Introduction to measurements and control concepts

Overview

Instrumentation refers to a group of devices that work together to control one or more variables. Although instruments serve different functions, and are installed in different locations, several process instruments will be connected to control one or more process variables.
Over the years, instruments and controls in gas plants, petroleum refineries, petrochemical plants, and chemical plants have greatly improved. Today's instrumentation and controls are capable of extremely precise measurement and control.
In addition, the systems can prevent equipment overloads and detect equipment problems. They can also perform complex mathematical calculations to ensure the units are operating efficiently.

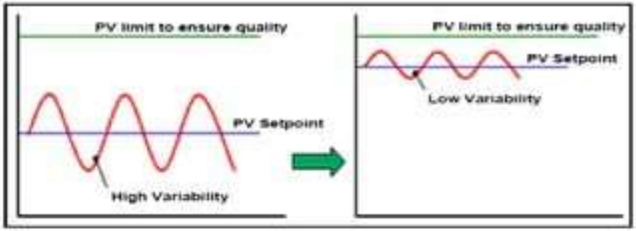
Process Control

Process as used in the terms process control and process industry, refers to the methods of changing or refining raw materials to create end products.

This is the physical system we wish to monitor and control.
Process control refers to the methods that are used to control process variables when manufacturing a product.

Manufacturers control the production process for three reasons:

- Reduce Variability.
- Increase Efficiency.
- Ensure Safety.



The Control Loop

A control loop is a group of instruments that work together to keep a process variable at its desired value, referred to as set point. There are four components in a control loop:

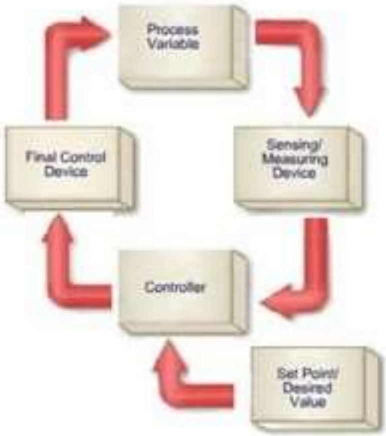
Process variable

Sensing/measuring device.

Controller.

Final control device.

Regardless of the process, measuring and control jobs are very similar. But, the instruments used to perform measuring and control will vary from one process to another.

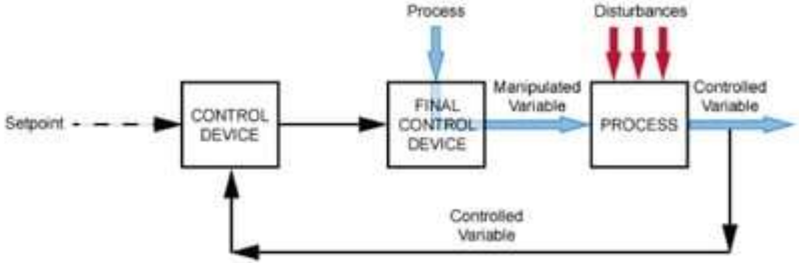


Control Loops and Controller Action

A control system is a mechanical or electronic system that is used to obtain and maintain the specific result.

Process control can simply be defined as the automated control of a process or the manipulation of a set of conditions to bring about a desired change in the output of the process.

A process can further be defined as a series of operations in the making, handling or treatment of a product. From these definitions it can be said that process control is the manipulation of conditions to produce a specific result.



Control Loop Definition

Controlled variable	A controlled variable is sometimes referred to as the process variable. It is the element that is to be controlled, for example, pressure, temperature, level, flow, chemical composition, etc.
Measured variable	A measured variable is a measurement signal of the controlled variable.
Setpoint	The setpoint is the desired value of a process. It is the value of the controlled variable that the process is required to operate at.
Error	An Error is the difference between the measured variable and the set point and can be either positive or negative.
Offset	The Offset is a sustained deviation of the process variable from the set point.
Manipulated variable	A manipulated variable is the actual variable changed by the final control element to obtain the desired effect on the controlled variable.
Disturbances	Disturbances (upsets) are any changes that can occur to the process to cause the controlled variable to change from the setpoint.

Process variable

A process variable is a condition of the process fluid (a liquid or gas) that can change the manufacturing process in some way. Common process variables include:

Basic Process Measurement

- Pressure
- Flow
- Level
- Temperature

Advanced Process Measurement

- Density
- Ph (acidity or alkalinity)
- Mass
- Conductivity

Sensing/measuring device.

Primary elements are devices that cause some change in their property with changes in process fluid conditions that can then be measured.

- Pressure Sensing Diaphragms,
- Strain Gauges,
- Capacitance Cells

- Orifice Plates
- Pitot Tubes
- Venturi Tubes
- Magnetic Flow Tubes
- Coriolis Flow Tubes
- Ultrasonic
- Annubar
- Vortex Sheddar

- Resistance Temperature Detectors (RTDs)
- Thermocouples
- Thermometers

- Radar
- Nuclear
- Ultrasonic
- Capacitive
- Displacer

Controller

Controllers also commonly reside in a digital control system such as.

Distributed Control Systems (DCS)
DCSs are controllers that, in addition to performing control functions, provide readings of the status of the process, maintain databases and advanced man-machine-interface.

Programmable Logic Controllers (PLC)
PLCs are usually computers connected to a set of input/output (I/O) devices. The computers are programmed to respond to inputs by sending outputs to maintain all processes at set point.

Supervisory Control and Data Acquisition (SCADA)
SCADA systems are generally used to control dispersed assets using centralized data acquisition and supervisory control.

Final control device

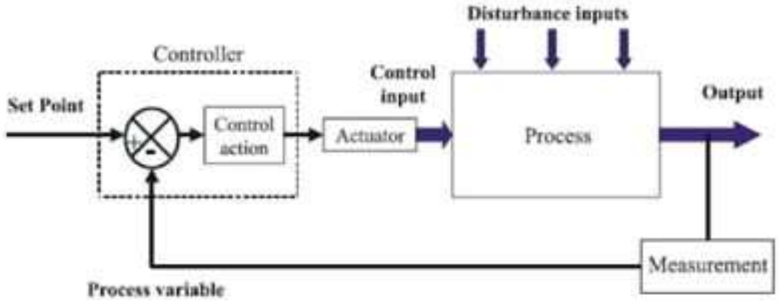
Final control element is the part of the control system that acts to physically change the manipulated variable.

The final control element may be
Control valve
Electrical motors
Pumps
Dampers

Closed and Open control loops

Closed Loop

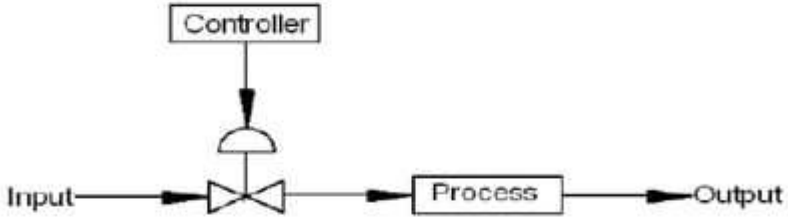
A closed control loop exists where a process variable is measured, compared to a set point, and action is taken to correct any deviation from set point.



Closed and Open control loops

Open Loop

An open control loop exists where the process variable is not compared, and action is taken not in response to feedback on the condition of the process variable, but is instead taken without regard to process variable conditions.

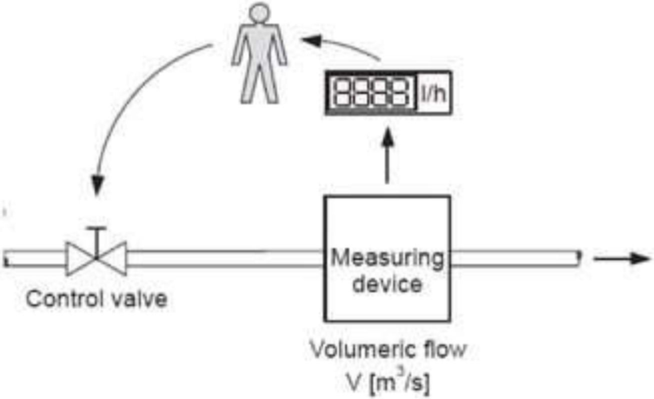


Open-Loop control diagram

Automatic and Manual control

Automatic Control

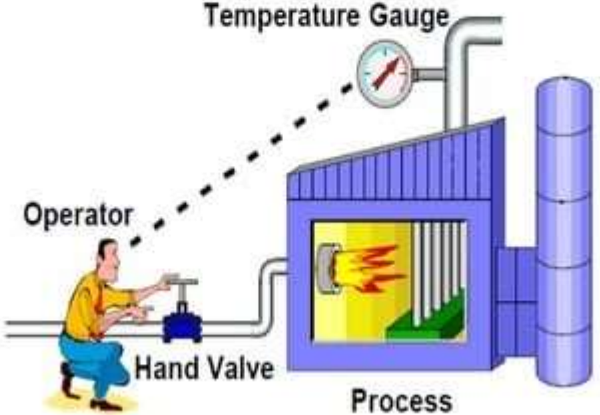
This term came into wide use when people learned to adapt automatic regulatory procedures to manufacture products or process material more efficiently. Such procedures are called automatic because no human (manual) intervention is required to regulate them.



Automatic and Manual control

Manual Control Loop

Without automatic controllers, all regulation tasks will have to be done manually. For example: To keep constant the temperature of water discharged from an industrial gas-fired heater, an operator has to watch a temperature gauge and adjust a gas control valve accordingly. If the water temperature becomes too high, the operator has to close the gas control valve a bit - just enough to bring the temperature back to the desired value. If the water becomes too cold, he has to open the valve again.



P&ID Symbols

P&IDs provide information about all equipment, all the instruments used to monitor or control the process, and all their associated lines or pipelines.

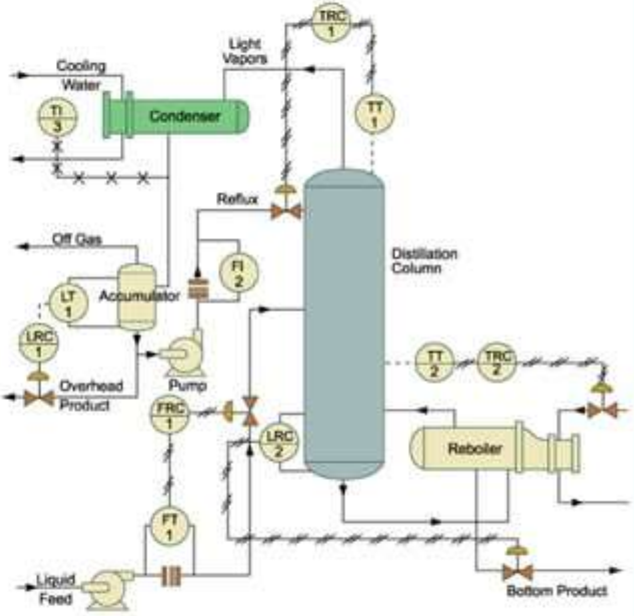
There are standard symbols and designations for P&IDs. They may use the International Society of Automation (ISA) standards, or your facility may use their own standards. All drawings must be done the same way, using the same symbols and designations for:

Equipment.

Instruments designations and symbols.

Pipeline designations.

Valve and miscellaneous symbols.



Identification letters

	Measured Variable	Modifier	Readout	Device Function	Modifier
A	Analysis		Alarm		
B	Burner, combustion		User's choice	User's choice	User's choice
C	User's choice			Control	
D	User's choice	Differential			
E	Voltage		Sensor (primary element)		
F	Flow rate	Ration (fraction)			
G	User's choice		Glass, viewing device		
H	Hand				High
I	Electrical Current		Indication		
J	Power	Scan			
K	Time, time schedule	Time rate of change		Control station	
L	Level		Light		Low
M	User's choice	Momentary			Middle, intermediate
N	User's choice		User's choice	User's choice	User's choice
O	User's choice		Orifice, restriction		
P	Pressure, vacuum		Point, test connection		
Q	Quantity	Integrate, totalizer			
R	Radiation		Record		
S	Speed, frequency	Safety		Switch	
T	Temperature			Transmit	
U	Multivariable		Multifunction	Multifunction	Multifunction
V	Vibration, mechanical analysis			Valve, damper, louver	
W	Weight, force		Well		
X	Unclassified	X axis	Unclassified	Unclassified	Unclassified
Y	Event, state, or presence	Y axis		Relay, compute, convert	
Z	Position, dimension	Z axis		Driver, actuator	

Instrument Designations

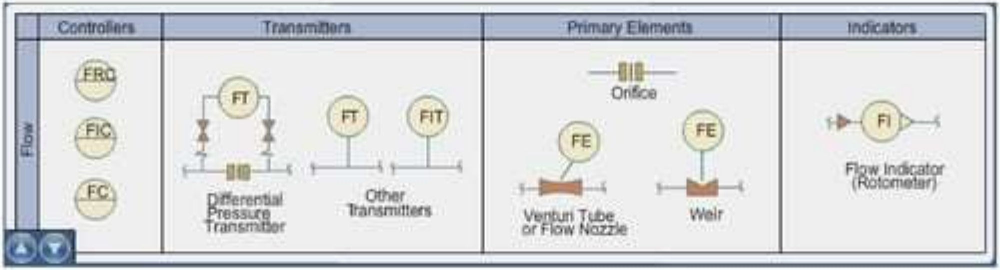
There are several different instrument designations for process variable control or monitoring. This table shows some of the most common ones.

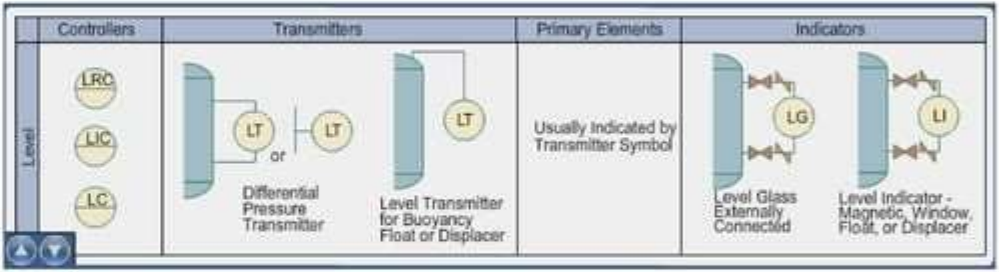
Designation	Condition	Designation	Condition
Flow		**Level**	
FAL	Flow alarm low	LAL	Level alarm low
FAH	Flow alarm high	LAH	Level alarm high
FC	Flow controller	LC	Level controller
FIC	Flow indicating controller	LIC	Level indicating controller
FIT	Flow indicating transmitter	LIT	Level indicating transmitter
FRC	Flow recording controller	LRC	Level recording controller
FS	Flow switch	LS	Level switch
Pressure		**Temperature**	
PAL	Pressure alarm low	TAL	Temperature alarm low
PAH	Pressure alarm high	TAH	Temperature alarm high
PC	Pressure controller	TC	Temperature controller
PIC	Pressure indicating controller	TIC	Temperature indicating controller
PIT	Pressure indicating transmitter	TIT	Temperature indicating transmitter
PRC	Pressure recording controller	TRC	Temperature recording controller
PS	Pressure switch	TS	Temperature switch

Instrument Symbols

	Primary Location, Normally Accessible to the Operator	Field-Mounted	Auxiliary Location, Normally Accessible to the Operator
Discrete Instruments			
Shared Display, Shared Control			
Computer Function			
Programmable Logic Control			

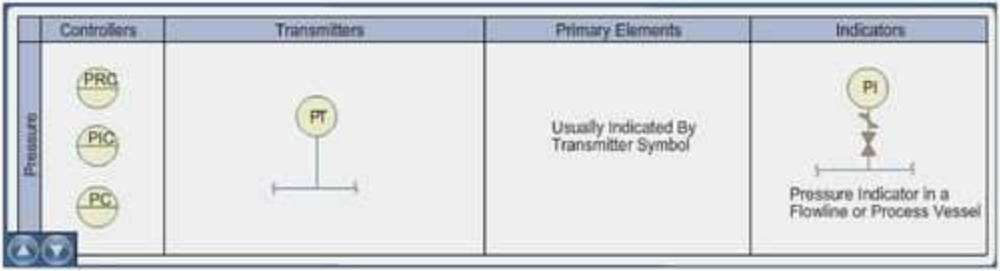
Process Variable Symbols

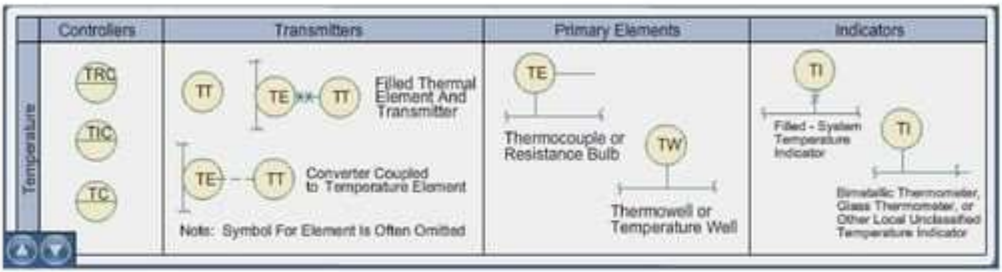




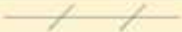
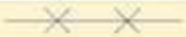
Piping and Instrumentation Diagrams

Process Variable Symbols





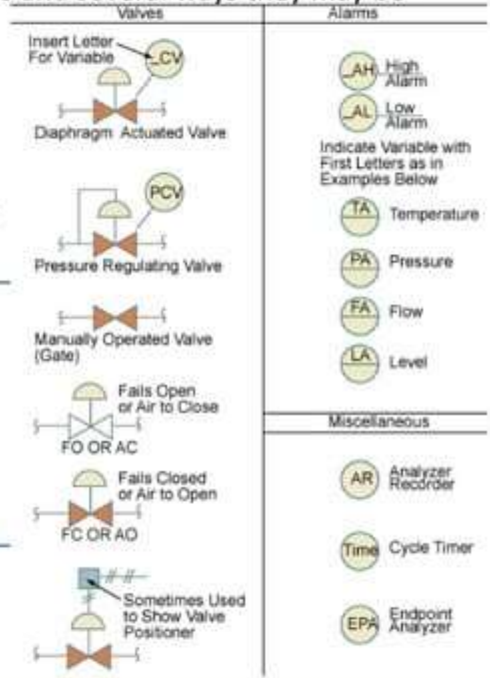
Instrument Line Symbols

Type of Line	Image Used
Instrument Supply or Connection to Process	
Undefined Signal	
Pneumatic Signal	
Electrical Signal	or 
Hydraulic Signal	
Capillary Tube	
Electromagnetic or Sonic Signal (Guided)	
Electromagnetic or Sonic Signal (Not Guided)	
Internal System Link (Software or Data Link)	
Mechanical Link	

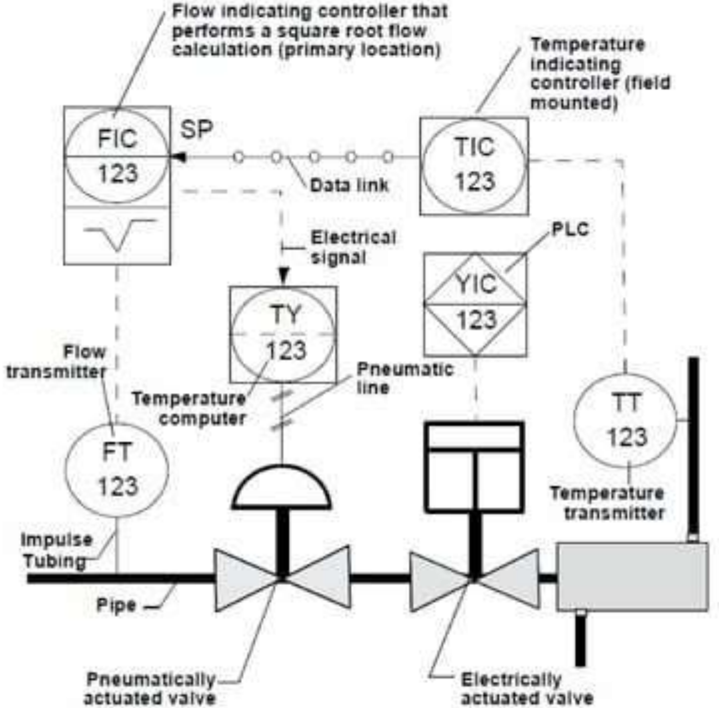
Valve Symbols

There are several types of valves used in a process and several ways they may be actuated. Examples of valve types include:

Methods of actuation include:



Example


Flow indicating controller that performs a square root flow calculation (primary location)
Temperature indicating controller (field mounted)
FIC
123
SP
Data link
TIC
123
Electrical signal
PLC
YIC
123
TY
123
Flow transmitter
Temperature computer
Pneumatic line
TT
123
FT
123
Temperature transmitter
Impulse Tubing
Pipe
Pneumatically actuated valve
Electrically actuated valve

Process Measurement Basics

Range and Span

Range is the upper and lower limits of a measurement or signal and is expressed in the units of the measurement or signal. For example a pressure transmitter is calibrated to measure from 100 bar to 1,000 bar, therefore its range is 100 to 1,000 bar.

Lower Range Limit is the lower limit of a measurement or signal and is expressed in the units of the measurement or signal. For example a pressure transmitter is calibrated to measure from 100 bar to 1,000 bar, therefore its lower range limit is 100 bar.

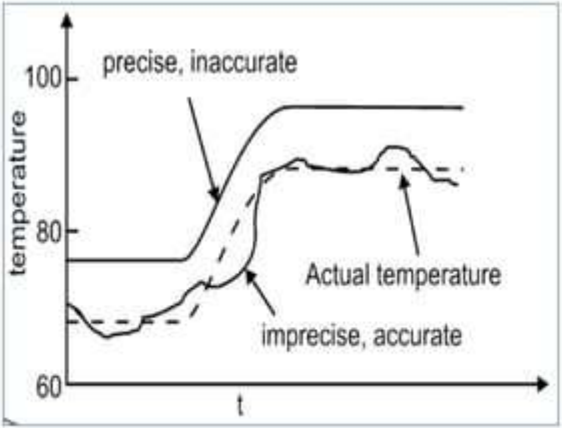
Upper Range Limit is the upper limit of a measurement or signal and is expressed in the units of the measurement or signal. For example a pressure transmitter is calibrated to measure from 100 bar to 1,000 bar, therefore its upper range limit is 1,000 bar.

Span is the mathematical difference between the upper and lower range limits of an instrument. In our example, for a range of 100 to 1,000 bar the span is 1,000 minus 100 or 900 bar.

Accuracy and Repeatability

Accuracy is the degree of closeness of the measured value to the actual value. It is usually expressed as a plus or minus percent of span. A typical example would be 500 bar plus or minus 0.5%.

Repeatability is the degree to which repeated measurements under the exact same conditions produce the same results. It is expressed as a plus or minus percent of span.



Measurement Terminology

Accuracy and Repeatability

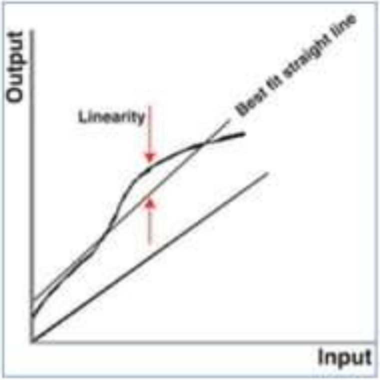
Poor repeatability
means poor accuracy
Low precision, low accuracy

Good repeatability does
not necessary means good accuracy
High precision, low accuracy

Good accuracy requires
good repeatability
High precision, high accuracy

Linearity

Linearity is the degree to which a measurement follows a straight line relationship between input and output and is expressed as a plus or minus percent of span.

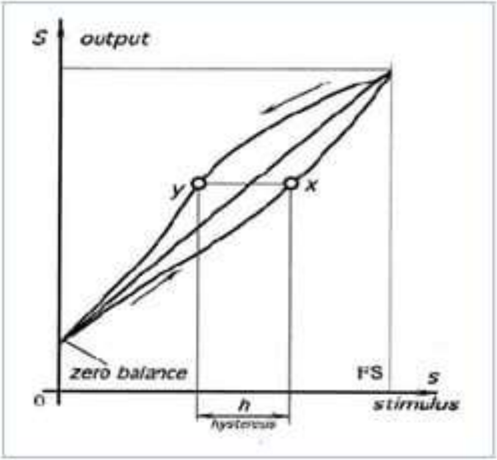


Linear and square root calibration table:

TRANSMITTER OUTPUT			READING		MEASURED VALUE
mA	psi	Kg/cm2	LINEAR SCALE	SQUARE ROOT SCALE	FLOW (m3 / Hr.)
4	3	0.2	0%	0%	0
8	6	0.4	25%	50%	100
12	9	0.6	50%	70.71%	200
16	12	0.8	75%	86.60%	300
20	15	1	100%	100%	400

Hysteresis

Hysteresis is an error due to the elastic property of a material. If a material is either stretched or compressed by a force and does not return to its original position when the force is removed, the difference is the amount of hysteresis. It is expressed as a plus or minus percent of span.



Other Terminology

Resolution is the smallest change of the measured value that will result in a change in output of a device.

Error is the difference between the measured value and the true or actual value. The cause of an error in measurement could be due to accuracy, repeatability, linearity, hysteresis or a combination thereof.

Measured or Process Value is the physical property that is being measured such as pressure, temperature, level or flow.

Actual Value is the true actual value of the physical property regardless of the value being generated by the instrumentation.

Common Measuring Instruments

Gauge or indicator is a device which directly measures and displays or indicates the value of the process variable. Pressure gauges and thermometers are examples.

Regulator is a device which maintains the process variable at a set value. Regulators can have an adjustable range.

Transducer is a device which converts one signal to another signal. Examples of a transducer are:
Current to pneumatic (I/P).
Volume booster.

Switch is a device which operates in an on/off manner to the process variable. When the process variable reaches the switch point, an electrical or pneumatic switch is activated. The switch or set point is adjustable.

Transmitter is a device that measures the process variable and converts that measurement into a signal that can be easily and safely transmitted to a control room and/or other devices.

Calibration

An **<u>Instrument Signal</u>** is the signal in an instrument loop that is proportional to the range of the process variable. Common instrument signals include:
Pneumatic: 3-15 psi.
Electronic: 4 to 20 mA and 1 to 5 Volt .

The formula for calculating the instrument signal of a transmitter is:

$$\text{Output} = \left(\frac{\text{measurement value}}{\text{measurement span}}\right)\text{signal span} + (\text{signal lower limit})$$

<u>where:</u> the measurement value is the value above the lower range limit

Examples

Example 1

For a measurement range of 0 to 600 bar, calculate the pneumatic output signal for a measurement value of 260 bar.

$$\text{Output} = \left(\frac{\text{measurement value}}{\text{measurement span}}\right)\text{signal span} + (\text{signal lower limit})$$

$$\text{Output} = \left(\frac{260\ \text{bar}}{600 - 0\ \text{bar}}\right)(1.0 - 0.2\ \text{bar}) + 0.2\ \text{bar}$$

$$\text{Output} = \left(\frac{260\ \text{bar}}{600\ \text{bar}}\right)(0.8\ \text{bar}) + 0.2\ \text{bar}$$

$$\text{Output} = (0.43)(0.8\ \text{bar}) + 0.2\ \text{bar}$$

$$\text{Output} = 0.35\ \text{bar} + 0.2\ \text{bar}$$

$$\text{Output} = \mathbf{0.55\ bar}$$

Example 2

For a measurement range of 100º C to 400º C milliamp output signal and a measurement value of 220º C.

$$\text{Output} = \left(\frac{\text{measurement value}}{\text{measurement span}}\right)\text{signal span} + (\text{signal lower limit})$$

$$\text{Output} = \left(\frac{220 - 100\ ^\circ\text{C}}{400 - 100\ ^\circ\text{C}}\right)(20 - 4\ \text{mA}) + 4\text{mA}$$

$$\text{Output} = \left(\frac{120\ ^\circ\text{C}}{300\ ^\circ\text{C}}\right)(16\ \text{mA}) + 4\ \text{mA}$$

$$\text{Output} = (0.4)(16\ \text{mA}) + 4\ \text{mA}$$

$$\text{Output} = 6.4\ \text{mA} + 4\ \text{mA}$$

$$\text{Output} = \mathbf{10.4\ mA}$$

Transmitter Calibration Equipment

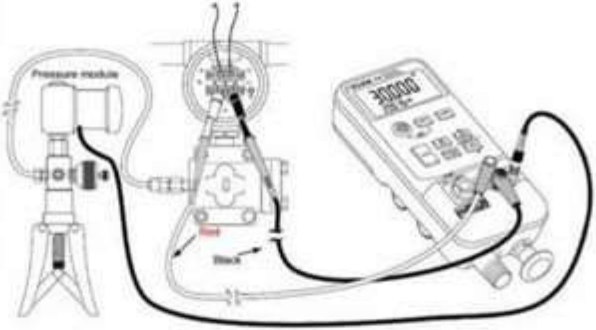
Most instruments can either be tested and/or calibrated in the field or in the shop. The equipment required for testing or calibrating is:

Multimeter: Tests the power supply and the output signal, it can be a function of a multivariable process calibrator.

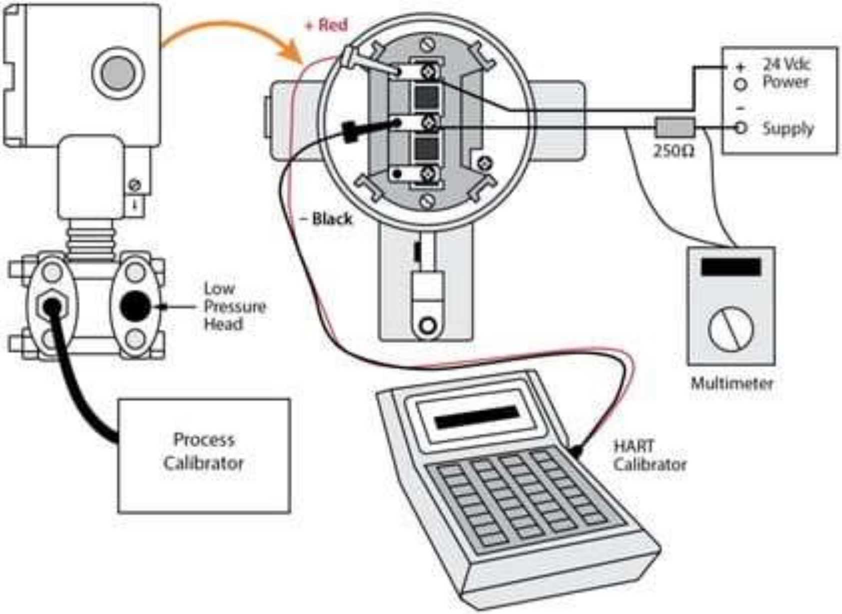
Process calibrator or calibration source: Provides the process variable to the instrument and/or the test meter for the output signal.

HART communicator: For smart instruments of the HART type for testing the function and configuration of the device.

Power supply: For shop testing and calibrating.

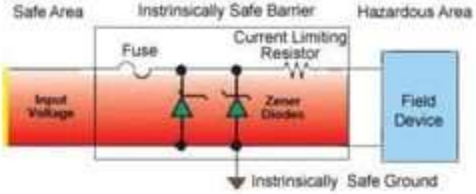


HART communicator



Intrinsic Safety

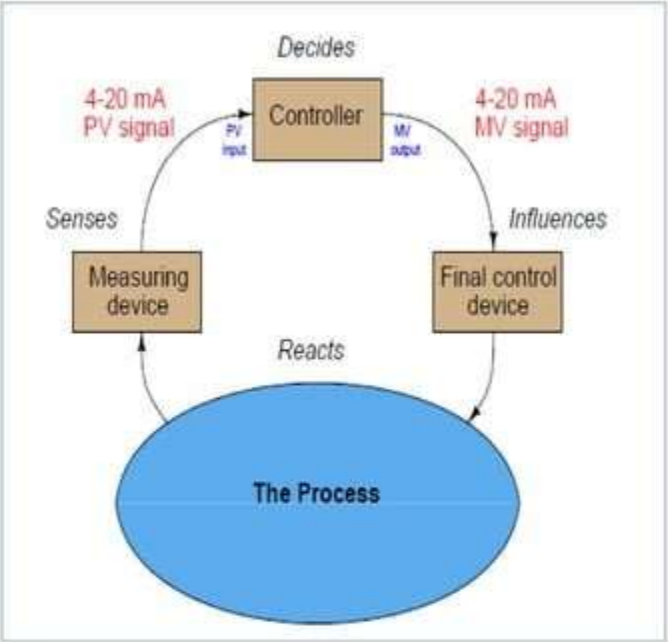
Intrinsic Safety prevents instruments and other low voltage devices and circuits in hazardous locations from releasing enough energy to ignite volatile gases. This is accomplished by using intrinsic safety barriers in the circuits of field devices.



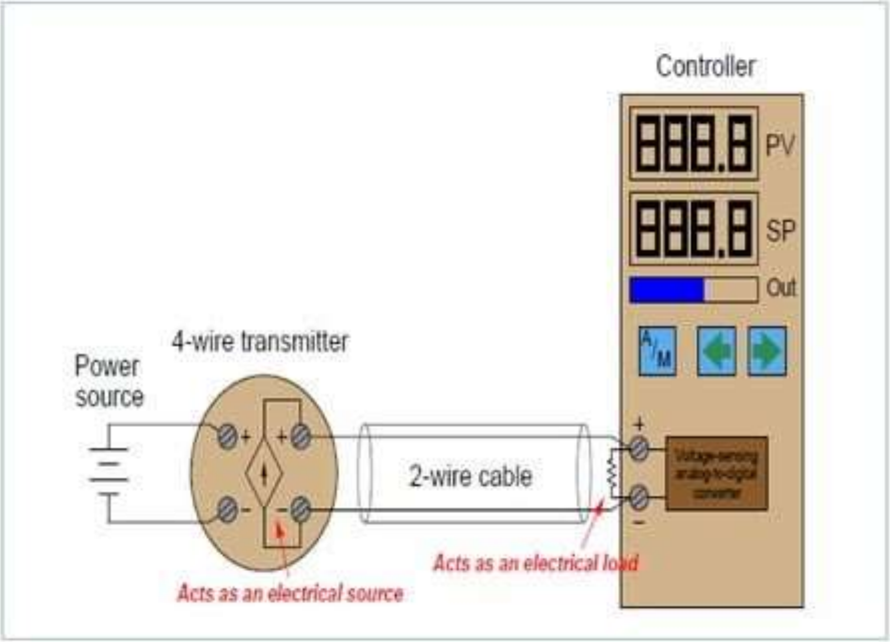
Using intrinsically safe barriers allows field equipment to be safely tested using live voltages since the barrier will prevent voltage from igniting gases present in a hazardous area.

Be careful when using testing equipment or circuits that have barriers, in so as not to create a short or ground, which could damage the barrier itself.

How information is sent in control loops

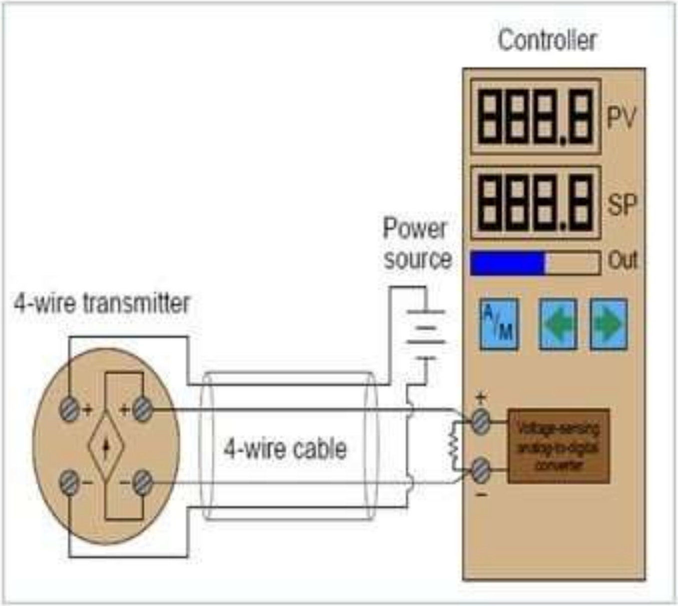


4-wire (“self-powered”) transmitter current loops

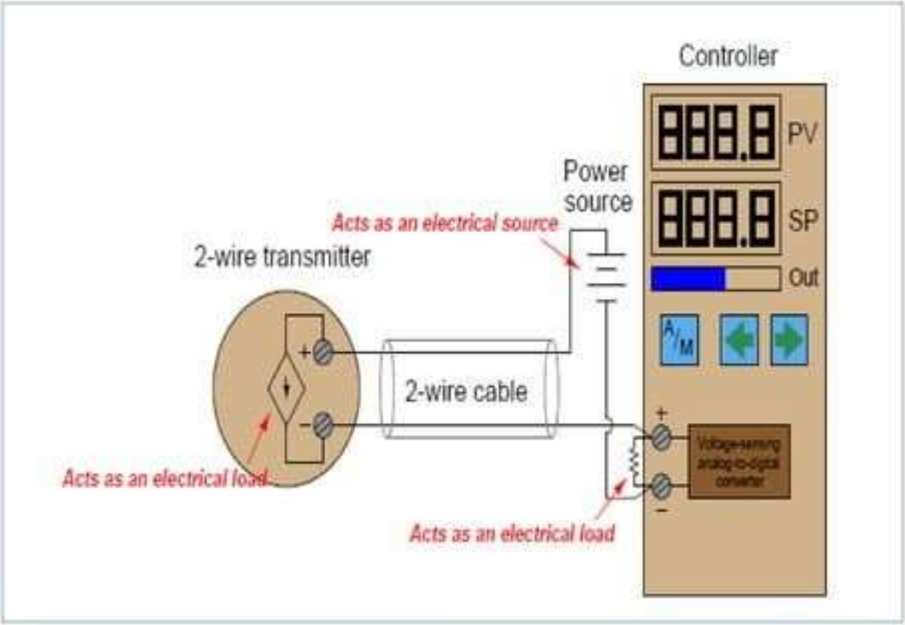


Electrical Control loops

Extended 4 wire cable



2-wire ("loop-powered") transmitter current loops

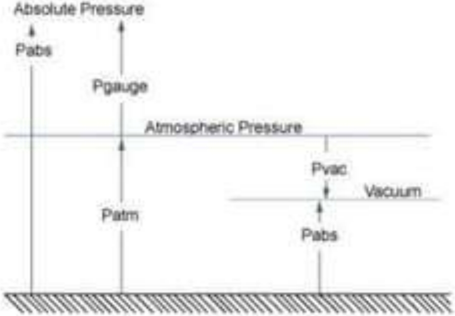


Pressure Measurement

Pressure Definitions

Pressure is force acting upon a surface area. Mathematically, pressure is force divided by area:

$$\text{Pressure (P)} = \frac{\text{Force (F)}}{\text{Area (A)}}$$



Static pressure refers to pressure caused by a fluid that is not moving and is contained within a vessel, piping, or channel that is either open or closed.

Head or hydrostatic pressures are collectively known as gauge pressure (Pg). Gauge pressure is the type of pressure most commonly referred to in industry.

Atmospheric pressure (Patm) is the pressure exerted by the atmosphere on the earth at sea level.

Absolute pressure (Pa) is the sum of gauge pressure and atmospheric pressure.

Primary Element

The device or component that actually measures pressure is referred to as the primary element, primary because it is that part which is actually in contact with the fluid.

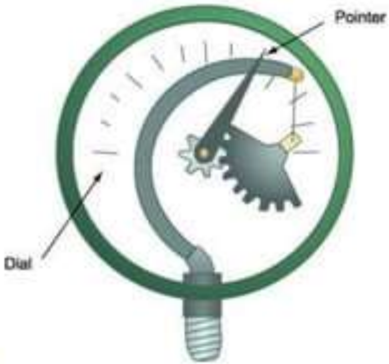
All of the different types of primary elements have one common property, their elasticity. Elasticity can be defined as the property of returning to an initial form or state following deformation, that is after a force distorts an object and is then removed, the object will return to its original position or shape.

Numerous types of primary elements have been devised, each with its own properties and applications. The types that we will discuss are:
Bourdon tube.
Diaphragm.
Bellows.
Capsule.
Strain Gauge.
Piezoelectric sensor.

Bourdan Tube

The bourdon tube is a tube that is constructed such that one end is open with the other end closed. The cross-sectional area is elliptical so that when pressure is applied to the open end, a displacement of the closed end or tip is caused. Bourdon tubes are typically constructed of bronze, Monel, stainless steel or other alloys depending on the fluid application. Bourdon tubes can measure pressures up to 29 bar (2,900 kPa), however they are not accurate for pressures of less than 0.3 bar (30 kPa).

C-type

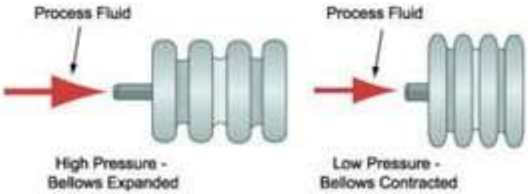


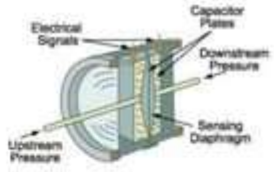
Spiral

Helical

Bellows

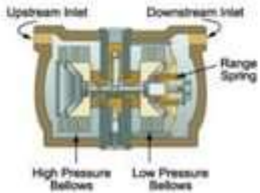
The bellows is basically a convoluted can with an opening on one side and that side being fixed. Pressure is applied internally causing the bellows to expand and this motion is utilized in the pressure instrument. When the pressure is relieved, the bellows returns to its original position.





Differential Pressure Transducer

Some applications can have a sealed bellows mounted inside a can and the pressure applied externally.



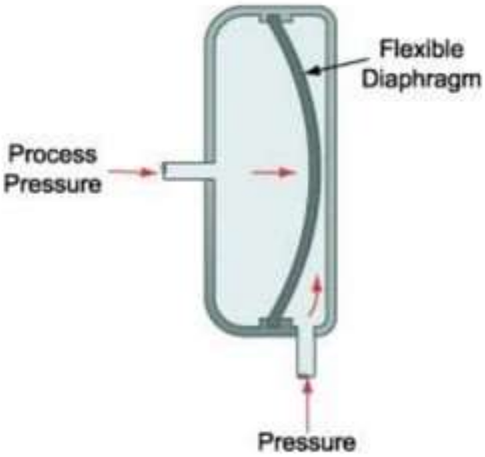
Differential Pressure Bellows

Bellows are usually made of brass, bronze or stainless steel, however for certain applications, various alloys can be used. Bellows are typically low pressure elements of up to 7 bar (700 kPa).

Diaphragm

The diaphragm is a flexible disk that has the pressure applied to one side, causing a deflection of the diaphragm. When pressure is relieved, the diaphragm returns to its original position. The displacement or movement of the diaphragm is detected by the instrument for which it is the primary element.

The diaphragm can either be flat or corrugated and are made of rubber, bronze, Monel, stainless steel or other alloys depending on the fluid application. The corrugated diaphragms can withstand much higher pressures than the flat type. Diaphragms are typically used in low pressure applications.



Capsule

The capsule consists of two diaphragms that have been welded together on their circumferences and are almost exclusively corrugated. The capsule is constructed of bronze, Monel, stainless steel or other alloys depending on the fluid application.

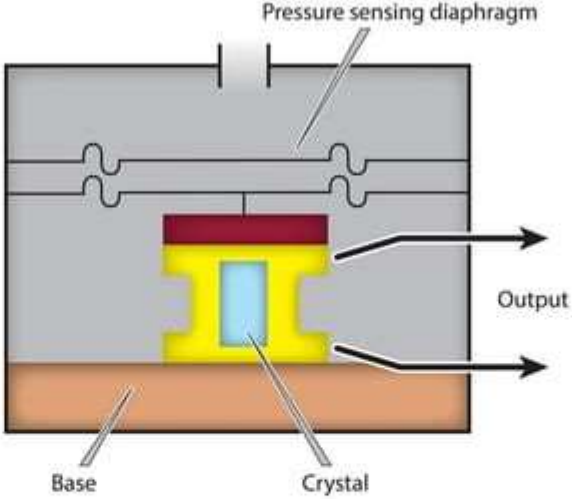
Its advantage over the bourdon tube is that is can withstand much higher pressures, up to 300 bar (30,000 kPa).

Capacitance capsules are a very popular primary element in pressure and differential pressure transmitters. Capacitance is the electrical property that permits an electrical circuit to store a charge. A capacitor is the electronic component that exhibits capacitance and consists of two conductive electrical plates separated by a non-conductive dielectric material. The amount of capacitance is dependent on the area of the plates and the distance between them.

A capacitance capsule consists of the capsule that is filled with a dielectric material. The two parts of the capsule are the plates and are of fixed area, therefore the only variable is the distance between them. If a pressure is applied to one side of the capsule, the distance between the two plates is decreased thereby increasing the capacitance since the relationship between the distance between the plates is inversely proportional to the capacitance. The change in capacitance is measured by an electronic circuit and is proportional to the pressure applied.

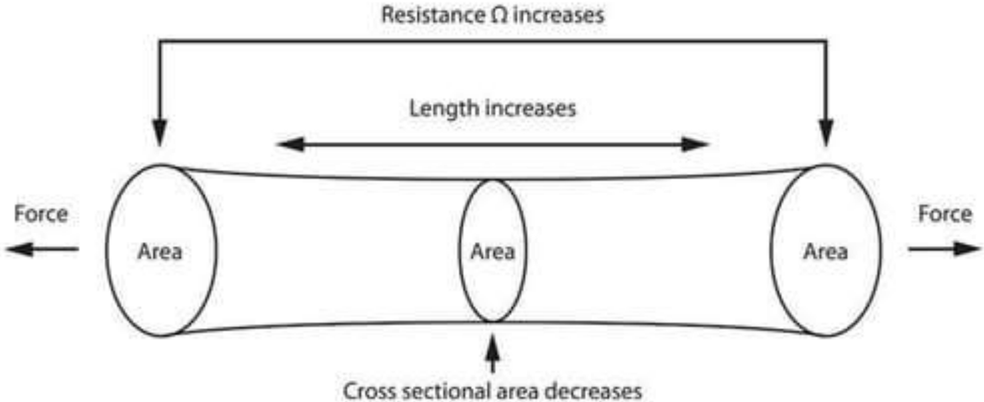
Piezoelectric Sensor

The piezoelectric sensor is based on the principle that when a quartz (or other suitable material) crystal is compressed an electrical potential is produced. This electrical potential is proportional to the pressure applied and is measured by an electronic circuit.



Strain Gauge

The strain gauge is based on the electrical conductivity of a conductor which is a constant property of individual materials. When a conductor is stretched or compressed without breaking, itsconductance or electrical resistance changes. On compression, the resistance decreases while on elongation (or stretching) the resistance increases. This relationship can be expressed in the simple formula that resistance is proportional to the length of the conductor divided by the area of the conductor times the resistance coefficient of the material.



Differential Pressure Transmitter

Capable of measuring differential pressure (that is, the difference between a high pressure input and a low pressure input) and therefore called DP transmitters or DP cells.

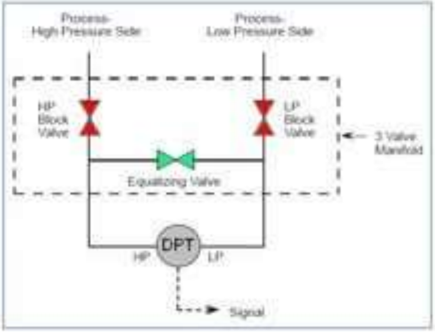
The DP transmitter consists of:
Body containing display, electronic module & power module.
Manifold with isolation, bypass & vent valves.
The transducer (DP cell) inserted in a pressure capsule .

A pressure capsule has to be used to obtain maximum sensitivity.

A pressure capsule has a sensitivity range that closely matches the anticipated pressure of the measured fluid.

Three Valve Manifold

A three-valve manifold is a device that is used to ensure that the capsule will not be over-ranged during bringing the transmitter in/out of the service.
Allows isolation of the transmitter from the process loop.



Installation

When installing any pressure measuring device, consider:
Excessive (high or low) process pressure or temperature – select the proper materials of the parts exposed to the process for safe operation.

Corrosive process fluids - select the proper materials of the parts exposed to the process for safe operation or use seals on the input lines.
Instrument range - the primary element must be chosen to match the desired range, however, the range shouldn't be selected to be too large as this will lead to less accuracy.
Select overpressure stops and/or blow out (rupture) disc to prevent damage to the instrument or unsafe conditions to personnel.
High vibration installations – install the instrument away from high vibration equipment.
High process pressure fluctuations – install pulsation dampers (snubbers) on the instrument input lines.
Steam installations – install pigtail seals (siphons) on the instrument input lines to prevent steam from being present in the instrument.
Corrosive or extreme temperature environment – install the instrument in an enclosure and use heat tracing or cooling where required.

Flow Measurement

Commonly Used Flow Devices

Differential Pressure (Head) Type
Orifice Plate
Venturi Tube
Flow Nozzles
Elbow
Pitot Tube, Averaging Pitot Tube (Annubar)
Wedge Meter
V-Cone
Velocity Type
Magnetic
Ultrasonic - Transit Time, Doppler
Turbine
Vortex
Mass Type
Coriolis
Thermal
Variable Area meter
Rotameter

Differential Pressure (Head) Type

Differential pressure flow measurement is the most common method used in industry. However, before the device used to measure flow by the differential pressure method can be studied, a good understanding of flow theory is required.

The equation of continuity states that: "The volume rate of flow (Q) passing any given point in a pipe is equal to the cross-sectional area of the pipe (A) times the velocity (v) at that point."

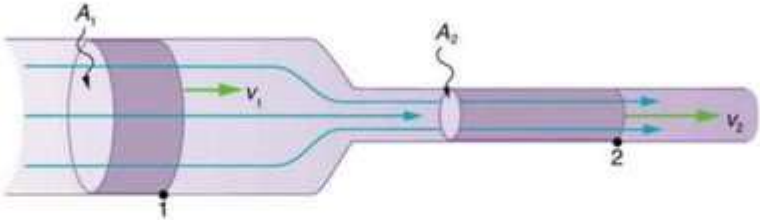


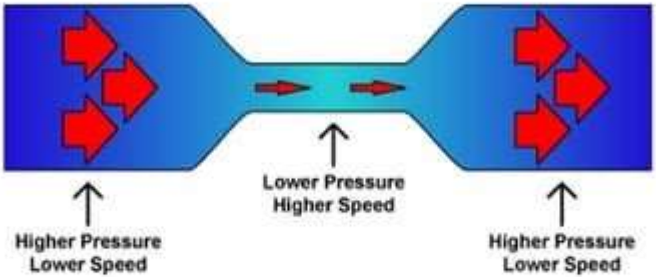
Figure 1. Equation of Continuity

$$Q = A_1 v_1 = A_2 v_2$$

where $v_2 > v_1$

Bernoulli's theorem

A fluid flowing in a pipe is governed by Bernoulli's theorem which states: "The sum of the pressure head, velocity head and elevation head at one point is equal to their sum at another point."



Energy Per Unit Volume Before = Energy Per Unit Volume After

$$P_1 + \frac{1}{2} r\, V_1^2 + r\, gh_1 = P_2 + \frac{1}{2} r\, V_2^2 + r\, gh_2$$

Pressure Energy

Kinetic Energy Per Unit Volume

Potential Energy Per unit Volume

Fluid Flow

Accurate flow measurement using the pressure differential principle involves many other factors. When fluids are flowing through a pipe at different velocities, they exhibit different flow patterns. At low velocities, the fluid appears to "tumble" as it flows past a point. This is called turbulent flow.

At higher velocities, the fluid flows in parallel layers, with the outer layers (that are in contact with the pipe) moving slightly slower due to friction. This is called laminar flow.

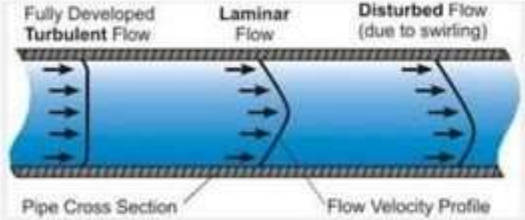
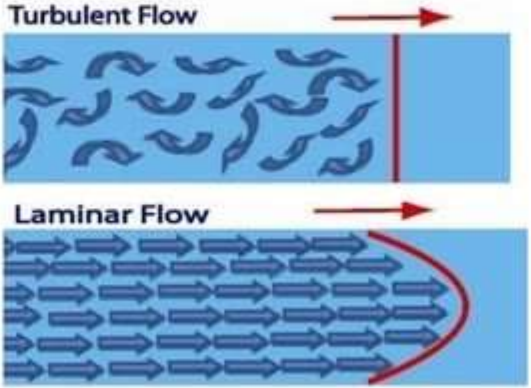


Figure 5. Turbulent and Laminar Flow profiles



Reynold's Number

Reynold's Number

The Reynold's number (R_e) is a measurement of turbulent and laminar flow. It is a dimensionless number that reflects the flow profiles and is a factor of the fluid's:

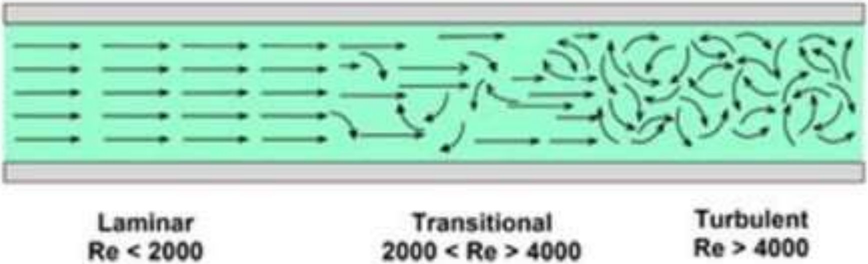
Density (ρ).

Flow velocity (v).

Pipe diameter (D).

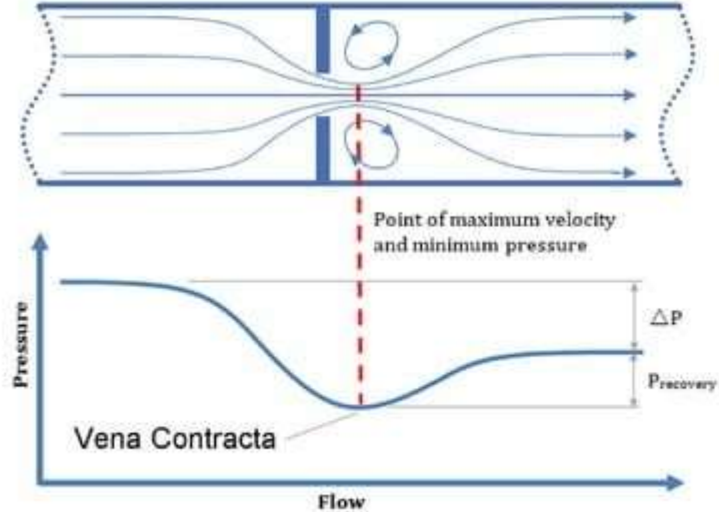
Fluid viscosity (μ).

Reynold's number is calculated by the formula: $R_e = (\rho v D/\mu)$

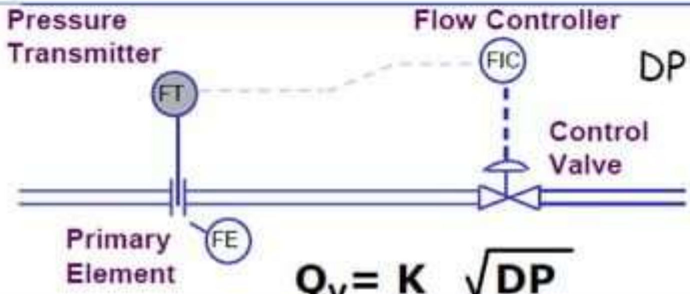


Differential Pressure Flow Measurement Principle

If a restriction is introduced into a pipe and according to Bernoulli's Theorem, there will be a differential pressure across the restriction. As in control valves, the pressure recovers after passing through the restriction, but never back to 100%. There will be a small permanent pressure loss, one of the disadvantages of differential pressure flow meters.



Flow Equation



DP volumetric flow

$$Q_V = K \sqrt{DP}$$

$$Q = \sqrt{2} A_2 \frac{1}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}} \sqrt{\frac{P_1 - P_2}{\rho}}$$

Orifice Plate

By far the most common device used as a restrictor to create the differential pressure used in flow measurement is the orifice plate. In its most simple form, the orifice plate is nothing more than a steel plate with a hole drilled in it and placed in the pipe. However basic the concept is, developing an orifice plate to produce the greatest accuracy with the least pressure drop is a science which has developed several design types. Accuracy is dependent on the orifice plate design, tap location and the piping.

Advantages:

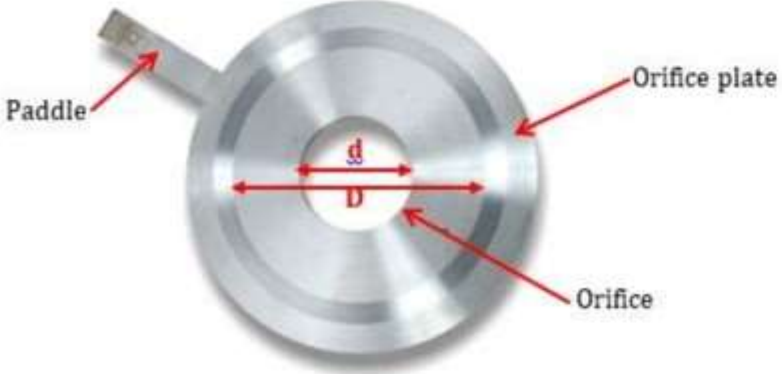
- Low cost.
- Easy maintenance.
- Small size, compact.
- Can be field fabricated.

Disadvantages:

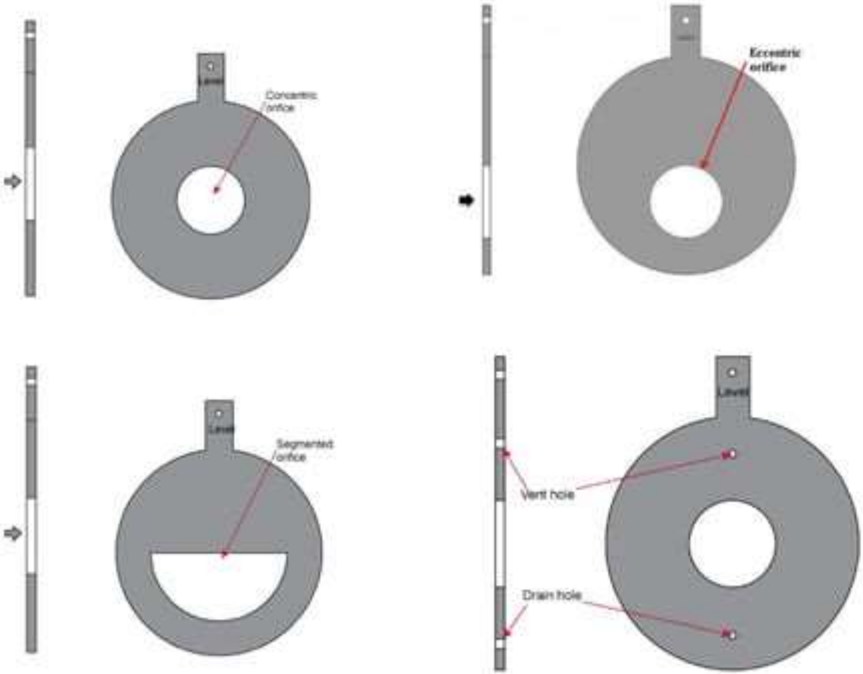
- Poor accuracy (0.5 – 2%).
- Requires a transmitter.
- Square root (not linear output).
- High pressure loss.
- Requires specific upstream and downstream distances from disturbances (bends or valves).

Orifice Plate Construction

Orifice plates are generally constructed from stainless steel with the hole being machined to close tolerances. They usually have a paddle or handle attached on which is stamped critical information such as material, thickness, orifice diameter, tag number and which side faces upstream (if not marked, the text always faces upstream). Orifice plates without the paddle are called universal plates.

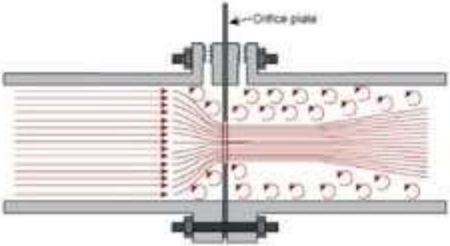


Orifice types

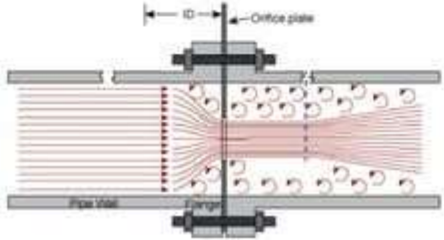


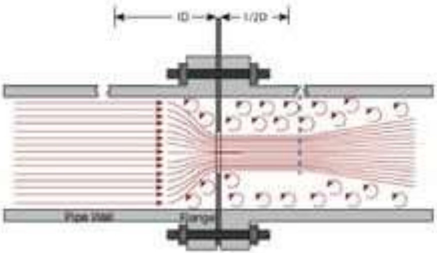
Pressure Taps

Flange taps

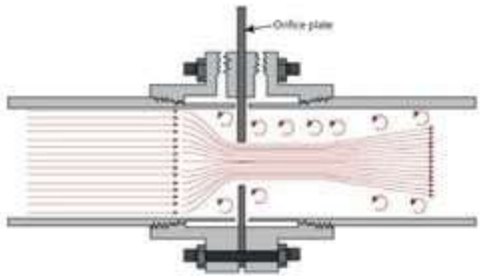


Vena contracta taps



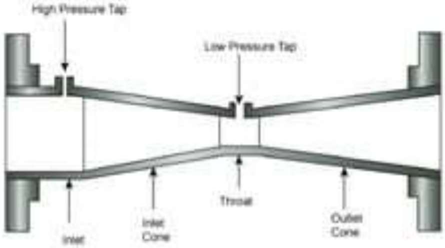


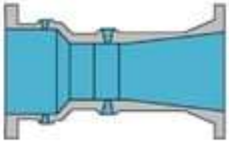
Corner taps

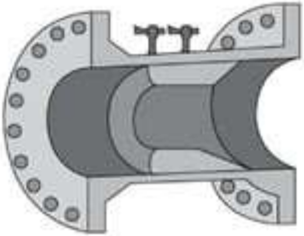


Venturi Tube

The Venturi tube is an elongated pipe that is shaped like the vena contracta flow pattern. The design has an inlet cone and an outlet cone. The inlet cone angle is 19-23º and the outlet cone angle is 5-15º. The pressure taps are located upstream (¼ -½D) of the inlet cone and downstream at the throat.



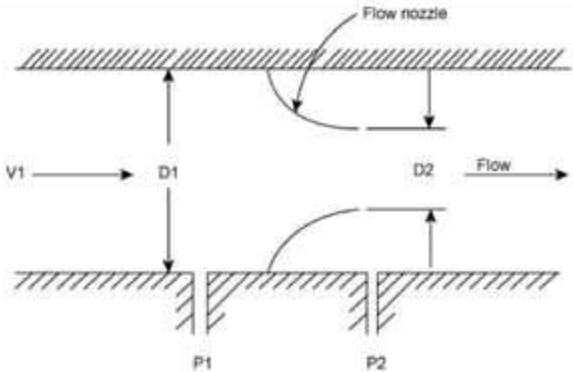




There are many advantages to the Venturi tube:
More accurate than the orifice plate; 0.5 – 3%.
Lower pressure drop.
Higher flow rate than the orifice plate.
Can handle slurries and solids.
Less straight pipe run upstream.
The disadvantages of the Venturi tube is
the higher cost and the fact that it is difficult to maintain or replace.

Flow Nozzle

The flow nozzle is a cone shaped insert into the pipe whose properties, advantages and disadvantages fall in between those of the orifice plate and venturi tube. A typical application is high flow rates of superheated steam. The nozzle itself can have many different shapes as determined by the manufacturer.



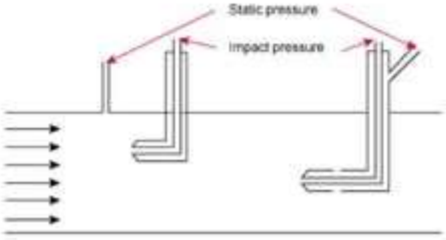
Pitot Tube

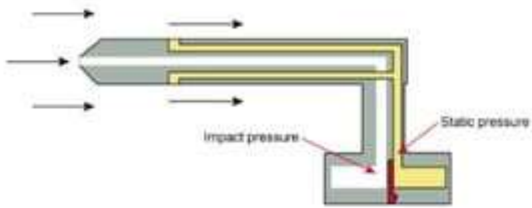
Pitot Tube

The pitot tube is a bent hollow tube with the point facing upstream in a pipe. The differential pressure is the static (line) pressure of the pipe and the impact pressure in the tube (caused by the velocity of the flowing fluid). It is usually inserted into the center of the pipe

Its characteristics are similar to the orifice plate but with a lesser pressure loss. Due to its installation, it only measures the flow at one point and which is an average of the flow rate.

Its most common uses are for measuring air or gas flows in pipes but can also be used to measure velocity (in airplanes).

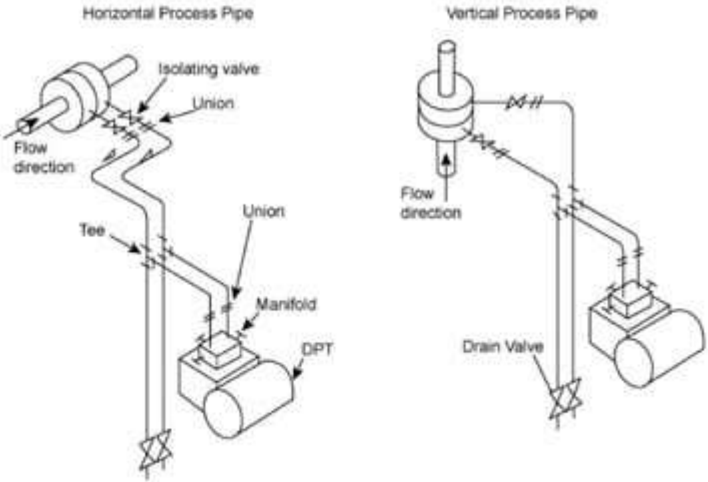




Standard Installations

Liquid Service

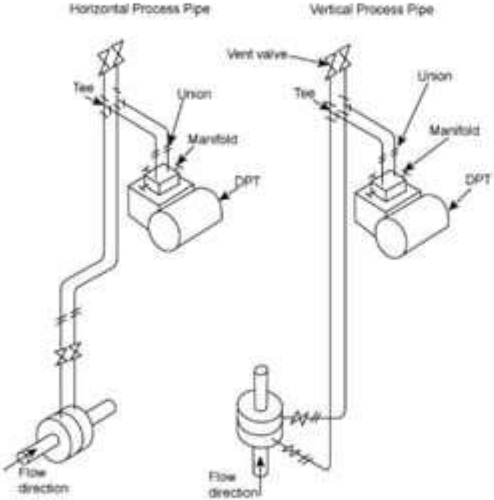
For liquid service always mount the D/P cell below the orifice plate to ensure the sensing (impulse) lines are always filled with liquid and not entrapped gas bubbles.



Standard Installations

Gas Service

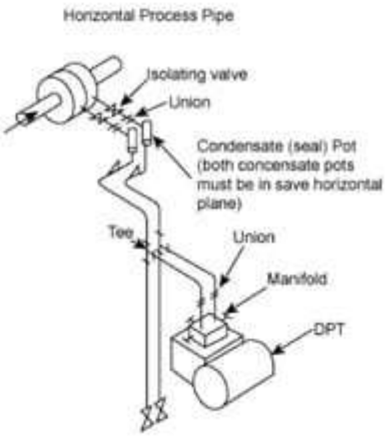
For gas service always mount the D/P cell above the orifice plate to ensure the sensing (impulse) lines are always filled with the gas and not condensed liquids or entrained solids.

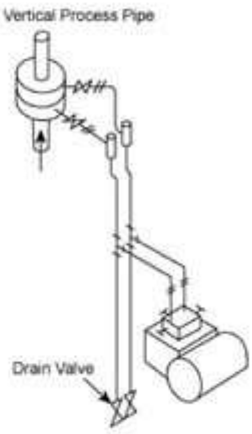


Standard Installations

Steam Service

For steam service always mount the D/P cell below the orifice plate to ensure the sensing (impulse) lines are always filled with water. To ensure this condensate pots can be installed at the orifice.



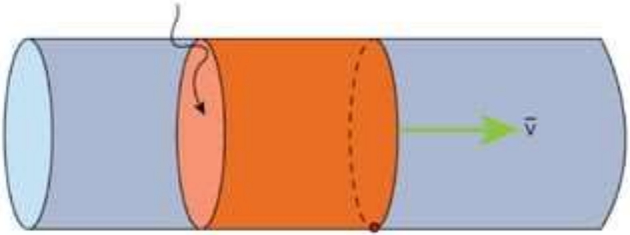


Velocity Meters

Velocity based flow meters operate on the principle of measuring the velocity of the fluid that is flowing. The equation of continuity states that: "The volume rate of flow (Q) passing any given point in a pipe is equal to the cross-sectional area of the pipe (A) times the velocity (v) at that point." Stated mathematically: $Q=Av$.

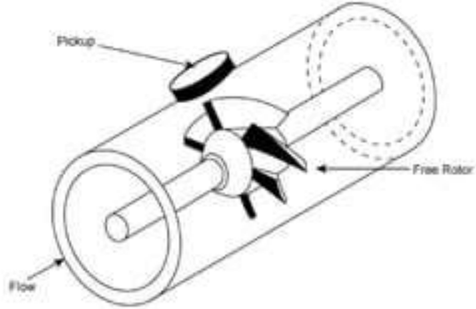
Since the area is constant, flow (Q) is proportional to velocity (v). The signals that the different types of velocity meters produce vary, but all are electronically modified by a meter constant (particular to the individual meter) to produce a volumetric flow rate. There are four main types of velocity meters:

Turbine Meter
Vortex Shedder Meter
Ultrasonic Meter
Magnetic Flow Meter



Turbine Meters

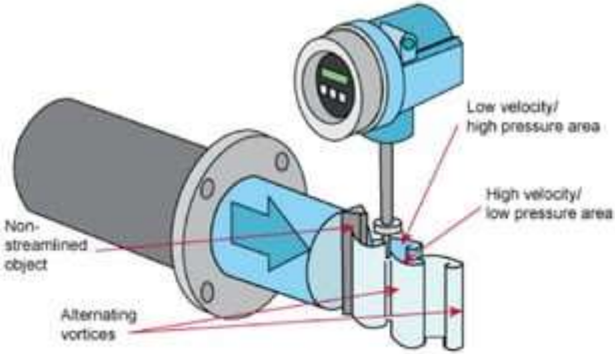
The turbine meter is comprised of a multi-blade rotor assembly, resembling a propeller, mounted in the pipe. The fluid flowing past the blades of the turbine meter causes it to turn at a velocity proportional to the flow rate. Used for liquids and gases, but low viscosity liquid service is more common. Bearing wear is a common problem with turbine meters.



The rotor is suspended by and rotates on precise bearings offering little resistance. The rotor blade diameter is just slightly smaller than the internal diameter of the pipe. Turbine rotation is detected by solid state devices, most commonly reluctance or inductance types. The rotor is suspended in the pipe by upstream and downstream supports that not only act as supports but also offer some flow conditioning, much like straightening vanes.

Vortex Shedding Meters

The vortex meter is based on the principle that when a flowing fluid strikes a non-streamlined object, the flow is separated as it flows around the object. The flow cannot follow the contour of the object on the downstream side and it separates itself from the object in the form of eddy currents or vortices. When this occurs, the separation causes an alternating high velocity/low flow cycle to happen.

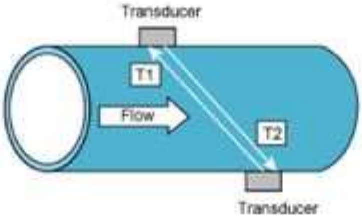


Ultrasonic Meters

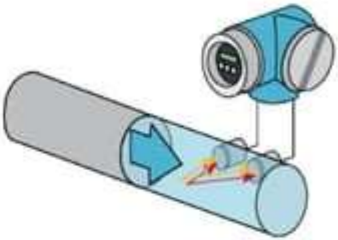
Ultrasonic meters measure difference in upstream vs. downstream transit time of a sonic signal across the path of a flowing fluid. They have no moving parts and a very high rangeability.

Ultrasonic meters can be divided into two distinct types: Transit time and Doppler.

The transit time ultrasonic flow meter is based on the principle of measuring the time it takes for an ultrasonic wave to move from the transmitter to the receiver.



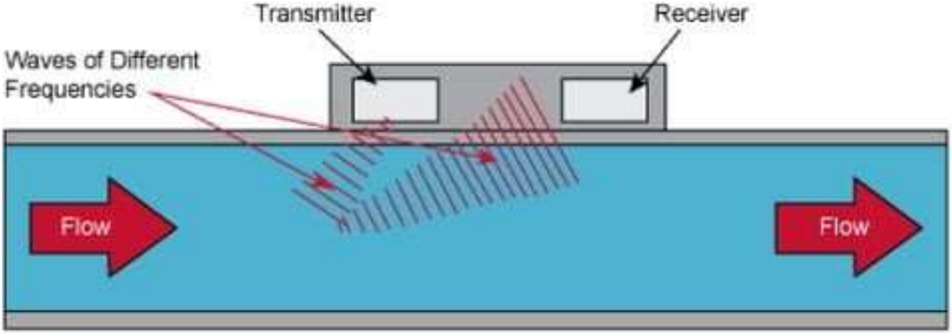
Sensor Opposite



Sensor On Same Side

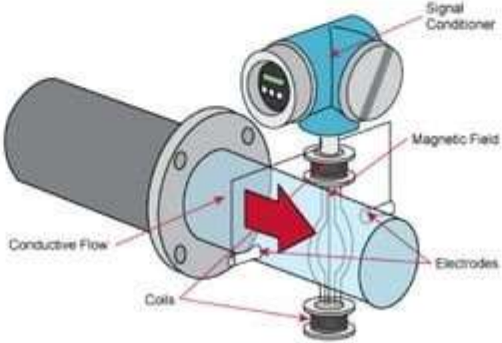
Doppler ultrasonic flow meter

The Doppler ultrasonic flow meter uses reflected ultrasonic waves to measure the fluid velocity. The frequency of the ultrasonic waves will be reflected back from particles in the flowing fluid, however it will experience a phase shift which is proportional to the velocity of the fluid.



Magnetic Flow Meters

Commonly referred to as the magflo or mag meter, it is based on the principle of Faraday's law of electromagnetic induction which states: "A voltage will be induced when a conductor moves through a magnetic field." The meter consists of an electromagnetic coil attached to the outside of the pipe. Two electrodes protrude through the pipe and are in contact with the fluid. The fluid, which must be conductive (or have conductive particles in it) acts as the conductor. When the coil is energized and the fluid flows through the pipe, a small voltage is generated. The amount of voltage is dependent on the speed to the fluid passing through the coil (fluid velocity) and is proportional to the flow rate.



Mass Flow Measurement

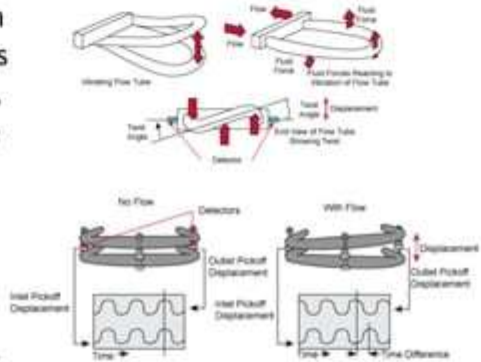
Mass flow measurement is the volumetric flow rate multiplied by the constant density of the fluid. If the density varies slightly, which occurs in most processes, then the mass measurement accuracy is affected. Also, if pressure and temperature vary, then the density varies, which once again will produce an inaccurate reading.

Mass flow measurement can be accomplished by using a flow computer which receives temperature, pressure, density and volumetric flow readings from various devices and computes the mass flow. The calculation of the mass flow is dependent on the accuracy of the devices. If any of the devices is out of calibration the accuracy of the final mass flow is affected.

Another means of determining mass flow is the use of mass flow meters that measure the mass directly. This method is independent of changes in temperature, pressure, density, and volumetric flow readings.

Coriolis Meter

The most common type of mass flow meter is the coriolis meter. It operates on the principle of motion mechanics. As it moves through the tube, the fluid is forced to take on the vertical movement of the tube, in one direction on the inlet side and in the opposite direction on the outlet side causing a "twisting" (Coriolis effect) of the tube. This occurs for half the cycle of the vibration. On the other half cycle, the opposite occurs with the twisting motion in the opposite direction. Detectors on either side of the tube detect this small motion caused by the twisting action. The amount of twist is directly proportional to the mass flow through the tube. The frequency of the vibration is directly proportional to the density of the fluid.



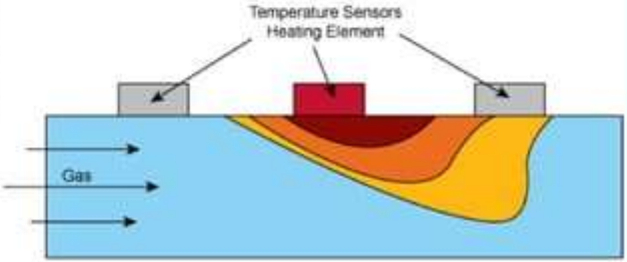
A phase shift is generated between the vibration of the two tubes. This amplifies the movement to be detected.

Coriolis Meter Design

Many manufacturers produce coriolis mass flow meters. Most use a proprietary design. Some of the meters have single, double, or even triple tubes in straight, curved, or bent tube configurations.

Thermal Mass Meter

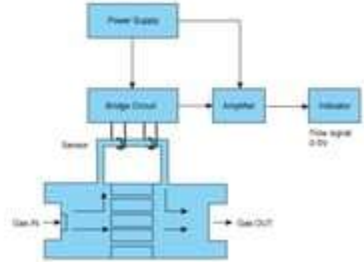
Another type of mass flow meter is the thermal mass meter. It is based on the theory that if a heated electrode is placed in contact with the fluid (either directly or indirectly), the amount of heat conducted away from the electrode is proportional to the mass flow.



In practice, the electrode is heated to a constant temperature with no flow. When flow occurs the fluid conducts away some of the heat. The temperature loss is proportional to the mass flow.

The thermal mass meter is almost used exclusively on gases. Typical designs include in-line, insertion or capillary type with single or double electrodes.

Attributes



Attributes

Mass flow meters attributes include:

Small.

Handles low flows.

High accuracy (0.5%).

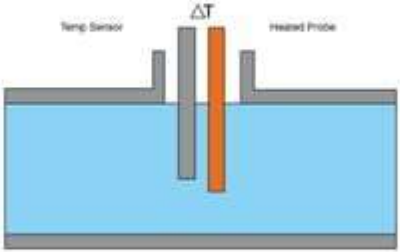
Average pressure drop.

Generally low maintenance.

Produce a mass flow without having to use any other sensors (density, pressure, temperature).

Relatively expensive.

Equipped with their own signal conditioner, most being of the smart type.



Level Measurement

Types of level measurement

Contact type instrument

Sight-type Instruments

Float-type Instruments

Hydrostatic Pressure-type

Displacer-type Instrument

Electrical-type Instruments

Non-contact type instruments

Sonic-type Instruments

Radiation-type Instruments

Sight glass

The level gauge, or sightglass is to liquid level measurement as manometers are to pressure measurement: a very simple and effective technology for direct visual indication of process level.

Types of Sight glasses
Reflex-type
Transparent type
Magnetic type
Tubular type

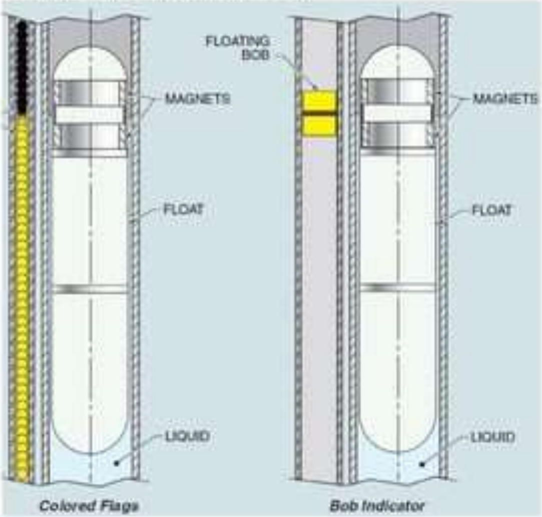
Tubular type water / liquid level gauge

Reflection type water level gauge

Transparent type water level gauge

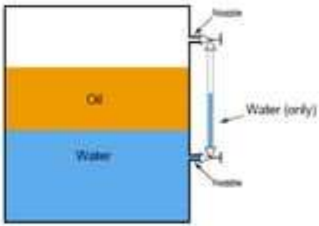
Magnetic type

Magnetic type Sight gauges have a float inside a nonmagnetic chamber. The float contains a magnet, which rotates wafers over as the surface level increases or decreases. The rotating wafers present the opposite face, which has a different colour. It is more suitable for severe operating conditions where liquids are under high pressure or contaminated.

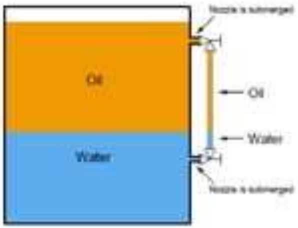


Interface level gauges

If a lighter (less dense) liquid exists above
a heavier (denser) liquid in the process vessel,
the level gauge may not show the proper interface

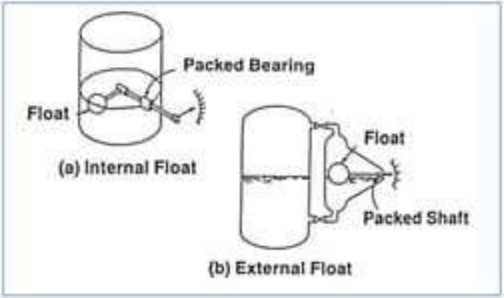


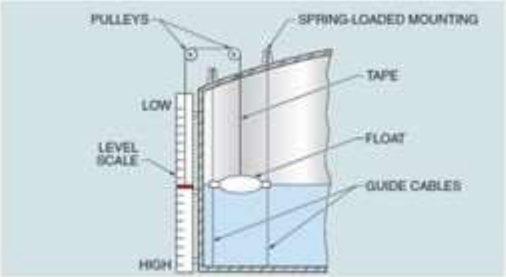
The only way to ensure proper two-part liquid interface level indication in a sightglass is to keep both ports (nozzles) submerged



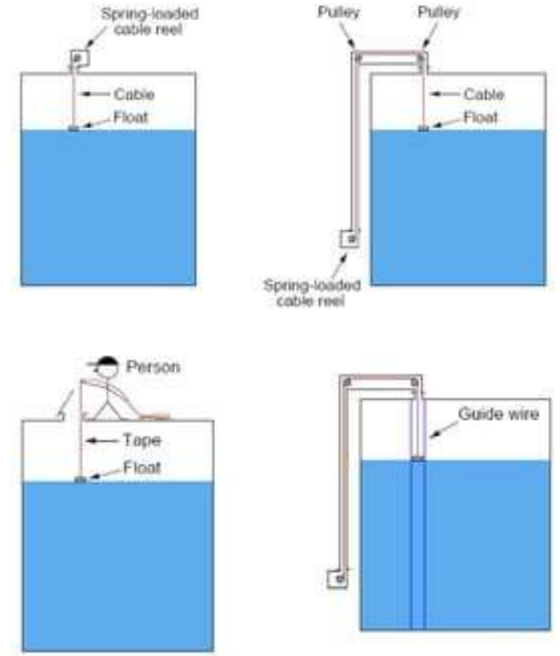
Float type instruments

Floats give a direct readout of liquid level when they are connected to an indicating instrument through a mechanical linkage. A simple example of this is the weighted tape tank gauge. The position of the weighted anchor against a gauge board gives an indication of the liquid level in the tank. The scale of the gauge board is in reverse order, i.e. the zero level indication is at the top and the maximum level indication is at the bottom of the gauge board.





Different types of level measurements

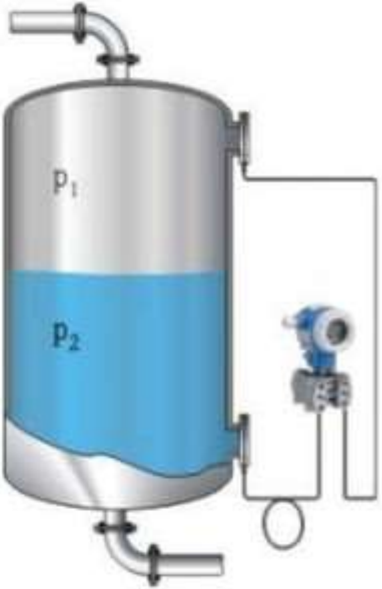


Level Measurement

Example

Introduction to Hydrostatic Head Level Measurement

Hydrostatic head level measurement is based on the principle that the pressure at the bottom of a column of liquid is directly related to the height of the liquid (h, in inches or millimeters) and the relative density (RD) of that liquid. If the pressure exerted by the head or height of liquid is measured then the level can be determined. Hydrostatic head is an indirect method of level measurement as the level is inferred by the pressure that is measured.

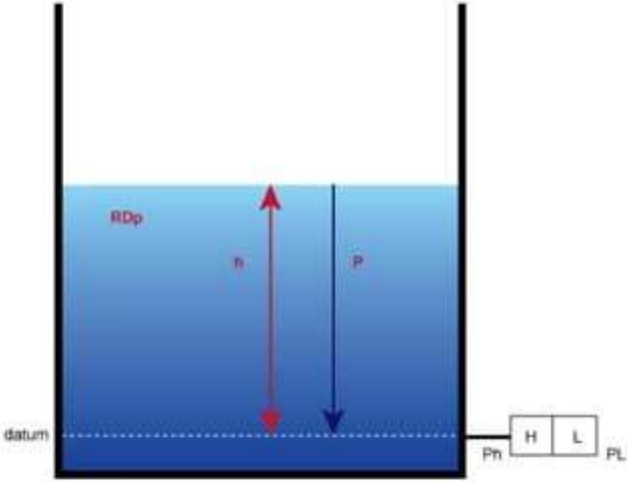


The relationship between the height of liquid or level and pressure can be defined by the formula:

$$P = SG_p \times \rho_p \times h$$

Measuring Liquids Using Hydrostatic Head

Measuring Liquids Using Hydrostatic HeadThere are two methods for measuring liquids using hydrostatic head, open tank and closed tank. In both cases, the most common instrument used to measure the pressure is the differential pressure cell or transmitter (D/P cell). A D/P cell is used instead of a simple pressure transmitter or pressure gauge to eliminate any error due to changes in atmospheric pressure. Any changes in atmospheric pressure will be applied to both sides of the D/P cell and will cancel each other.



Open Tank Measurement

Example 1

An open tank containing sea water of relative density 1.05 exerts a pressure of 0.3 bar on the high side of the D/P cell, what is the height of the liquid?

We know $P = RD_p \times h$

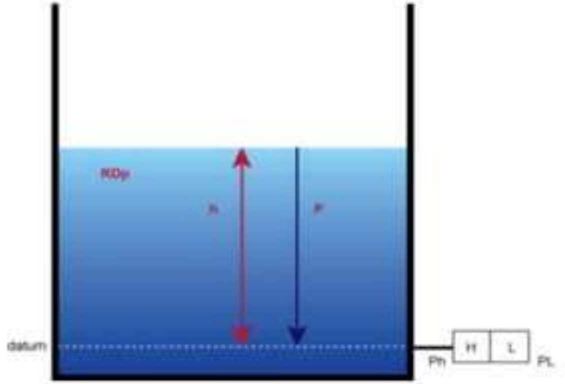
We can derive the equation for h and substitute in the known values:

$h = P/(RD_p)$

$h = (0.3\ \text{bar})/1.05$

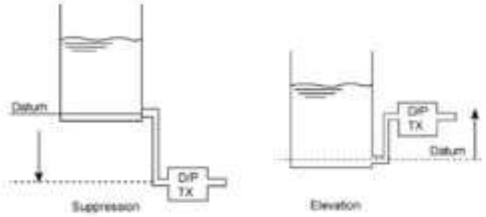
$h = (0.3\ \text{bar} \times 10197\ \text{mm/bar})/1.05$

$h = 2913\ \text{mm or } 2.913\ \text{m}$



Elevation and Suppression Adjustments

Elevation and Suppression AdjustmentsThe calculations in the examples are only valid if the differential pressure transmitter (D/P cell) is mounted at the datum point. In practice, the D/P cell is quite often either mounted above or below the datum point, in which case the following adjustments must be made:



Suppression – is the adjustment made when the D/P cell (or any measuring device) is mounted below the datum line. <u>Zero suppression</u>indicates you need to lower the nominal zero point.
Elevation – is the adjustment made when the D/P cell is mounted above the datum line. <u>Zero elevation</u> indicates you need to raise the nominal zero point.

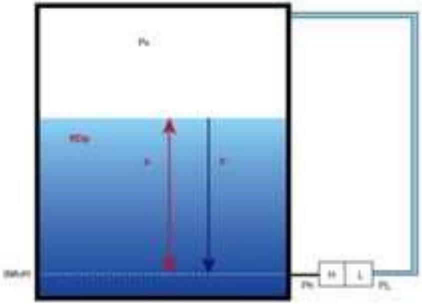
Closed Tank Measurement

Closed Tank Measurement
Most level applications in industry involve closed tanks under some pressure. The differential pressure transmitter (D/P cell) is also used for closed tank applications. Note: $P_s = P_{static}$, the pressure inside the tank.

In order to accurately measure the head pressure of the liquid alone, closed tank applications must compensate for the static pressure of the vapor above the liquid. Both pressure input taps for the transmitter are connected to the tank. As in open tank measurement, the high pressure (P_H) side of the transmitter is connected to the base, or 0% datum of the tank. The low pressure (P_L) side of the transmitter is connected to the top of the tank through a pipe referred to as a "reference leg." The reference leg must be either completely dry (empty) or completely filled with liquid.

Dry Leg Closed Tank Measurement

A "dry leg" on the low side refers to the low side piping being completely void of liquids. This application only works with non-condensing liquids in the tank. If used with condensing liquids, some liquid could build up on the low or dry side and would then create an error since this height of liquid would induce an uncompensated pressure on the low side.

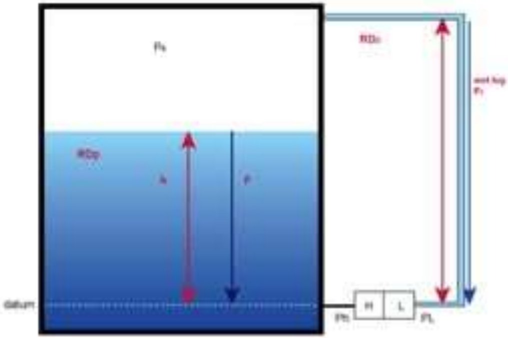


The equation for calculating the pressure exerted by the liquid in a closed tank with a dry leg is:

$$P = RD_p \times h \text{ but } P = P_H - P_L \text{ and } P_H = P + P_S \text{ and } P_L = P_S$$

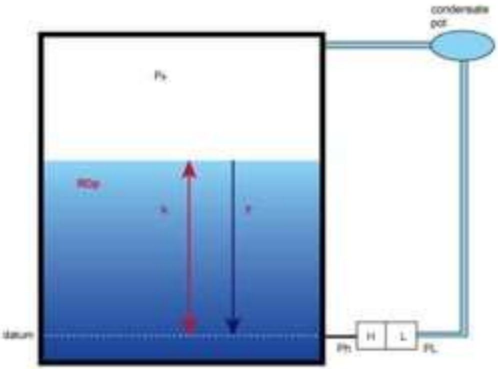
Wet Leg Closed Tank Measurement

Wet Leg Closed Tank MeasurementIf condensing liquids or steam are to be measured, then the installation must contain a "wet leg" on the low side. It is called a wet leg since the low side piping is always completely filled with the condensate liquid of the tank or some other inert liquid such as glycol. In this manner, a constant pressure is generated on the low side and can be accounted for when calibrating the instrument. To calculate the differential pressure ($P_H - P_L$) at the D/P cell, two calculations are required; one for the pressure resulting from the process liquid in the tank minus that of the pressure resulting from the liquid in the wet leg.



Condensate Pot

Condensate PotTo ensure the wet leg is always filled, a condensate pot is installed at the top of the leg to provide adequate liquid. The condensate pot is located at the top of the tank close to where the wet leg is connected to the tank and is filled with sufficient volume of liquid to completely fill the wet leg piping. It can be filled with the process fluid, but more often is filled with an inert liquid such as glycol. In any case, it must be a liquid that will not vaporize.



Bubbler System

Used If the process liquid contains suspended solids or is chemically corrosive or radioactive.

It is desirable to prevent it from coming into direct contact with the level transmitter.

A bubbler tube is immersed to the bottom of the vessel in which the liquid level is to be measured.

A gas (called purge gas) is allowed to pass through the bubbler tube.

Consider that the tank is empty, so, the gas will escape freely at the end of the tube and therefore the gas pressure inside the bubbler tube will be at atmospheric pressure.

As the liquid level inside the tank increases, pressure exerted by the liquid at the base of the tank (and at the opening of the bubbler tube) increases.

As a result, the gas pressure in the bubbler tube will continue to increase until it just balances the pressure of the liquid & any excess supply pressure will escape as bubbles through the liquid.

The bubbler tube is connected to the high-pressure side of the transmitter, while the low pressure side is vented to atmosphere.

Bubbler System

Bubbler system Considerations

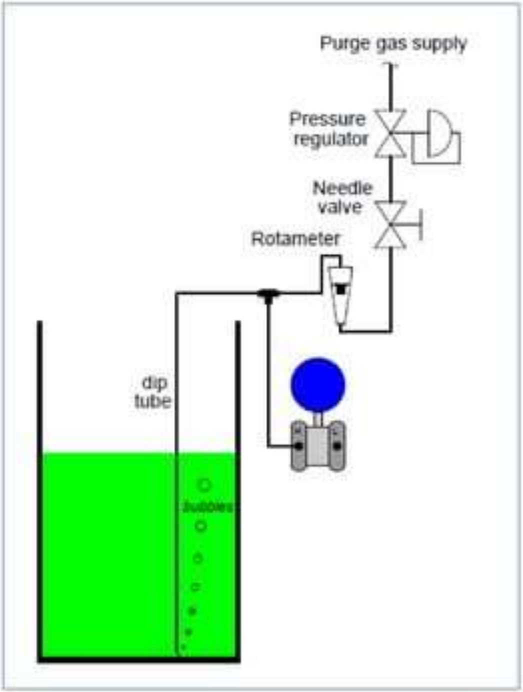
The purge gas supply must be reliable, if the flow stops for any reason, the level measurement will cease to be accurate.

The purge gas supply pressure must exceed the hydrostatic pressure at all times, or else the level measurement range will fall below the actual liquid level. (preferred to be better by 10 psi)

The purge gas must not adversely react with the process.

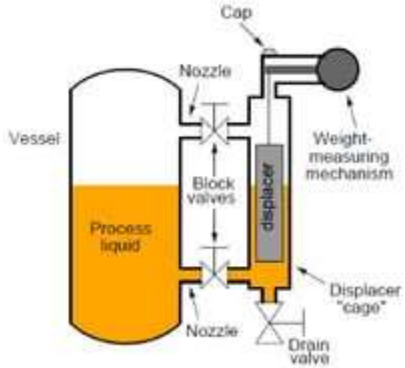
The purge gas must not contaminate the process.

The purge gas must be reasonable in cost, since it will be continuously consumed over time.



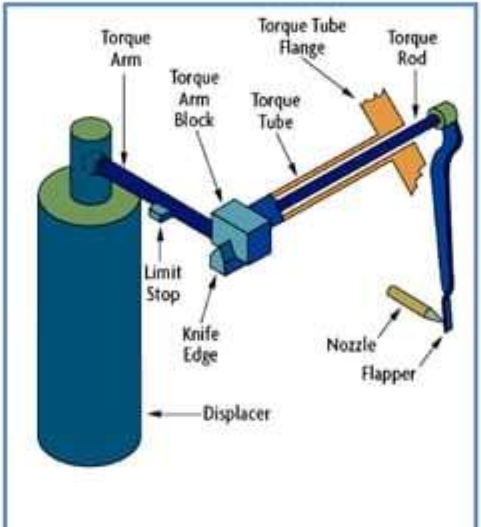
Displacer

It is based on Archimedes' principle of Buoyancy
Displacer level instruments exploit Archimedes' Principle to detect liquid level by continuously measuring the weight of the displacer immersed in the process liquid. As liquid level increases, the displacer experiences a greater buoyant force, making it appear lighter to the sensing instrument, which interprets the loss of weight as an increase in level and transmits a proportional output signal.



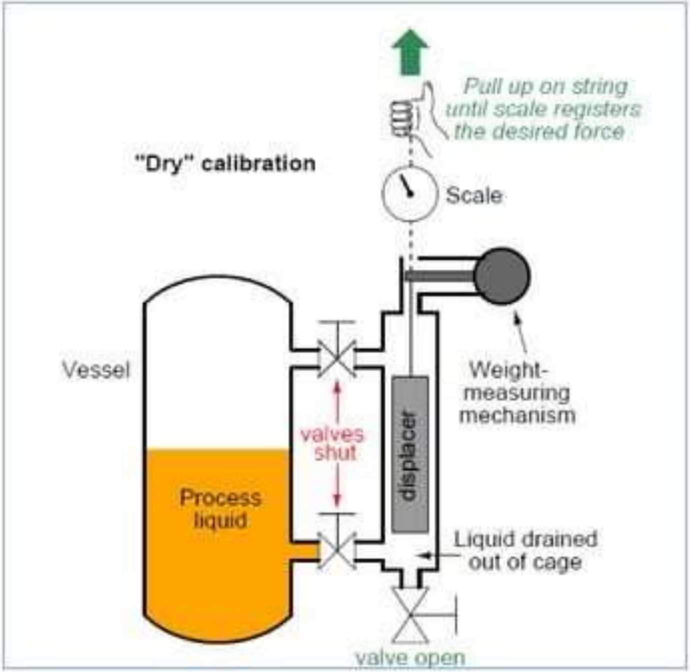
Torque Tube

Used in clean liquids of constant density
Apparent weight causes an angular displacement of the torque tube (a torsion spring, a frictionless pressure seal).
This angular displacement is linearly proportional to the displacer's weight
Standard displacer volume is 100 cubic inches and the most commonly used lengths are 14, 32, 48, and 60 in.
the buoyant force can also be detected by other force sensors, including springs and force-balance instruments



B) Continuous Transmitter

Dry Calibration



Displacement interface level measurement

Suppose we have a displacer instrument measuring the interface level between two liquids having specific gravities of 0.850 and 1.10, with a displacer length of 30 inches and a displacer diameter of 2.75 inches (radius = 1.375 inches).

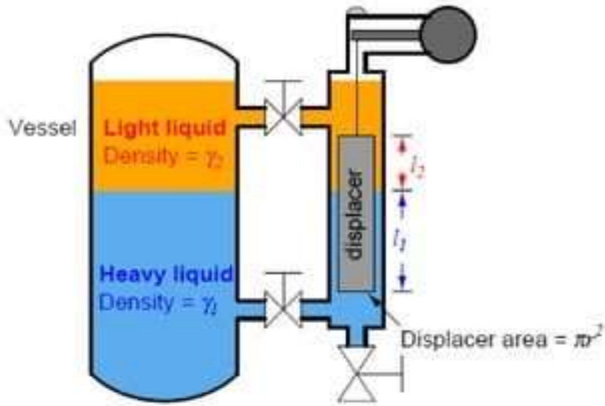
Fbuoyant = $\gamma_1 V_1 + \gamma_2 V_2$

Fbuoyant = $\gamma_1 \pi r^2 l_1 + \gamma_2 \pi r^2 l2$

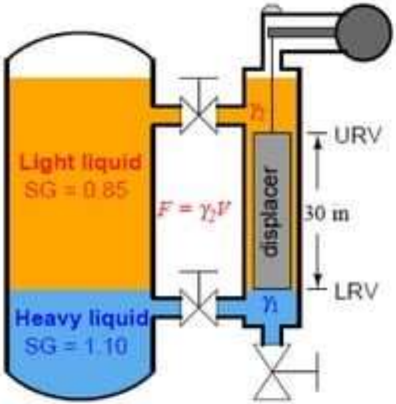
Fbuoyant (LRV) = $\pi r^2 \gamma_2 L$

Fbuoyant (URV) = $\pi r^2 \gamma_1 L$

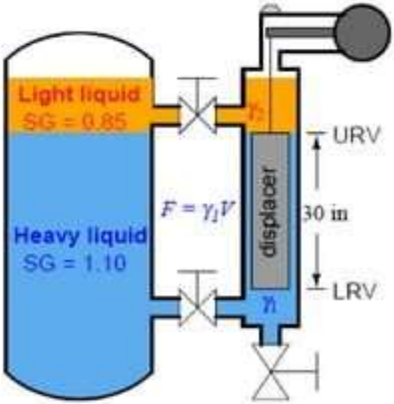
Interface level (inches)	Buoyant force (pounds)
0	5.47
7.5	5.87
15	6.27
22.5	6.68
30	7.08



Calibration example



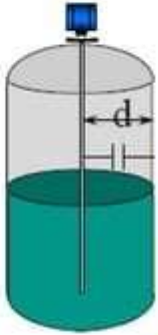
$$F_{buoyant}\ (\text{LRV}) = \gamma_2 V = \gamma_2 \pi r^2 l$$



$$F_{buoyant}\ (\text{URV}) = \gamma_1 V = \gamma_1 \pi r^2 l$$

Capacitive level measurement

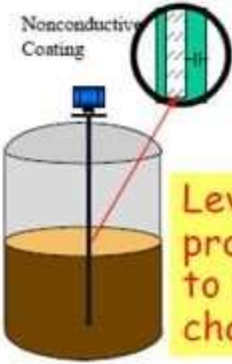
How Capacitance varies with process fluid?



Level is proportional to dielectric change

Nonconductive Fluid

- Process fluid is the dielectric barrier
- Tank Wall forms second plate
- The variation of dielectric is the measurement



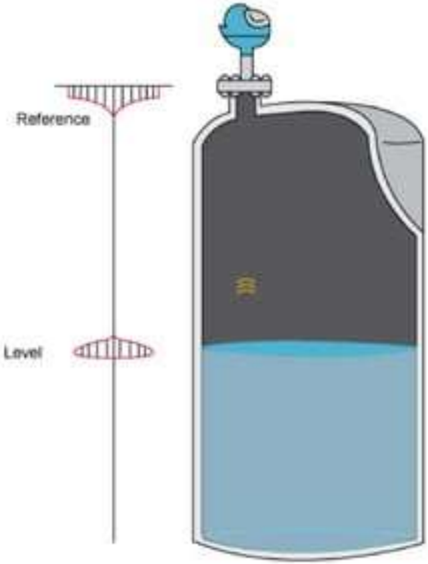
Level is proportional to plate area change

Conductive Fluid

- Process fluid is the second plate
- Insulation on probe is dielectric
- The variation of the plate size is the measurement

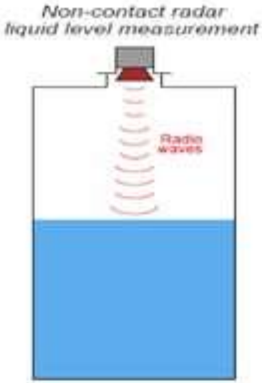
Ultrasonic Level Measurement

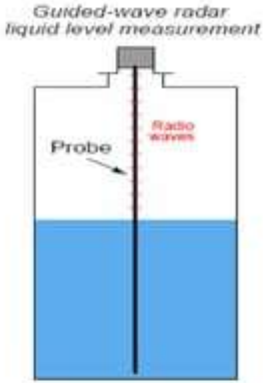
The ultrasonic transmitter operates by:
Applying a voltage pulse to a piezoelectric crystal which generates an ultrasonic pulse.
The pulse travels to the surface and is reflected.
The reflected wave (or echo) returns to strike the crystal generating a small voltage spike of the same frequency.
The time is measured for the round trip and compared to the reference height of the transducer and is proportional to the level.



Radar level measurement

The fundamental difference between a radar instrument and an ultrasonic instrument is the type of wave used: radio waves instead of sound waves. Radio waves are electromagnetic in nature (comprised of alternating electric and magnetic fields), and very high frequency (in the microwave frequency range – GHz). Sound waves are mechanical vibrations (transmitted from molecule to molecule in a fluid or solid substance) and of much lower frequency than radio waves.

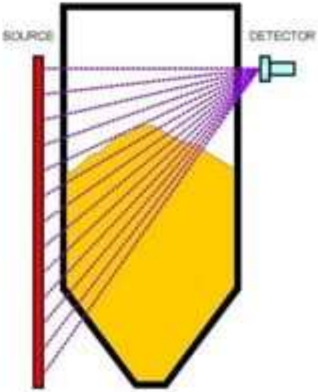




Example for radar level transmitters

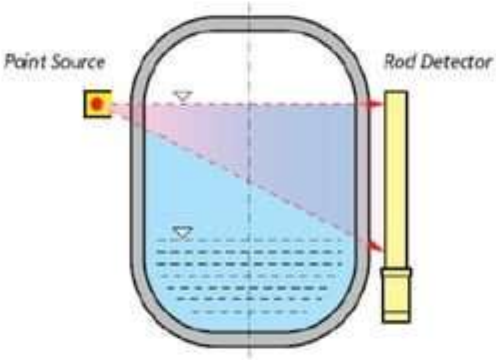
Nuclear level instrument

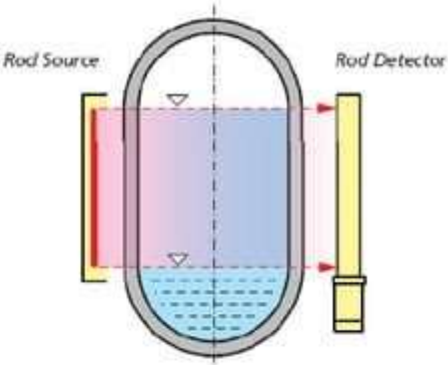
Nuclear radiation systems have the ability to “see” through tank walls, and thus they can be mounted on the outside of process equipment.
Suitable for liquid or solid material detection.
Composed of a radioactive source material and a radiation detector, the two are mounted across the diameter of a storage vessel for either solid or liquid material.
The product to be measured is attenuating the radiation coming from the radioactive source and according to the height of the product in the vessel, more or less of the original radiation is reaching the detector.
This measuring signal is then transferred to an output signal which directly correlates to the actual Level of the product.



Nuclear level instrument

Two typical nuclear level instruments:
Using a single low-level gamma-ray source on one side of the process vessel and a radiation detector on the other side of the tank.
Using several gamma sources at different heights on the tank.





Temperature Measurement

Temperature Measurement

Temperature is the amount of hotness or coldness in a body. It is the amount of heat in that body.

Heat is a form of energy that is transferred between one body to another as a result of a difference in temperature. This transfer is from a body with a higher temperature to one with a lower temperature.

Heat is transferred between bodies by three distinct methods:
Conduction
Convection
Radiation

Temperature Units

Temperature UnitsA calorie is an SI heat unit. One calorie is the amount of heat required to raise the temperature of one gram of water one degree Celsius.

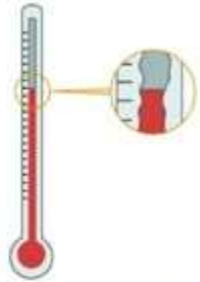
Temperature is the amount of hotness or coldness, that is, the thermal energy in a body. It is the amount of heat in that body.

The unit of temperature in the SI system is degrees Celsius and is commonly used in laboratory and scientific work. Fahrenheit is a temperature scale commonly used in the United States. The scientific community uses the absolute temperature scale.

	Degrees Kelvin (° K)	Degrees Celsius (° C)	Degrees Fahrenheit (° F)
Absolute Zero	0	-273	-460
Freezing Point	273	0	32
Boiling Point	373	100	212
	°K = °C +273	°C = °K -273	°F = °C * 1.8 + 32

Thermometers

The liquid-in-glass thermometer was the first temperature measuring device. It consists of a glass bulb at the bottom and a thin glass or capillary tube extending upward. The glass tube and bulb are closed and have a liquid partially filling them. The empty space is usually a vacuum.



When the bulb is heated, liquid volume will increase and travel up the glass tube. The tube is calibrated in the temperature scale that the thermometer was designed for.

Thermometer fills include mercury (not produced anymore, due to health and safety concerns) or colored water, alcohol, or oil.

A disadvantage of the glass thermometer is that it is very fragile. To protect the thermometer in industrial uses, a metallic protective sleeve can be used.

Bimetallic Strip

Another type of thermometer is the bi-metallic strip thermometer. The main component is a strip of metal consisting of two different metals bonded together.

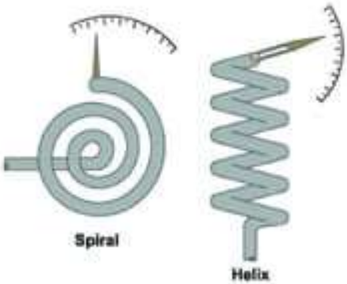
The two metals have different coefficients of thermal expansion. When heated, each will expand at a different rate. Since they are bonded together, if one end is heated, one metal will expand faster than the other. This results in a curving or rotational movement of the free end. The free end is attached to an instrument's linkage, much like a C-type bourdon tube in a pressure gauge. The rotational movement will cause a deflection in the pointer that is attached to the linkage, and the temperature can be read from the dial. When cooled, the strip returns to its original position.

The bi-metallic strip can be a spiral, single helix, or multiple helical.

Bimetallic Strip

While a thermometer has a round dial, the stem containing a bi-metallic strip can be different lengths.

Thermometers are also referred to as temperature gauges and in industry, the bi-metal strip primary element is the most common one in use. Typical temperature ranges include:
Glass-filled thermometer are -150º C to 500º C (-238ºF to 932º F).
Bi-metallic elements are -75º C to 550ºC (-103º F to 1022º F).
These are typically used in thermometers and in temperature compensation devices for other instruments.

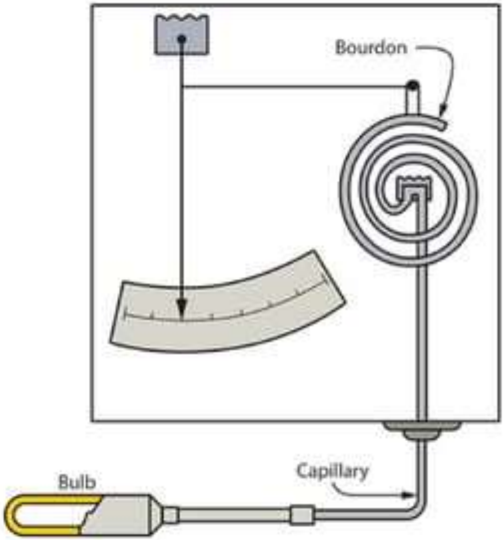


Filled Thermal Systems

A filled thermal system has a liquid or gas filled bulb and a long, metal capillary tube which is connected to a spiral bourdon tube.

When the bulb is heated, the liquid or gas expands, increasing pressure in the fixed volume of the bulb, capillary, or bourdon tube assembly.

Increasing pressure causes the tip to rotate, which moves the instrument's link and lever system. When cooled, the pressure in the filled system returns to its original condition. Capillary length can range from a few centimeters (1 in) to 15 meters (49 ft) in length.



Filled Thermal Systems

There are four types of filled thermal systems. The type is determined by the fill liquid or gas and the type of compensation.

Class I – filled with a liquid.
Class II – filled with a vapor.
Class III – filled with a gas.
Class IV – filled with mercury.

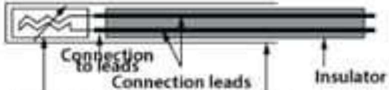
An <u>ambient temperature compensation</u> is required due to the long length of the capillary tube. The measurement may be outside a building in a high, low, or changing ambient temperature, while the instrument could be inside the building at a constant temperature. The liquid or gas would experience both temperatures, causing an error in measurement. Ambient compensation adjusts for this temperature differential.

Resistance Temperature Detector (RTD)

A resistance temperature detector (RTD) is based on the principle that when a conductor is heated, its electrical resistance increases. Temperature is directly and linearly proportional to a conductor's resistance. If we measure resistance, we can convert that measurement to a temperature reading.

The conductor most commonly used in industrial RTDs is platinum, but copper and silver conductors are also used. The Platinum 100 RTD is the most common element in industry and is referred to as the Pt-100 RTD. The resistance of the RTD is 100 ohms at 0º C (32º F), the reference point.

The conductor is usually wound in a coil and is sheathed in a 6 mm stainless-steel tube. The entire assembly is referred to as the probe.



$$R_T = R_{ref}[1 + \alpha(T - T_{ref})]$$

Nickel = 0.00672 $\Omega/\Omega°C$

Tungsten = 0.0045 $\Omega/\Omega°C$

Silver = 0.0041 $\Omega/\Omega°C$

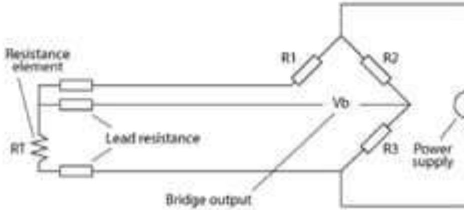
Gold = 0.0040 $\Omega/\Omega°C$

Platinum = 0.00392 $\Omega/\Omega°C$

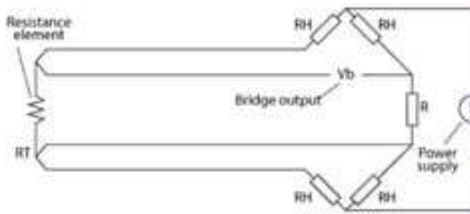
Copper = 0.0038 $\Omega/\Omega°C$

Resistance Temperature Detector (RTD)

The electronic circuit used to measure the resistance change is called a Wheatstone bridge. The RTD is on one leg of the bridge measuring circuit. The bridge output is proportional to the temperature.



3-Wire RTD Compensation



4-Wire RTD Compensation

Since the bridge circuit measures the total resistance, it measures the resistance of the RTD and the lead wires are measured. Lead wires can be relatively long and can be exposed to a different temperature than that of the RTD probe. This may produce an error in measurement. Lead length compensation is therefore required. The most common type is the 3-wire lead compensation, in which a dummy wire is placed in the same leg of the bridge circuit as the RTD itself.

RTDs are almost exclusively used as primarily elements for temperature transmitters, they are very rarely used as a stand-alone device.

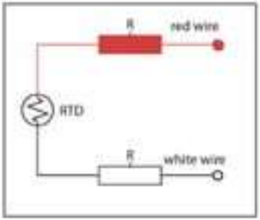
Resistance Temperature Detector (RTD)

The wires of the RTD are universally color coded to indicate which lead wire is which. The color coding is dependent on whether the probe is a 2-wire, a 3-wire or 4-wire configuration.

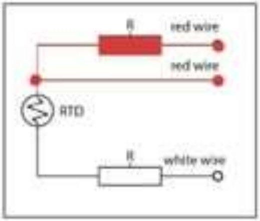
Typical ranges for RTD elements are -250º C to 650º C (-418º F to 1200º F).

They almost exclusively used in transmitters, but may also be used as temperature probes for machine monitoring equipment. Compared to the other types of elements, the RTDs are more accurate, linear, rugged and inexpensive.

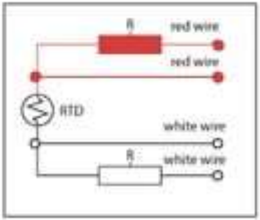
2-Wire RTD



3-Wire RTD



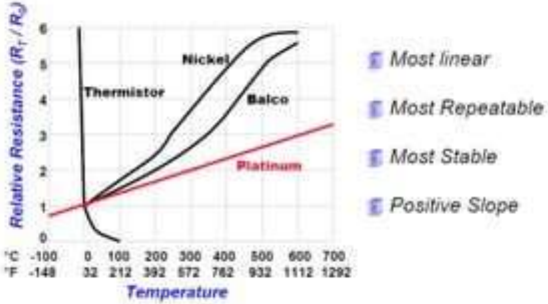
4-Wire RTD



Resistance Temperature Detector (RTD)

Platinum has been accepted as the material which best fist all the criteria and has been generally accepted for industrial measurement between –300 and 1200° F (-150 and 650 °C). The effect of resistances inherent in the lead wires of the RTD circuit on the temperature measurement can be minimized by increasing the resistance of the sensor; however, the sensor will also be increased. RTDS are commercially available with resistances from 50 to 1000 ohms at 32°F (0°C) and increase resistance 0.385 ohms for every °C of temperature rise.

PT 100 means that resistance of the element at reference temperature(0°C) equal to 100 Ω while PT 1000 resistance equal to 1 kΩ .



Thermistor

The thermistor is a primary element that is very similar to the RTD. It, too, is based on the theory that the resistance of a material increases or decreases with a change in temperature. The amount of change is proportional to the thermistor's coefficient of resistance.

$R \alpha kT$
where
R = a material's resistance
k = a material's coefficient of resistance
T = the temperature of the material

Thermocouples

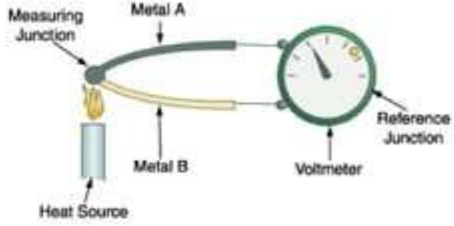
Thermocouples are based on the principle that when the junction of two dissimilar metals is heated, a small millivoltage signal is generated that is proportional to the temperature.

To generate a current flow, the two metals must be joined at the other end.

The sensing or measuring junction is referred to as the hot junction, while the other end (which is connected to the measuring device), is referred to as the reference or cold junction.

The formula for calculating the voltage generated in a thermocouple circuit is:

$$mV_{total} = mV_{hot\ junction} - mV_{cold\ junction}$$



Thermocouple Types

International Thermocouple Color Codes

ANSI Code	Alloy Combination		US & Canadian		International	Czech/ British	Dutch/ German	French	Maximum Temperature Range
	Positive Lead	Negative Lead	Thermocouple Grade	Extension Grade					
J	IRON Fe (magnetic)	COPPER-NICKEL Cu-Ni (CONSTANTAN)							Thermocouple Grade -210°C to 1200°C -346°F to 2193°F Extension Grade 0°C to 200°C 32°F to 392°F
K	NICKEL-CHROMIUM Ni-Cr (CHROMEL)	NICKEL-ALUMINUM Ni-Al (magnetic) (ALUMEL)							Thermocouple Grade -270°C to 1372°C -454°F to 2501°F Extension Grade 0°C to 200°C 32°F to 212°F
T	COPPER Cu	COPPER-NICKEL Cu-Ni (CONSTANTAN)							Thermocouple Grade -270°C to 400°C -454°F to 752°F Extension Grade -60°C to 100°C -76°F to 212°F
E	NICKEL-CHROMIUM Ni-Cr (CHROMEL)	COPPER-NICKEL Cu-Ni (CONSTANTAN)							Thermocouple Grade -270°C to 1000°C -454°F to 1832°F Extension Grade 0°C to 200°C 32°F to 392°F
N	NICKEL-CHROMIUM-SILICON Ni-Cr-Si	NICKEL-SILICON-MAGNESIUM Ni-Si-Mg					NO STANDARD, USE US COLOR CODES		Thermocouple Grade -270°C to 1300°C -454°F to 2372°F Extension Grade 0°C to 200°C 32°F to 392°F
R	PLATINUM-13% RHODIUM Pt-13% Rh	PLATINUM Pt	NOT ESTABLISHED						Thermocouple Grade -50°C to 1768°C -58°F to 3214°F Extension Grade 0°C to 150°C 32°F to 302°F
S	PLATINUM-10% RHODIUM Pt-10% Rh	PLATINUM Pt	NOT ESTABLISHED						Thermocouple Grade -50°C to 1768°C -58°F to 3214°F Extension Grade 0°C to 150°C 32°F to 302°F
B	PLATINUM-30% RHODIUM Pt-30% Rh	PLATINUM-6% RHODIUM Pt-6% Rh	NOT ESTABLISHED		–	NO STANDARD USE COPPER WIRE		NO STANDARD USE COPPER WIRE	Thermocouple Grade 50°C to 1820°C 122°F to 3308°F Extension Grade 0°C to 100°C 32°F to 212°F

Thermocouple Construction

Thermocouple extension wires connect the hot or measurement junction with the measuring device or cold junction. They must be the same material and have the thermoelectric properties of the thermocouple itself. This is required to avoid a measurement error by making another junction if, for instance, copper wire was used as the extension wire for both leads.

Typical ranges vary between -270° C to 2320° C (-454° F to 4208° F), depending on the type of thermocouple. Thermocouples are used for high temperature applications, in-flame applications, and as the primary element for transmitters and machine monitoring equipment. Advantages include:

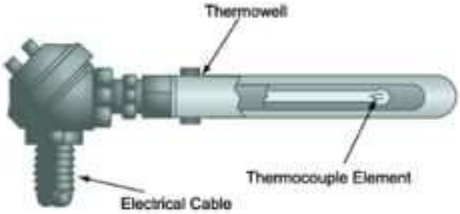
Linear.

Wide and high range.

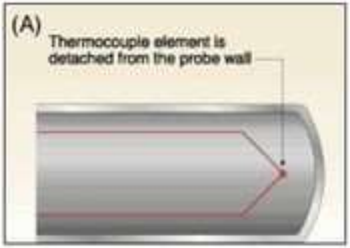
Inexpensive.

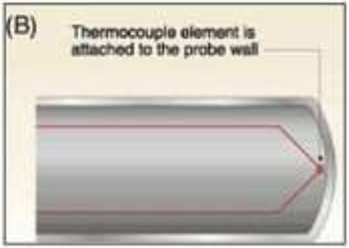
Rugged.

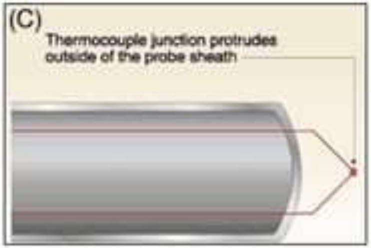
Does not require an external power supply.



Thermocouple tip style





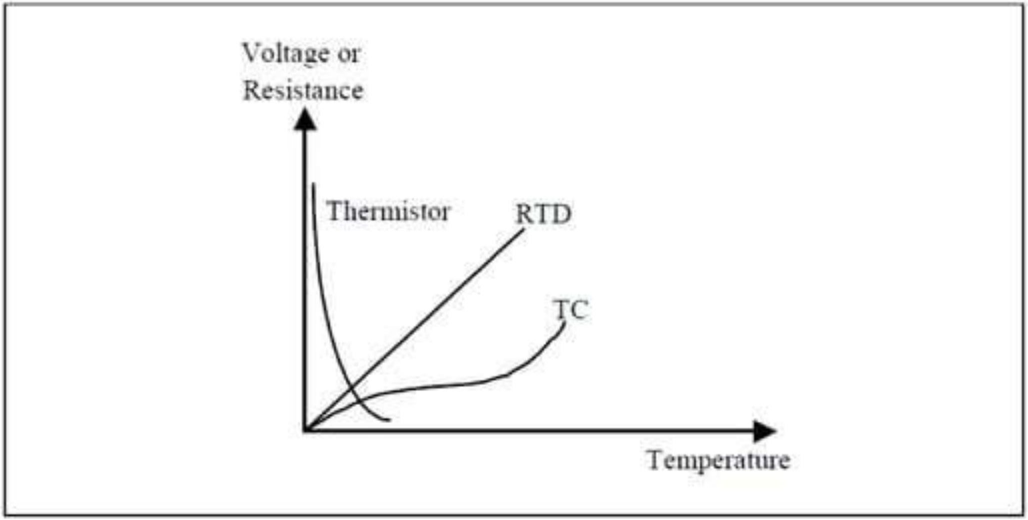


<u>Ungrounded</u> – For use in corrosive and pressurized apps. Slow response time. Offers electrical isolation.

<u>Grounded</u> – For use in corrosive and pressurized apps. Quicker response time than ungrounded due to improved heat transfer.

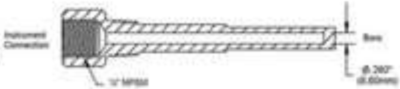
<u>Exposed</u> – For use in dry, non-corrosive, non-pressurized apps. Quickest response time of all three.

Thermocouple VS RTD VS Thermistor



Thermowells

The thermowell is used to protect the temperature element from process hazards while enabling an accurate measurement. A thermowell must be mounted to contact process fluid. This means it is subjected to corrosion, abrasion, high pressures, open flames, and other potential hazards.



The thermowell is a hollow tube closed on one end and open on the other. The closed end is inserted into the process through standard threads or flanges, or by welding. The temperature element is inserted into the open end, which allows it to measure the temperature while isolated from the process fluid.

The thermowell also allows the temperature element to be removed easily for calibration, maintenance, or replacement, without the need for a process shutdown. Thermowells are usually constructed out of stainless steel, but could be made from other alloys depending on the process fluid.

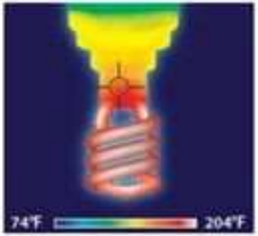
Infrared Thermometers

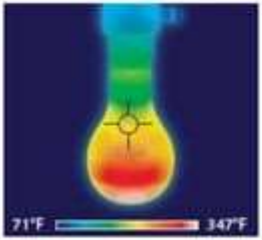
Infrared thermometers measure temperature using the infrared energy emitted from objects. They are sometimes called laser thermometers, pyrometers, or non-contact thermometers to describe the device's ability to measure temperature from a distance.

Infrared sensors measure the amount of radiation emitted by a surface. Electromagnetic energy radiates from all matter, regardless of its temperature. In many process situations, the energy is in the infrared region. As the temperature increases, the amount of infrared radiation and the average frequency go up. By measuring the amount of infrared energy emitted by the object, the object's temperature can be determined.

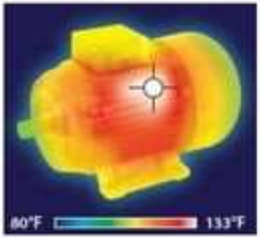
Thermography (Thermal Imaging)

A thermal imaging camera allows the user to see a two dimensional image displayed in heat. This infrared image is created using a tiny grid of infrared detectors inside the thermal imaging camera behind a lens.





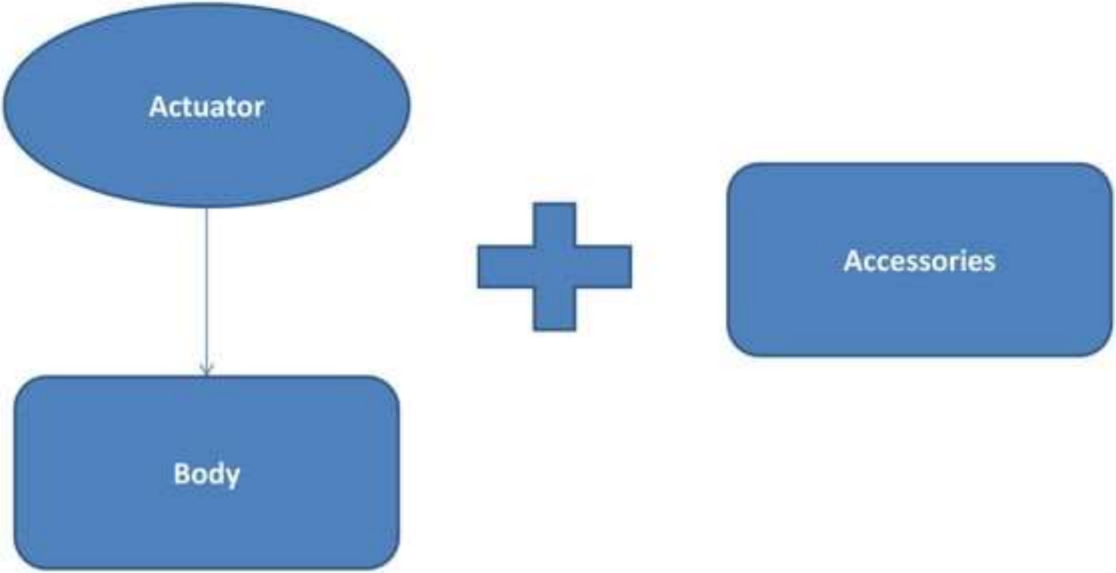
When all of the individual temperature values are converted from a numeric temperature value to a color associated with a temperature, a thermal image is generated. Thermal images are useful for many industrial applications. Most industrial problems such as overloaded panels or failing bearings in a motor generate heat as a by-product.



In this diagram, it is easy to see the greatest source of heat inside the motor.

Final Control Elements
Control Valves

Control Valve Components



Basic Valve Components

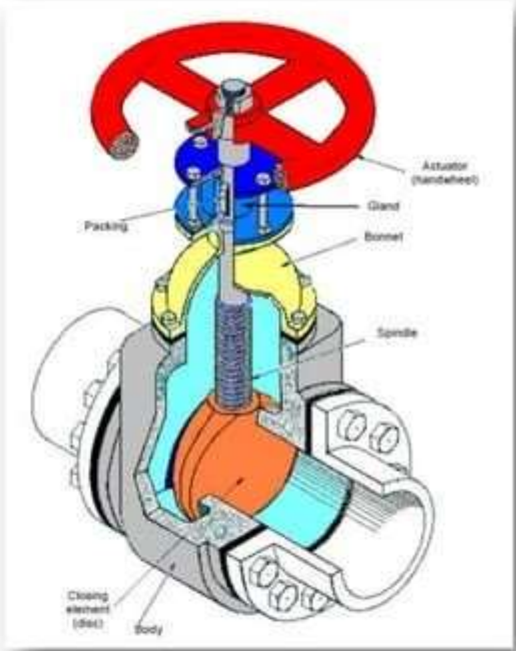
Body

Bonnet

Trim

Packing

Actuator



Basic Valve Components

Body

Is the main part of the valve. All other parts fit onto the body.
It is usually cast or forged and the shape varies with the type of valve.
Inlet and outlet pipes fit onto the valve body through threaded, bolted (flanged) or welded joints.
The fluid passes through the valve body when the valve is open.
The valve body must be strong enough to take the maximum pressure of the process fluid. It must also be made of a material that is not attacked by the fluid.

Bonnet

Is a removable cover fitted to the body. Some bonnets support the moving parts of the valve. Others just close the hole in the body through which the moving parts pass for assembly and dismantling.

Basic Valve Components

Trim (Plug and Seat)

Is the name given to the parts inside a valve. This normally includes:

The opening/closing element—closes the fluid path through the valve body

The valve stem—connects the actuator to the closing element

The valve seat—makes a seal with the closing element when the valve is closed

Packing

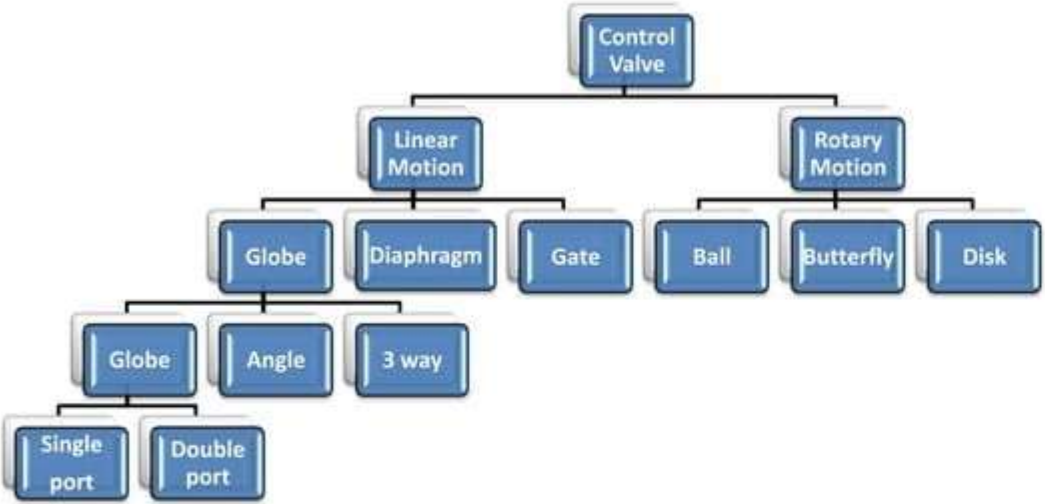
It allows the valve stem to pass into the valve body without loss of fluid or fluid pressure from the valve. It forms a dynamic seal between the valve stem and the bonnet.

Actuator

Operates the stem and closing element assembly.

Control Valve Body

Control Valve Classification

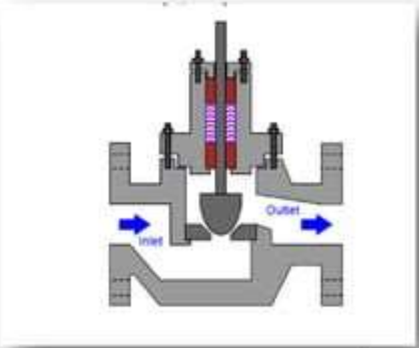


Globe Valves

Globe valves restrict the flow of fluid by altering the distance between a movable plug and a stationary seat (in some cases, a pair of plugs and matching seats). Fluid flows through a hole in the center of the seat, and is more or less restricted by how close the plug is to that hole. The globe valve design is one of the most popular sliding-stem valve designs used in throttling service.

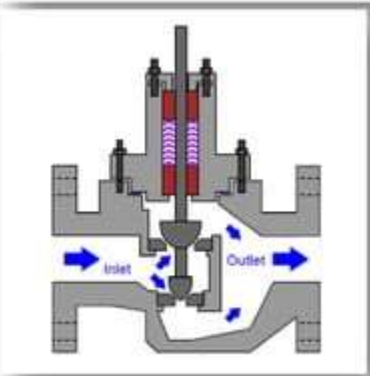
Globe valve

Single-ported Globe
- Large amount of force required to drive the stem
- Tight shut off
- Used in small diameter applications



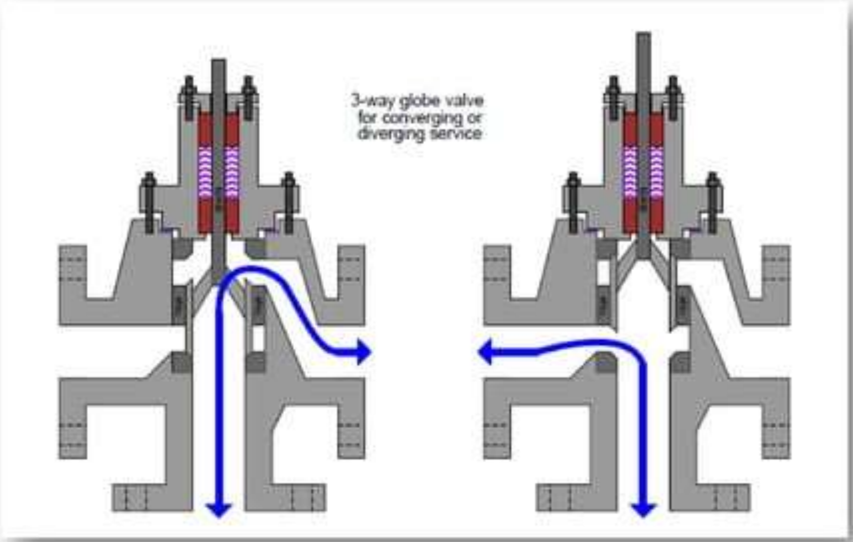
Double-ported Globe Valve

The purpose of a double-ported globe valve is to minimize the force applied to the stem by process fluid pressure across the plugs which comes in trade of tight shutoff of the valve



3-way Valves

Three-way valves are useful in services where a flow stream must be diverted (split) between two different directions, or where two flow streams must converge (mix) within the valve to form a single flow stream.



Angle Valves

The inlet and outlet ports are at right angle to each other .

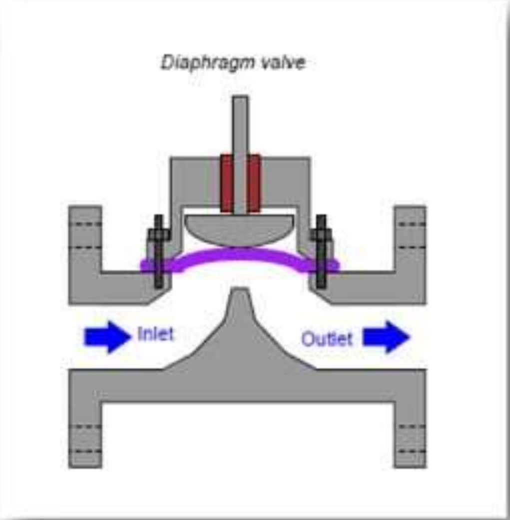
Can be installed in case of no inline globe valve can be installed

Diaphragm Valve

Diaphragm valves use a flexible sheet pressed close to the edge of a solid dam to narrow the flow path for fluid. These valves are well suited for flows containing solid particulate matter such as slurries.

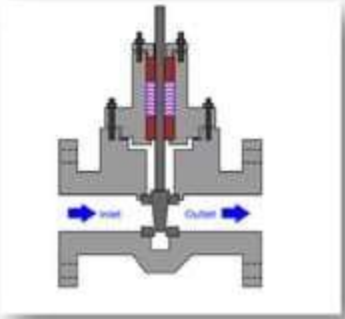
Precise throttling may be difficult to achieve due to the elasticity of the diaphragm.

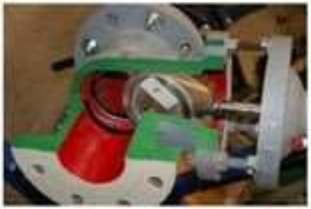
This diaphragm completely separates the valve trim from the fluid flowing through the valve. This means that the fluid does not contact the trim and the stem does not need any gland packing.



Gate Valve

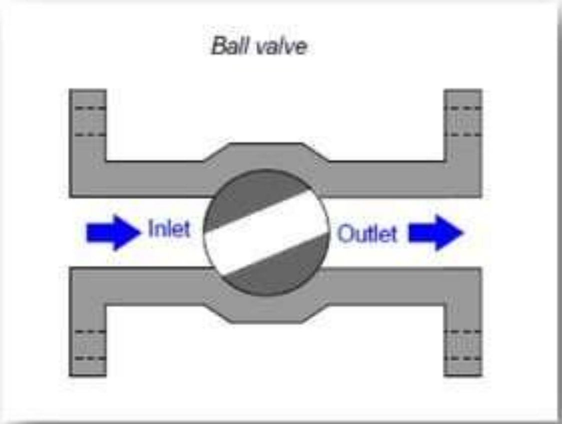
Gate valves work by inserting a dam (gate) into the path of the flow to restrict it, in a manner similar to the action of a sliding door. Gate valves are more often used for on/off control than for throttling.





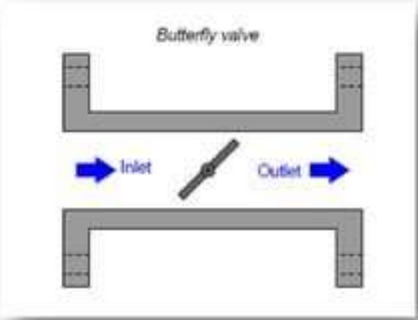
Ball Valve

In the ball valve design, a spherical ball with a passageway cut through the center rotates to allow fluid more or less access to the passageway. When the passageway is parallel to the direction of fluid motion, the valve is wide open; when the passageway is aligned perpendicular to the direction of fluid motion, the valve is fully shut (closed).



Butterfly Valves

Butterfly valves are quite simple to understand: the "butterfly" element is a disk that rotates perpendicular to the path of fluid flow. When parallel to the axis of flow, the disk presents minimal obstruction; when perpendicular to the axis, the disk completely blocks any flow. Fluid-tight shutoff is difficult to obtain in the classic butterfly design unless the seating area is lined with a soft (elastic) material.



Disc Valve

Disk valves (often referred to as eccentric disk valves, or as high-performance butterfly valves) are a variation on the butterfly design intended to improve seat shut-off. The disk's center is offset from the shaft centerline, causing it to approach the seat with a "cam" action that results in high seating pressure. Thus, tight shut-off of flow is possible even when using metal seats and disks.

Actuators

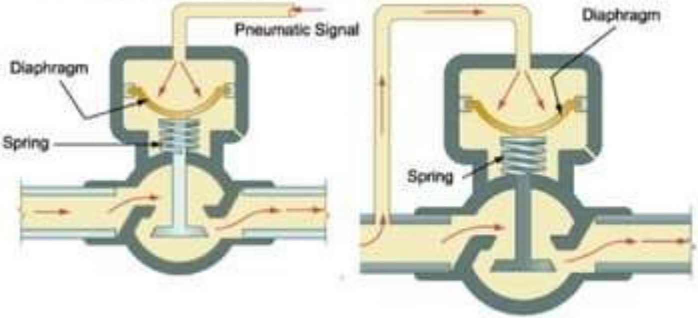
PNEUMATIC ACTUATORS

They are basically of two types
Diaphragm actuator
Piston actuator

These actuators are designed so that with a specific change of air pressure, the spindle will move sufficiently to move the valve through its complete stroke from fully-closed to fully-open.

Diaphragm Valve Actuator

This actuator contains a diaphragm and a spring. When no pressure acts on the diaphragm, the spring keeps the valve in a fully closed position.
As process pressure increases above the spring's back force, the diaphragm is pushed down and the valve opens. The process itself supplies the energy used to move the valve, but the device responsible for the actual movement is the diaphragm actuator.

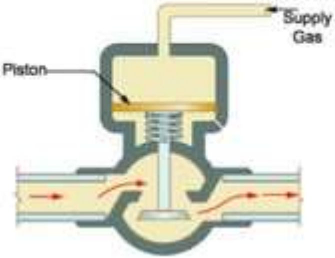


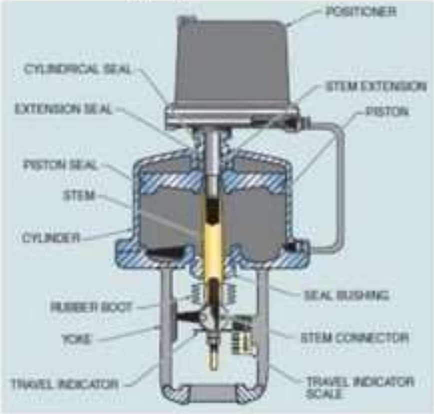
Piston Actuator

This piston actuator works much like a diaphragm actuator except that a piston is used to move the valve stem.

The piston is much stronger than the diaphragm. Therefore, piston-actuated valves are used for higher differential pressures than diaphragm-operated actuators.

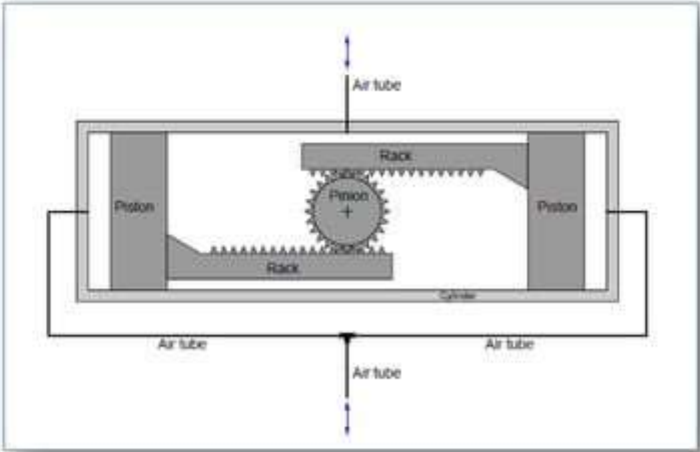
Piston actuators are designed to safely operate on supply pressures up to 150 PSIG (1,034 kPag).

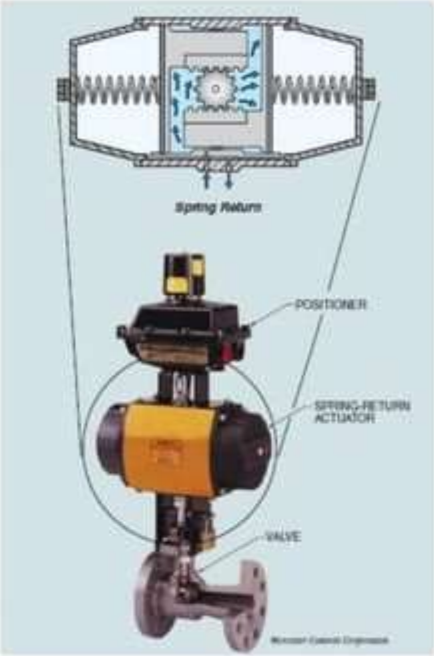




Rotating Actuators (RACK-AND PINION MECHANISM)

A pair of pneumatically-actuated pistons move a rack and pinion mechanism to convert linear piston motion into rotary shaft motion to move the butterfly trim.





Electric Actuators (MOV)

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.

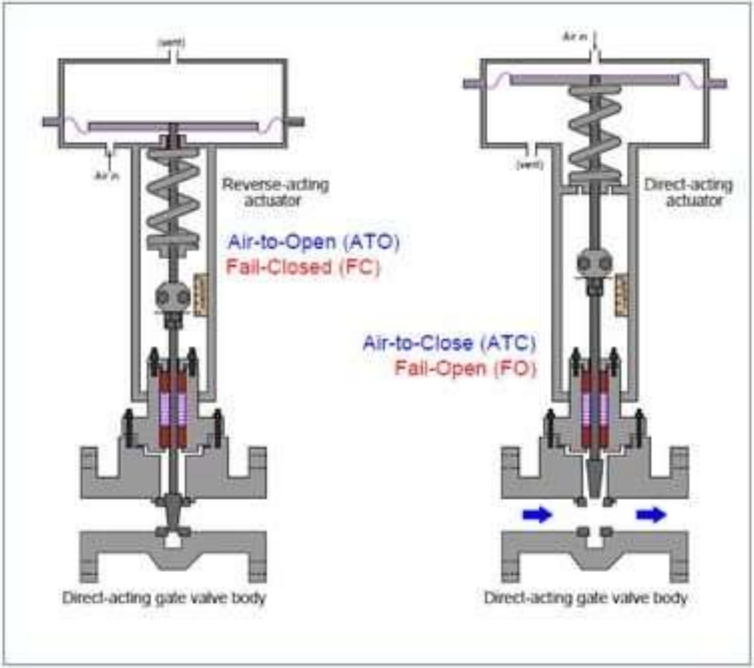
Electric motors have long been used to actuate large valves, especially valves operated as on/off ("shutoff") devices. Advances in motor design and motor control circuitry have brought motor operated valve (MOV) technology to the point where it now competes with legacy actuator technologies such as pneumatic in actuating throttling valves as well.

Electric Actuators (MOV)

An electric actuator providing on/off rotary actuation to a ball valve. This particular electric actuator comes with a hand crank for manual operation, in the event that the electric motor (or the power provided to it) fails

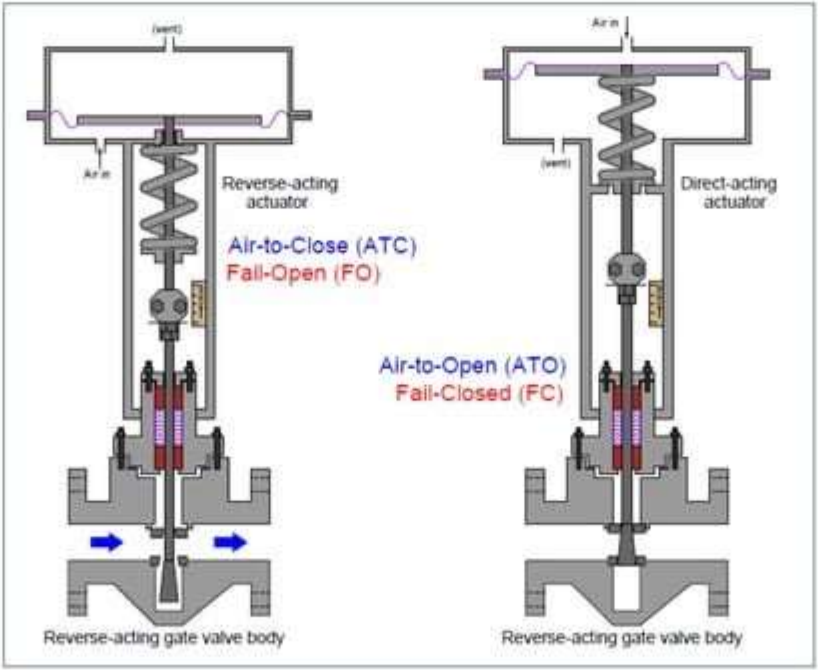
Valve Failure modes

Direct Body



Valve Failure modes

Reverse Body



Control Valve Accessories

The purpose of valve accessories is to obtain the best operational and safety performance from the control valve and actuator combination. Most control valves do not operate with simply an actuator but rather with a variety of accessories to maximize the performance of the valve.

The most common control valve accessories are:

Hand wheel or manual level.
Air set.
Transducer.
Volume booster.
Fail-safe system.
Limit switches.
Quick Exhaust valve
Positioner.

Final Control Element

Hand Wheel/Manual Lever

The hand wheel or manual lever is used to open or close a valve if the automatic control system fails. It can also be used to "torque" close a valve that might be slightly leaking. The types available are the typical hand wheel or a variety of different levers. It is mounted to either the actuator or valve bonnet so that it is attached to the stem (either actuator or valve stem) and can override the actuator.

Air Set

The air set provides the required instrument air for the control valve and its accessories. The usual components are an air regulator and a filter to ensure dry air for the instruments. In many cases, a combined filter regulator is used.

Regulator with Separate Filters

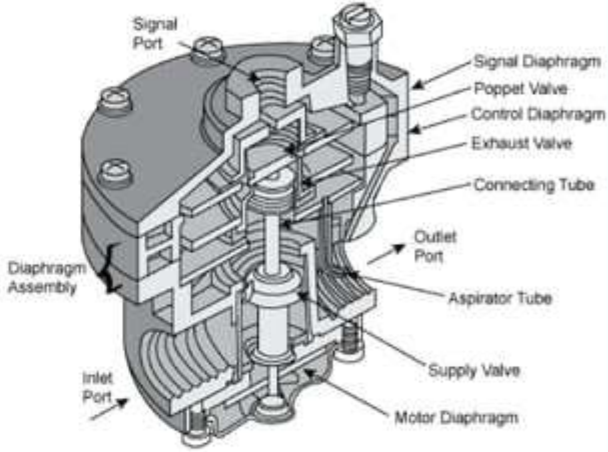
Filter Regulator

Transducer (I/P)

In most modern industrial facilities, the control system is electronic or digital, however most of the control valves are operated by pneumatic actuators. The transducer will convert the standard 4 to 20 mA electronic signal to the required 3-15 psi signal. The current-to pneumatic (air) transducer, commonly referred to as an I/P transducer is a relatively simple device and literally produced by all instrument manufacturers. Although the appearance may vary, the principle of operations is similar for all manufacturers.

Volume Booster

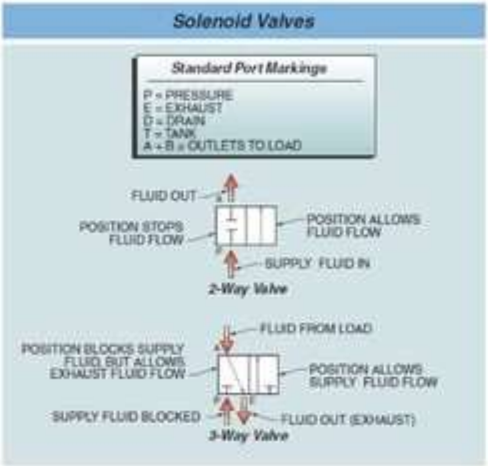
A volume is sometimes required on larger actuators. A large actuator is required for larger pipe valves. The normal air set regulator cannot provide the required volume of air to operate the actuator and valve in the desired response time. The volume booster is a pneumatic 1:1 relay in which it receives the pneumatic 3-15 psi signal and transmits the same signal only with a much larger volume or flow rate. It also vents at a higher rate so that on a decrease of pressure, the response time is similar. The volume booster has an input signal (3-15 psi), an output signal and an air supply. The volume booster is physically located between the device supplying the control signal to the actuator and the actuator.

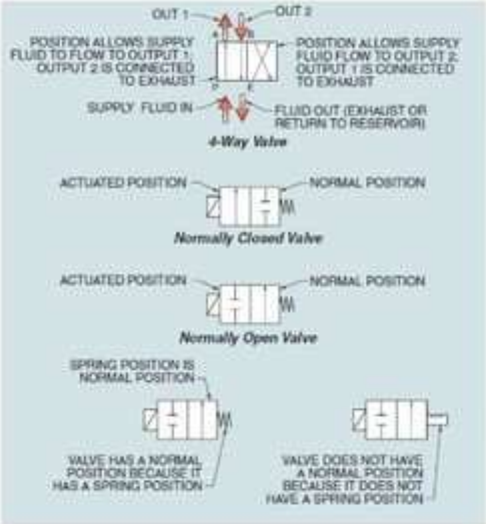


Solenoid Valve

A very common form of on/off valve used for pneumatic and hydraulic systems alike is the solenoid valve.

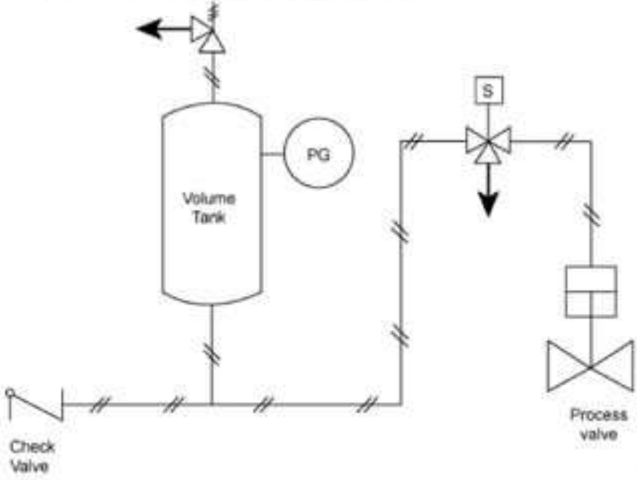
A "solenoid" is nothing more than a coil of wire designed to produce a magnetic field when energized. Solenoid actuators work by attracting a movable iron armature into the center of the solenoid coil when energized, the force of this attraction working to actuate a small valve mechanism.





Fail-safe System

A simple fail safe system consists of a solenoid valve and an optional air volume tank. The purpose of the fail-safe system is to ensure the control valve either closes or opens (determined by process conditions) in the case of an instrument failure and loss of signal to the valve. Depending on the action of the valve, either air-to-open or air-to-close, on an emergency or control system failure, a signal will be sent to the solenoid valve to operate the valve and move it to its fail safe position.

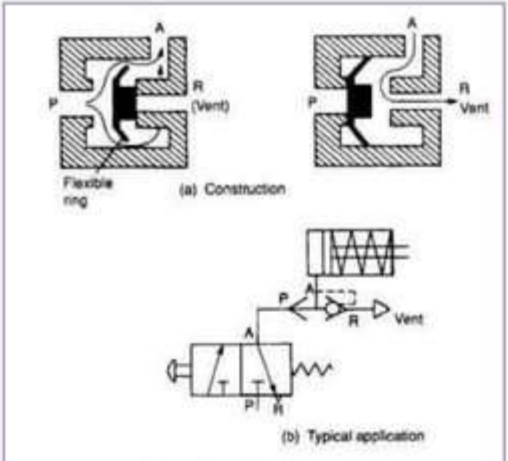


Limit Switches

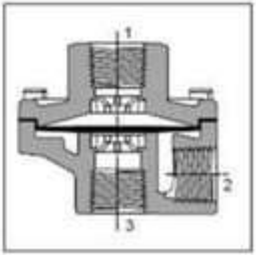
Limit switches can be attached to the actuator stem or the valve stem on globe valves to provide feedback to the control room on the actual position of the valve. These are usually set to indicate fully open or fully closed. They are also easily attached to rotary valves and can provide an easy-to-see local indication of the valve position. In the case of MOV (motor operated valves) block valve, they can also be used to start and stop the motor and safe-guard the valve shaft from being over-torqued and possible damage. The limit switch is merely a micro switch that is tripped by a small lever when the valve reaches its predefined limit.

Quick Exhaust valve

It is used in case of quick venting is important in a control valve .



Fast exhaust valve

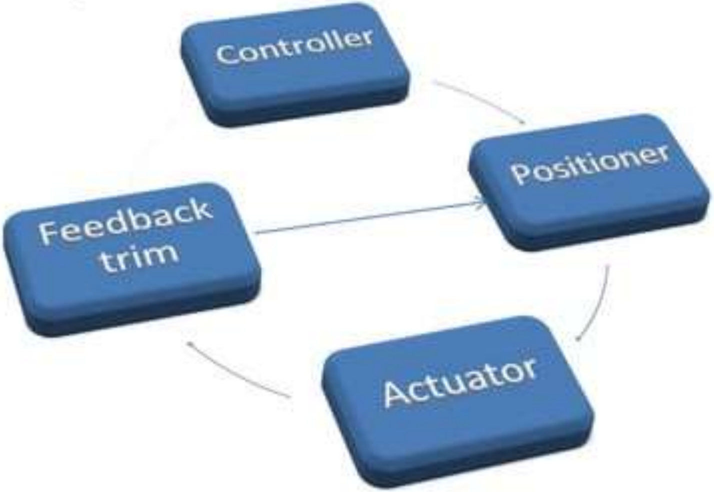


Positioner

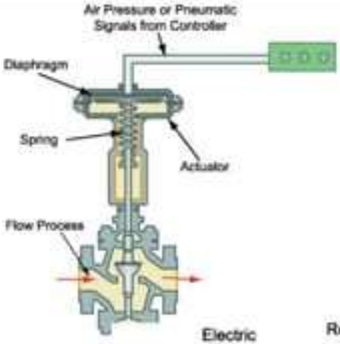
The valve positioner is a device which receives the control signal and compares that signal to the actual position of the valve then sends a signal to the actuator to move the valve to the exact position called for by the control system. The positioner senses the valve opening through a position feedback link connected to the valve stem which acts as the positioner's input signal. The control signal from the I/P is its setpoint. The difference between these two is the error signal. The positioner reacts to this error signal which is the difference between where the valve opening actually is and where the control system wants it. Based on this difference, the positioner sends a signal to reposition the valve to the exact desired position. In actuality, the positioner acts like a pneumatic feedback controller. Not all control valves are equipped with positioners, but the vast majority are. The term control valve is generally thought of as the combination of the positioner, actuator and valve.

Positioner

Positioners essentially act as control systems within themselves the valve's stem position is the process variable (PV), the command signal to the positioner is the set point (SP), and the positioner's signal to the valve actuator is the manipulated variable (MV) or output.



Psitioner types

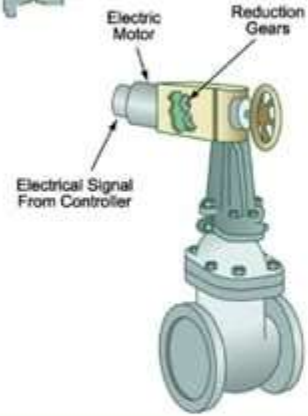


Pneumatic Positioners

They are intrinsically safe and can provide a large amount of force to close a valve.

Single-acting positioners send air to one side of a single-acting valve actuator that is opposed by a range spring.

Double-acting positioners send and exhaust air from both sides of the actuator.



Electric Valve Positioners

Electric valve positioners send and receive electrical signals.

Digital or "Smart" Devices

Digital or "smart" devices use digital electronics to position the valve actuator and can monitor and record data. They are very accurate, use less air than analog positioners and allow for online digital diagnostics.

Many modern positioners are multi-functional and can incorporate many features into one device, the smart positioner features are:

Link less connection to the valve stem, feedback is provided using a magnetic follower.

Integral position transmitter.

Integral I/P transducer.

Integral air set.

Limit switches.

Split-range capability.

Field changeable action: direct or reverse to operate either air-to-open or air-to-close valves.

Customizable flow characteristics.

Adaptable to both globe and rotary valves.

HART communication accessing:

- Calibration data.
- Diagnostics.
- Configuration data.
- Data trending.
- Wireless capabilities.

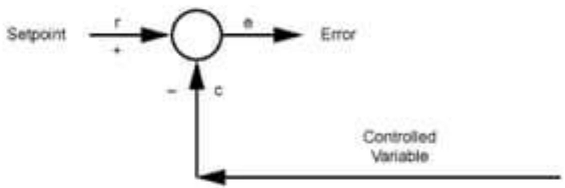
Process Control Loops

Controllers

The controller itself must contain some method of comparing the controlled variable (now the measured variable) to the setpoint. This device is known as a summing junction or comparator. The setpoint is given an arbitrary designation as a positive (+) value while the measured variable is given a negative (-) designation so that when the comparator examines both values a numerical difference is obtained.

For the control block the following symbols have been assigned:

Setpoint: r.
Controlled variable: c.
Error: e.



Variables

Not all manipulated variables are the same as the controlled variable. A common example where they are the same is the controlled variable being flow rate and the manipulated variable is changing the flow.

Examples of where they are different are:
The controlled variable being the output temperature of a heat exchanger and the manipulated variable being the steam flow in. Flow is being manipulated to control temperature.
The controlled variable being the level in a tank and the manipulated variable being the flow out. Flow is being manipulated to control level.

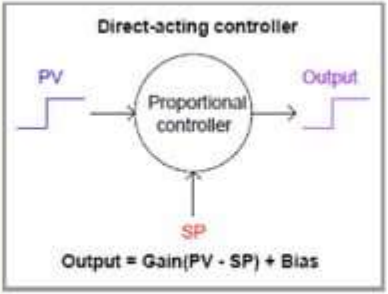
Direct/Reverse Acting Controllers

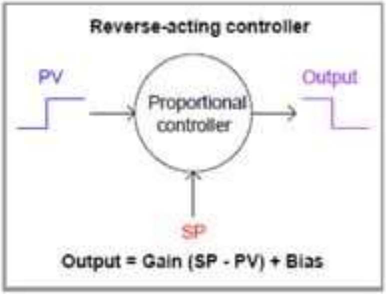
Direct/Reverse Acting Controllers

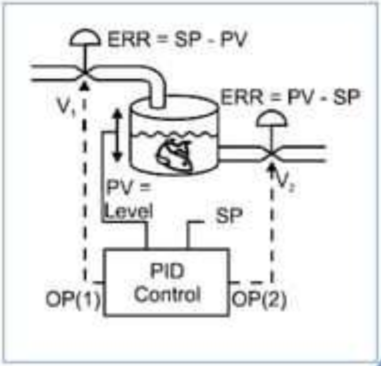
Another feature of the controller is its ability to be a direct or reverse acting controller.

A direct acting controller increases its output for an increase in the controlled variable.

A reverse acting controller operates in the opposite manner. This is required to maintain the integrity of a fail-safe system where control valves may be air-to-open or air-to-close depending on the process.







Control Modes

Control Modes

How the controller reacts to an error signal is known as controller response. Continuous control (a controller is continually receiving the controlled variable signal and comparing it the setpoint) can have many different modes. The most common control modes are:

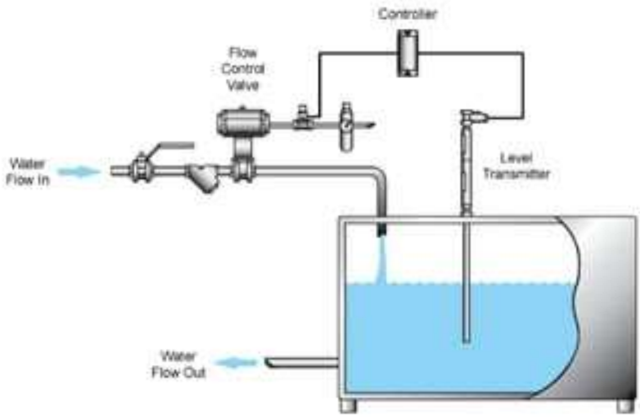
On-Off control.

Proportional control (P).

Proportional plus integral control (PI).

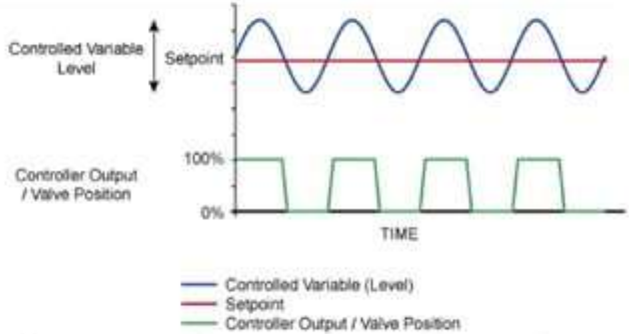
Proportional plus integral plus derivative (PID).

Lesser used control modes are integral only (I) and proportional plus derivative (PD).



On-Off Control

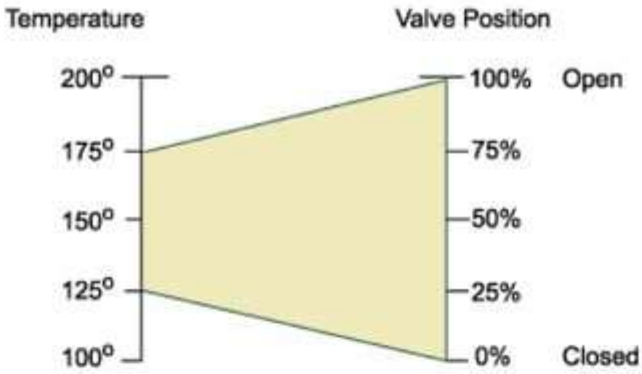
On-Off control is also known as two-position control. In on-off control the controller only has two outputs, 0% or 100%, therefore the valve will either be fully open or completely closed.



If the level of the tank drops due to usage downstream, the transmitter will sense this and send a signal to the controller. The controller compares the lower signal to the setpoint and generates a signal to the control valve to open and allow more water into the tank to raise the level. Since the controller is an on-off controller the signal to the valve is 100%, the valve opens and water flows into the tank raising the level. The level now is higher than the setpoint so the controller reacts and gives 0% signal. This closes the valve and the water drops below the required level and the cycle begins again. The characteristics of on-off control are a cycling controlled variable and the final control element being either at 0% or 100% (180º out of phase with the level). The process is depicted in the graphic.

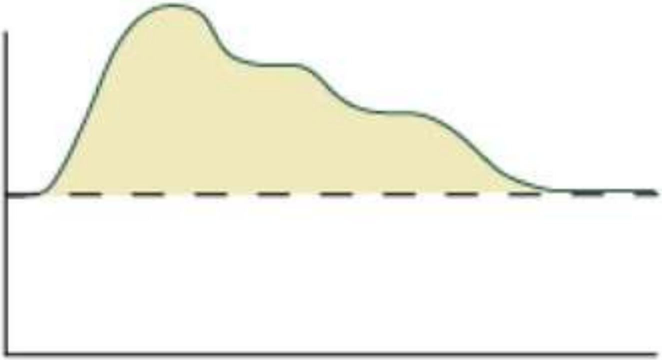
Proportional Control (P)

A proportional control mode amplifies the controller's output to the final control element. This is an illustration of a 50% proportional band. When a controller with this proportional band receives a 10% change in measurement value, the output from the controller changes by 20%. The result is instantaneous.



Reset Control (I)

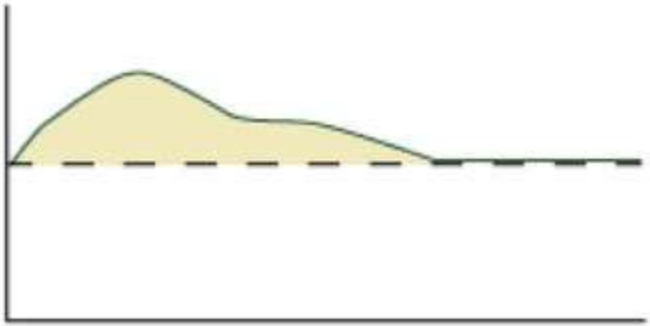
A reset control repeats a controller's actions and returns the variable to set point. It is a time-weighted response that corrects the value based on the amount of error over time.



Proportional + Reset

Rate (Derivative) Control (D)

A rate control adjusts the controller's output according to the speed at which the variable is moving toward or away from set point. It is also a time-weighted response, but it acts in response to an input value.



Proportional + Reset + Rate

Proportional Control (P)

Most processes cannot tolerate a constant cycling of the controlled variable, not to mention the wear-and-tear on a control valve that is continuously cycling between opened and closed positions.

Proportional control was developed to give a more steady process response. The output of the proportional controller is algebraically proportional to the error signal and therefore the controlled variable signal. The output response is also adjustable by changing the gain (Kp) of the controller. A gain of 1 will produce and equal percentage of output change for the same input change.

This means that if the controlled variable changes by 10% then the output will also change by 10%. A gain of 5 means that if the controlled variable changes by 10% the output will change by 50%. The higher the gain, the more the output will respond (faster).

Conversely, a gain of 0.5 means that for a 10% change in controlled variable, the output will only change 5% so for a lower gain the output will respond less (slower). An older term for gain is proportional band. An On-Off controller has a very high gain.

Proportional band

Proportional band is defined as the range of values of the input required to produce a 0 to 100% change in output. If the proportional band is 100 then 100% input will produce an output change of 100% (same as a gain of 1). Similarly, a proportional band of 50 will result in a 100% change in output (same as a gain of 2). Proportional band is expressed in terms of % and can be related to gain by the formula:

$$PB = \frac{1}{Gain} \times 100$$

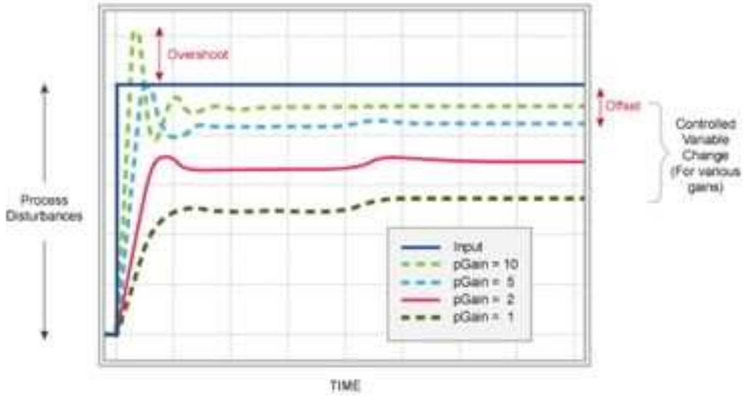
$$Gain = \frac{1}{PB} \times 100$$

PB	Gain
10%	10
25%	4
50%	2
100%	1
200%	0.5

If a sudden change (step change) occurs to a steady state process such as a setpoint change or major disturbance, the controller will respond by changing its output to counter that change. The process will respond and once again the water flow in will equal the water flow out producing a steady state condition. How fast this occurs is dependent on the controller gain, Kp.

Offset Problem

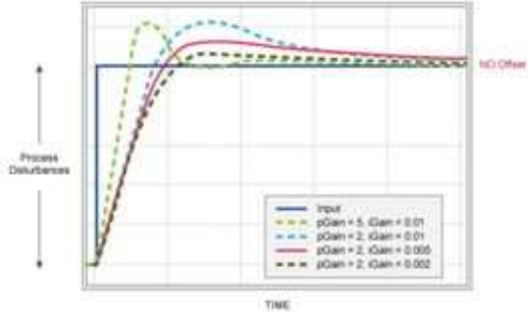
The major disadvantage of proportional control is that of offset. Offset always occurs after a disturbance and is only eliminated if the process returns to its original steady state condition of 50%. Offset occurs due to the dynamics of the process. These include dead times, process and measurement lags friction in valves and other factors. In other words, the process cannot and does not react to any change instantaneously.



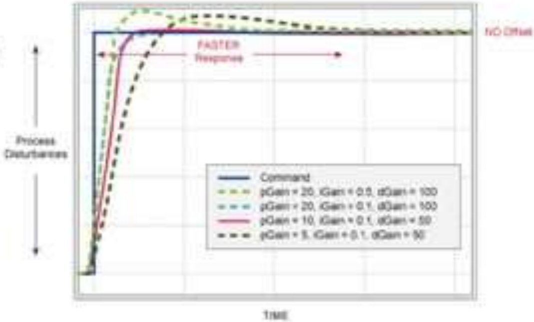
Proportional Plus Integral (PI) Control

To eliminate offset, another control mode is applied, that of integral (or reset). Integral basically keeps applying the output change again and again until the offset is eliminated. In actuality, integral action is the mathematical integration of the error signal. Integral action is not usually employed by itself, but is combined with proportional to produce a proportional + integral (PI) control action.

The output of the controller is the sum of the proportional action plus the integral action. Proportional action occurs only once, when the initial error is detected, integral action continues until the error is reduced and eliminated. Like the units of proportional control (proportional band [%] or gain) integral is expressed in two different terms, it can be reset time (minutes) or repeats per minute.



Proportional Plus Integral Plus Derivation (PID) Control



In slow reacting processes like temperature or large level tanks, the reaction time with just a PI controller may not be quick enough to prevent significant overshoot, which in a level process could be dangerous. To speed up the response of a controller in these situations a third mode or action is introduced, that of derivative or rate.

Adding derivative actually adds lead to a process which inherently is slow or lagging. Derivative action applies an initial step to the output as soon as an error is detected, thereby moving the valve just as an error occurs. The initial amount that the output changes is determined by the gain(proportional setting of the controller) and then by how much the process is still changing.

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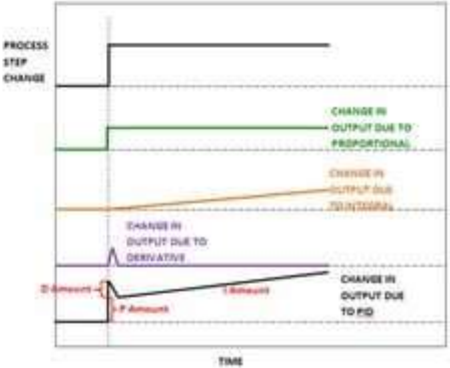
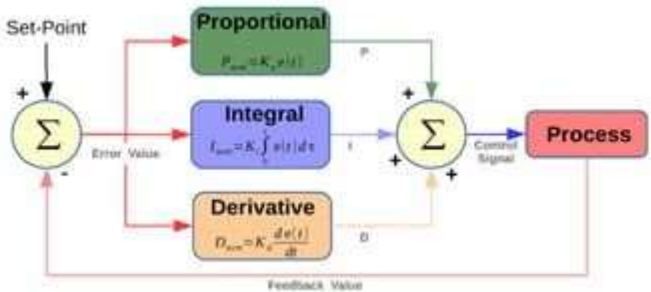
The total reaction of a controller is the sum of the actions of the different modes applied, for example in a PID controller the output change is the sum of the change due to proportional + the change due to integral + the change due to derivative.



A block diagram of the controller shows the additive properties of a PID controller output:



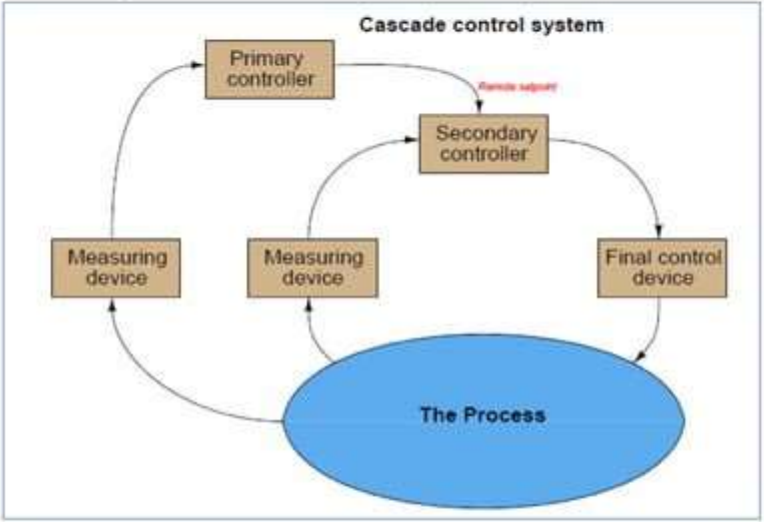
Types of Control Schemes

The control scheme of a PID feedback controller is the most common control scheme used in industry today. However, due to the different process dynamics, sometimes PID control is not enough to maintain good control. Other control schemes have been developed to improve the response of the process to disturbances, some being:

Cascade control.
Ratio control.
Split range.
Feedforward control.
Selectors, Overrides, and Interlocks.
Multivariable control.
Adaptive control.

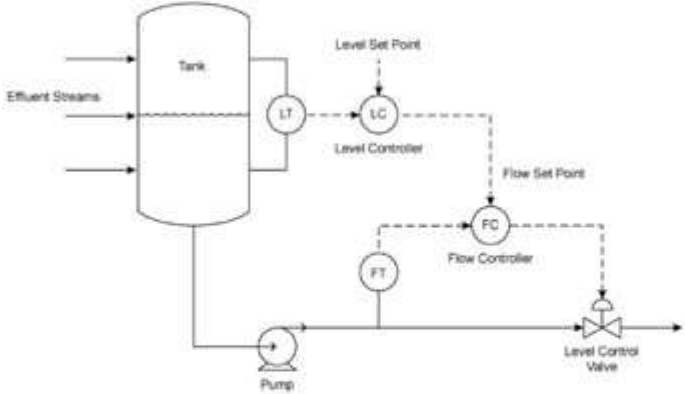
Cascade Control

Cascade control is the use of two PID feedback controllers together to produce better process dynamics (response). Two controllers are arranged so that the output of one controller provides the setpoint for the other controller which controls the one control valve in the loop.



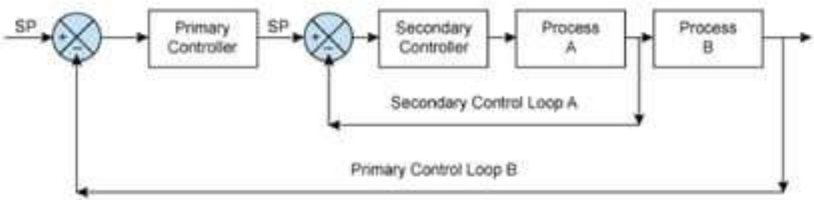
Cascade Control Application

The main objective of the control scheme is to maintain a specific level in the tank by manipulating the control valve. If only feedback control were used, the output of the level controller (LC) would go directly to the level control valve and there would be no need for the flow loop (FT and FC). However, tighter control of the process can be achieved by implementing cascade control by adding the flow loop.



Control loop design

The control loops are designated:
Primary or outer loop is the level control loop with its output being the setpoint for the secondary loop.
Secondary or inner loop is the flow control loop and it receives its setpoint from the level controller.



Cascade Control Considerations

When implementing a cascade control loop, the following apply:

The secondary loop need only be a Proportional controller but adding the PI action will improve response.

The primary loop should be a PI controller to eliminate offset and will probably benefit from PID control.

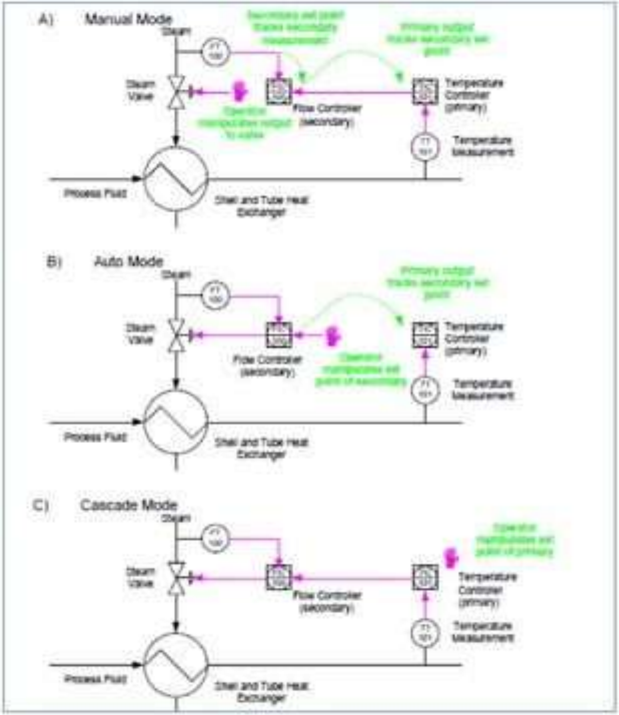
Cascade consists of two controllers but only one control valve.

The secondary loop should be faster responding than the primary loop.

When tuning the loop:

- Place the primary loop on manual.
- Tune the secondary loop.
- Tune the primary loop with the secondary loop on automatic.

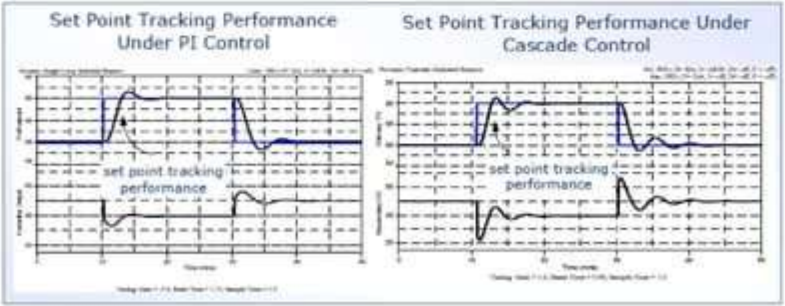
Cascade Control Modes



Cascade Control Effect

Disturbance Rejection Comparison

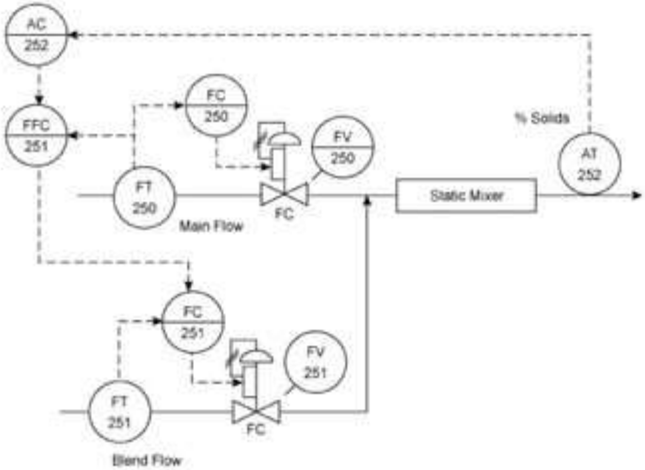
Set Point Tracking Comparison



Ratio Control

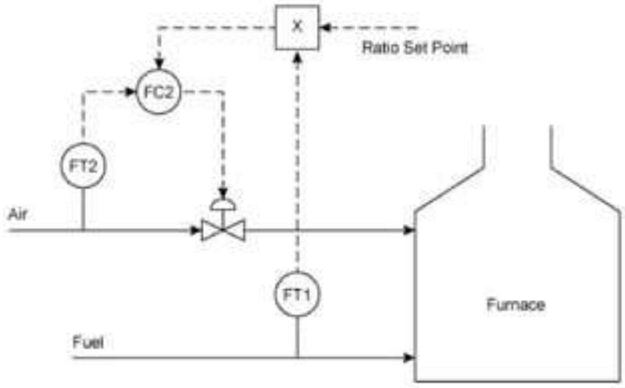
Ratio control consists of two flow controllers and two control valves controlling the mixing of two process variables (such as fuel and air for combustion). One stream is required to be a specific ratio (or fraction) to the other stream.

There are many ratio control configurations. Some are quite complex. In a simple ratio controller the output of one controller feeds a ratio or fraction controller (station).



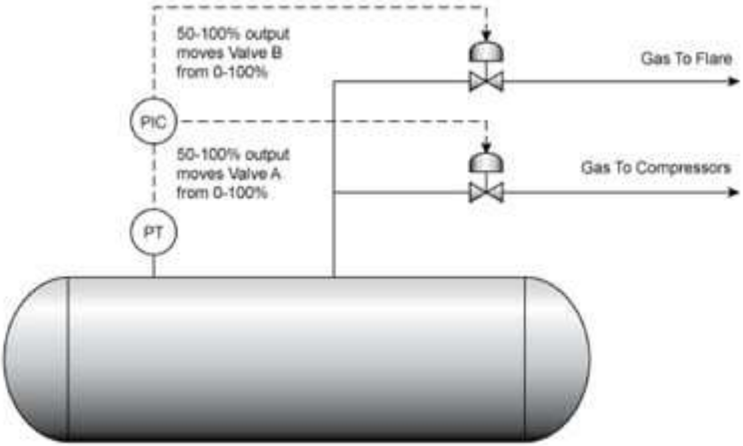
Types of Control Schemes

Another type is the “uncontrolled” ratio where there is only one controller, that being on the primary stream. A transmitter on the secondary stream provides a signal to the ratio controller station where the ratio is calculated and its output becomes the setpoint for the primary flow controller.



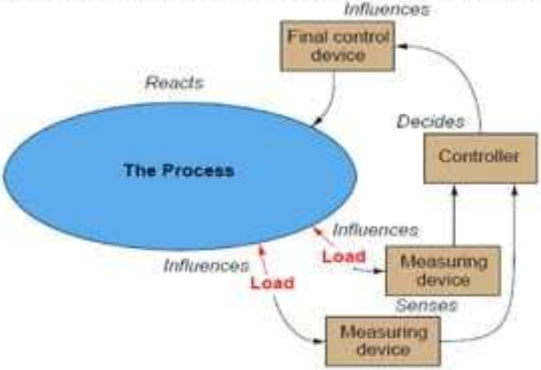
Split Range Control

In a split range control application, the output of one controller feeds two control valves. The loop is usually calibrated so that one control valve is operated by the 0 to 50% output signal from the controller and the other valve from the 50 to 100% signal. A typical PID controller can be used in the split range application.



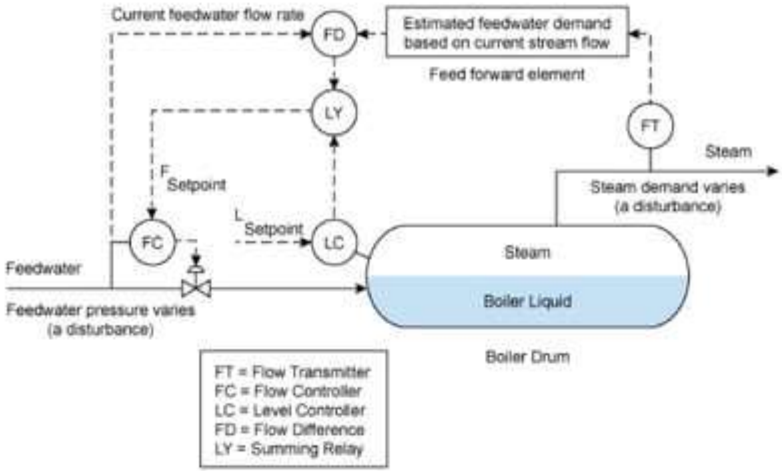
Feedforward Control

Feedforward control is much different than feedback control. Feedback control works to eliminate errors after they occur. Feedforward control operates to prevent errors from occurring in the first place. However, feedforward control is very complex and requires more hardware. Sensors are used on potential disturbances and when a disturbance is sensed action is taken before the disturbance can affect the process and create an error. A significant theoretical knowledge of process dynamics is required plus the capability for process modeling to make feedforward control a success. It is usually only applied in complex or critical control applications.



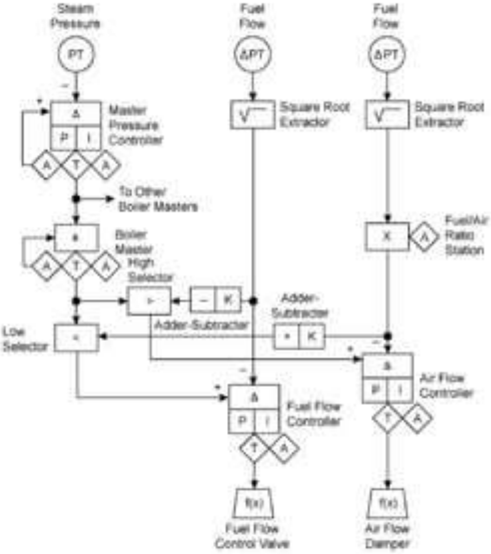
Feedforward Application

A simple example is shown in the first graphic.
The feedforward element is the estimated steam demand as sensed by the steam flow transmitter. If demand increases, the feedforward element will open the feedwater valve before the drop in level is sensed.



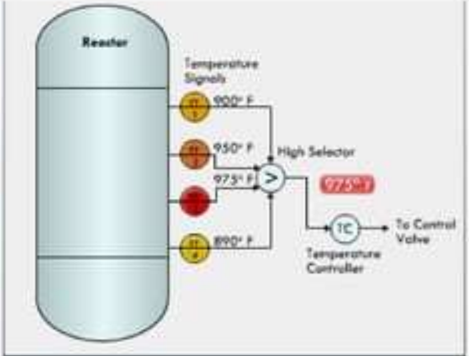
Feedforward Application

A more complex scheme is for a lead-lag boiler combustion control scheme, shown in the second graphic. Both the fuel flow and air flow control loops are receiving feedforward information from the master pressure controller and boiler master.



Selectors

Selectors provide one of several signals to a controller. For example, a number of temperatures from a reactor may be sent to a selector that identifies the highest of the temperatures and sends it to the controller. This system keeps the highest of the temperatures at the controller set point. This type of system is seen on Fluid Catalytic Cracking Unit Regenerators and on Hydrocracker Reactors.

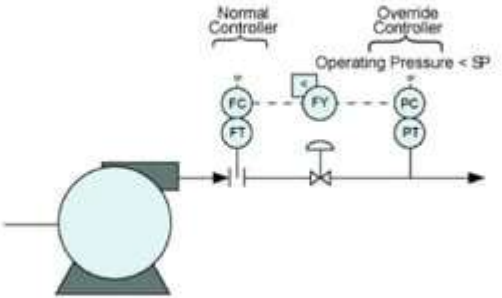


As the temperature signals indicate their readings, the high selector reports the highest value to the temperature controller.

Overrides

An override is similar to a selector, but it is used where the measurements are different types of variables. For example, suppose a unit has a pump feeding a unit with a downstream flow controller and control valve. The control valve opens and closes as needed to control the flow.
But in some cases, the pressure downstream of the control valve must be kept below a certain value. In these cases, an override can be provided from a pressure controller to the speed controller. Note that the override controller selects the lower signal from the flow and pressure controller. Overrides are found throughout process facilities.

Override Control System



Interlocks

Interlock systems prohibit certain actions until certain conditions are met. For example, a car has an interlock that will allow it to start only when it is in park. In a gas home furnace, the valve on the gas to the burner will not open unless a temperature detector mounted near the pilot shows the pilot is burning. Interlocks are present for safety reasons. In a process facility, interlocks are found on:

Boilers in the light-off system.

Fully regenerative catalytic reformers (as part of the reactor switching system).

Cokers in the drum switching system.

You must never disable interlock systems without first reviewing established safety procedures.

Multivariable Control

Multivariable control is employed when there is more than one control loop and variable in a single process. This is quite often the case. For example, there are two control loops in a process. When there is a change in one manipulated variable, it affects both controlled variables causing both controllers to react. Similarly, the same can occur with the second loop. This can cause innumerable problems as one loop starts chasing the other and stability may never be reached. When feedback loops are interacting with each other, they need to be decoupled and multivariable control can accomplish this. It is, however a very complex and mathematical process to determine the proper decoupling. It is even more complicated when two or more loops interact with each other.

Modern DCS systems with their built-in algorithms make the implementation of feedforward and multivariable control easier, but these control schemes still remain in the domain of the engineer.

Adaptive Control

Adaptive control is another benefit of the DCS and computer control era. Adaptive control can tune and program controllers “on the go” by collecting live process data and determine controller operating parameters for the optimum results and performance and then input these parameters without taking the system off line. Controllers basically “self-tune” themselves when operating parameters or conditions change.

Control Systems
DCS/PLC/SCADA

Introduction

Industrial Control Systems is a general term that includes several types of control systems:
Relay Control Systems (Classic Control/Hard wired Control)
Programmable Logic Controllers (PLC).
Distributed Control Systems (DCS).
Supervisory Control And Data Acquisition (SCADA) systems.

ICS are typically used in industries such as electrical, water and wastewater, oil and natural gas, chemical, transportation, pharmaceutical, food and beverage, and discrete manufacturing (e.g., automotive).

These control systems are used for critical infrastructures that are often highly interconnected and mutually dependent systems

DCS

DCS are used to control industrial processes such as electric power generation, oil refineries, water and wastewater treatment, and chemical, food, and automotive production.

DCS are integrated as a control architecture containing a supervisory level of control overseeing multiple, integrated sub-systems that are responsible for controlling the details of a localized process.

Product and process control are usually achieved by deploying feedback or feedforward control loops whereby key product and/or process conditions are automatically maintained around a desired set point

PLC

PLCs are computer-based solid-state devices that control industrial equipment and processes.

While PLCs are control system components used throughout SCADA and DCS systems, they are often the primary components in smaller control system configurations used to provide operational control of discrete processes such as automobile assembly lines and power plant soot blower controls.

PLCs are used extensively in almost all industrial processes

Different Function between DCS & SCADA and PLC

SCADA systems are generally used to control dispersed assets using centralized data acquisition and supervisory control.

DCS are generally used to control production systems within a local area such as a factory using supervisory and regulatory control.

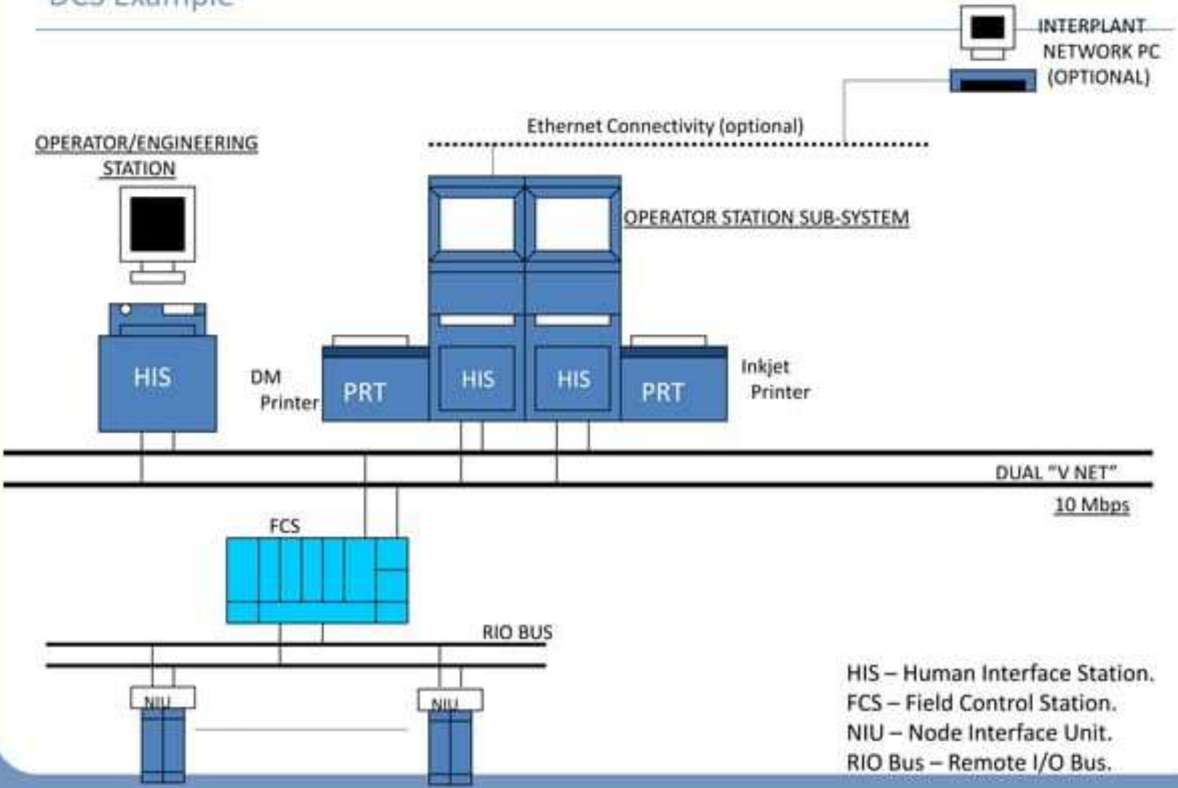
PLCs are generally used for discrete control for specific applications and generally provide regulatory control.

Comparison between DCS and PLC

DCS	PLC
Mfr sells a complete system of integrated components.	Mfr sells some components; an SI acquires others and engineers the system.
Mfr supports the system.	Mfr supports the components.
On-line repair/ maintenance are the norm.	Off-line repair/ maintenance are the norm.
Users expect to evolve/upgrade/expand a system over 10/20/30 years.	System is a one-off project (like a house). Upgrades / expansions are new projects.
Large number of I/O's	Small number of I/O's
Slower response	Fast response
Handles complex control loops	Handles simple control loops
Mainly used as BPCS	Mainly Used in Packages and safety systems

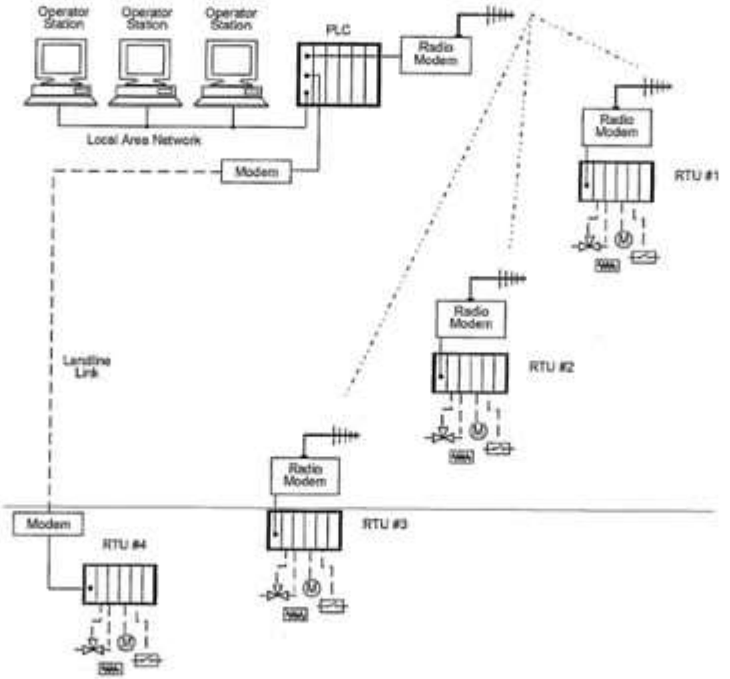
Control System

DCS Example

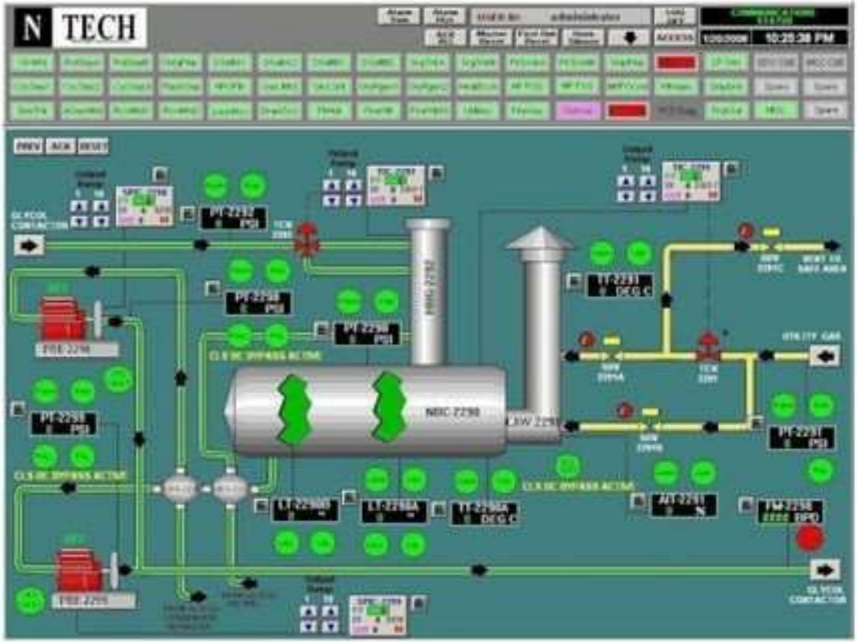


HIS – Human Interface Station.
FCS – Field Control Station.
NIU – Node Interface Unit.
RIO Bus – Remote I/O Bus.

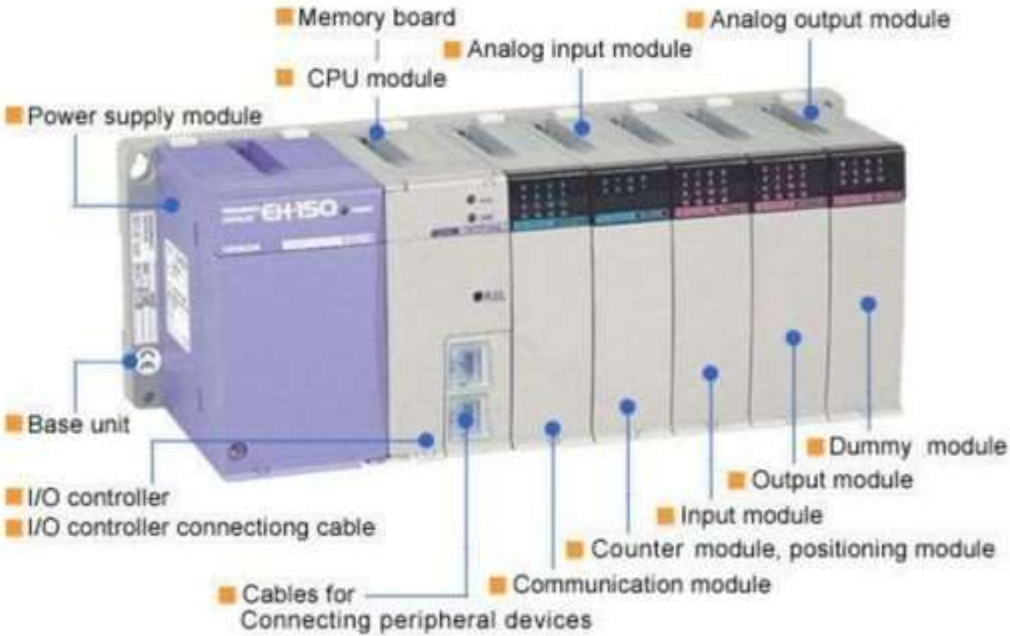
SCADA System Hardware Example



SCADA System Software Example



PLC Example


Memory board
CPU module
Analog input module
Analog output module
Power supply module
EH-150
Base unit
I/O controller
I/O controller connectiong cable
Cables for
Connecting peripheral devices
Communication module
Counter module, positioning module
Input module
Output module
Dummy module

DCS Architecture

DCS

Hardware

- Main
  - Field Control Station
  - Operator Work Station
  - Engineering Work Station
  - Communication Bus
  - Gateways
- Auxiliary
  - Operator Keyboard
  - Mouse
  - Printer

Software

- Graphic Interface
- History Modules (Trends)
- Faceplates
- Alarm Systems
- Maintenance Guide
- Control Loop Configuration
- Input Output Definition

Field Control Station

Controller Module

Power Supply

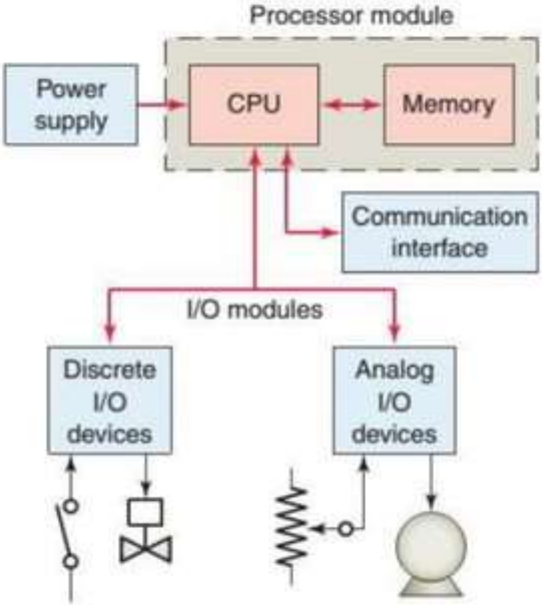
Permanent Memory

Communication Interface Card

Discrete I/O Modules

Analogue I/O Modules

CPU diagram


Processor module
Power supply
CPU
Memory
Communication interface
I/O modules
Discrete I/O devices
Analog I/O devices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Redundancy and Fault tolerance

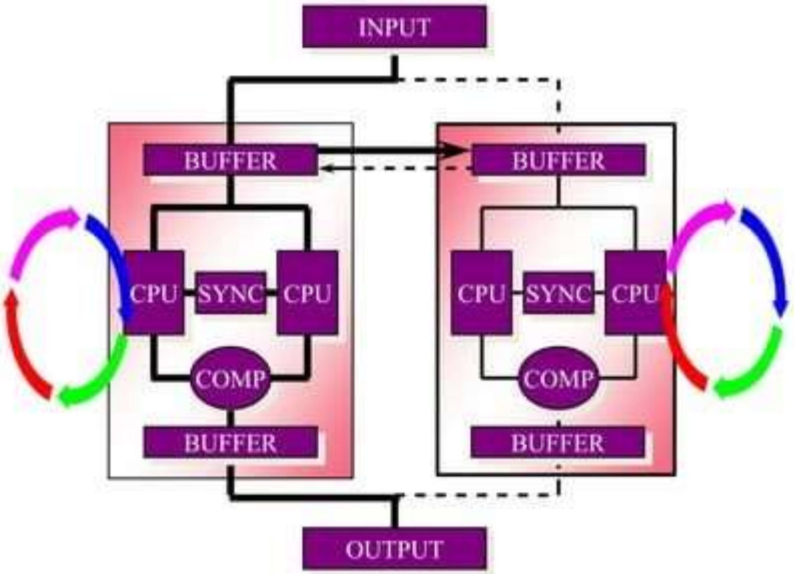
Redundancy

- To use more than one component to do same task .
- Ex : Full redundant system

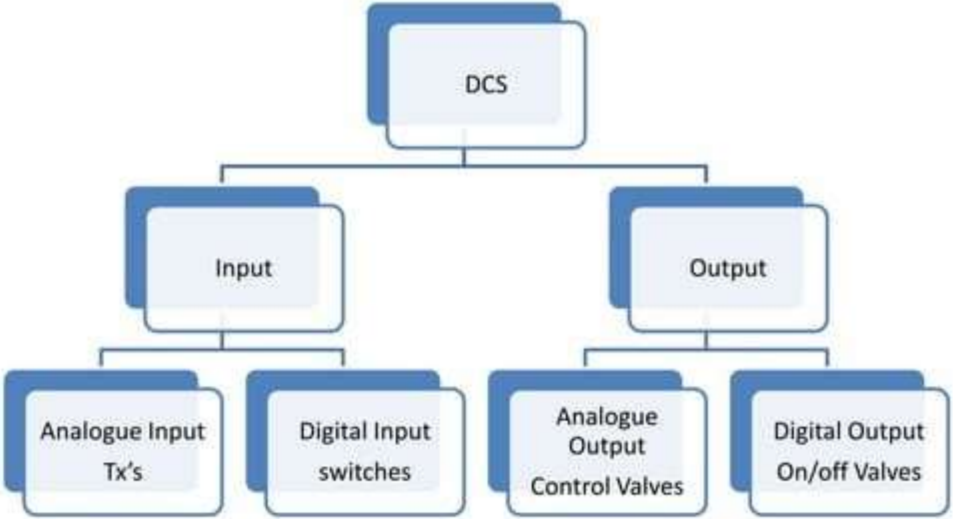
Fault tolerance

- To use more than one component to exclude faulted modules or increase system availability
- 1oo2 , 2oo3

Redundancy

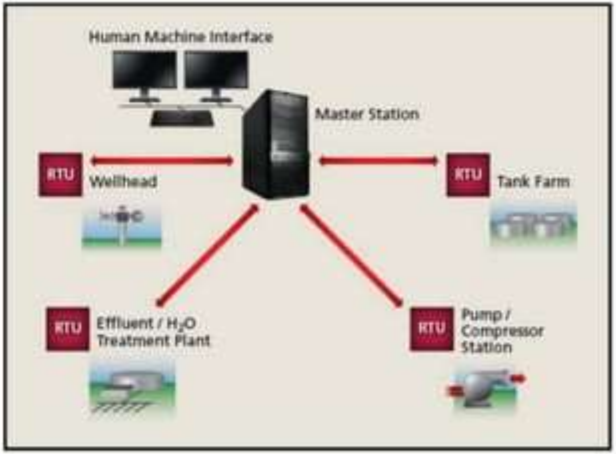

INPUT
BUFFER
CPU
SYNC
CPU
COMP
BUFFER
BUFFER
CPU
SYNC
CPU
COMP
BUFFER
OUTPUT

Types Of interface Cards



SCADA Architecture

Components in the SCADA system include:
Field I/O
Master Station (Human-Machine Interface/HMI)
Remote Station (Remote Terminal Units/RTU)
Communications Network



Field I/O

Field Instrumentation refers to the sensors and actuators that are directly interfaced to the plant or equipment. They generate the analog and digital signals that will be monitored by the Remote Station.

Signals are also conditioned to make sure they are compatible with the inputs/outputs of the RTU or PLC at the Remote Station.

The important characteristic of the remote site is that control loops are independent of the master site. The master site only reads and sends set point changes, while the actual feedback control is performed by the controllers at the remote site.

Master Station

The Central Monitoring Station (CMS) is the master unit of the SCADA system. It is in charge of collecting information gathered by the remote stations and of generating necessary action for any event detected. The CMS can have a single computer configuration or it can be networked to workstations to allow sharing of information from the SCADA system.

Remote Station

Field instrumentation connected to the plant or equipment being monitored and controlled are interfaced to the Remote Station to allow process manipulation at a remote site. It is also used to gather data from the equipment and transfer them to the central SCADA system. The Remote Station may either be an RTU (Remote Terminal Unit) or a PLC (Programmable Logic Controller). It may also be a single board or modular unit.

The RTU (Remote Terminal Unit) is a rugged computer with very good radio interfacing. It is used in situations where communications are more difficult. One disadvantage of the RTU is its poor programmability. However, modern RTUs are now offering good programmability comparable to PLCs.

Communications Network

The Communication Network refers to the communication equipment needed to transfer data to and from different sites. The medium used can either be internet, cable, telephone, satellite, or radio.