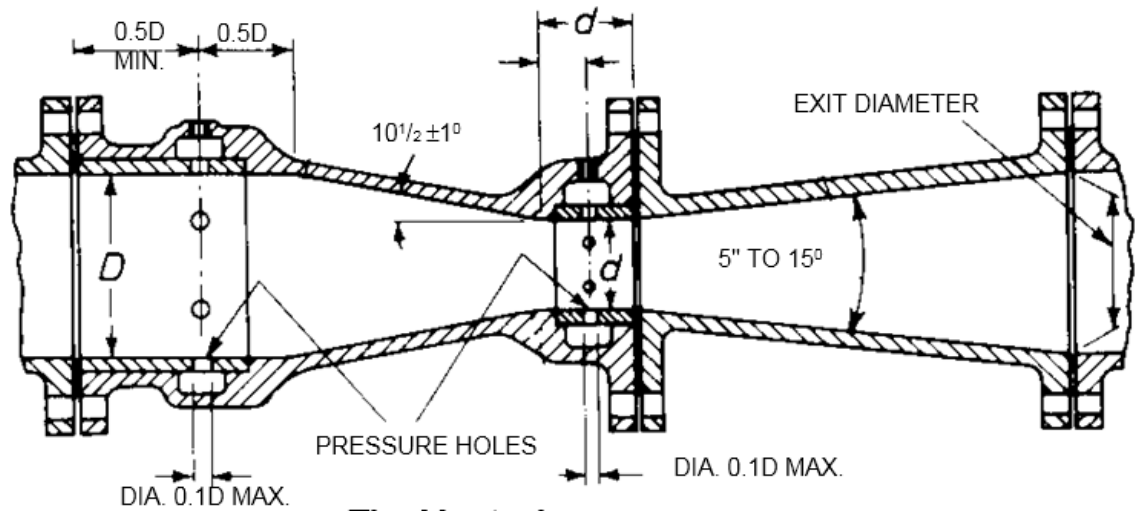
Disadvantages

1. Square root relationship
2. Difficult to install
3. Range of measurement small. Operator has to change plate (hole size) to change the range.

Note :- The orifice plate is the only suitable device when measuring high gas flow rates.

• THE VENTURI

This is a very expensive device. It is used when the energy of the flow is so low that the restriction could stop the flow (low pressure loss). The diagram below shows a typical Venturi with its pressure tapings (see Figure 4-9).



The Venturi

The advantages and disadvantages of the venturi.

Advantages

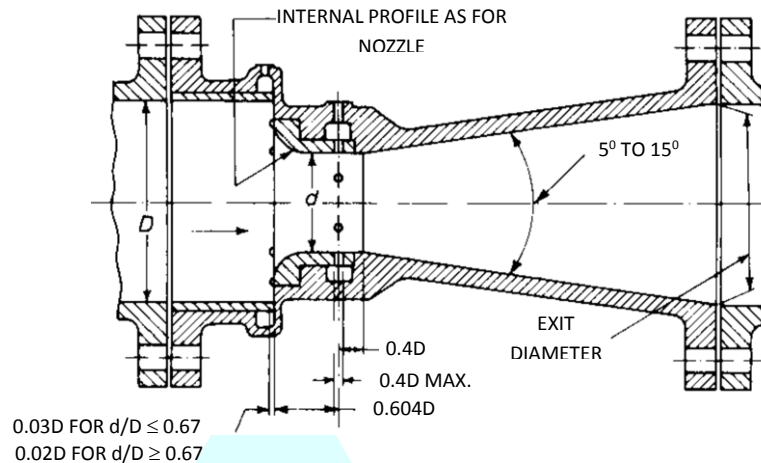
1. Simple in operation
2. Low pressure loss
3. Can be used with liquids that contain solids
4. Reliable for a long time
5. No moving parts

Disadvantages

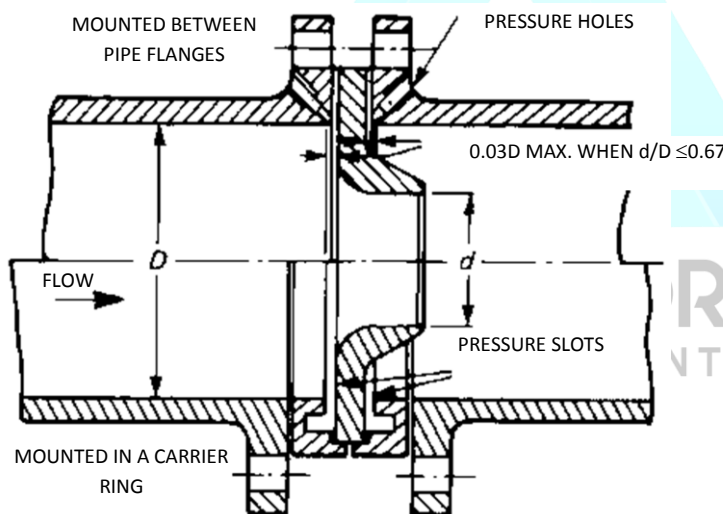
1. Expensive
2. Square root relationship
3. Poor range. Designed for one job only
4. Difficult to install

- NOZZLES

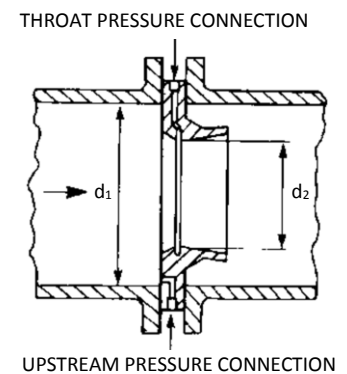
These are a compromise between the orifice plate and the venturi. They are cheaper than a venturi but have a high pressure loss. They are more expensive than an orifice plate, but have lower pressure loss. A few examples are shown below.



VENTURI - NOZZLE



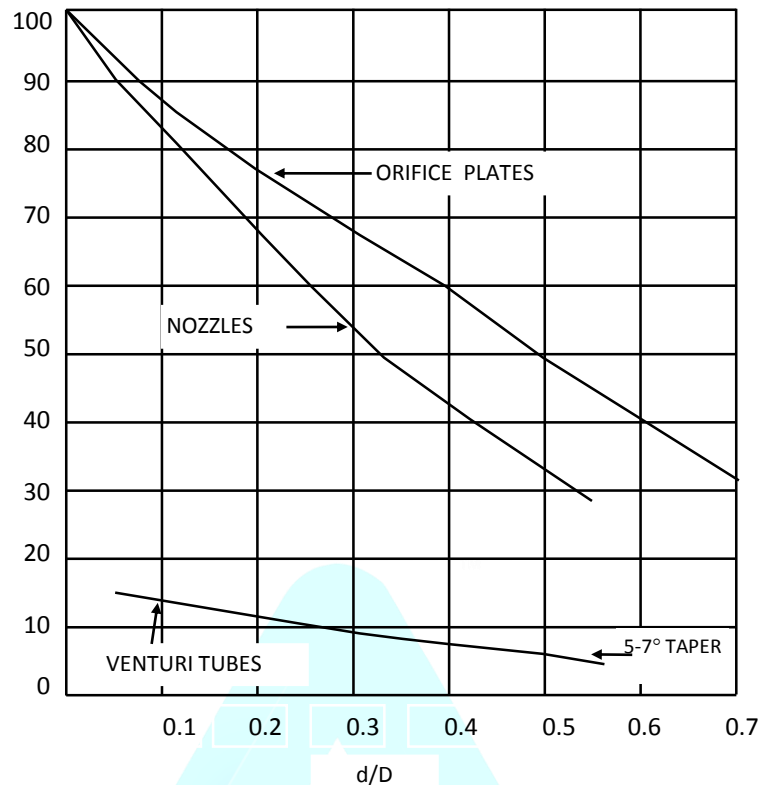
FLOW NOZZLE



DALL TUBE INSERT

- PRESSURE LOSS GRAPH

The graph below shows how much pressure is lost when these devices are used. The Y axis shows the hole size and the X axis shows the percentage of pressure lost. This shows the advantages of the venturi over the orifice plate. It also shows how the nozzle is between the two.



Pressure Loss Graph

Variable area meters

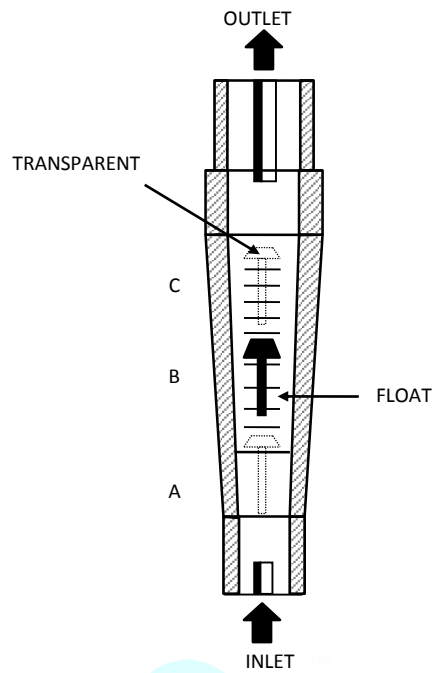
These are simple devices used to indicate small rates of flow. They are used by an operator out in the field. Typical uses are:

- In seal oil and lubrication oil flow lines on large rotating machines; eg, diesel engines and gas compressors.
- In cooling water lines for machines and processes.

The graph below shows a variable area meter (Rotameter).

Operation

The Rotameter is fitted vertically into the flow line. The flow of the fluid is from bottom to top through the cylinder. The cylinder increases in area from bottom to top. With no flow, the float is at the bottom (position A). When the flow increases, the pressure makes the float rise. It will rise to a position where the flow pressure on the float equals the weight of the float, (position B). If the flow gets faster there is more pressure on the float and it will rise higher (position C). The flow rate indicated depends on the size of the device. It is pre-calibrated by the manufacturer. The operator reads the flow rate from the transparent scale using the top of the float as a marker.



The Rotameter

Magnetic flow meter

The magnetic flow meter is a volumetric device used for electrically conductive liquids and slurries.

The magnetic flow meter design is based on Faraday's law of magnetic induction, which states that:

"The voltage induced across a conductor as it moves at right angles through a magnetic field proportional to the velocity of that conductor." That is, if a wire is moving perpendicular to its length through a magnetic field, it will generate an electrical potential between its two ends.

Based on this principle, the magnetic flow meter generates a magnetic field perpendicular to the flow stream and measures the voltage produced the fluid passing through the meter. A set of electrodes detects the voltage.

The voltage produced is proportional to the average velocity of the volumetric flow rate of the conductive fluid.

The tube is constructed of non-magnetic material (to allow magnetic field penetration) and is lined with a suitable material to prevent short-circuiting of the generated voltage between the electrodes. The tube is used to support the coils and transmitter assembly.

Generally the electrodes are of stainless steel but other materials are also available. These electrodes have to be chosen with care to avoid corrosion.

Dirty liquids may foul the electrodes, and cleaning methods such as ultrasonic may be required.

Theoretically, it can measure flow down to zero, but in reality its operating velocity should be less than 3 ft / s (1 m/s). A velocity of 6 to 9 ft/s (2 to 3 m/s) is preferred to minimise coating.

It should be noted that at velocities greater than 15 ft/s (5 m/s) accelerated liner wear could result.

This meter has no moving parts; and is unaffected by changes in

- Fluid
- Viscosity
- Pressure

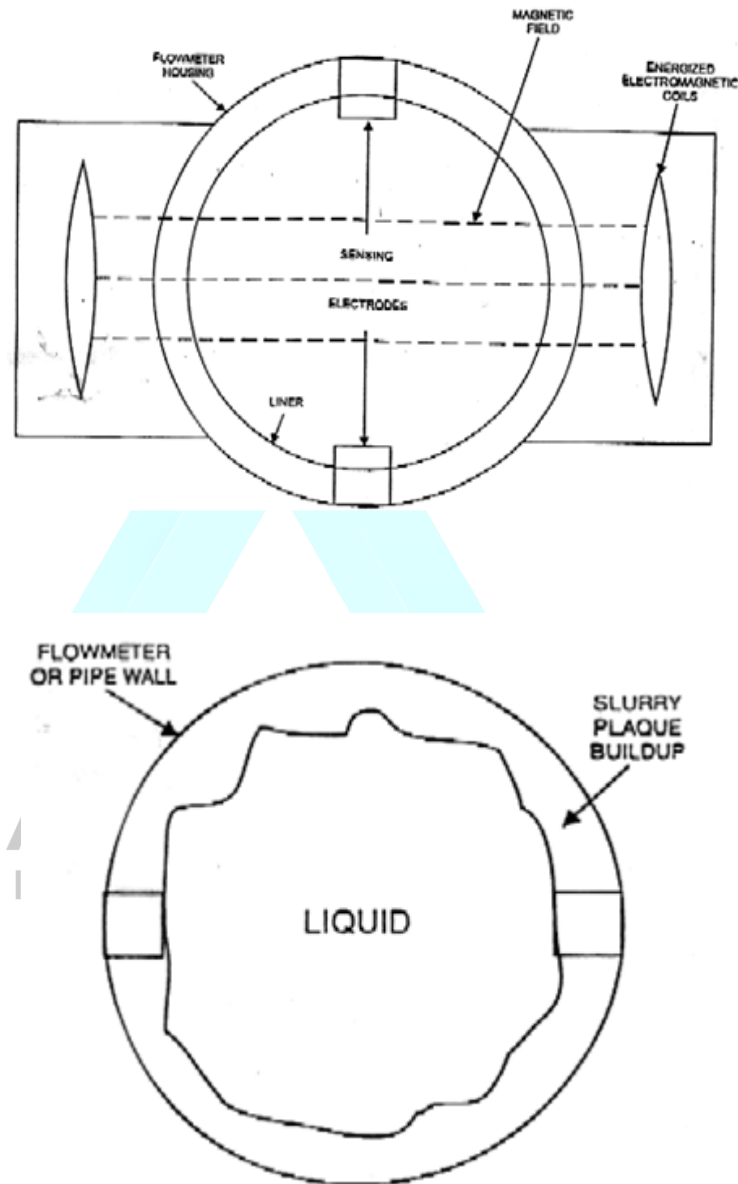
Advantages

- Are bi-directional
- Have no flow obstruction
- Are easy to re-span
- Are available with DC or AC power
- It can measure pulsating and corrosive flow.
- It can measure multiphase; however, all components should be moving at the same speed; the meter can measure the speed of the most conductive component.
- It can install vertically or horizontally (the line must be full, however) and can be used with fluids with conductivity greater than 200 umhos/cm.
- Changes in conductivity value do not, affect the instrument performance.

Disadvantages

- It's above average cost
- It's large size
- Its need for a minimum electrical conductivity of 5 to 20 umhos / cm
- Its accuracy is affected by slurries containing magnetic solids (some meters can be provided with compensated output in this case).
- Electrical coating may cause calibration shifts

- The line must be full and have no air bubbles (air and gas bubbles entrained in the liquid will be metered as liquid, causing a measurement error).
- Vacuum beakers may require in some applications to prevent the collapse of the liner under certain process conditions
- In some applications, appropriate mechanical protection for the electrodes must be provided.

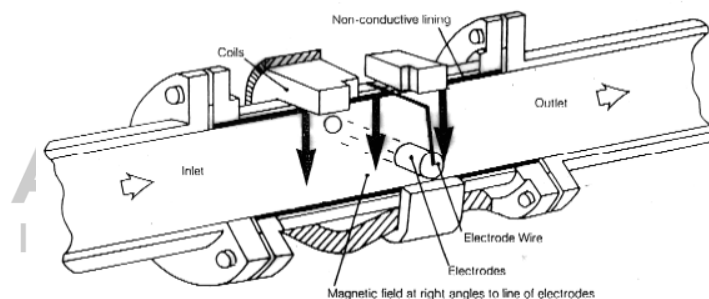
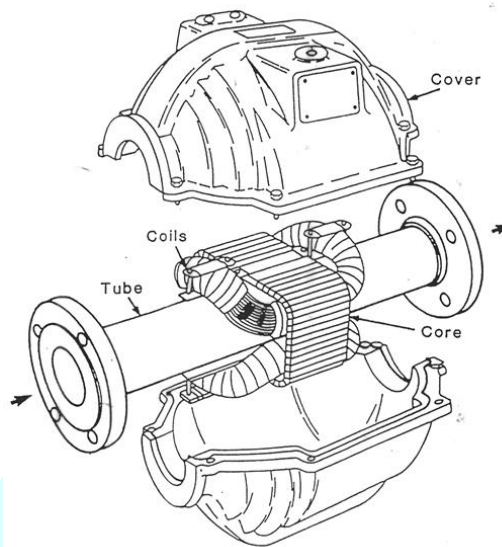


DC types are unaffected by variations fluid conductivity and thus are generally preferred. However, AC types are used for.

- Pulsating flow applications
- Flow with large amounts of entrained air
- Applications with spurious signals that may be generated from small

Electro-Chemical reactions

- Slurries with non-uniform particle size (they may clamp together)
- Slurries with solids not g well mixed into the liquid.
- Quick response.



MASS FLOW MEASUREMENT

Traditionally fluid flow measurement has been made in terms of the volume of the moving fluid even though the meter user may be more interested in the weight (mass) of the fluid. Volumetric flow meters also are subject to ambient and process changes, such as density, which changes with temperature and pressure. Viscosity changes also may affect volumetric flow sensors.

Thus for a number of years there has been much interest in finding ways to measure mass directly rather than to use calculating means to convert volume to mass. As of the early 1990s, there are three ways to determine mass flow:

1. The application of microprocessor technology to conventional volumetric meters.
2. Use of Coriolis flow meters, which measure mass flow directly.
3. The use of thermal mass flow meters that infer mass flow by way of measuring heat dissipation between two points in the pipeline.

Microprocessor-Based Volumetric Flow meters

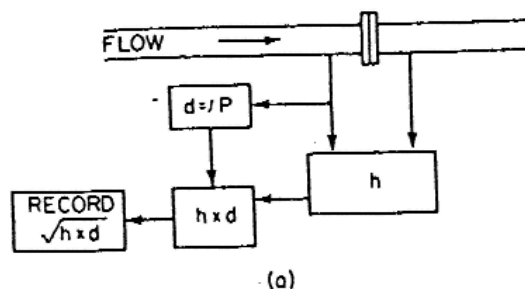
As shown in the figure below, with microprocessors it is relatively simple to compensate a volumetric flow meter for temperature and pressure. With reliable composition (density) information, this factor also can be entered into a microprocessor to obtain mass flow readout. However, when density changes may occur with some frequency, and particularly where the flowing fluid is of high monetary value (for example, in custody transfer), precise density compensation (to achieve mass) can be expensive.

For example, a gas mass flow meter system may consist of a vortex gas velocity meter combined with a gas densito-meter. The densito-meter can be located upstream of the flow device and produce a pressure difference that is linearly proportional to the density of the flowing gas at line conditions. This unit will automatically correct for variations in pressure, temperature, specific gravity, and super-compressibility.

The gas sample from the pipeline passes across a constant-speed centrifugal blower and returns to the pipeline. The pressure rise across the blower varies directly with the gas density. A differential-pressure signal from the densito-meter is combined with a flow-rate signal from the gas meter. The cost of such instrumentation can be several times more than an uncompensated meter.

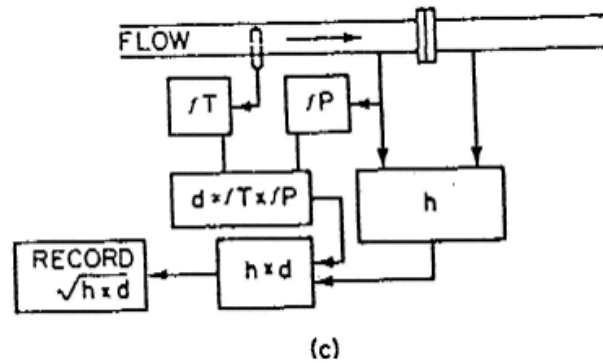
The relatively high cost of this instrumentation, combined with an increasing need for reliable mass-flow data, established the opportunity for direct mass-flow instruments of the Coriolis and thermal types.

Pressure-compensated meter wherein the differential pressure is measured by an appropriate sensor and the signal is fed into a combining module, along with a signal representing the pressure correction. The output from the combining module is used for display and to regulate the meter integrator.



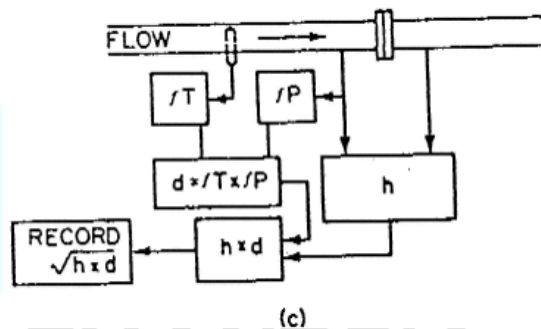
Pressure compensated Flow loop

Temperature-compensated meter wherein the differential pressure is measured by an appropriate sensor and the signal is fed into a combining module, along with a signal representing the temperature correction. The output from the combining module is used for display and to regulate the meter integrator.



Pressure and Temp compensated Flow loop

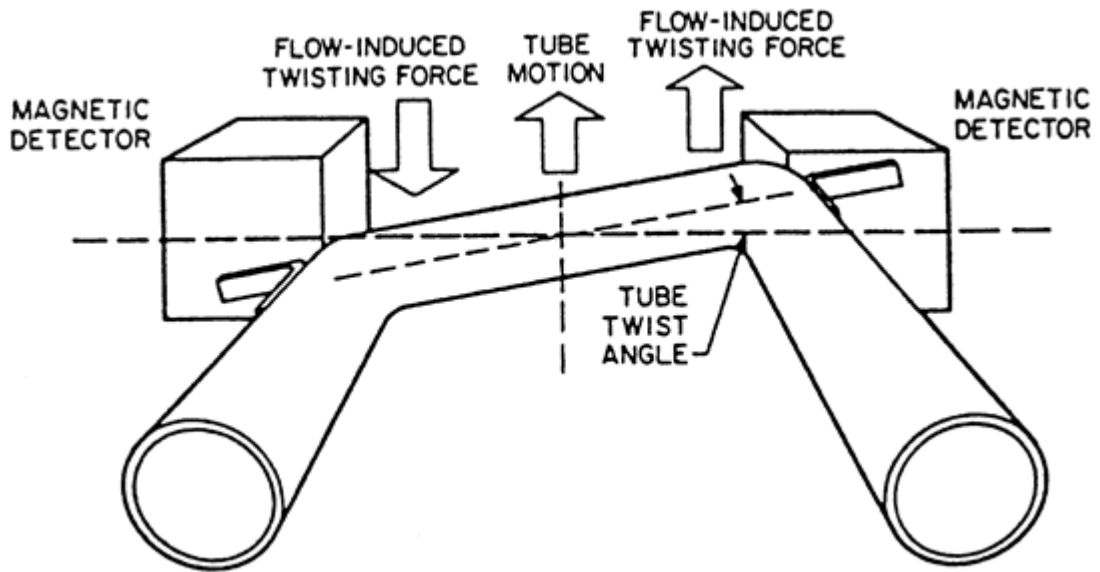
Flow measurement where the flow is compensated for any change in the operating temperature and pressure.



Pressure and Temp compensated Flow loop

Coriolis Flow Meters

The complete Coriolis unit consists of (1) a Coriolis force sensor and (2) an electronic transmitter. The sensor comprises a tube (or tubes) assembly, which is installed in the process pipeline. As shown in the below figure, an U-shaped sensor tube is vibrated at its natural frequency. The angular velocity of the vibrating tube, in combination with the mass velocity of the flowing fluid, causes the tube to twist. The amount of twist is measured with magnetic position detectors, producing a signal, which is linearly proportional to the mass flow rate of every parcel and particle passing through the sensor tube.



Typical Coriolis Meter

The output is essentially unaffected by variations in fluid properties, such as viscosity, pressure, temperature, pulsation, entrained gases, and suspended solids.

The detectors are not in contact with the flowing fluid, except the fluid at the inside wall of the tube. The tube is usually made of stainless steel. In some other application it is made of corrosion and erosion resistant material. Two magnetic position detectors, one on each side of the U-shaped tube, generate signals that are routed to the associated electronics for processing into an output.

There are two common tube types:

- Straight
- Curved

Straight Tube

The straight tube is used mainly for multiphase and for fluids that can coat or clog (since the straight type can be easily cleaned). In addition, the straight tube requires less room, that can be drained, has a low-pressure loss. Straight tube reduces the probability of air and gas entrapment, which would affect meter performance. However, the straight tube must be perfectly aligned with the pipe.

Curved Tube

Compared to the straight tube, the curved tube has a wider operating range measures low flow more accurately, is available in larger sizes, tends to be

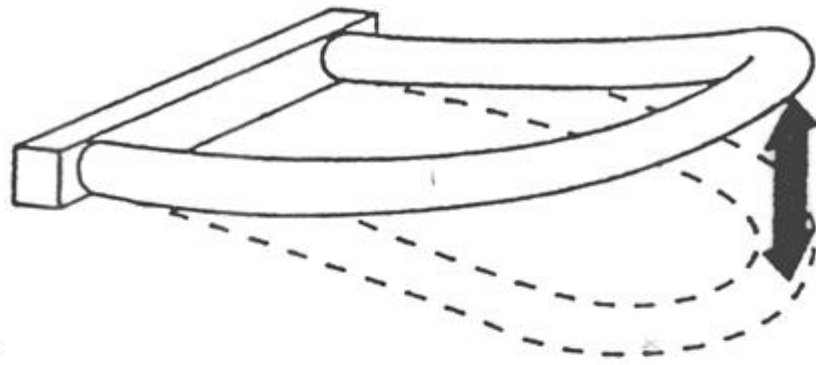
lower in cost (due to low cost of materials), and has a higher operating temperature range. However it is more sensitive to plant vibrations than the straight type.

Advantages

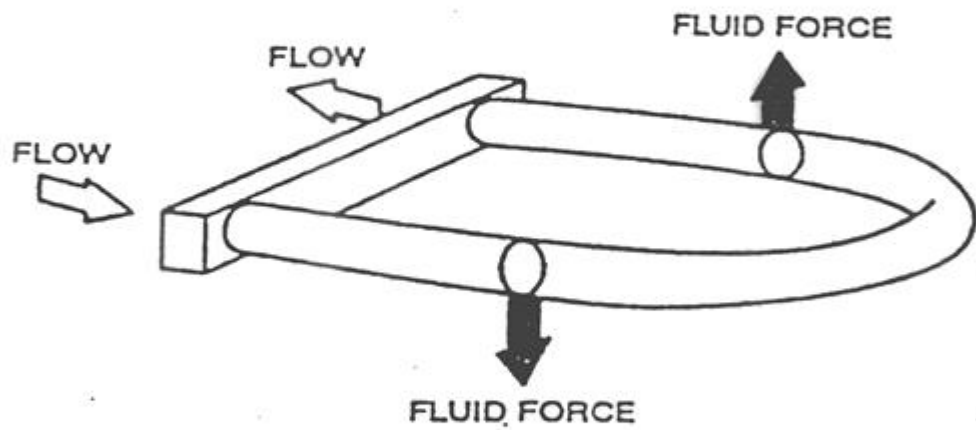
- It measures mass flow directly.
- One device that measures flow and density. Some Coriolis meter also measures temperature.
- It can handle difficult applications.
- It is applicable most fluids that has no Reynolds number limitation.
- It is not affected by minor changes in specific gravity or by viscosity.
- This type of device requires low maintenance.
- It is not sensitive to velocity profiles
- It can be used bi-directional
- It can handle abrasive fluids

Disadvantage

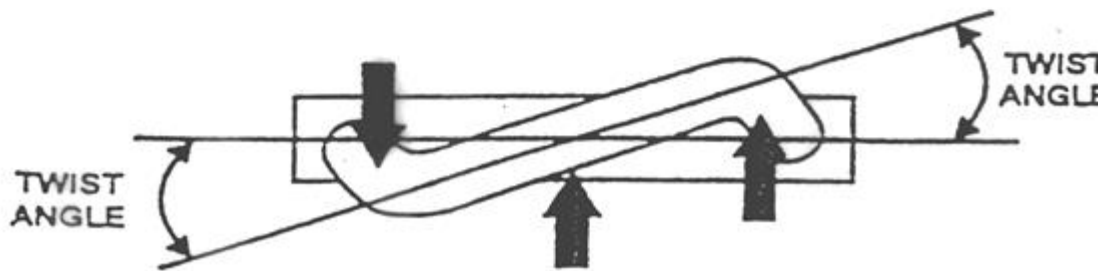
- Its purchase cost is high
- Inaccurate measurement when air and gas pockets in the liquid and by slug flow.
- The pipe must be full and must remain full to avoid trapping air gases inside the tube.
- A high-pressure loss is generated due to the small tube diameters
- It needs re-calibration if the density of the liquid being measured is very different from the one for which calibration was performed.
- Coating of the tube affects the density measurement (since it will affect the measured frequency), but not the flow measurement (since the degree of tube twist is independent of tube coating).



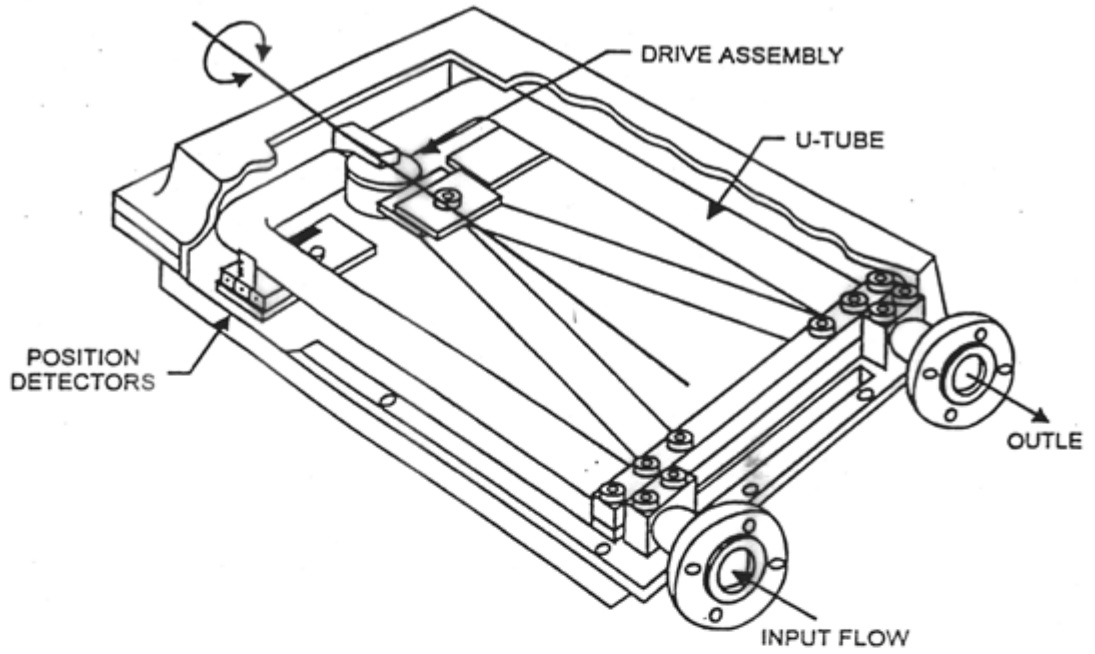
VIBRATING FLOW TUBE



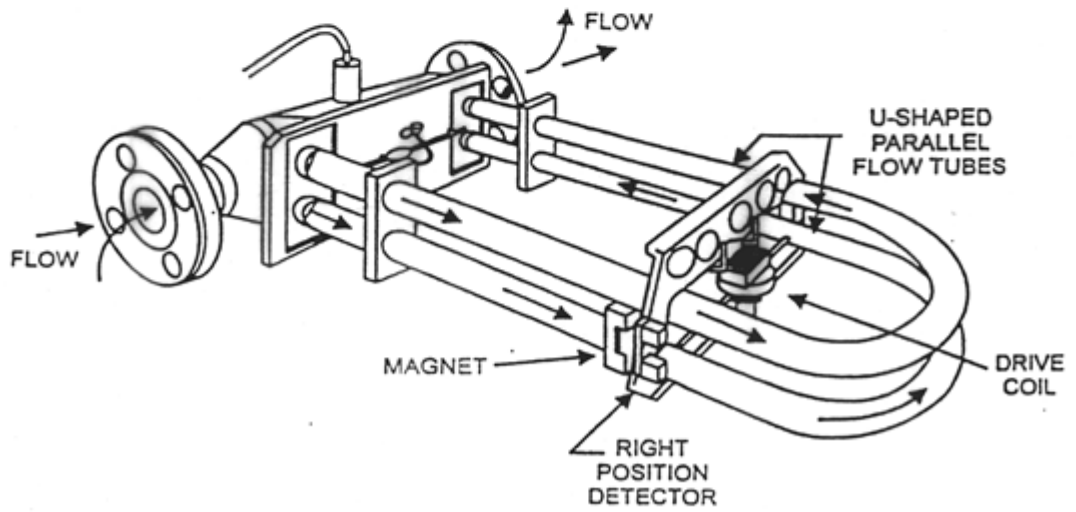
FLUID FORCES REACTING TO VIBRATION OF FLOW TUBE



END VIEW OF FLOW TUBE SHOWING TWIST



(A) SINGLE U-TUBE DESIGN



(B) DUAL U-TUBE DESIGN

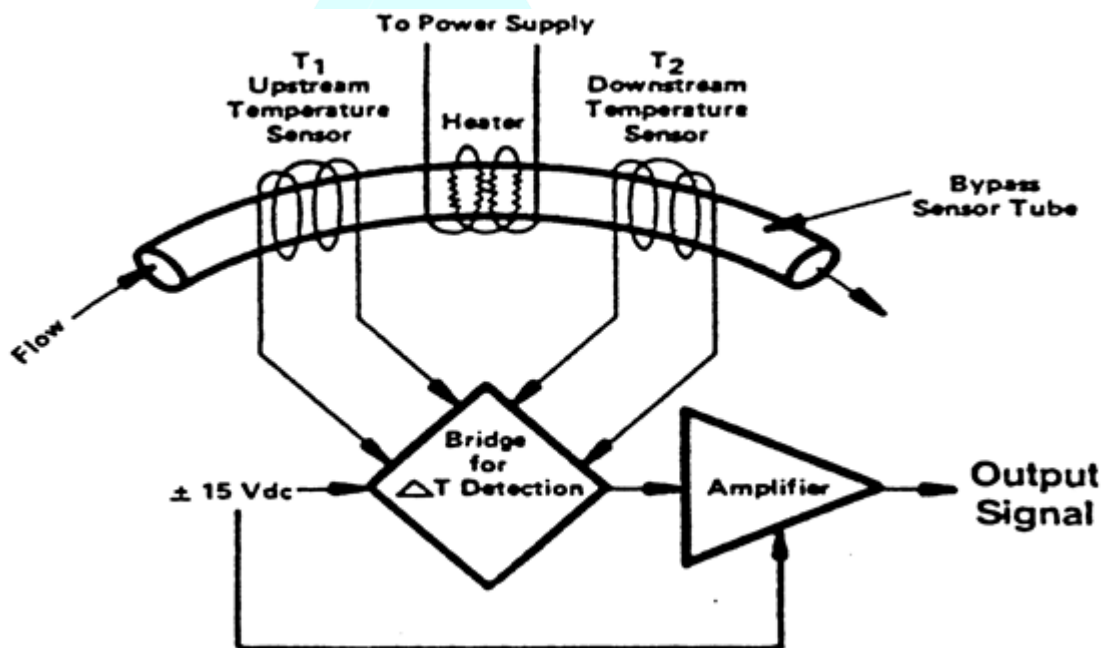
Thermal Mass Flow meters

Like the Coriolis flow meter, after many years of design work and limited applications, the thermal mass flow meter did not become widely accepted until the late 1970s and early 1980s. In Thermal Mass Flow Meter's thermodynamic operating principle is applied.

As shown in the below figure, a precision power supply directs heat to the midpoint of a sensor tube that carries a constant percentage of the flow. On the same tube at equidistant two temperature elements (RTD) are installed upstream and downstream of the heat input. With no flow, the heat reaching each temperature element (RTD) is equal. With increasing flow the flow stream carries heat away from the upstream element T1 and an increasing amount toward the downstream element T2. An increasing temperature difference develops between the two elements.

This temperature difference detected by the temperature elements is proportional to the amount of gas flowing, or the mass flow rate.

A bridge circuit interprets the temperature difference and an amplifier provides the 0- to 5-volt dc and 4- to 20-mA output signal.



Typical Thermal Mass Flow meter construction

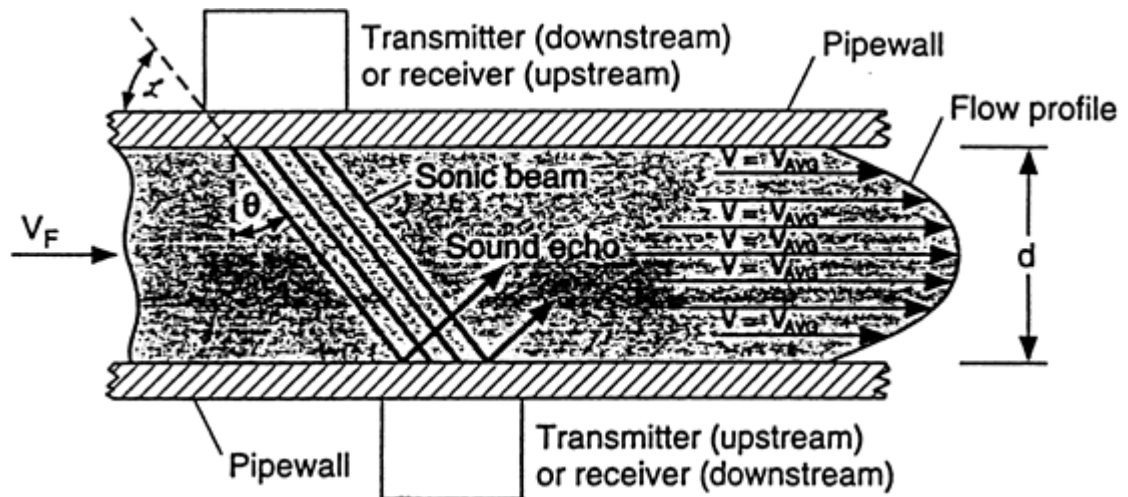
FLOW METERS WITH SENSORS MOUNTED EXTERNALLY

These offer no obstruction to the fluid and have no wetted parts. They cannot be used in all applications due to their inherent limitations.

Ultrasonic Flow meters

Transit Time, Time-of-Travel, Time-of-flight

In an ultrasonic (transit time) flow meter two transducers are mounted diametrically opposite, one upstream of the other. Each transducer sends an ultrasonic beam at approximately 1 MHz generated by a piezoelectric crystal. The difference in transit time between the two beams is used to determine the average liquid velocity. The beam that travels in the direction of the flow travels faster than the opposite one.



Ultrasonic Flow Meter

This figure shows the principle of transit-time ultrasonic flow meter, clamp-on type. Transducers alternately transmit and receive bursts of ultrasonic energy.

Each transducer acts as a transmitter and receiver. Two transducers are used to cancel the effect of temperature and density changes on the fluid sound transmission properties. The speed of sound is not a factor since the meter looks at differential values.

The crystals producing the ultrasonic beam can be in contact with the fluid or mounted outside the piping (clamp-on transducers).

Advantages

- It does not cause any flow obstruction
- It can be installed bi-directional
- It is unaffected by changes in the process temperature
- It is suitable to handle corrosive fluids and pulsating flows.
- It can be installed by clamping on the pipe and is generally suited for measurements in very large water pipes.

Disadvantages

- This type of meters are highly dependent on the Reynolds number (the velocity profile)
- It requires nonporous pipe material (cast iron, cement and fibreglass should be avoided)
- It requires periodic re-calibration
- It is generally used where other metering methods are not practical or applicable.

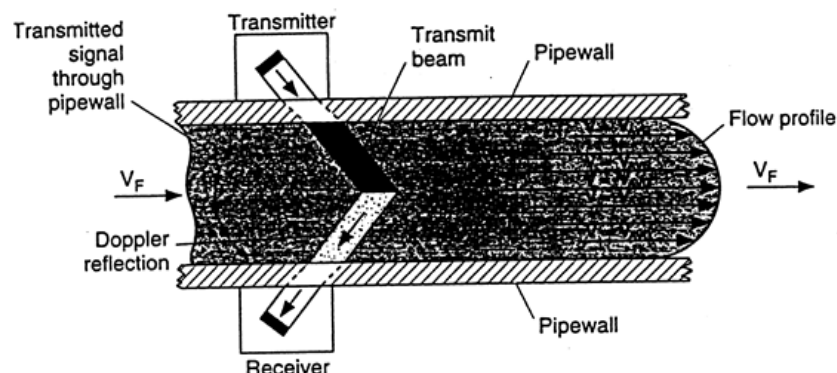
Doppler-Effect Flow Meter

The configuration shown utilises separated dual transducers mounted on opposite sides of the pipe.

It is mandatory in a Doppler-Effect Flow Meter the flowing stream contains sonically reflective materials, such as solid particles or entrained air bubbles. Without these reflectors, the Doppler system will not operate. In contrast, the transit-time ultrasonic flow meter does not depend on the presence of reflectors.

Doppler-effect flow meters use a transmitter that projects a continuous ultrasonic beam at about 0.5 MHz through the pipe wall into the flowing stream. Particles in the stream reflect the ultrasonic radiation, which is detected by the receiver. The frequency reaching the receiver is shifted in proportion to the stream velocity. The frequency difference is a measure of the flow rate. When the measured fluid contains a large concentration of particles or air bubbles, it is said to be sonically opaque. More opaque the liquid, greater the number of reflections that originate near the pipe wall, a situation exemplified by heavy slurries. It may be noted from the flow profile, that the fluid velocity is greatest near the centre of the pipe and lowest near the pipe wall.

The Doppler Flow meter works satisfactorily for only some applications and is generally used when other metering methods are not practical or applicable. It should not be treated as a “universal“ portable meter.



Doppler-effect Ultrasonic Flow Meter

This figure shows the principle of Doppler-effect ultrasonic flow meter with separated opposite-side dual transducers.

Advantage

- The common clamps-on versions are easily installed without process shutdown.
- It can be installed bi-directional
- Flow measurement is not affected due to change in the viscosity of the process.
- Generally suitable for measurements in large water pipes
- The meter produces no flow obstruction
- Its cost is independent of line size.

Disadvantage

- The sensor may detect some sound energy travelling in the causing interference reading errors.
- Its accuracy depends on the difference in velocity between the particles, the fluid, the particle size, concentration, and distribution.
- The instrument requires periodic re-calibration.

Alexandria Industrial Control



INSTRUMENTATION

ALEXANDRIA

Chapter 4: FINAL CONTROL ELEMENTS

FINAL CONTROL ELEMENTS

Introduction

In process systems, the final control element is normally a pneumatically actuated control valve, which is used to regulate the flow of a fluid. It provides the necessary power to translate the controller's output to the process. Pneumatics is used because of the original popularity of pneumatic control systems and the comparatively low operating pressures used, also for safe operation in the oil & gas facilities.

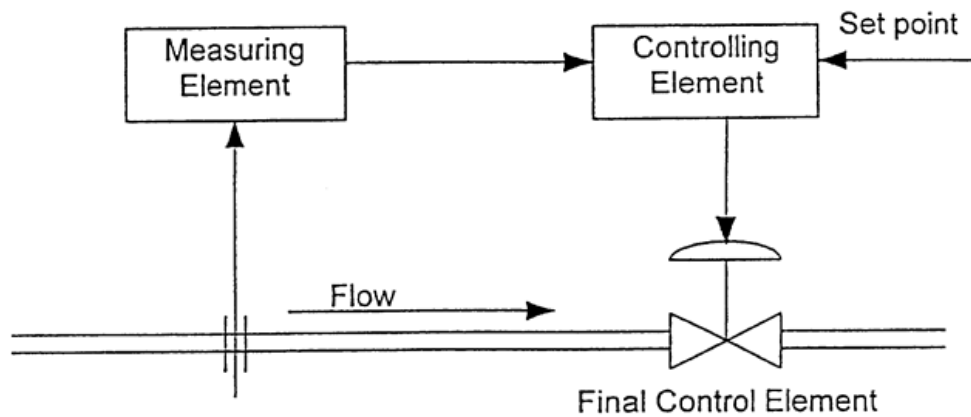


Figure 1. Final control element in a control loop.

As shown in figure 1, in the basic components of a control loop, the control valve is subject to the harshest conditions. A control valve is also the most expensive item and the most prone to incorrect selection.

Major Parts of the Control Valve:

The major parts of any control valves are:

1. The actuator
2. The valve body assembly

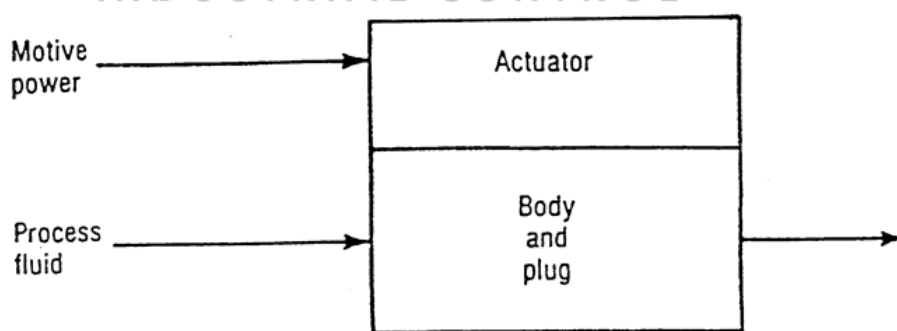


Figure 2. Major parts of the control valve

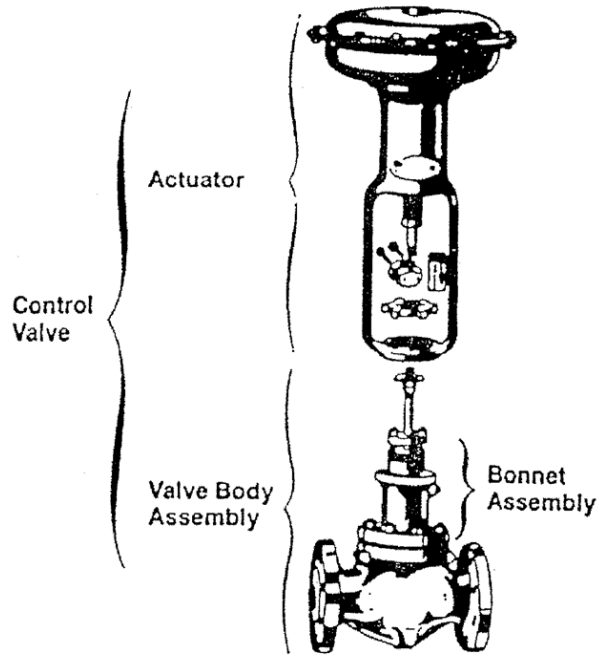
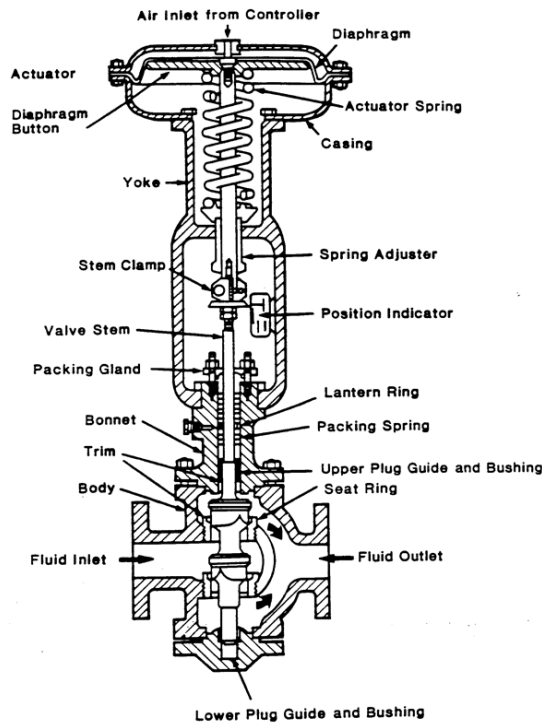


Figure 3. Major Parts of the Control Valve

There are also several types of body designs, flow characteristics, actuator types and trim designs.



CONTROL VALVE TERMINOLOGY

Figure 4. Control Valve Terminology

Functional block Diagram of the control valve:

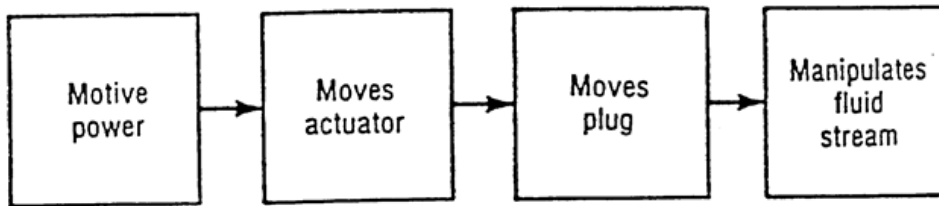


Figure 5. Functional Block of the control valve

In most cases a control valve is expected to respond to a control signal to keep a process variable steady.

Main Types of Control Valves:

Control valves can be classified based on body design as follow:

1) Sliding Stem Control Valves

1.1- Globe Bodies

Globe valves are the most common type in use today. They may single port, double port and three-way. Split body and angle valves are classified as special type globe valves

a) Single Port

Single port valves are simple in construction, frequently used in sizes 2 inches and below,

provides tight shutoff, but may have high unbalanced forces on the plug requiring large actuators. These valves can be constructed to have the valve plug move into or out of the port with increasing actuator-loading pressure. Figure 6 shows a typical design for a single port body unbalanced design.

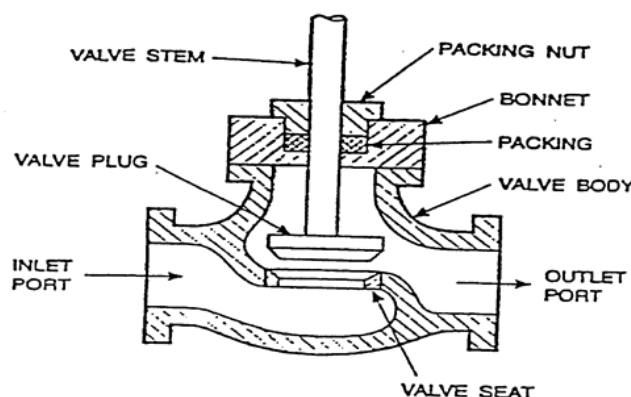


Figure 6. Single port - globe body with plug to move into the seat with increasing signal pressure.

b) Double Port

Double port valves balance the forces acting on single port valves (figure 7). They have higher flow capacities and require smaller stem forces compared to the same size single port valve. They are frequently specified for sizes larger than 2 inches but should not be used when leakage is unacceptable. Reversible plug design is available to open or close the valve with increasing loading pressure.

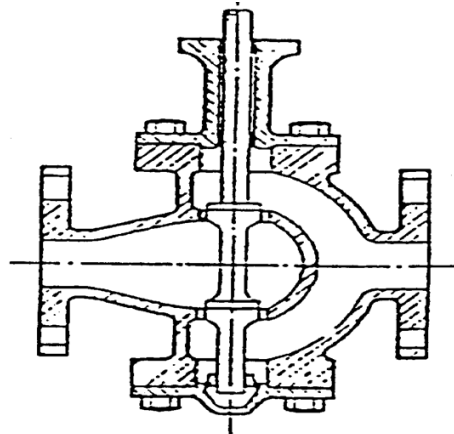


Figure 7. Double port globe body provides fewer imbalances of plug forces.

c) Three- Way

Three-way valves are designed to blend (mix) or to divert (split) flowing streams. Total flow is proportioned only, not controlled, in either service. Most three-way valves have the characteristic of unbalanced forces on the valve plug and require large operators. They are usually installed with the flow tending to open the valve plug discs to prevent "slamming" of the valve plug.

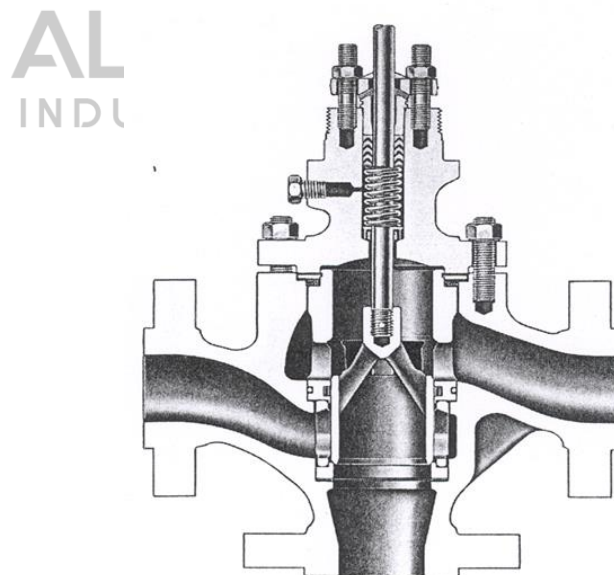


Figure 8. Three-way valve have three connections for converging (mixing) or diverting (splitting) operation.

d) Angle valves

Angle valves nearly always single ported are often used where space is at a limited. They are easily removed from the line and can handle sludge and erosive materials.

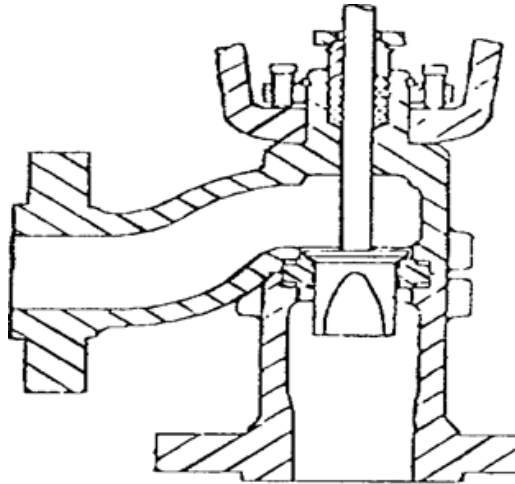


Figure 9. Angle valve with split body construction is easily removed and reinstalled.

1.2- Diaphragm Valve

The diaphragm valve consists basically of a body, bonnet and flexible diaphragm (figure 10). It is more often referred to as a Saunders-Type valve. Closure is made by using a flexible dome-like diaphragm against a weir.

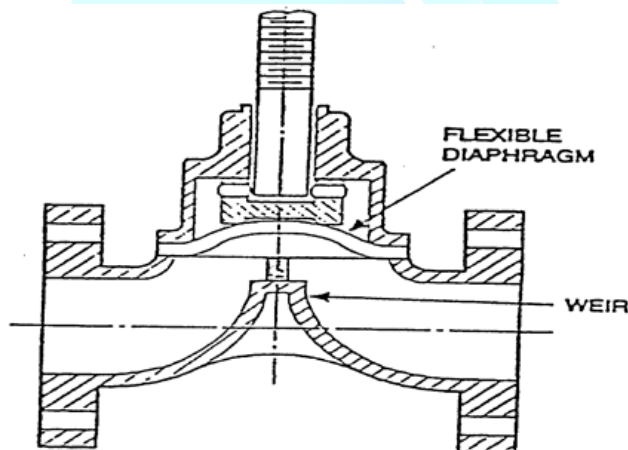


Figure 10. Diaphragm/Saunders' Valve

This type is suited for slurries and viscous fluids the diaphragm valve has high capacity, its cost is relatively low. The diaphragm seals the working parts of the valve from the process fluid and is the only wearing part of the valve. The Saunders-Type valve exhibits relatively poor control characteristics and has a low turndown ratio.

2) Rotary Stem (Shaft) Control Valves.

a) Full Ball and Vee notch Ball valves

Figure 11 shows ball valve design made for hard-to-handle fluids such as paper stock polymer slurries, heavy crude and other fluids with entrained solids. These high-recovery (low-pressure loss) valves have good control characteristic and high range abilities. Full Ball valves are used mainly for S/D and isolation, but not for control. Vee notch ball valves are used for control.

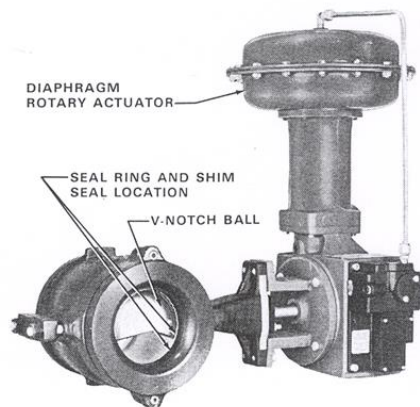


Figure 11. Partial ball (Vee notch ball) body design for hard to handle fluids as paper stock, heavy crude and polymer slurries.

b) Eccentric Rotating Plug (desk)

The "Camflex" valve is a rotating plug valve that has a centre of rotation eccentric to the centreline of the seat (figure 12) When the plug rotates to close the valve port, the plug face moves into the seat with a cam-like motion. Design is such that little or no rubbing action occurs after contact is made between plug and seat and the stem elastically deforms to give a tight shutoff. Some valve designs permit installation of reduced-trim seats without replacement of the plug. Valve flow characteristics are between equal percentage and linear but are nearly linear. It can be used for hard to handle fluids. It has good tightness class and can be used at relative high pressure.

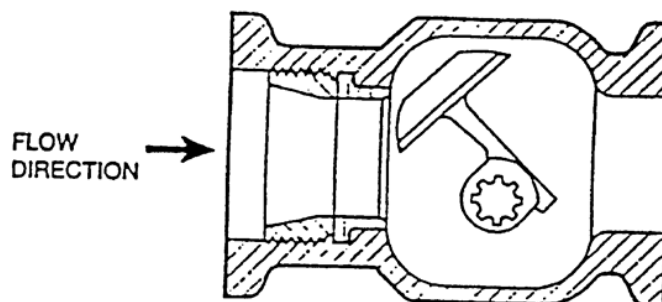


Figure 12. The Camflex valve has a centre of rotation eccentric to the centre line of the seat.

c) Butterfly

A butterfly valve consists of a shaft-supported vane or disc capable of rotating within a cylindrical body. In early industry use butterfly valves were specified primarily for low-pressure drop applications at low static pressures where control was not critical and where high leakage rates could be tolerated. In the last few years butterfly designs have been upgraded for high-pressure drops high static pressures and tight shutoff. Tight shutoff is accomplished through use of soft composition seats for seating the metal vanes (figure 13)

Butterfly valves are economical especially in larger sizes because of their simple design and high capacity. They require a minimum space for installation and often reduce pumping costs because of their low-pressure drop characteristic.

One of the disadvantages of the butterfly valve is the high operating torque requirement due to fluid flow through the valve. Butterfly valves commonly have been used for throttling control between 10° and 60° openings because torque conditions cause instability beyond this range. Its tightness class is relatively low.

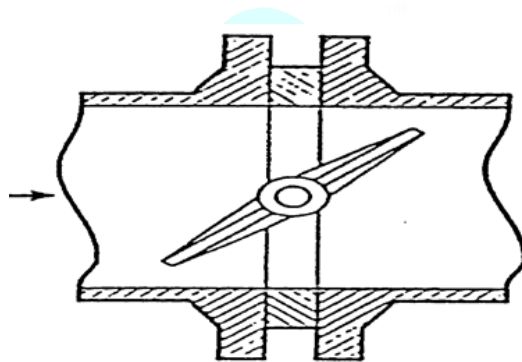
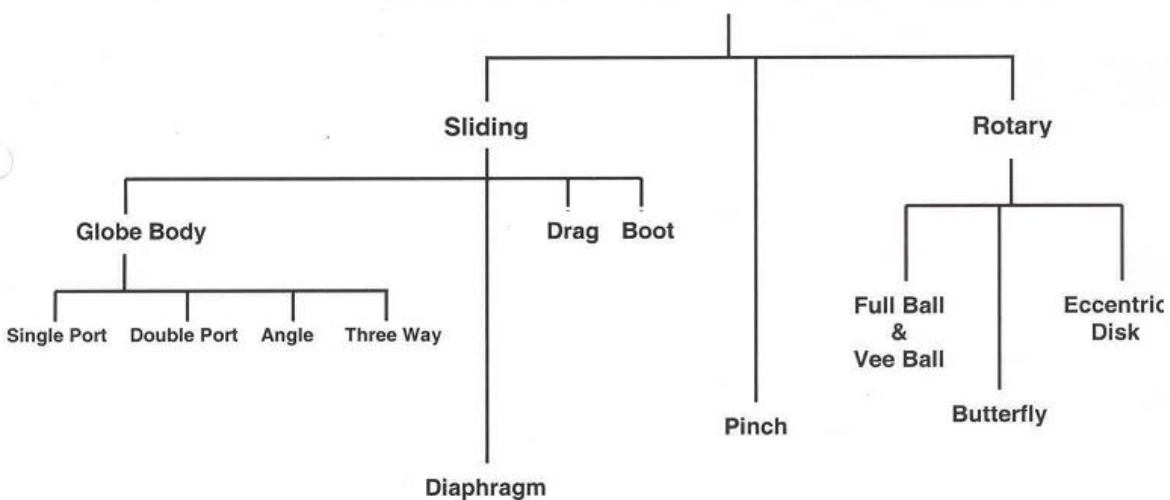


Figure 13. Butterfly valve with rubber lining (soft seat) for tight shutoff characteristic

TYPES OF CONTROL VALVES “BODY DESIGNS”



Control Valve Body definition and components

As shown in figure 14, valve body is a housing for internal parts that having inlet and outlet flow connections. Among the most common valve body constructions are:

- a) Single-ported valve bodies having one port and one valve plug,
- b) Double-ported valve bodies having two ports and two valve plugs on the same stem,
- c) Two-way valve bodies having two flow connections, one inlet and one outlet,
- d) Three-way valve bodies having three flow connections, two of which may be inlets with one outlet (for converging or mixing flows), or one inlet and two outlets (for diverging or diverting flows).

(The term Valve Body, or even just Body, frequently is used in referring to the valve body together with its bonnet assembly and included trim parts. More properly, this group of components should be called the Valve Body Assembly)

Valve Body Assembly

An assembly of a body, bonnet assembly, bottom flange (if used), and trim elements. The trim includes the valve plug, which opens, closes, or partially obstructs one or more ports.

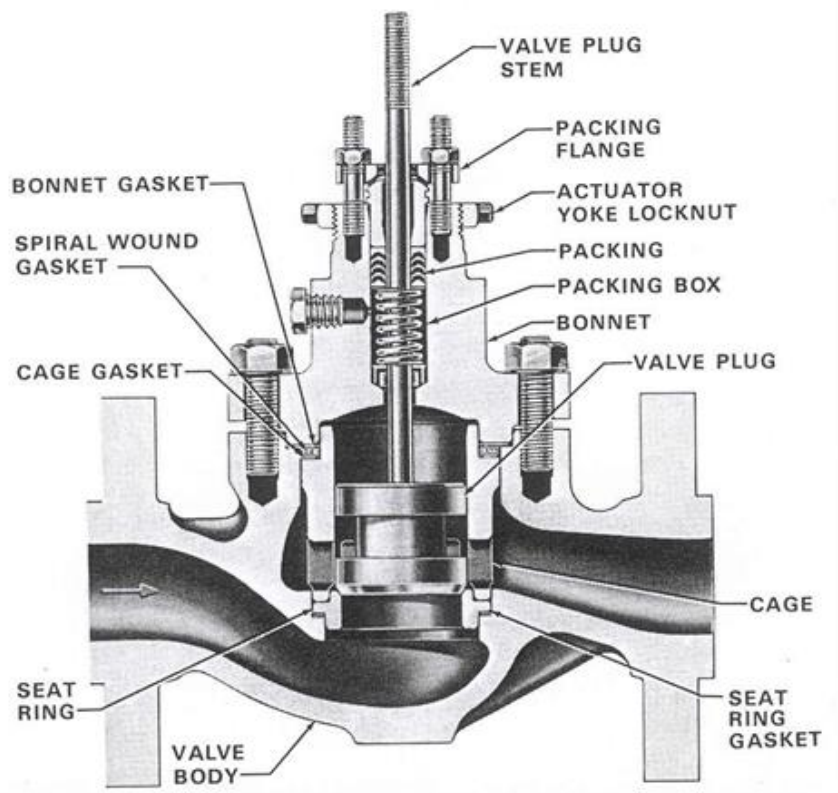
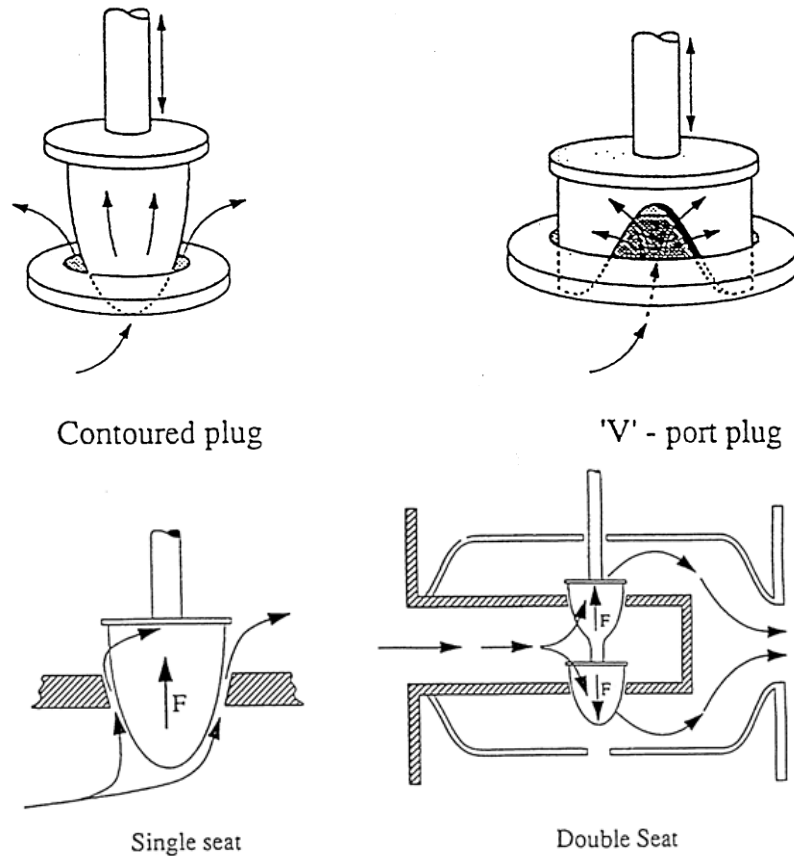


Figure 14. Valve Body Assembly.

Valve trim:

Valves control the rate of flow by introducing a pressure drop across the valve trim. (In a globe valve, the valve trim would be typically include valve plug, seat ring, cage, stem and stem pin. These are usually sold as matched sets, which have been ground to a precise fit in the fully closed position). Figure 15 illustrates some of valve plugs and seats.



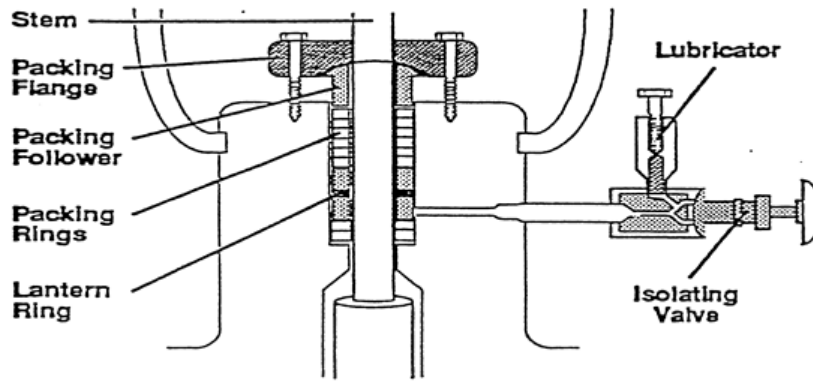
ALEXANDRIA
INDUSTRIAL CONTROL
Figure 15. Valve Trim.

Bonnet Assembly:

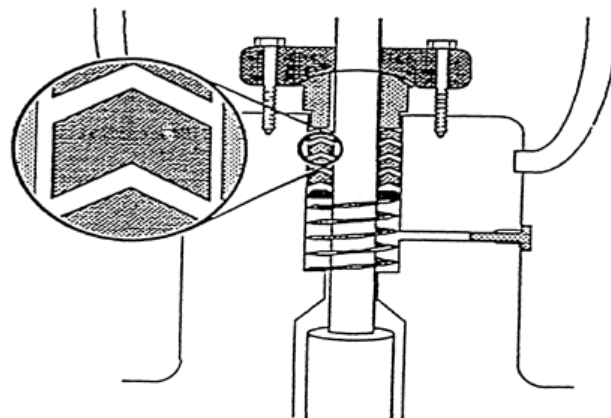
Bonnet Assembly: An assembly including the part through which a valve plug-stem moves and a means for sealing against leakage along the stem. It usually provides a means for mounting the actuator.

Packing Box Assembly:

The part of the bonnet assembly used to seal against leakage around the valve plug stem. Included in the complete packing box assembly are various combinations of some or all of the following component parts: Packing, Packing Follower, Packing Nut, Lantern Ring, Packing Spring, Packing Flange, Packing Flange Studs or Bolts, Packing Flange Nuts, Packing Ring, Packing Wiper Ring, Felt Wiper Ring. Figure 16 shows packing box assembly.



Bolted Packing Box Assembly



V-Shape Teflon Packing

Figure 16. Packing box assembly.

Valve Flow Characteristics

Valve flow characteristic was defined as the relationship that exists between valve flow and valve position. Almost any kind of characteristic can be obtained by proper shaping of the seat and plug. The purpose of characterising is to provide control loop stability over the expected range of operating conditions.

Flow characteristics fall into three major types (figure 17):

- **Quick opening**
- **Linear**
- **Equal percentage.**

Many variations of these types occur because of inherent valve design or because changes are engineered into the plug and seat design. The three major types are discussed below as well as some of their modifications.

Quick Opening

A quick opening characteristic provides for a maximum change in flow rate at low stem travel while maintaining a linear relationship through most of the stem travel. In Figure 17 about 90 percent of valve capacity is obtained at 30 percent valve opening and a straight-line relationship exists to that point.

Quick opening valve plugs are used primarily for on-off service or in self-actuated control valves or in regulators. They are also suitable for systems with constant pressure drops where linear characteristics are needed.

Linear

A valve with a linear flow characteristic produces flow directly proportional to the valve lift. Fifty percent of valve lift produces 50% of valve flow etc. This proportional relationship produces a constant slope so that each incremental change in valve plug position produces a like incremental change in valve flow if the pressure drop is constant. Linear valve plugs are commonly specified for liquid level control and for control applications requiring constant gain.

Equal Percentage

An equal percentage flow characteristic is one in which equal increments of stem travel produce equal percentage changes in existing flow. For example when the flow is small the change in flow (for an incremental change) is small; when the flow is large the change in flow (for an incremental change) is large. The change is always proportional to the quantity flowing before the change. Equal percentage valve plugs are used on pressure control applications where only a small percentage of the system drop is available for the control valve. It can be used for flow control.

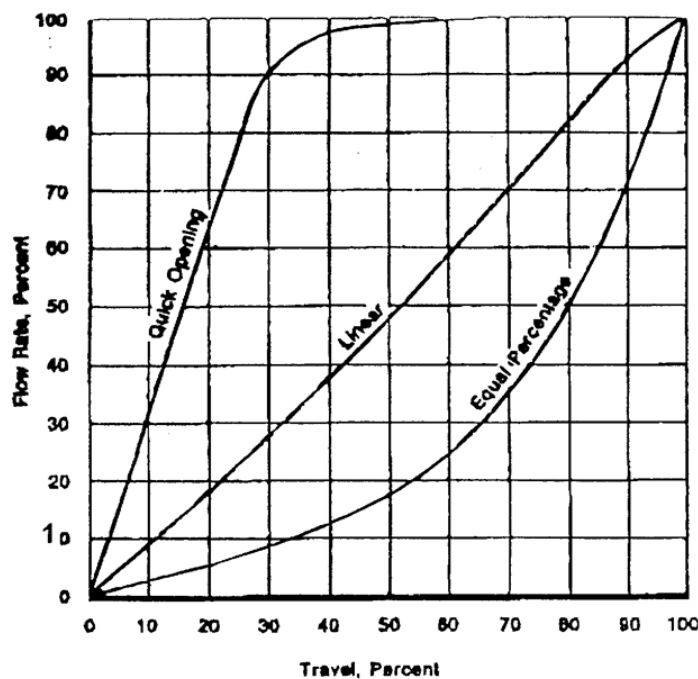


Figure 17. Percentage Flow Characteristics

Trim Design and Components of Globe Valves

The shaping of plugs, seats and cages to obtain the desired flow characteristic would logically be a function of trim design. This section however covers other design concepts relating to valve trim that affect not only the characteristic curve but also how the valve responds to problems such as erosion, cavitation, vibration, high pressure drop, noise and other similar problems. The term trim applies to the parts of a valve (except the body housing) that come into contact with the flowing fluid another term often used is wetted parts.

Plugs

Primarily valve plug shapes or patterns determine valve flow characteristics. Figure 18 shows some typical plugs for linear trim single port valve, equal percentage trim and quick opening characteristic valves.

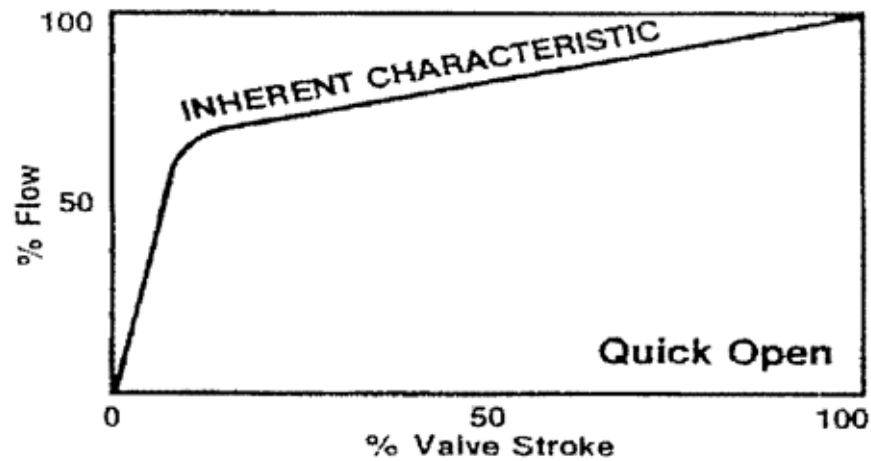
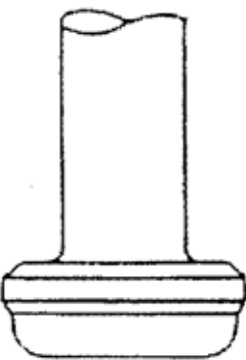
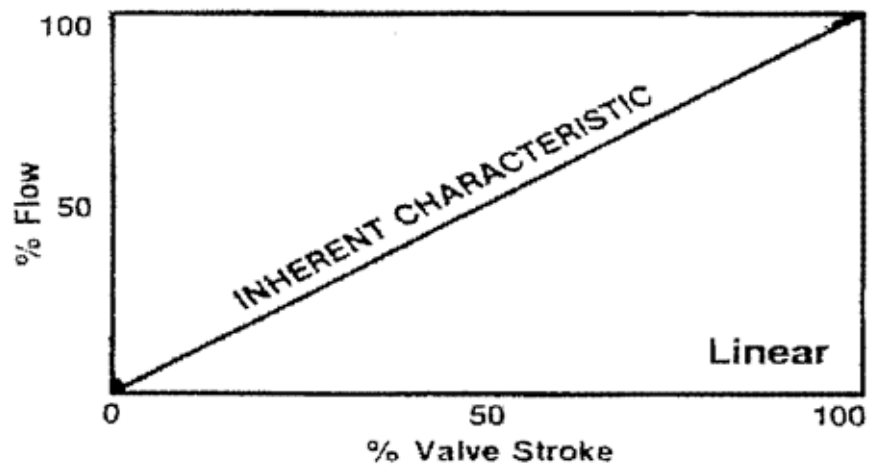
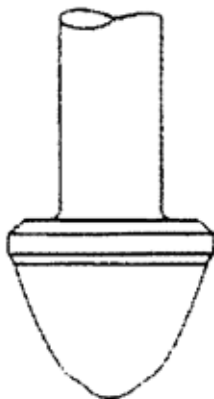
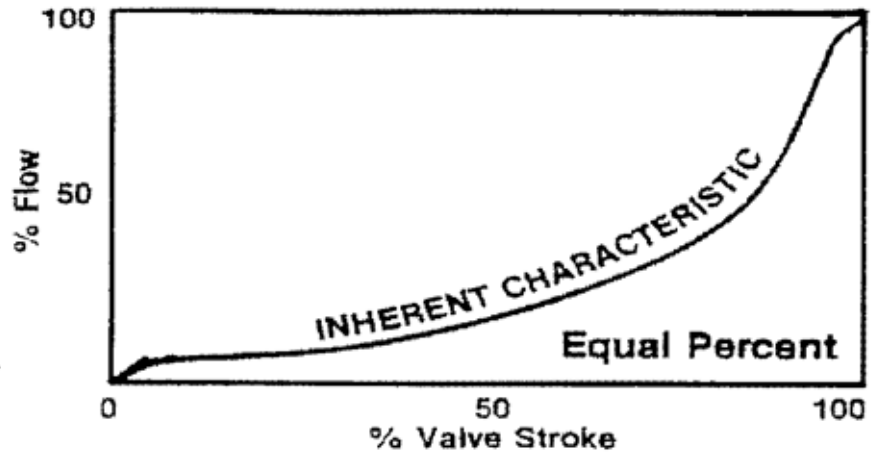
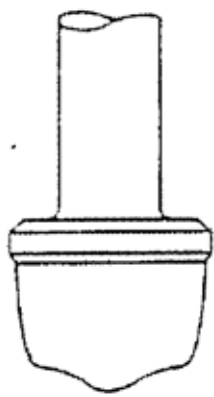
Seats

The seat or seat ring is that portion of the valve trim or body that the plug contacts for closure. The seat ring may be screwed or welded to the body.

Metal-to-metal contact between plugs and seats is standard practice. They can be machined accurately enough to prevent high leakage rates. However, when tight shut-off is required, soft seats made of Teflon, hard rubber or other resilient composition materials, are used to provide the necessary tight closure. The resilient part may be an insert in the seat.

Cages

Cage is a hollow cylindrical trim element that is a guide to align the movement of a valve plug with a seat ring in the valve body. The walls of the cage contain openings, which usually determine the flow characteristic of the control valve. As shown in figure 19.



Globe valve plugs for the three main inherent flow characteristics

Figure 18. Typical examples of linear plug, equal percentage plug and quick opening plug with type guiding shown.

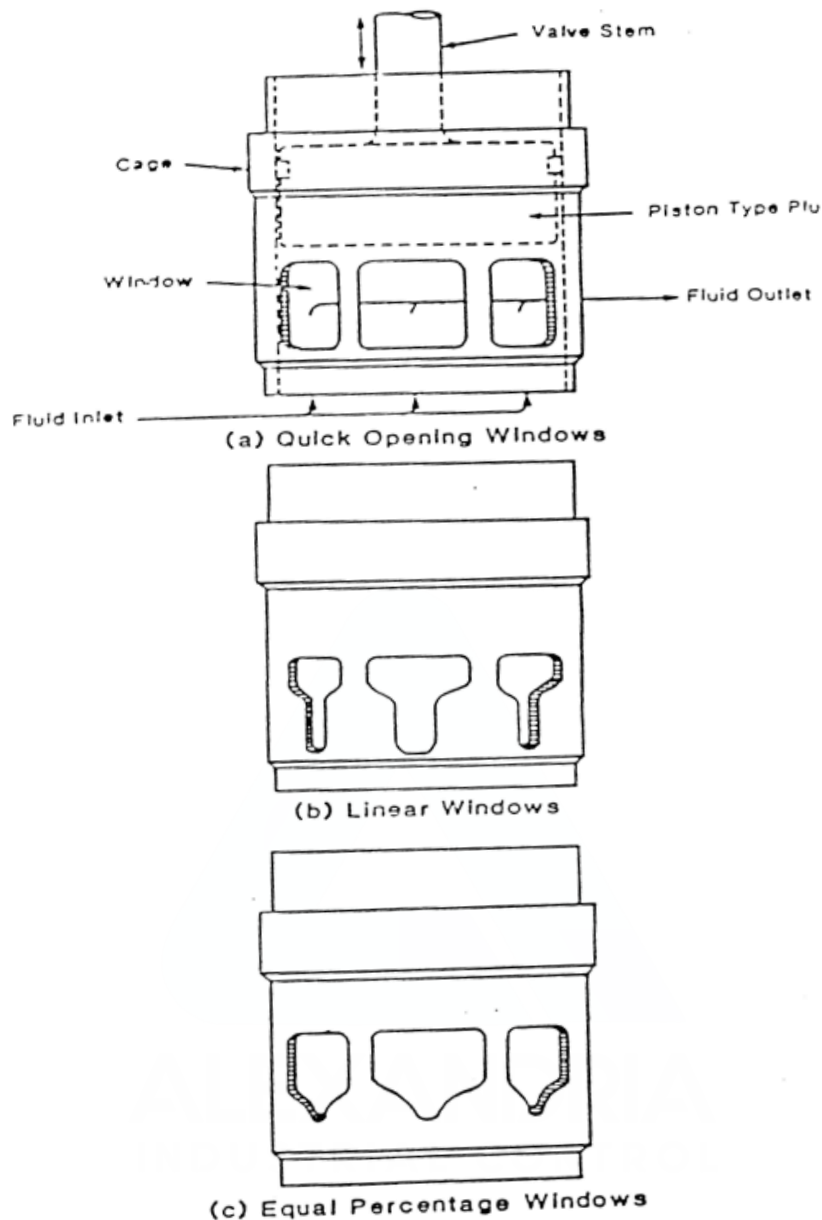


Figure 19. Flow Characterised Cage Windows

Use of each characteristic

Normally the choice of valve characteristic required by the loop is established by carrying out a dynamic analysis of the control loop but there are rules of thumb that can be applied to general situations.

- ▶ **Linear trims** are used in situations, such as level control, where the pressure drop across the valve is constant.
- ▶ **Equal percentage trims** are best used in flow situations where the pressure drop across the valve will vary as the flow goes from its minimum value to its

maximum value. This is especially true on pumped systems (pressure & flow control).

- ▶ **Quick opening valves** are useful in by-pass or re-cycle lines where a basic on-off control of flow is required.

Valve shutoff

There are six classes of valve leakage

- ▶ Class I no test
- ▶ Class II 0.5% of rated valve capacity
- ▶ Class III 0.1% of rated valve capacity
- ▶ Class IV 0.01 % of rated valve capacity
- ▶ Class V 0.0005 mL/min of water per inch of port diameter per psi differential
- ▶ Class VI bubble tight (1 to 45 bubbles per minute for port sizes 1" to 8" diameter).

If tight shutoff is required, it is good practice to provide a tight shutoff isolation valve in series with the throttling valve. The soft seat in a throttling valve will need to be frequently replaced if it used to carry out tight shutoff.

Control Valve Selection Criteria

Normally a valve is designed to handle its maximum flow when it is at 75% open. Making the valve too big or too small would be detrimental to the operation of the valve and the loop. Valves should not operate below the 10% open position or above the 90% open position. The choice of control valve will depend upon the application, i.e. flow control, ESD etc. The main factors to take into account to select a valve for service are:

1. The valves' ability to regulate the flow.
2. The pressure loss/recovery when the valve fully open.
3. The shut-off leakage when the valve fully closed.
4. Suitable flow characteristics to match the process
5. Fail safe mode
6. Proper choice of valve body type and accessories.
7. Correct installation

For instance a globe valve gives good flow regulation, has poor pressure recovery at high flow rates and does not give tight shut-off, whereas a ball valve has poor flow regulation characteristics, low pressure loss at high flow rates and has the advantage of tight shut-off. Space is another factor that can come into the consideration.

To determine the control valve size, the process data are required to find out the valve-sizing coefficient by relevant calculations.

The process data required for control valve selections are:

1. Type of fluid to be controlled.
2. Flowing pressure (max., min. and normal),
3. Flowing temperature (max., min. and normal),
4. The differential pressure across the valve (Max. and Min.),
5. The maximum and minimum flows and the degree of shutoff required,
6. Fluid viscosity,
7. Fluid specific gravity,
8. Inlet and outlet pipe size and schedule,
9. Maximum permissible noise level.

Valve Sizing Coefficient (CV): The following is the definition of the valve sizing coefficient which is to be calculated in view of the above factors and then the control valve could be selected from any manufacturer product guide.

“Valve flow coefficient (cv) is defined as the number of US gallons of water at 60 F that will flow through the valve in one minute when pressure differential across the valve is 1 psi”.

Flashing & Cavitation

All valves have a throttling action that causes a reduction in pressure. If the pressure increases again too rapidly, gas bubbles, entrained in the fluid implode, causing rapid erosion of the valve plug and seat surfaces. This process is known as cavitation.

Refer to course attachment No. 1 for more details about flashing and cavitation

Control Valve Noise

Control Valves have long been recognised as a major source of excessive noise levels inherent to many fluid process and transmission systems.

There are different sources of noise in the control valves and therefore different methods are used for noise abatement in order to have better process operation, less effect on the valve and equipment parts and better environment for personnel.

Actuators

The actuator provides the power to vary the orifice area of the valve in response to a signal received.

Control valve actuators may be operated pneumatically electrically, hydraulically, manually or by a combination of electrical, pneumatic and hydraulic forces. Pneumatic operation is the most widely used method. The forces actuators must overcome are the unbalanced forces caused by the pressure drop across the valve, friction between and weight of moving parts and stem unbalance. The actuators have mainly two actuating modes which are air to close and air to open (see fig. 21).

Types of Actuators

A) Pneumatic Actuators

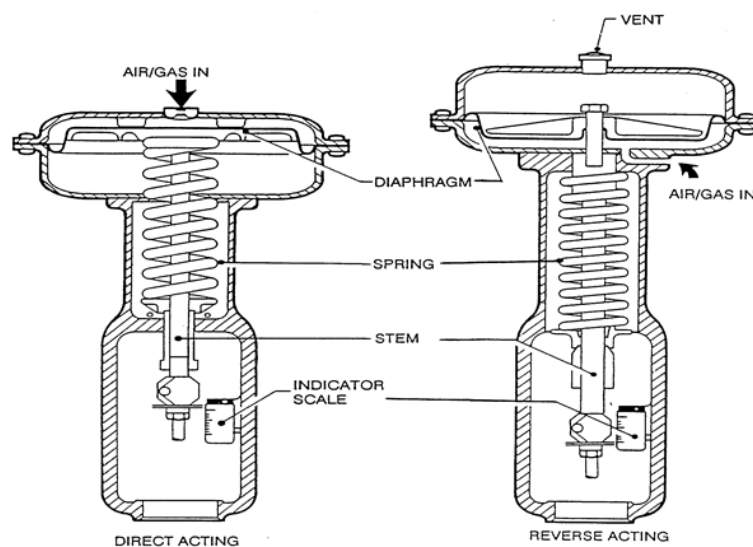
Pneumatic operators may be classified into two basic types:

- 1) Spring type (diaphragm or piston actuator)
- 2) Spring-less (piston actuator).

1) Spring Type Actuators.

a) Diaphragm Type

Diaphragm type actuator is the most frequently used type. These actuators may be direct acting or reverse acting. As shown in figure 20, a direct acting operator is designed so that air pressure (usually 3-15 psi) on the top of the diaphragm moves the stem downward, closing the valve. This action is termed fail-open (air-to-close). This force opposed by compression of the spring, and loss of the operating medium (usually air) allows the compressed spring to open the valve.



Air to lower actuator

Air to left actuator

Figure 20. Spring type diaphragm actuators

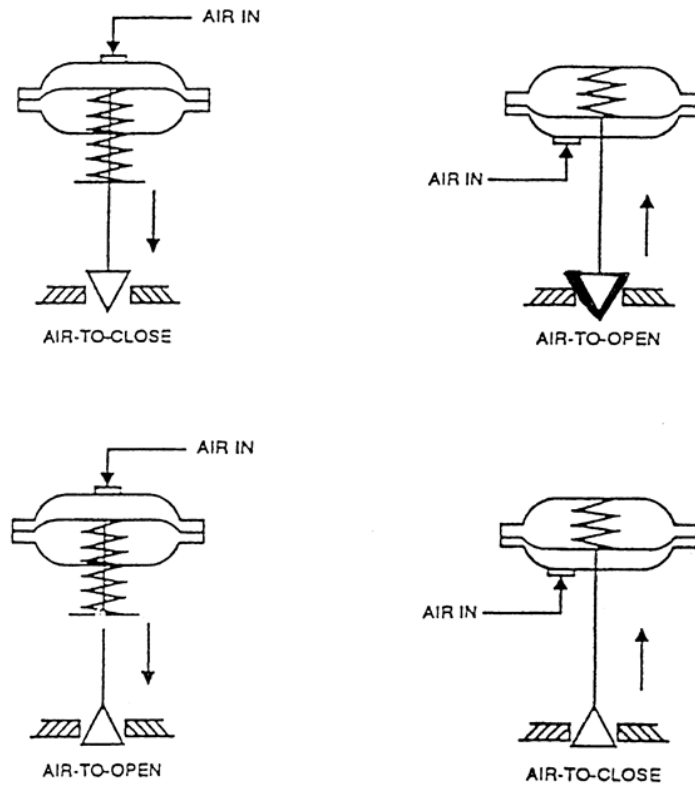


Figure 21. Valve failure mode with different valve/actuator set-ups.

b) Piston Type

The air piston provides high torque or force and has a fast stroking speed. It provides a high power to weight ratio, has few moving parts and an excellent dynamic response. It can handle high differential pressures and provides high shutoff capability. It is also easily adapted to services where high ambient temperature is involved. Figure 22 illustrates a single acting piston type actuator.

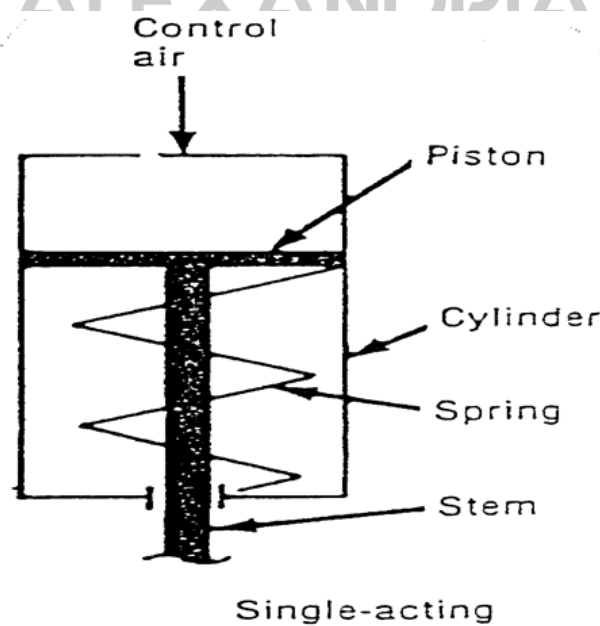


Figure 22. Single acting piston type actuator.

2) Spring-less (Piston type).

Spring-less operators include pneumatic cylinder or piston operators. Cylinder or piston operators are increasing in usage because of the need for increased power and fast action. Increased power results from their ability to use higher-pressure supply air. These operators sometimes include built-in valve positioners.

Figure 23, shows how the piston is forced upward by a constant pressure from a reducing regulator, adjustable to suit the stem load. The chamber above the piston is dynamically loaded. An increase in instrument air pressure increases the pressure in the chamber above the piston, moving it downward. This extends the range spring until the positioner forces are brought back into balance, at which point the positioner stabilises the pressure on top of the piston to hold the new position. A decrease in instrument air pressure reverses the procedure. Higher supply pressures provide greater power and faster stroking speeds. To provide fail-closed or fail-open modes, cylinder operators can be furnished with spring-return features. For fail-safe operation on electric power loss and for air supply loss, bottled gas with appropriate regulators and trip valves is sometimes employed.

Valves are sometimes required to maintain the position they were in when supply pressure or signal is lost. Such a state is known as "fail-last position," and can be accomplished by trapping the last signal pressures within the cylinder or piston assembly using a special trip relay.

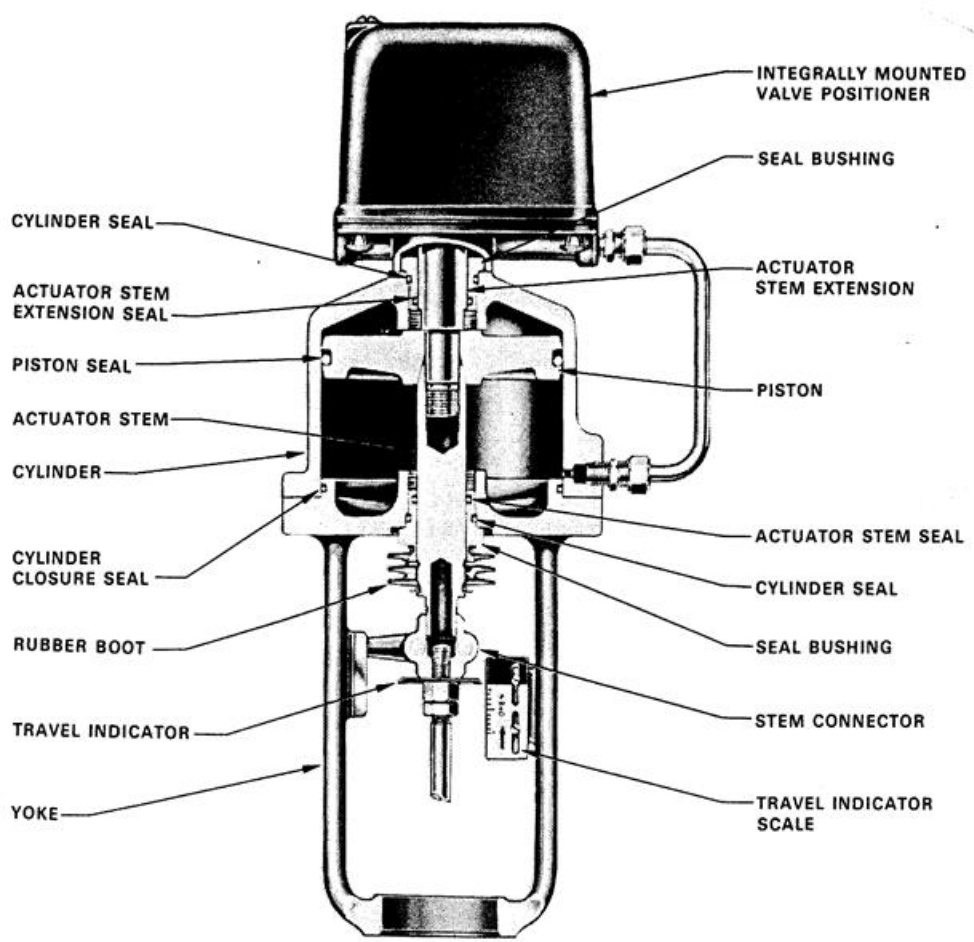


Figure 23. Typical Double Acting Piston Actuator.

B) Electro-Hydraulic Actuators

- Require only electrical power to the motor and an electrical input signal from the controller.
- Ideal for isolated locations where pneumatic supply pressure is not available but where precise control of valve plug position is needed.
- Units are normally reversible by making minor adjustments and are usually self-contained, including motor, pump, and double acting hydraulically operated piston within a weatherproof or explosion proof casing.

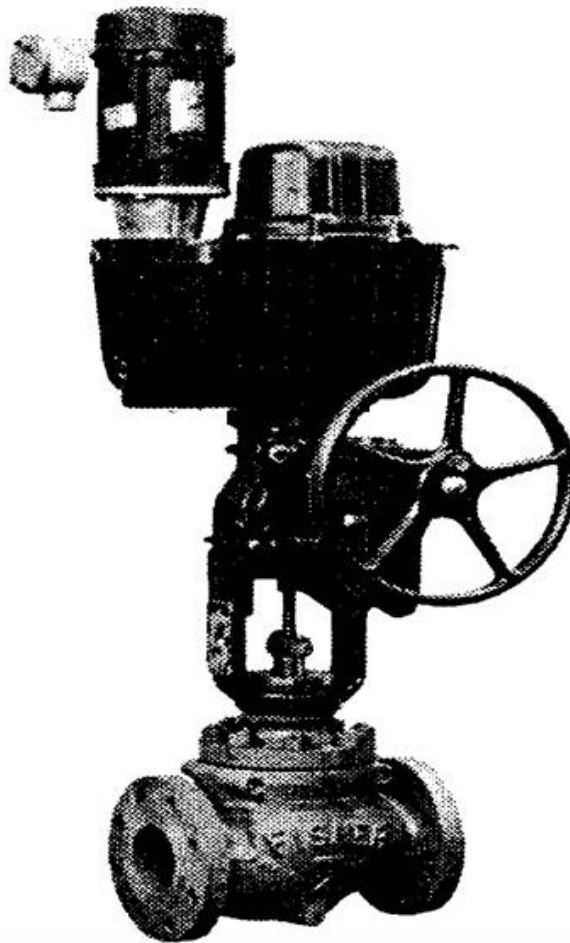


Figure 24. Control Valve with Double-Acting Electro-Hydraulic Actuator and Handwheel.

C) Electrical Actuators

Electric operators with proportional or infinite positioning control have limited use in the process industries. Their primary use has been in remote areas, such as tank farms and pipeline stations, where no convenient air supply is available. Slow operating speeds, maintenance problems in hazardous areas and economics have prevented wide acceptance for throttling applications. However, several companies have offered electrically powered units. Figure 25 shows an electrically operated butterfly valve, which can be supplied with an automatic amplifier-relay control package for use with a

remote command potentiometer. The remote potentiometer is part of a Wheatstone bridge arrangement with the feedback potentiometer in the actuator. Changes in the command potentiometer cause the actuator to reposition to a pint where bridge balance is re-established.

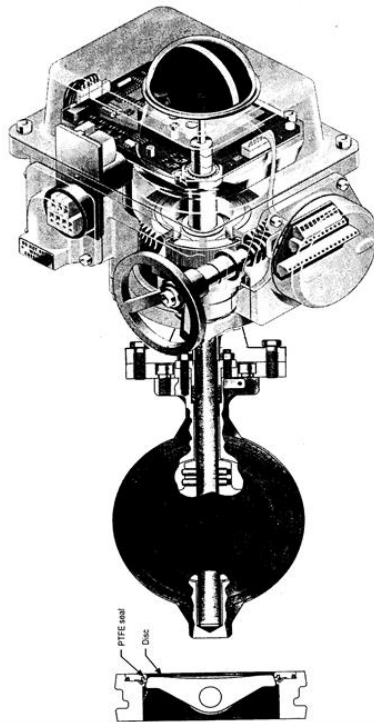


Figure 25. Butterfly valve with electric actuator for remote positioning control.

Solenoid actuators

Solenoid actuator is an electromagnetic device, which moves its plunger/valve plug when electrical power is applied on its coil. These are only used on small control systems where on-off control is required. Mostly they are found in the form of three way valves on the signal lines from the controller to the valve for ESD use. On removal of the power the valve will disconnect the controller from the valve and vent the air in the valve to atmosphere. Figure 26 illustrates a solenoid valve.

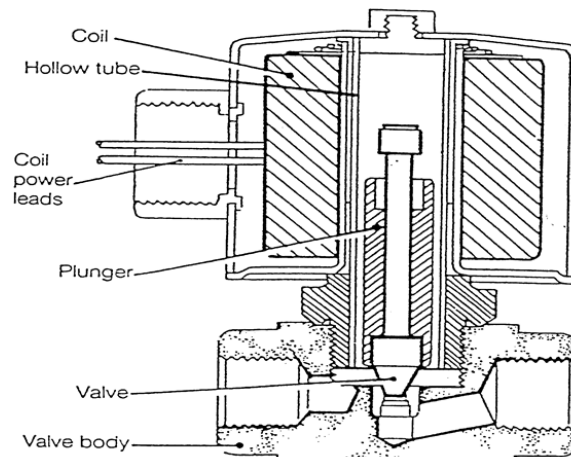
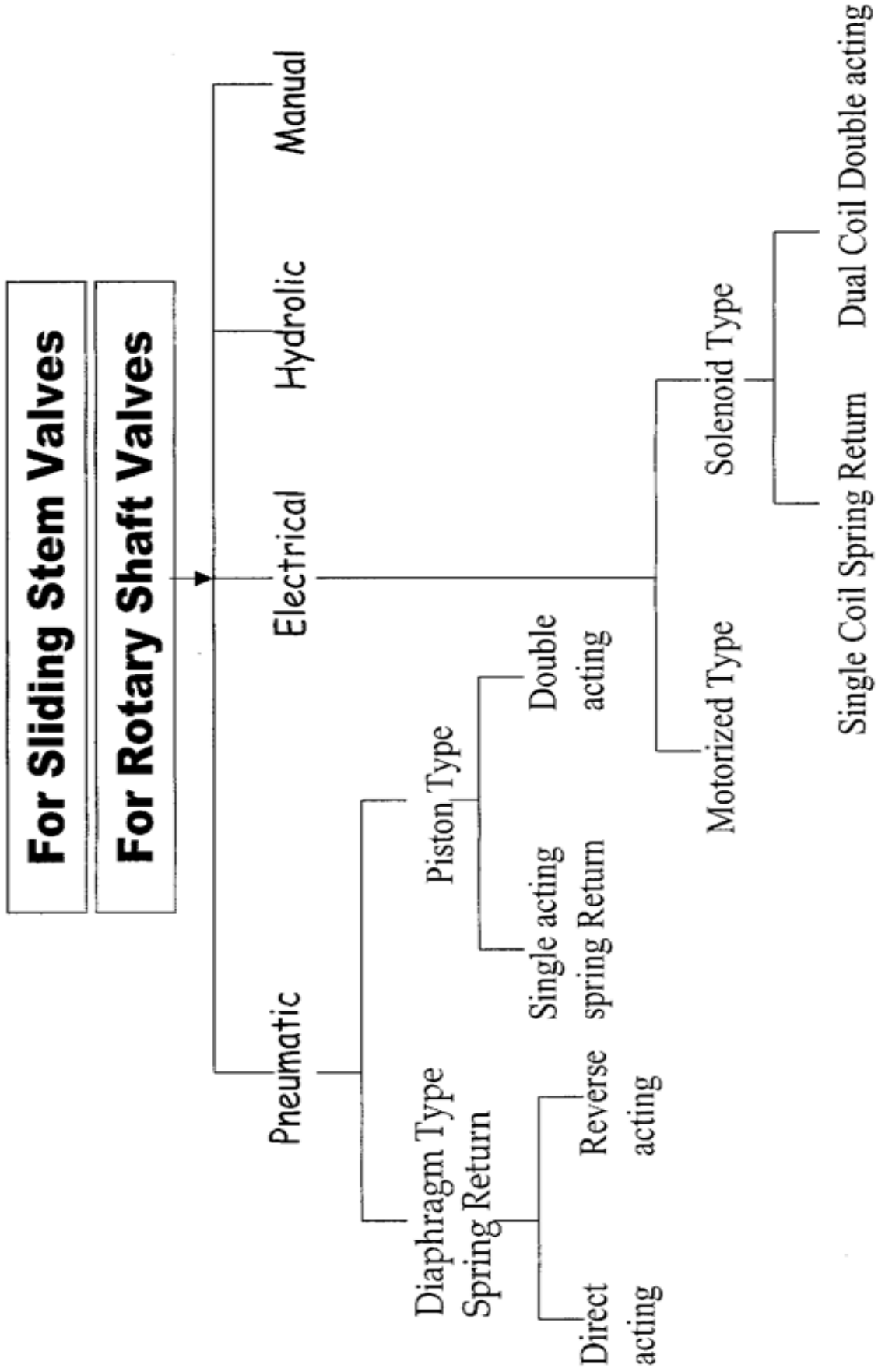
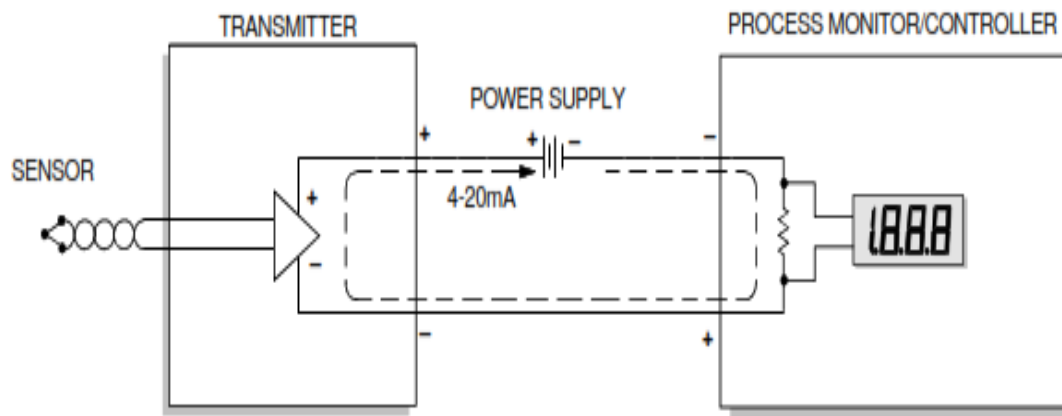


Figure 26. Solenoid Valve.

Types of Control Valve actuators



Alexandria Industrial Control



INSTRUMENTATION

Chapter 5: Process Control Loops

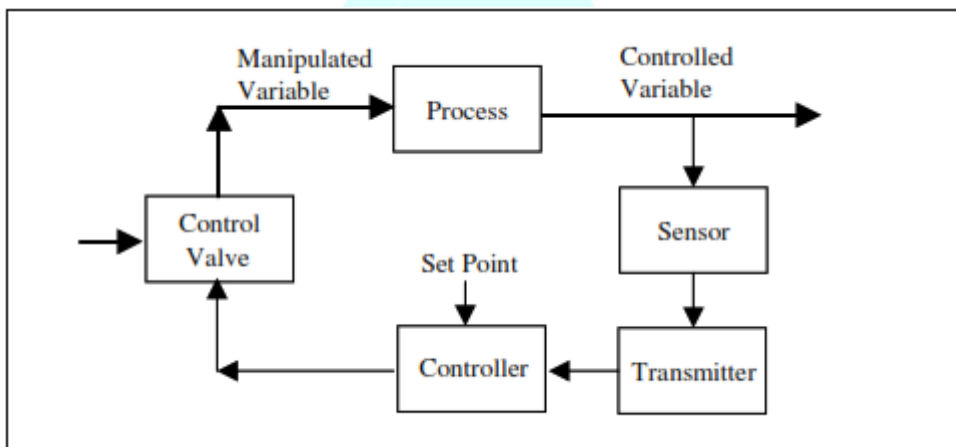
Introduction

We discussed the general concepts of process control in Chapter 5. In this chapter, we will cover the basic principles of process control loops. Single-loop feedback control is the most common type of control used in industrial processes, so it will be discussed in the greatest detail. We will then discuss other types of control loops, such as cascade, ratio, and feedforward. Finally, we will examine several common methods used to tune control loops.

Single-loop Feedback Control

In a feedback control loop, the variable to be manipulated is measured. This measured process value (PV) is then compared with a set point (SP) to generate an error signal ($e = PV - SP$). If a difference or error exists between the actual value and the desired value of the process, a process controller will take the necessary corrective action to return the process to the desired value. A block diagram of a single-feedback control loop is shown in Figure 5-1.

The measured process variable is sensed or measured by the appropriate instrumentation, such as temperature, flow, level, or analytical sensors. This measured value is then compared with the set point. The controller uses this comparison to adjust the manipulated variable appropriately by generating an output signal. The output signal is based in turn on whichever control strategy or algorithm has been selected. Because in the process industries the manipulated variable is most often a flow, the output of



the controller is usually a signal to a flow control valve, as shown in Figure 5-1.

During the operation of the process, disturbances can enter the process and drive the process variable in one direction or another. The single manipulated variable is used to compensate for all such process changes produced by the disturbances. Furthermore, if changes occur in the set point, the manipulated variable is altered to produce the needed change in the process output.

Process Controllers

The most dynamic device in a feedback control loop is the process controller. There are three types of controllers (mechanical, pneumatic, electronic and they all serve the same function). They compare the process variable with the set point and generate an output signal that manipulates the process to make the process variable equal to its set point. Figure 5-2 shows a block diagram of a feedback control loop with an expanded view of its common functions. In this diagram the measurement transducer has been expanded into its two components: the

sensor and the transmitter. The sensor measures the process variable, and then the transmitter converts the measurement into a standard signal such as 4 to 20 mA DC or 3 to 15 psig.

The controller consists of a feedback transmission system, a comparator with a set point input, controller functions, and an output transmission system. The comparator block measures the difference between the set point and the process variable. For this comparison to be useful, the set point and the process variable must have the same units of measure. For example, if the set point has the units of 0 to 10 mv, then the signal from

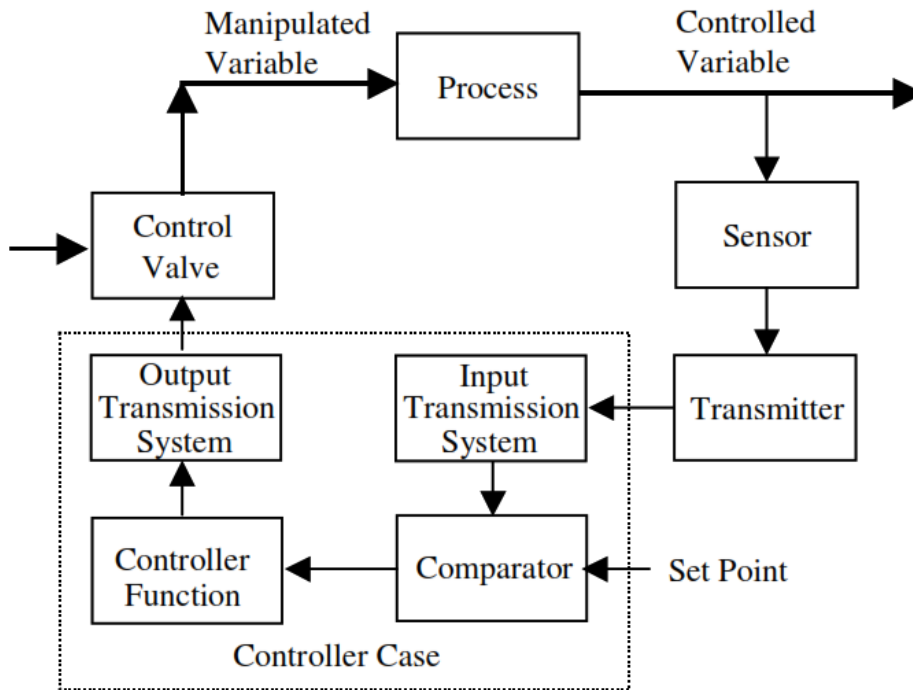


Figure 5-2. Functional block diagram of feedback loop

the sensor must be converted into the same units. The purpose of the feedback transmission system is to convert the sensor signal into the correct units. For example, if the input signal is 4 to 20 mA DC the feedback circuit in the controller will convert the signal to 0 to 10 mv. The function of the output transmission system is to convert the signal from the feedback circuit into the form required by the final control device. The four common controller functions are proportional, proportional plus integral (PI), proportional plus derivative (PD), and proportional plus integral plus derivative (PID).

A front-panel view of a typical electronic process controller is shown in Figure 5-3. The controller has two vertical bar displays to give the operator a pictorial view of the process variable and the set point. It also has two short horizontal digital displays just above the vertical bars to give the operator a direct digital readout of the process variable and the set point. The operator uses dual push buttons with indicating arrows to adjust the set point and the manual output functions. The operator must depress the manual (M) push button to activate the manual output function.

During normal operation, the operator will select automatic (A) mode. Manual is generally used only during system startup or during a major upset condition when the operator must take control to stabilize the process. The controller shown in Figure 5-3 has both a horizontal bar display and a digital indicator to provide the operator with the value of the output

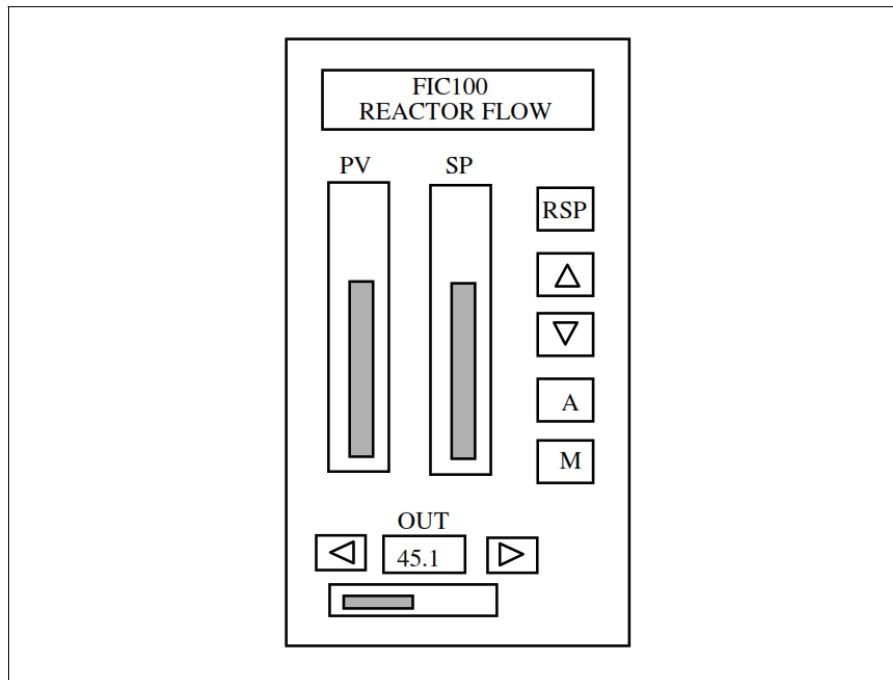


Figure 5-3. Typical electronic controller

Signal from the controller. The square indicator marked (RSP) is used to indicate that the controller is using a remote set point.

Advanced Control Loops

Up to this point, we have discussed only single-loop feedback control. This section will now expand the discussion to include cascade, ratio, and feedforward control loops.

Cascade Control Loops

The general concept of cascade control is to place one feedback loop inside another. In effect, one takes the process being controlled and finds some intermediate variable within the process to use as the set point for the main loop. Cascade control exhibits its real value when a very slow process is being controlled. In such circumstances, errors can exist for a very long time, and when disturbances enter the process there may be a significant wait before any corrective action is initiated. Also, once corrective action is taken one may have to wait a long time for results. Cascade control allows the operator to find intermediate controlled variables and to take corrective action on disturbances more promptly. In general, cascade control offers significant advantages and is one of the most underutilized feedback control techniques. An important question you may confront when implementing cascade control is how to select the most advantageous secondary controlled variable. Quite often, the designer has a large number of choices. The overall strategy or goal should be to get as much of the process lag into the outer loop as possible while, at the same time, getting as many of the disturbances as possible to enter the inner loop.

Figures 5-4 and 5-6 illustrate two different cascade control arrangements for a furnace that is used to increase the temperature of a fluid that is passing through it. In both cases, the primary controlled variable is the same, but in each case a different intermediate controlled variable has been selected. The question then is which type of cascade control is best.

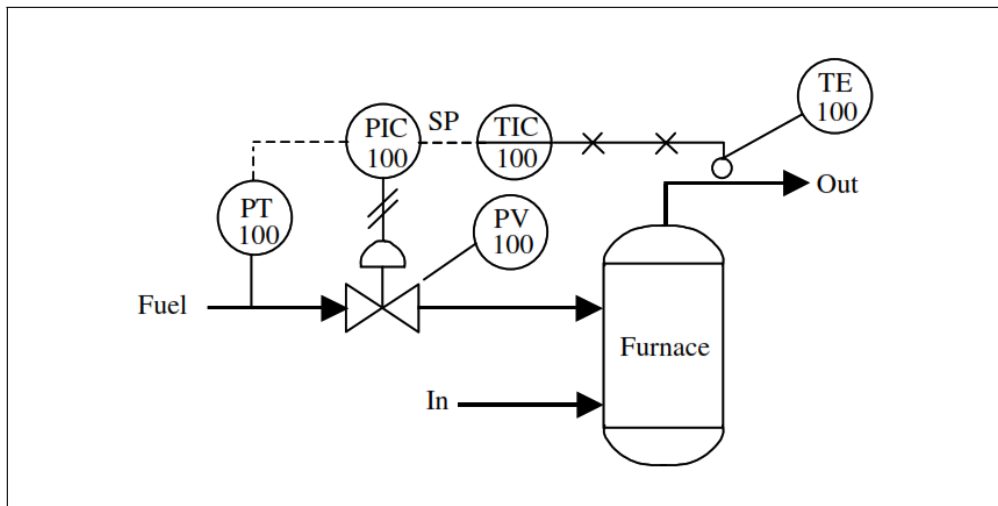


Figure 5-4. Pressure and temperature cascade control

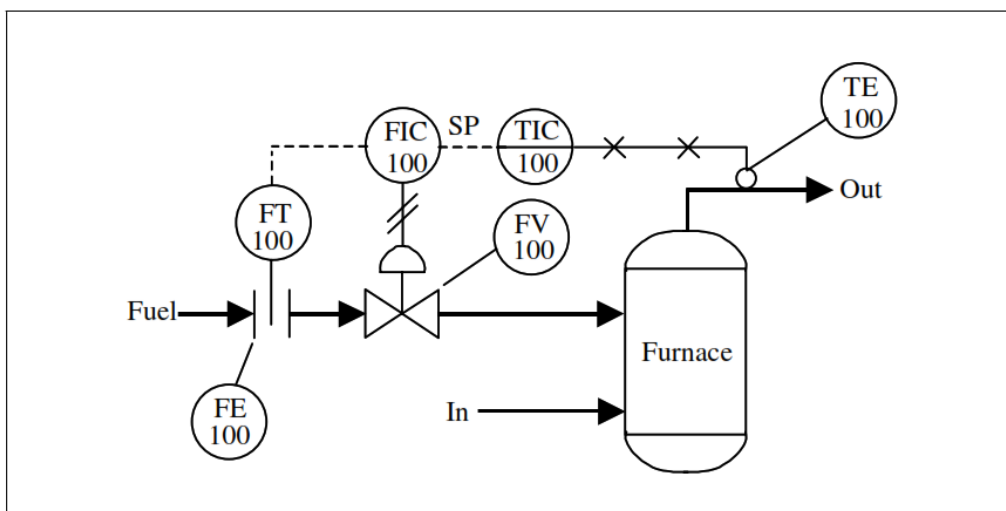


Figure 5-5. Flow and temperature cascade control

To determine the best cascade control arrangement, you must identify the most likely disturbances to the system. It is helpful to make a list of these in order of increasing importance. Once this has been done, the designer can review the various cascade control options available and determine which one best meets the overall strategy outlined earlier: to make the inner loop as fast as possible while at the same time receiving the bulk of the important disturbances.

If both controllers of a cascade control system are three-mode controllers, there are a total of six tuning adjustments. It is doubtful that such a system could ever be tuned effectively. Therefore, you should select with care the modes to be included in both the primary and secondary controllers of a cascade arrangement.

For the secondary (inner or slave) controller, it is standard practice to include the proportional mode. There is little need to include the reset mode to eliminate offset because the set point for the inner controller will be reset continuously by the outer or master controller. For the outer loop, the controller should contain the proportional mode. If the loop is sufficiently important to merit cascade control then you should probably include reset to eliminate offset in the outer loop. You should undertake rate or derivative control in either loop only if it has a very large amount of lag.

The tuning of cascade controllers is the same as the tuning of all feedback controllers, but the loop must be tuned from the inside out. The master controller should be put on manual (i.e., the loop broken), and then the inner loop can be tuned. Once the inner loop is properly tuned, the outer loop can be tuned. This allows the outer loop to “See” the tuned inner loop functioning as part of the total process or as the “all else” that is being controlled by the master controller. If you follow this general inside first principle when tuning cascade controllers, you should encounter no special problems.

Ratio Control Loops

Another common type of feedback control system is ratio control. Based on hardware, ratio control is quite often confused with cascade control. The basic operation of ratio control, however, is quite different.

Ratio control is often associated with process operations in which two or more streams must be mixed together continuously to maintain a steady composition in the resulting mixture. A practical way to do this is to use a conventional flow controller on one stream and to control the other stream with a ratio controller that maintains flow in some preset ratio or fraction to the primary stream flow. A preset ratio regulates the flow of the controlled variable. For example, if the ratio is 10 to 1, then for every gallon per minute of the uncontrolled variable that is flowing, ten gallons per minute of the controlled variable are allowed to flow. A typical ratio control system is shown in Figure 5-6.

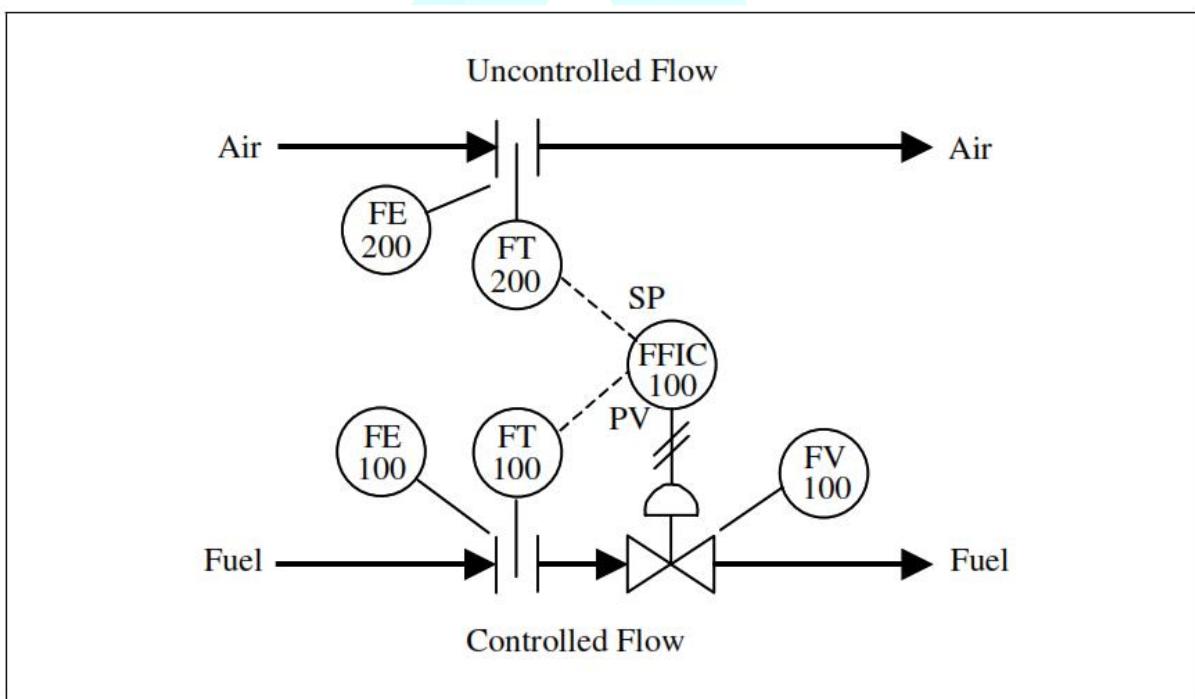


Figure 5-6. Ratio control

Use the signal from the uncontrolled flow transmitter, or wild flow, as the ratio input of the ratio controller. Multiply the value by an adjustable factor or ratio setting to determine the set point of the flow controller. The process variable to the controller is the flow of the controlled stream. The output from the ratio controller adjusts the control valve. You can use a ratio control loop with any combination of suitably related process variables, and the control action selected

is normally proportional plus integral. The response to process upsets of a control loop with ratio control is the same as the response found in a single-feedback loop.

Feedforward Control Loops

A feedback control loop is reactive in nature and represents a response to the effect of a load change or upset. A feedforward control loop, on the other hand, responds directly to load changes and thus provides improved control. In feedforward control, a sensor is used to detect process load changes or disturbances as they enter the system. A block diagram of a typical feedforward control loop is shown in Figure 2-7. Sensors measure the values of the load variables, and a computer calculates the correct control signal for the existing load conditions and process set point.

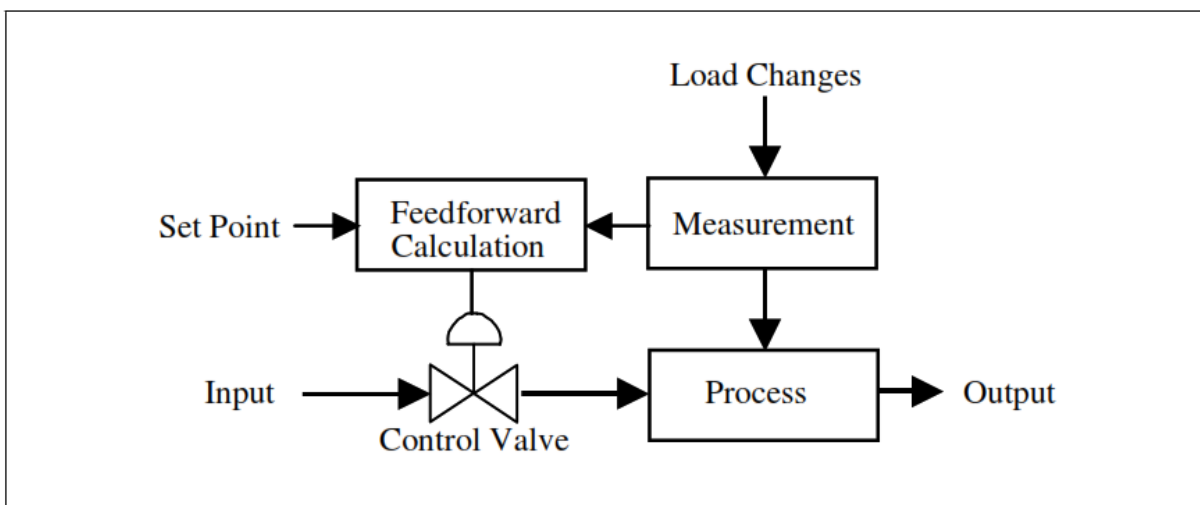


Figure 5-7. Feedforward control

Feedforward control poses some significant problems. Its configuration assumes that the disturbances are known in advance, that they will have sensors associated with them, and that no important undetected disturbances will occur. Therefore, feedforward control is more complicated and more expensive, and it requires the operator to have a better understanding of the process than does a standard feedback control loop. So, feedforward control is generally reserved for well-understood and critical applications.

Tuning Control Loops

There are three important factors to consider when tuning a PID controller: the characteristics of the process, the selection of controller modes, and the performance criteria of the control loop.

Selecting Controller Modes

Which controller mode to select is an important consideration when tuning controllers. Four basic control combinations are used: proportional only, proportional plus integral (PI), proportional plus derivative (PD), and proportional plus integral plus derivative (PID).

The most basic continuous control mode is proportional control. Here, the controller output (m) is algebraically proportional to the error (e) input Signal to a controller.

The equation for proportional control is given by the following equation:

$$m = K_c e$$

This equation is also called the proportional control algorithm. This control action is the simplest and most commonly encountered of all the continuous control modes. In effect, there is a continuous linear relationship between the controller input and output.

The proportional gain of the controller is the term K_c , which is also referred to as the proportional sensitivity of the controller. K_c indicates the change in the manipulated variable per unit change in the error signal. In a true sense, the proportional sensitivity or gain is a multiplication term. It represents a parameter on a piece of actual hardware that must be adjusted by a technician or engineer; for example, the gain may be an adjustable knob on the process controller.

On many industrial controllers, this gain-adjusting mechanism is not expressed in terms of proportional sensitivity or gain but in terms of proportional band (PB). Proportional band is defined as the span of values of the input that corresponds to a full or complete change in the output. This is usually expressed as a percentage. It is related to proportional gain by the following equation:

$$PB = 100\% / K_c$$

Most controllers have a scale that indicates the value of the final controlled variable. Therefore, the proportional band can be conveniently expressed as the range of values of the controlled variable that corresponds to the full operating range of the final control valve. As a matter of practice, wide bands (high percentages of PB) correspond to less sensitive response, and narrow bands (low percentages) correspond to more sensitive response of the controller.

Proportional control is quite simple and is the easiest of the continuous controllers to tune since there is only one parameter to adjust. It also provides very rapid response and is relatively stable. Proportional control has one major disadvantage, however: at steady state, it exhibits offset. That is, there is a difference at steady state between the desired value or set point and the actual value of the controlled. To correct for this problem proportional control is combined with integral action.

Integral action or reset action is the integration of the input error signal e over a very small time period dt . In effect, this means that for integral action, the value of the manipulated variable V is changed at a rate that is proportional to the amount of error e that exists for a given duration. In other words, integral control responds to the duration of the error as well as to its magnitude and direction. When the controlled variable is at the set point, the final control element remains stationary. In effect, this means that at steady state, when integral action is present there can be no offset; therefore, the steady-state error is zero. This combination of proportional and integral action is called PI control. The control equation for PI control action is as follows:

$$V = K_c e + \frac{K_c}{t_i} \int_0^t e dt$$

where

K_c	=	the proportional gain
t_i	=	the <i>integral time</i>
e	=	the error signal
V	=	controller output

The advantage of including the integral mode with the proportional mode is that the integral action eliminates offset. Typically, there is some decreased stability due to the presence of the integral mode. In other words, the addition of the integral action makes the total loop slightly less stable. One significant exception to this is in liquid flow control. Liquid flow control loops are extremely fast and tend to be very noisy. As a result, plants often add integral control to the feedback controller in liquid flow control loops to provide a dampening or filtering action for the loop. Of course, the advantage of eliminating any offset is still present, but this is not the principal motivating factor in such cases.

Tuning a PI controller is more difficult than tuning a simpler proportional controller. Two separate tuning adjustments must be made, and each depends on the other. The difficulty of tuning a controller increases dramatically with the number of adjustments that must be made.

It is conceivable to have a control action that is based solely on the rate of change or derivative of the error signal e . Although this is possible, it is not practical because, while the error might be large, if it were unchanging the controller output would be zero. Thus, rate control or derivative control is usually found in combination with proportional control. The equation for a proportional-derivative (PD) controller is as follows:

$$V = K_c e + K_c t_d \frac{de}{dt}$$

where t_d is the derivative time.

By adding derivative action to the controller, lead time is added in the controller to compensate for lag around the loop. Almost any process has a time delay or lag around the loop; therefore, the theoretical advantages of lead in the controller are appealing. However, it is a difficult control action to implement and adjust, and its usage is limited to cases of extensive lag in the process. This often occurs with large temperature-control systems. Taking the derivative of the error signal has the side effect of producing upsets whenever the set point is changed, so most controllers take the derivative of the process signal.

Adding derivative control to the controller makes the loop more stable if it is correctly tuned. Since the loop is more stable, the proportional gain may be higher, and it can thus decrease offset better than proportional action alone. It does not, of course, eliminate offset.

The equation for a three-mode controller, or PID (proportional-integral-derivative) controller, is as follows:

$$V = K_c e + \frac{K_c}{t_i} \int_0^t e dt + K_c t_d \frac{de}{dt}$$

The three-mode control gives rapid response and exhibits no offset, but it is very difficult to tune because of the three terms that must be adjusted. As a result, it is used only in a very small number of applications, and operators often must adjust it extensively and continuously to keep it properly tuned. The PID mode, however, offers excellent control when proper tuning is used. Five common types of control loops are encountered in process control: flow, level, temperature, analytical, and pressure. Table 5-1 provides basic guidelines for the controller modes that are generally used for each type of process control loop.

Control Loop	Controller Mode		
	Proportional	Integral	Derivative
Flow	Always	Usually	Never
Level	Always	Usually	Rarely
Temperature	Always	Usually	Usually
Analytical	Always	Usually	Sometimes
Pressure	Always	Usually	Sometimes

Table 5-1. Guidelines for Selecting Controller Modes

Performance Criteria

The final factor plants must consider before tuning a loop is the performance criteria that are to be used. There are four widely used criteria; each is based on a different method for minimizing the integral error of the deviation of measured control signal from the set point. The first three are the minimum integral of square error (ISE), the minimum integral of absolute error (IAE), and the minimum integral of absolute error multiplied by time (ITAE). In equation form, these three criteria are, respectively,

$$ISE = \int_0^{\infty} e^2 dt$$

$$IAE = \int_0^{\infty} |e| dt$$

$$ITAE = \int_0^{\infty} t|e| dt$$

These three integral criteria methods are best suited for computer-based control applications. They are recommended only for such applications, where they can give excellent tuning and control results. The fourth and most commonly used performance criterion was presented by J. G. Ziegler and N. B. Nichols at the annual meeting of the American Society of Mechanical Engineers in New York City in December 1941. It is known as the Ziegler and Nichols one-quarter wave decay criterion and is the basis of their tuning methods. A decay ratio of one-quarter means that the ratio of the overshoot of the first peak in the process response curve to the overshoot of the second peak is 4:1 (this is illustrated in Figure 5-8). Using a decay ratio of one-quarter represents a compromise between a rapid initial response and a fast return to the set point.

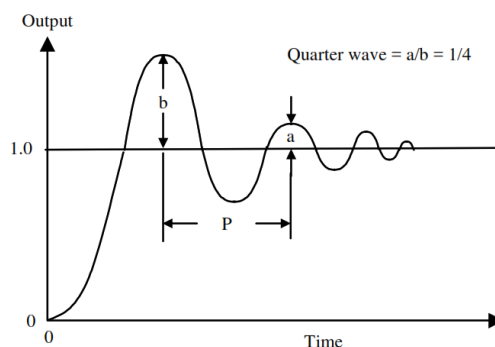


Figure 5-8 Process response curve for one-quarter decay ratio

Ziegler-Nichols Tuning Methods

Ziegler and Nichols called their tuning procedures the ultimate method because they required users to determine the ultimate gain and ultimate period for the closed control loop. The ultimate gain is the maximum allowable value of gain for a controller that has only a proportional mode in operation for which the closed-loop system shows a stable sine wave response to a disturbance.

Suppose we have a closed-loop feedback control system that has the controller in the automatic mode, as shown in Figure 5-9c. If we increase the proportional gain the loop will tend to oscillate. If the gain is increased more, continuous cycling or oscillation in the controller output variable occur, as shown in Figure 5-9b. This is the maximum gain at which the system can be operated before it becomes unstable. This gain is called the ultimate gain or sensitivity (S_u). The period of these sustained oscillations is called the ultimate period (P_u). If the gain is increased past this point, the system will become unstable, as shown in Figure 5-9a.

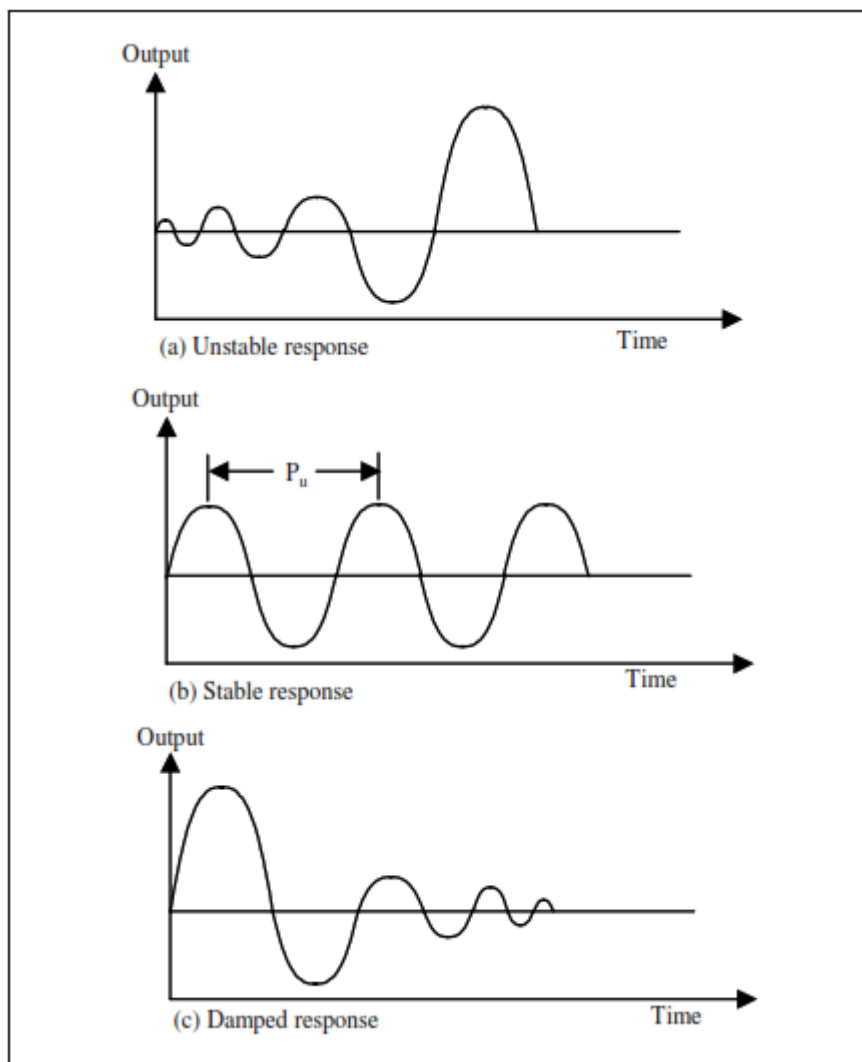


Figure 5-9. Typical process response curves

To determine the ultimate gain and the ultimate period, we perform the following steps:

1. Remove the reset and derivative action from the controller by setting the derivative time to zero, the reset time to infinity or the highest value possible, and the proportional gain to one.

2. Place the controller in automatic and make sure the loop is closed.
3. Impose an upset on the control loop and observe the response. The easiest way to impose an upset is to change the set point by a small amount.
4. If the response curve produced by step 3 does not damp out but is unstable (Figure 5-9a), the gain is too high. You should decrease gain and repeat step 3 until you obtain the stable response shown in Figure 5-9b.
5. If the response curve in step 3 damps out (Figure 5-9c), the gain is too low. You should increase the gain and repeat step 3 until you obtain a stable response.
6. When you obtain a stable response, record the values of the ultimate gain and ultimate period for the associated response. You can determine the ultimate period by measuring the time between successive peaks on the stable response curve. The ultimate gain (S_u) is the gain setting of the controller when a stable response is reached.

You can then use the ultimate gain (S_u) and ultimate period (P_u) to calculate the settings for the controller. Ziegler and Nichols recommended that for schemes based solely on proportional control, the value of gain should be equal to one-half the ultimate gain to obtain a one-quarter-wave response curve. In equation form, this can be written as follows:

$$K_c = 0.5S_u$$

They also recommended the following equations for more complex control schemes.

PI control:

$$K_c = 0.45S_u$$

$$T_i = \frac{P_u}{1.2}$$

PD control:

$$K_c = 0.6S_u$$

$$T_d = \frac{P_u}{8}$$

PID control:

$$K_c = 0.6S_u$$

$$T_i = 0.5P_u$$

$$T_d = \frac{P_u}{8}$$

These equations are empirical and are intended to achieve a decay ratio of one-quarter wave, which Ziegler and Nichols defined as good control. In many cases, this criterion is insufficient for specifying a unique combination of controller settings, each with a different period. (In two-mode or three-mode controllers an infinite number of settings will yield a decay ratio of one-quarter.) This illustrates the problem of defining what constitutes sufficient control.

In some cases, it is important that you tune the system so there is no over-shoot. In other cases, a slow and smooth response is required. Some applications require a very rapid response in which high oscillations are not a problem. You will have to determine the proper control scheme for each specific loop.

The only parameter that needs to be adjusted in a single-mode controller is the proportional gain K_c . Two parameters must be adjusted in a two-mode PI controller: the proportional gain K_c and the integral time t_i . Three parameters must be adjusted in a PID controller: the controller gain K_c for the proportional mode, the integral time t_i for the integral mode, and the derivative time t_d for the derivative mode. When the controller is being adjusted, the gains around the loop will tend to dictate what the optimum gain in the controller should be. Similarly, the time constants and dead times that characterize the lag dynamics of the process will tend to dictate the optimum value of the reset time and the proper derivative time in the controller. In other words, before you can calculate or select the best values for the tuning parameters in the controller, you must obtain quantitative information about the overall gain and the process lags that are present in the balance of the feedback loop. This illustrates why controllers must be individually tuned at the process plant, rather than at the factory.

Example

Problem: The Ziegler-Nichols ultimate method was used to determine an ultimate sensitivity of 0.3 psi/ft and an ultimate period of 1 min for a level control loop. Determine the PID controller settings that are needed for good control.

Solution: Using the equations for PID control,

$$K_c = 0.6S_u = (0.6)(0.3 \text{ psi/ft}) = 0.18 \text{ psi/ft}$$

$$T_i = 0.5P_u = 0.5(1 \text{ min}) = 0.5 \text{ min}$$

$$T_d = \frac{P_u}{8} = \frac{1 \text{ min}}{8} = 0.125 \text{ min}$$

Process Reaction Curve Method

Another method proposed by Ziegler and Nichols for tuning control loops was based on data from the process reaction curve for the system under control. The process reaction curve is simply the reaction of the process to a step change in its input signal. This process curve is the reaction of all components in the control system (excluding the controller) to a step change to the process. It is first-order process with a time delay, which is the most common process encountered in control applications.

To obtain a graph of a process reaction curve, place a high-speed recorder in the control loop, as shown in Figure 5-10. To obtain a recording of the reaction curve, perform the following steps:

1. Allow the control system under study to come to a steady state.
2. Place the process controller for the system in the manual mode.
3. Manually adjust the controller output signal to the value at which it was operating automatically.
4. Wait until the control system comes to a steady state.
5. With the controller still in manual mode, introduce a step change in the controller output signal. Normally, this is done by making a small step change in the controller set point.
6. Record the response of the measured variable.
7. Then, return the process controller output signal to its previous value and place the controller in the automatic mode.

Once you have completed these steps, you can use the recorded process reaction curve to calculate the tuning parameters that are needed for the process controller. To use this process reaction curve method, you must determine only the parameters R_r and L_r . A sample determination of these parameters for a control loop is illustrated in Figure 5-11. To obtain process information parameters in the process reaction curve method, draw a tangent to the curve at its point of maximum slope. This

Figure 5-10. Determining process reaction curve

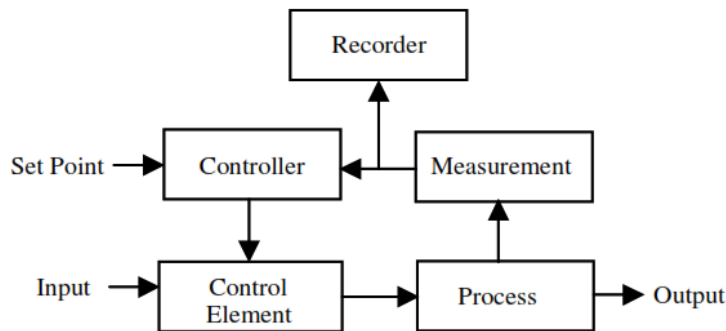
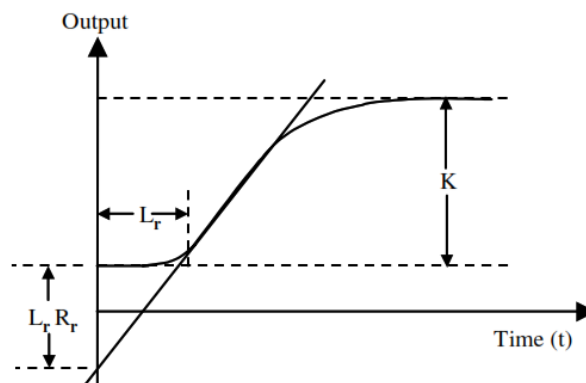


Figure 5-11. Process reaction curve



Slope, R_r , is the process reaction rate. The intersection of this tangent line with the original baseline gives an indication of L_r , the process lag. L_r is really a measure of overall dead time for the control valve, the measurement transducer, and the process. If you extrapolate this tangent drawn at the point of maximum slope to a vertical axis that drawn when the step was imposed, then the amount by which this is below the horizontal baseline will represent the product $L_r R_r$. Using these parameters, Ziegler and Nichols recommended that the following equations be used to calculate appropriate controller settings for optimal control.

Proportional-only control:

$$K_C = 1/L_r R_r$$

PID control:

$$K_C = 0.9/L_r R_r$$

$$t_i = 3.3L_r$$

PID control:

$$K_C = 1.2/L_r R_r$$

$$t_i = 2.0L_r$$

$$t_d = 0.5L_r$$

Ziegler and Nichols indicated that using these equations to tune a PID controller should produce a decay ratio of one-quarter, which they defined as good control. The use of the Ziegler-Nichol open-loop method is illustrated by the following example.

Problem: Using Ziegler and Nichols's open-loop method, determine the PID controller settings if the following values were obtained from the process reaction curve for a temperature-control loop:

$$L_r = 0.8 \text{ min}$$

$$L_r R_r = 20^\circ\text{C}/\text{psi}$$

Solution: Using the equations for PID control,

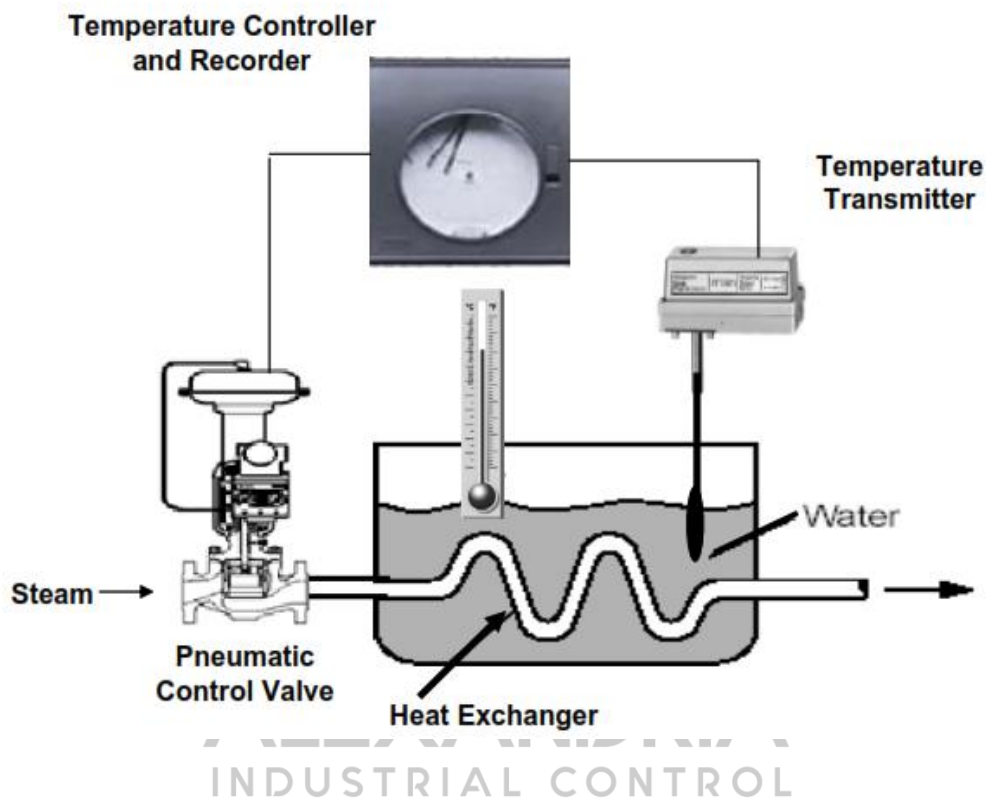
$$K_C = 1.2/L_r R_r = 1.2/(20^\circ\text{C}/\text{psi}) = 0.06 \text{ psi}/^\circ\text{C}$$

$$t_i = 2.0L_r = 2.0(0.8 \text{ min}) = 1.6 \text{ min}$$

$$t_d = 0.5L_r = 0.5(0.8 \text{ min}) = 0.4 \text{ min}$$

We have presented several practical and theoretical approaches for tuning controllers in this chapter. You can use many other mathematical equations to predict the ideal proportional, integral, and derivative settings for a given process. Some process personnel tune controllers by relying on their experience or trial-and-error methods. However, it is generally best to use one of the methods presented here until you have gained some experience in tuning control loops.

Alexandria Industrial Control



INSTRUMENTATION

Chapter 6: P&ID SYMBOLS

ISA Symbols and Loop Diagrams

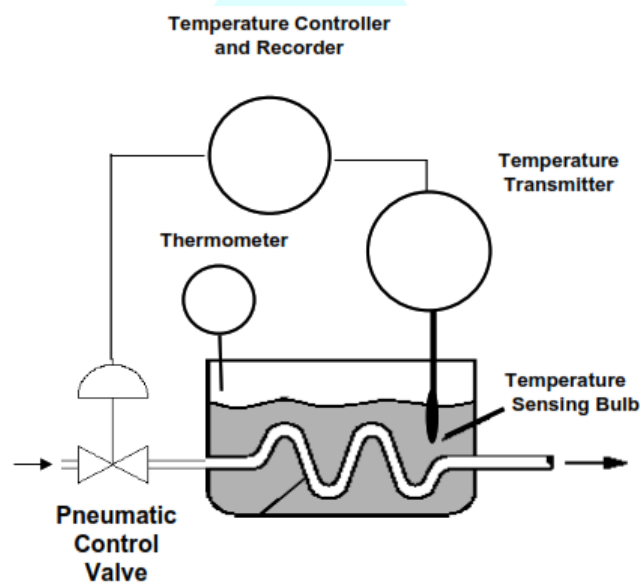
P&IDs

Piping and Instrumentation Diagrams or simply P&IDs are the “schematics” used in the field of instrumentation and control (Automation). The P&ID is used to by field techs, engineers, and operators to better understand the process and how the instrumentation is inter connected. Most industries have standardized the symbols according to the ISA Standard S5.1 Instrumentation Symbol Specification.

- ▶ Piping & Instrumentation Drawing (original)
- ▶ Process & Instrumentation Diagram (also used)
- ▶ Process Flow Diagram – PFD (simplified version of the P&ID)

Building the P&ID

The P&ID will use symbols and circles to represent each instrument and how they are inter-connected in the process.



Process Monitoring Instrument Codes

- Flow rate (F)
- Level (L)
- Pressure (P)
- Quality (Q)
- Speed (S)
- Temperature (T)

Emergency or Safety Instrument Codes

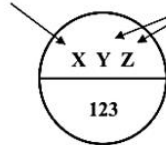
- High level (H) initiates an alarm.
- Extreme high level (HH) trips the inlet valve shut.
- Low level (L) initiates an alarm.
- Extreme low level (LL) trips the outlet valve shut

Tag numbers

Tag “numbers” are letters and numbers placed within or near the instrument to identify the type and function of the device.

The first letter is used to designate the measured variable

The succeeding letter(s) are used to designate the function of the component, or to modify the meaning of the first letter.



Pressure

Level

Flow

Temperature

Indicator

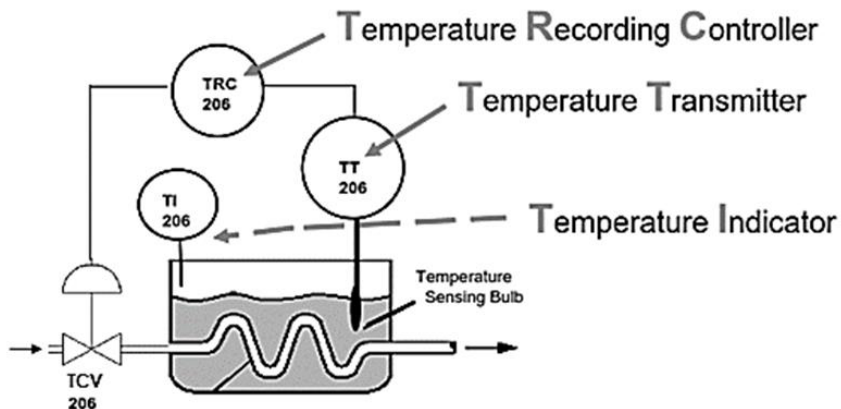
Recorder

Controller

Transmitter

ALEXANDRIA
INDUSTRIAL CONTROL

General instrument or function symbols



ISA Symbols

Process Measurement	Element Type	
	Code	Element
Analysis	A	AE
	AE	AT
Conductivity	C	CE
	CE	CT
Density	D	DE
	DE	DT
Voltage	E	EE
	EE	ET
Flow	F	FE
	FE	FT
Dimension	G	GE
	GE	GT
Hand	H	HE
	HE	HT
Current	I	IE
	IE	IT
Time	K	KE
	KE	KT
Level	L	LE
	LE	LT
Humidity	M	ME
	ME	MT
Power	N	NE
	NE	NT
Pressure	P	PE
	PE	PT
Delta Pressure	dP	dPE
	dPE	dPT
Quantity	Q	QE
	QE	QT
Radioactivity	R	RE
	RE	RT
Speed	S	SE
	SE	ST
Temperature	T	TE
	TE	TT
Delta Temperature	dT	dTE
	dTE	dTT
Viscosity	V	VE
	VE	VT
Weight	W	WE
	WE	WT
Vibration	Y	YE
	YE	YT
Position	Z	ZE
	ZE	ZT
	I	Indicator
	IC	Indicator Controller
	C	Controller
	FC	Ratio Controller
	R	Recorder
	HS	Hand switch
	HV	Hand Valve
	Q	Totalizer
	IQ	Indicating Totalizer
	XV	Solenoid valve
	V	Control Valve
	Y	Calculation
	FY	Ratio Calculation
	SL	Switch Low
	SH	Switch High
	AL	Alarm Low
	ALL	Alarm Low-Low
	AH	Alarm High
	AHH	Alarm High-High

LIST OF ABBREVIATIONS

bara	bar (absolute)
barg	bar (gauge)
BPD	Barrels Per Day
BS&W	Basic Sediment and Water
BTU	British thermal unit
cc	cubic centimetre
CCR	Central Control Room
CCTV	Closed Circuit Television
CPU	Central Processing Unit
CSP	Collector Separator Platform
DAU	Data Acquisition Unit
DCS	Distributed Control System
ESD	Emergency Shutdown
FC	Fail Closed
FCV	Flow Control Valve
FG	Fuel Gas
FI	Flow Indicator
FO	Fail Open
ft	feet
ft²	square feet
ft³	cubic feet
gal	gallon
GG-II	Gas Gathering – Phase II Platform

GOW	Gas/Oil/Water
gpm	gallons per minute
GT	Gas Turbine
H₂S	Hydrogen Sulphide
HHP	High-High Pressure
HP	High Pressure
hr	hour
HSE	Health, Safety and Environment
HVAC	Heating/Ventilation/Air-conditioning
in	inch
IR	Infra Red
KO	Knock-out
lb	pound (weight)
LC	Locked Closed
LCR	Local Control Room
LCV	Level Control Valve
LED	Light Emitting Diode
LEL	Lower Explosive Limit
LER	Local Equipment Room
LI	Level Indicator
LIC	Level Indicator Controller
LNG	Liquefied Natural Gas
LO	Locked Open
LP	Low Pressure
LPG	Liquefied Petroleum Gas
LT	Level Transmitter

M	Thousand
m²	square metres
m³	cubic metres
MAC	Manual Alarm Callpoint
MAWP	Maximum Allowable Working Pressure
MGL	Main Gas Line
MM	Million
mmscfd	million standard cubic feet per day
MOL	Main Oil Line
MOOCS	Modernization of Offshore Control Systems
MOV	Motor Operated Valve
MSF	Main Structure Frame
MTU	Master Telemetry Unit
N₂	Nitrogen
NGL	Natural Gas Liquids
NO	Normally Open
NRV	Non-return Valve
NTP	Normal Temperature and Pressure
OCCP	Original Central Collection Platform
O/I	Output/Input
OIS	Operator Interface Station
P&ID	Piping and Instrument Diagram
PAH	Pressure Alarm High
PAHH	Pressure Alarm High-High
PAL	Pressure Alarm Low
PALL	Pressure Alarm Low-Low
PC	Personal Computer

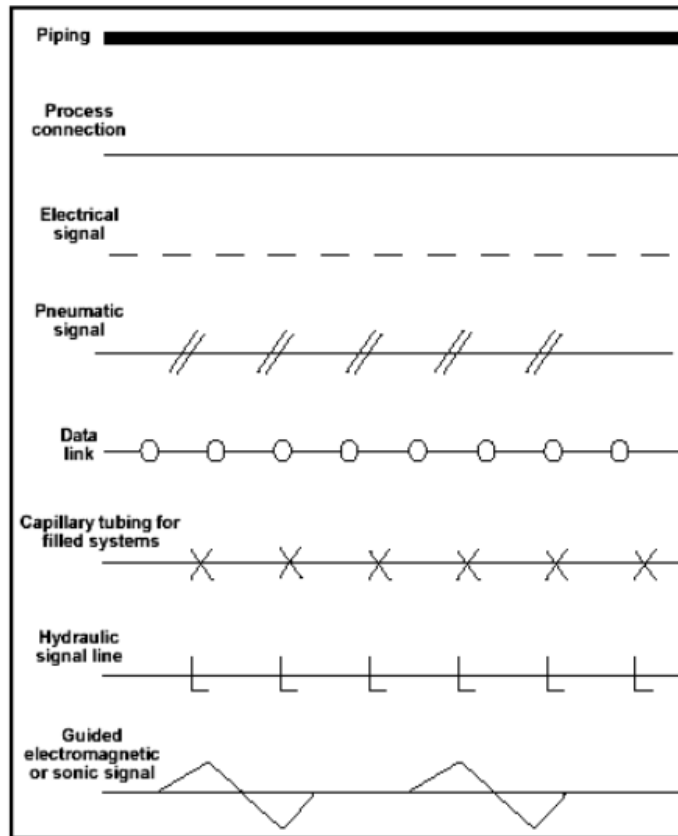
PCS	Process Control System
PCV	Pressure Control Valve
PDIC	Pressure Differential Indicator Controller
PDRC	Pressure Differential Recorder Controller
PFD	Process Flow Diagram
PGP	Power Generation Platform
PIC	Pressure Indicator Controller
PLC	Programmable Logic Controller
ppm	parts per million
psia	pounds per square inch (absolute)
psig	pounds per square inch (gauge)
PSLL	Pressure Switch Low-Low
PSU	Power Supply Unit
PSV	Pressure Safety Valve
PTB	Pounds per Thousand Barrels
RFIS	Remote Flare Ignition System
RO	Restriction Orifice
RTU	Remote Telemetry Unit
RV	Relief Valve
SCADA	Supervisory Control and Data Acquisition
SDV	Shutdown Valve
sec	second(s)
SG	Specific Gravity
SOV	Solenoid Operated Valve
SSV	Surface Safety Valve
TAH	Temperature Alarm High
TAHH	Temperature Alarm High-High

TAL	Temperature Alarm Low
TALL	Temperature Alarm Low-Low
Temp	Temperature
TIC	Temperature Indicator Controller
TSSL	Temperature Switch Low-Low
UPS	Uninterruptible Power Supply
US	Umm Shaif
US gal	United States Gallons
USSC	Umm Shaif Super Complex
UTC	Unique Tracking Commodity (used in PASSPORT)
UV	Ultra Violet
VDU	Visual Display Unit
wg	water gauge (inches pressure)
WI	Water Injection
WIP	Water Injection Platform
WO	Work Order
WV	Wing Valve
XV	Emergency Shutdown Valve
ZCC	ZADCO Central Complex
°C	degrees Centigrade
°F	degrees Fahrenheit

Table 1 — Identification Letters

	FIRST-LETTER (4)		SUCCEEDING-LETTERS (3)		
	MEASURED OR INITIATING VARIABLE	MODIFIER	READOUT OR PASSIVE FUNCTION	OUTPUT FUNCTION	MODIFIER
A	Analysis (5,19)		Alarm		
B	Burner, Combustion		User's Choice (1)	User's Choice (1)	User's Choice (1)
C	User's Choice (1)			Control (13)	
D	User's Choice (1)	Differential (4)			
E	Voltage		Sensor (Primary Element)		
F	Flow Rate	Ratio (Fraction) (4)			
G	User's Choice (1)		Glass, Viewing Device (9)		
H	Hand				High (7, 15, 16)
I	Current (Electrical)		Indicate (10)		
J	Power	Scan (7)			
K	Time, Time Schedule	Time Rate of Change (4, 21)		Control Station (22)	
L	Level		Light (11)		Low (7, 15, 16)
M	User's Choice (1)	Momentary (4)			Middle, Intermediate (7,15)
N	User's Choice (1)		User's Choice (1)	User's Choice (1)	User's Choice (1)
O	User's Choice (1)		Orifice, Restriction		
P	Pressure, Vacuum		Point (Test) Connection		
Q	Quantity	Integrate, Totalize (4)			
R	Radiation		Record (17)		
S	Speed, Frequency	Safety (8)		Switch (13)	
T	Temperature			Transmit (18)	
U	Multivariable (6)		Multifunction (12)	Multifunction (12)	Multifunction (12)
V	Vibration, Mechanical Analysis (19)			Valve, Damper, Louver (13)	
W	Weight, Force		Well		
X	Unclassified (2)	X Axis	Unclassified (2)	Unclassified (2)	Unclassified (2)
Y	Event, State or Presence (20)	Y Axis		Relay, Compute, Convert (13, 14, 18)	
Z	Position, Dimension	Z Axis		Driver, Actuator, Unclassified Final Control Element	












Instrument line symbol



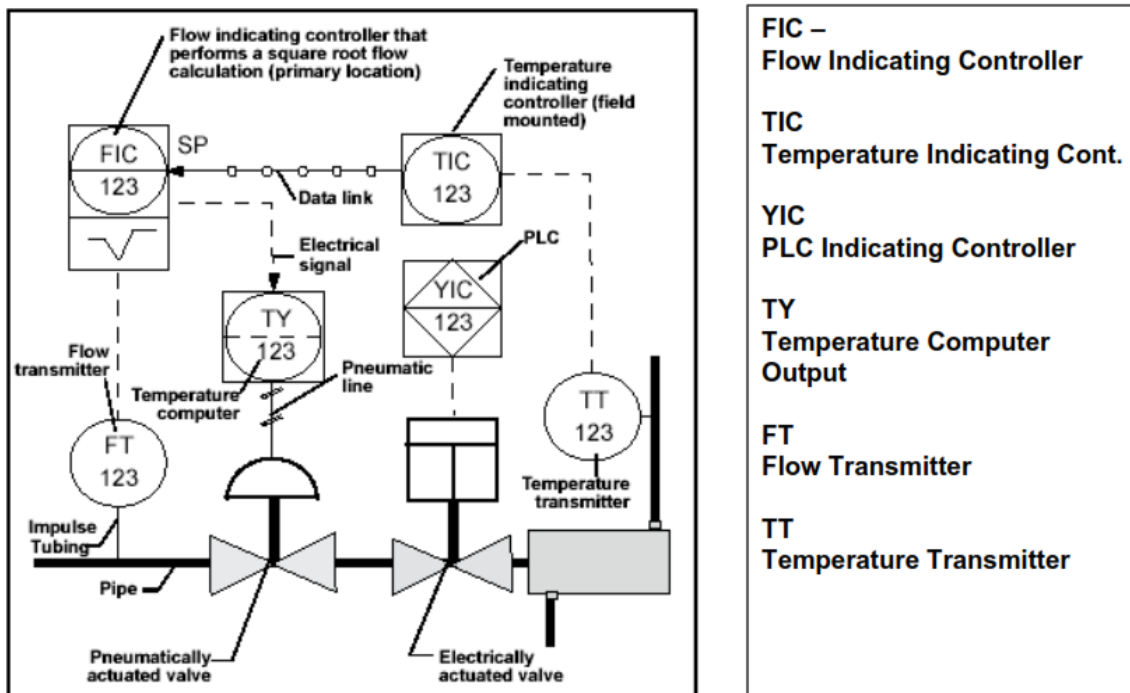
General instrument or function symbols

	PRIMARY LOCATION ***NORMALLY ACCESSIBLE TO OPERATOR	FIELD MOUNTED	AUXILIARY LOCATION ***NORMALLY ACCESSIBLE TO OPERATOR
DISCRETE INSTRUMENTS	1 * IP1** 	2 	3
SHARED DISPLAY, SHARED CONTROL	4 	5 	6
COMPUTER FUNCTION	7 	8 	9
PROGRAMMABLE LOGIC CONTROL	10 	11 	12

Valves

- | | |
|---|--|
|  Gate Valve, Hand-operated |  Control Valve |
|  Globe Valve, Hand-operated |  Solenoid Valve |
|  Plug or Cock Valve, Hand-operated |  Motor-operated |
|  Check Valve |  Piston-operated |
|  Butterfly Valve |  Safety Valve or Relief Valve |
|  Angle Valve, Hand-operated | |

مثال



Beast Regards

Eng. Hesham Abdelhady