



*Technical Information that Works*

**Presents**

Practical  
**Instrumentation for Automation  
and Process Control**

for Engineers and Technicians

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- Practical On-line Analytical Instrumentation for Engineers and Technicians
- Practical Flow Measurement for Engineers and Technicians
- Practical Intrinsic Safety for Engineers and Technicians
- Practical Safety Instrumentation and Shut-down Systems for Industry
- Practical Process Control for Engineers and Technicians
- Practical Programming for Industrial Control – using (IEC 1131-3;OPC)
- Practical SCADA Systems for Industry
- Practical Boiler Control and Instrumentation for Engineers and Technicians
- Practical Process Instrumentation for Engineers and Technicians
- Practical Motion Control for Engineers and Technicians
- Practical Communications, SCADA & PLC's for Managers

### Communications

- Practical Data Communications for Engineers and Technicians
- Practical Essentials of SNMP Network Management
- Practical FieldBus and Device Networks for Engineers and Technicians
- Practical Industrial Communication Protocols
- Practical Fibre Optics for Engineers and Technicians
- Practical Industrial Networking for Engineers and Technicians
- Practical TCP/IP & Ethernet Networking for Industry
- Practical Telecommunications for Engineers and Technicians
- Practical Radio & Telemetry Systems for Industry
- Practical Local Area Networks for Engineers and Technicians
- Practical Mobile Radio Systems for Industry

### Electrical

- Practical Power Systems Protection for Engineers and Technicians
- Practical High Voltage Safety Operating Procedures for Engineers & Technicians
- Practical Solutions to Power Quality Problems for Engineers and Technicians
- Practical Communications and Automation for Electrical Networks
- Practical Power Distribution
- Practical Variable Speed Drives for Instrumentation and Control Systems

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- Practical Project Management for Engineers and Technicians
- Practical Financial Management and Project Investment Analysis
- How to Manage Consultants

### Mechanical Engineering

- Practical Boiler Plant Operation and Management for Engineers and Technicians
- Practical Centrifugal Pumps – Efficient use for Safety & Reliability

### Electronics

- Practical Digital Signal Processing Systems for Engineers and Technicians
- Practical Industrial Electronics Workshop
- Practical Image Processing and Applications
- Practical EMC and EMI Control for Engineers and Technicians

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- Personal Computer & Network Security (Protect from Hackers, Crackers & Viruses)
- Practical Guide to MCSE Certification
- Practical Application Development for Web Based SCADA

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On-site training is a cost effective method of training for companies with many delegates to train in a particular area. Organizations can save valuable training \$\$\$'s by holding courses on-site, where costs are significantly less. Other benefits are IDC's ability to focus on particular systems and equipment so that attendees obtain only the greatest benefits from the training.

All on-site workshops are tailored to meet with clients training requirements and courses can be presented at beginners, intermediate or advanced levels based on the knowledge and experience of delegates in attendance. Specific areas of interest to the client can also be covered in more detail.

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# Contents

Preface

*xi*

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Basic measurements and control concepts	1
1.2	Basic measurement performance terms and specifications	2
1.3	Advanced measurement performance terms and specifications	3
1.4	Definition of terminology	6
1.5	Process and Instrumentation Diagram symbols	8
1.6	Effects of selection criteria	11
1.7	Measuring instruments and control valves as part of the overall control system	22
1.8	Typical applications	23
<b>2</b>	<b>Pressure Management</b>	<b>25</b>
2.1	Principles of pressure management	25
2.2	Pressure sources	26
2.3	Pressure transducers and elements – mechanical	28
2.4	Pressure transducers and elements – electrical	38
2.5	Installation considerations	44
2.6	Impact on the overall control loop	47
2.7	Selection tables	48
2.8	Future technologies	50
<b>3</b>	<b>Level Measurement</b>	<b>51</b>
3.1	Principles of level measurement	51
3.2	Simple sight glasses and gauging rods	52
3.3	Buoyancy type	54
3.4	Hydrostatic pressure	56
3.5	Ultrasonic measurement	65
3.6	Radar measurement	70
3.7	Vibration switches	71
3.8	Radiation measurement	72
3.9	Electrical measurement	78
3.10	Density measurement	89
3.11	Installation considerations	91
3.12	Impact on the overall control loop	91
3.13	Selection tables	93
3.14	Future technologies	95



<b>4</b>	<b>Temperature Measurement</b>	<b>97</b>
4.1	Principles of temperature measurement	97
4.2	Thermocouples	98
4.3	Resistance Temperature Detectors	110
4.4	Thermistors	118
4.5	Liquid-in-glass, filled, bimetallic	122
4.6	Non contact pyrometers	130
4.7	Humidity	133
4.8	Installation considerations	135
4.9	Impact on the overall control loop	136
4.10	Selection tables	137
4.11	Future technologies	139
<b>5</b>	<b>Flow Measurement</b>	<b>141</b>
5.1	Principles of flow measurement	141
5.2	Differential pressure flowmeters	146
5.3	Open channel flow measurement	160
5.4	Variable area flowmeters	165
5.5	Oscillatory flow measurement	167
5.6	Magnetic flowmeters	179
5.7	Positive displacement	185
5.8	Ultrasonic flow measurement	189
5.9	Mass flow meters	192
5.10	Installation considerations	198
5.11	Impact on overall control loop	199
5.12	Selection tables	201
5.13	Future technologies	202
<b>6</b>	<b>Control Valves</b>	<b>205</b>
6.1	Principles of control valves	205
6.2	Sliding stem valves	206
6.3	Rotary valves	220
6.4	Control valve selection and sizing	225
6.5	Control valve characteristics/trim	228
6.6	Control valve noise and cavitation	234
6.7	Actuators and positioners operation	237
6.8	Valve benchset and stroking	241
6.9	Impact on the overall control loop	242
6.10	Selection tables	243
6.11	Future technologies	244
<b>7</b>	<b>Other Process Considerations</b>	<b>247</b>
7.1	The new smart instrument and field bus	247
7.2	Noise and earthing considerations	253
7.3	Materials of construction	263
7.4	Linearisation	264
<b>8</b>	<b>Integration of the System</b>	<b>267</b>
8.1	Calculation of individual instruments and total error for the system	267
8.2	Selection considerations	270
8.3	Testing and commissioning of the subsystems	273

8.4	Linearisation	264
-----	---------------	-----

9	Weightometers	277
9.1	Introduction	277
9.2	Weightometers	284
9.3	Calibrating and testing weightometers	289
9.4	Operator checks	293
9.5	Other types of weightometers and weighing systems	294
9.6	Electrical disturbances for weighing systems	304
Appendix A	Thermocouple Tables	307
Appendix B	Process Instrumentation Practical Exercises	383
Appendix C	Ultrasonic Level Measurement	405
Appendix D	Multiple Choice Questions	443
Appendix E	Practical Exercises for Equipment Kit A	449
Appendix F	Practical Exercises for Equipment Kit B	493



# Preface

This workshop and accompanying manual is intended for engineers and technicians who need to have a practical knowledge for selecting and implementing industrial instrumentation systems and control valves. It can be argued that a clear understanding and application of the instrumentation and control valves systems is the most important factor in an efficient and successful control system.

The objectives of the workshop and manual are for you to be able to:

- Specify and design instrumentation systems.
- Correctly select and size control valves for industrial use.
- Understand the problems with installing measurement equipment.
- Troubleshoot instrumentation systems and control valves.
- Isolate and rectify instrumentation faults.
- Understand most of the major technologies used for instrumentation and control valves.

The chapters are broken down as follows:

## **Chapter 1 Introduction**

This gives an overview of basic measurement terms and concepts. A review is given of process and instrumentation diagram symbols and places instrumentation and valves in the context of a complete control system.

## **Chapter 2 Pressure Measurement**

This section commences with a review of the basic terms of pressure measurement and moves onto pressure sources. The various pressure transducers and elements are discussed with reference to installation considerations.

## **Chapter 3 Level Measurement**

The principles of level measurement are reviewed and the various techniques examined ranging from simple sight glasses to density measurement. Installation considerations are again discussed.

## **Chapter 4 Temperature Measurement**

The principles of temperature measurement are discussed and the various transducers examined ranging from thermocouples to non-contact pyrometers. Installation and impact on the overall loop are also briefly discussed.

## **Chapter 5 Flow Measurement**

Initially the basic principles of flow measurement are discussed and then each technique is examined. This ranges from differential pressure flowmeters to mass flow meters. The installation aspects are also reviewed.

## **Chapter 6 Control Valves**

The principles of control valves are initially reviewed. Various types of valves ranging from sliding stem valves to rotary valves are also discussed. Control valve selection and sizing, characteristics and trim are also examined. The important issues of cavitation and noise are reviewed. Installation considerations are noted.

## **Chapter 7 Other Process Considerations**

The new technologies of smart instruments and FieldBus are discussed. The important issues of noise and interference are then examined.

## **Chapter 8 Integration of the System**

Issues such as calculation of individual instruments error and total error are reviewed. A final summary of the selection considerations for instrumentation systems is discussed. The chapter is completed with a summary of testing and commissioning issues.

A set of Appendices is included to support the material contained in the manual. These include:

- Appendix A Thermocouple Tables**
- Appendix B RTD Tables**
- Appendix C Extracts from Supplier Specifications**
- Appendix D Chemical Resistance Chart**
- Appendix E Practical Sessions**

### ***Bibliography***

A detailed bibliography at the end of the manual gives additional reading on the subject.

# 1 Introduction

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# Chapter 1

## Introduction

In a time of constant and rapid technological development, it would be quite ambitious to develop and present a course that claimed to cover each and every industrial measuring type of equipment. This course is not intended to be an encyclopaedia of instrumentation and control valves, but rather a training guide for gaining experience in this fast changing environment.

This course is aimed at providing engineers, technicians and any other personnel involved with process measurement, more experience in that field. It is also designed to give students the fundamentals on analysing the process requirements and selecting suitable solutions for their applications.

### 1.1 Basic Measurement and Control Concepts

The basic set of units used on this course is the SI unit system. This can be summarised in the following table 1.1

Quantity	Unit	Abbreviation
Length	metre	m
Mass	kilogram	kg
Time	second	s
Current	ampere	A
Temperature	degree Kelvin	°K
Voltage	volt	V
Resistance	ohm	Ω
Capacitance	farad	F
Inductance	henry	H
Energy	joule	J
Power	watt	W
Frequency	hertz	Hz
Charge	coulomb	C
Force	newton	N
Magnetic Flux	weber	Wb
Magnetic Flux Density	webers/metre <sup>2</sup>	Wb/m <sup>2</sup>

**Table 1.1**  
**SI Units.**



## 1.2 Basic Measurement Performance Terms and Specifications

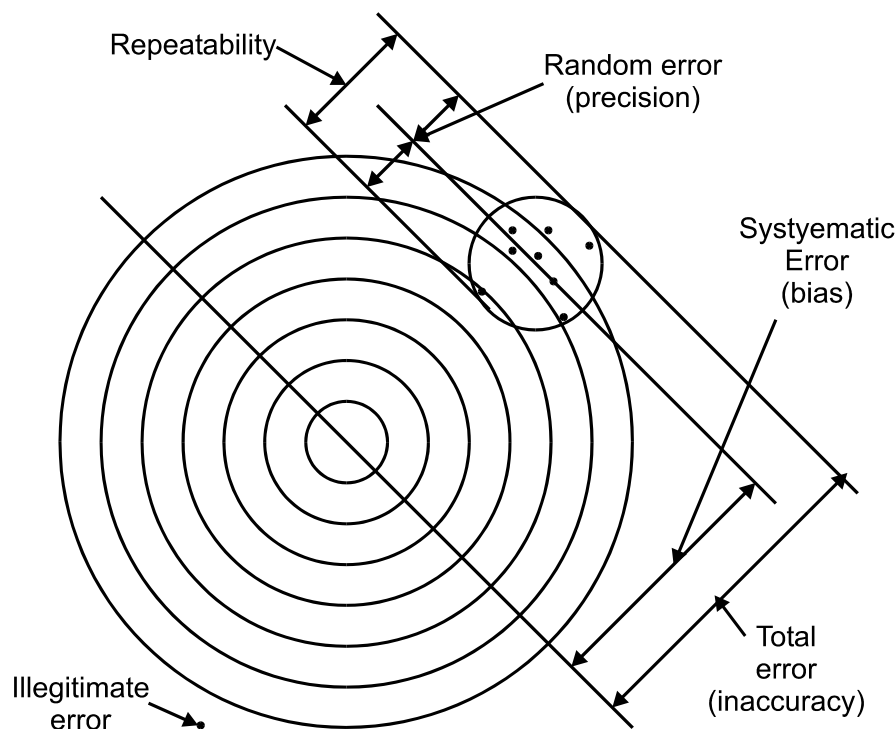
There are a number of criteria that must be satisfied when specifying process measurement equipment. Below is a list of the more important specifications.

### 1.2.1 Accuracy

The accuracy specified by a device is the amount of error that may occur when measurements are taken. It determines how precise or correct the measurements are to the actual value and is used to determine the suitability of the measuring equipment.

Accuracy can be expressed as any of the following:

- error in units of the measured value
- percent of span
- percent of upper range value
- percent of scale length
- percent of actual output value



**Figure 1.1**  
**Accuracy Terminology.**

Accuracy generally contains the total error in the measurement and accounts for linearity, hysteresis and repeatability.

Reference accuracy is determined at reference conditions, ie. constant ambient temperature, static pressure, and supply voltage. There is also no allowance for drift over time.

### 1.2.2 *Range of Operation*

The range of operation defines the high and low operating limits between which the device will operate correctly, and at which the other specifications are guaranteed. Operation outside of this range can result in excessive errors, equipment malfunction and even permanent damage or failure.

### 1.2.3 *Budget/Cost*

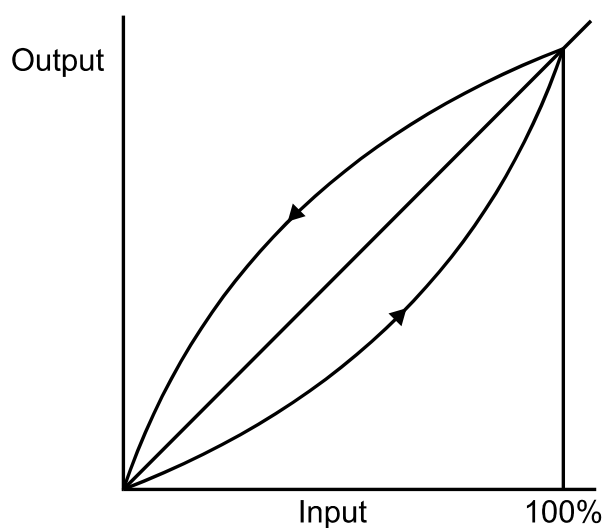
Although not so much a specification, the cost of the equipment is certainly a selection consideration. This is generally dictated by the budget allocated for the application. Even if all the other specifications are met, this can prove an inhibiting factor.

## 1.3 **Advanced Measurement Performance Terms and Specifications**

More critical control applications may be affected by different response characteristics. In these circumstances the following may need to be considered:

### 1.3.1 *Hysteresis*

This is where the accuracy of the device is dependent on the previous value and the direction of variation. Hysteresis causes a device to show an inaccuracy from the correct value, as it is affected by the previous measurement.

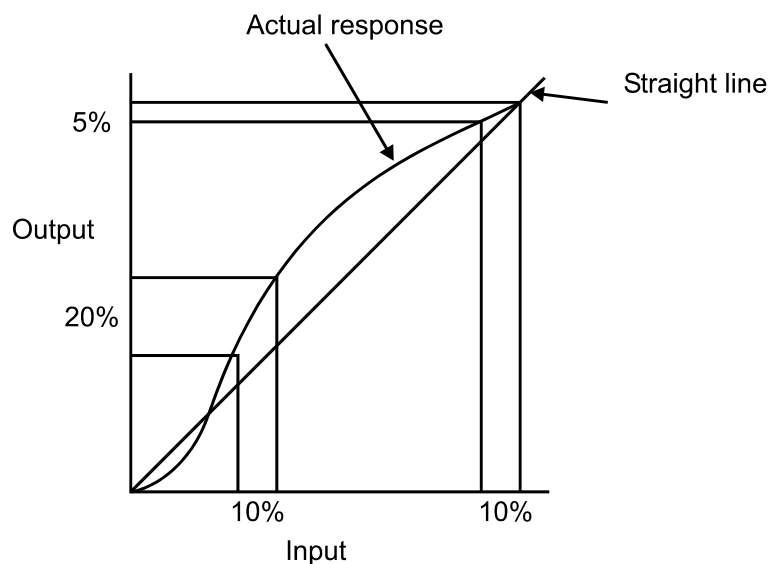


**Figure 1.2**  
**Hysteresis.**

### 1.3.2 Linearity

Linearity is how close a curve is to a straight line. The response of an instrument to changes in the measured medium can be graphed to give a response curve. Problems can arise if the response is not linear, especially for continuous control applications. Problems can also occur in point control as the resolution varies depending on the value being measured.

Linearity expresses the deviation of the actual reading from a straight line. For continuous control applications, the problems arise due to the changes in the rate the output differs from the instrument. The gain of a non-linear device changes as the change in output over input varies. In a closed loop system changes in gain affect the loop dynamics. In such an application, the linearity needs to be assessed. If a problem does exist, then the signal needs to be linearised.

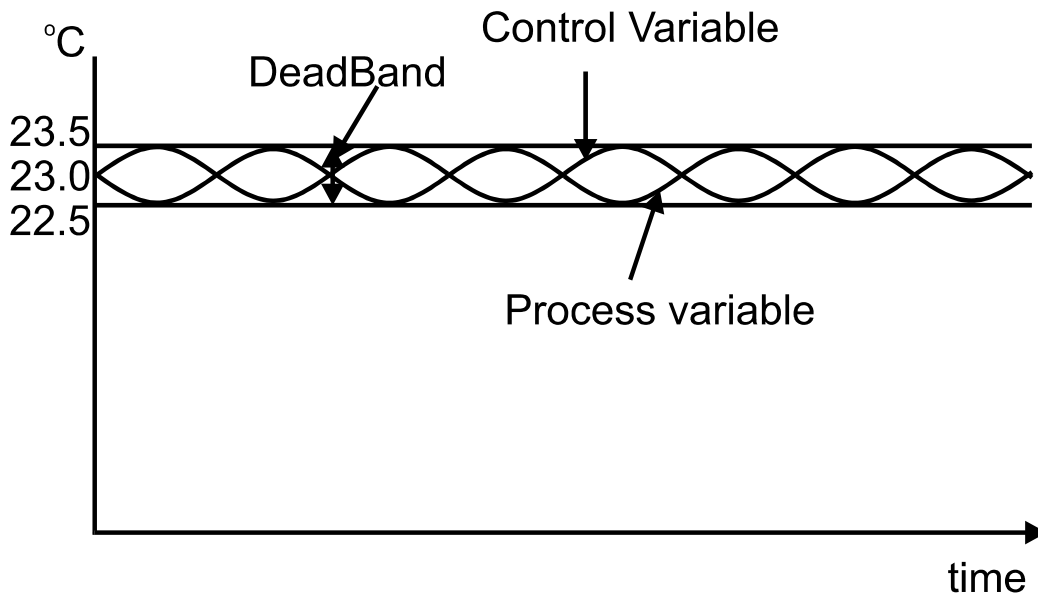


**Figure 1.3**  
**Linearity.**

### 1.3.3 Repeatability

Repeatability defines how close a second measurement is to the first under the same operating conditions, and for the same input. Repeatability is generally within the accuracy range of a device and is different from hysteresis in that the operating direction and conditions must be the same.

Continuous control applications can be affected by variations due to repeatability. When a control system sees a change in the parameter it is controlling, it will adjust its output accordingly. However if the change is due to the repeatability of the measuring device, then the controller will over-control. This problem can be overcome by using the deadband in the controller; however repeatability becomes a problem when an accuracy of say, 0.1% is required, and a repeatability of 0.5% is present.

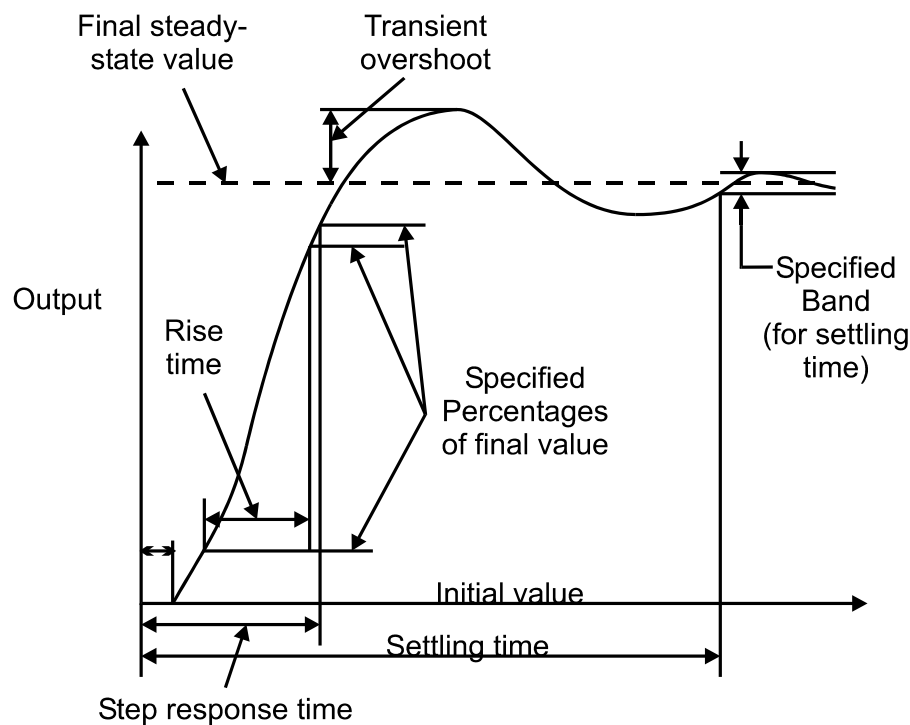


**Figure 1.4**  
**Repeatability.**

Ripples or small oscillations can occur due to overcontrolling. This needs to be accounted for in the initial specification of allowable values.

#### **1.3.4 Response**

When the output of a device is expressed as a function of time (due to an applied input) the time taken to respond can provide critical information about the suitability of the device. A slow responding device may not be suitable for an application. This typically applies to continuous control applications where the response of the device becomes a dynamic response characteristic of the overall control loop. However in critical alarming applications where devices are used for point measurement, the response may be just as important.



**Figure 1.5**  
*Typical time response for a system with a step input.*

## 1.4 Definition of Terminology

Below is a list of terms and their definitions that are used throughout this manual.

### ***Accuracy***

How precise or correct the measured value is to the actual value. Accuracy is an indication of the error in the measurement.

### ***Ambient***

The surrounds or environment in reference to a particular point or object.

### ***Attenuation***

A decrease in signal magnitude over a period of time.

### ***Calibrate***

To configure a device so that the required output represents (to a defined degree of accuracy) the respective input.

### ***Closed loop***

Relates to a control loop where the process variable is used to calculate the controller output.

***Coefficient, temperature***

A coefficient is typically a multiplying factor. The temperature coefficient defines how much change in temperature there is for a given change in resistance (for a temperature dependent resistor).

***Cold junction***

The thermocouple junction which is at a known reference temperature.

***Compensation***

A supplementary device used to correct errors due to variations in operating conditions.

***Controller***

A device which operates automatically to regulate the control of a process with a control variable.

***Elastic***

The ability of an object to regain its original shape when an applied force is removed. When a force is applied that exceeds the elastic limit, then permanent deformation will occur.

***Excitation***

The energy supply required to power a device for its intended operation.

***Gain***

This is the ratio of the change of the output to the change in the applied input. Gain is a special case of sensitivity, where the units for the input and output are identical and the gain is unitless.

***Hunting***

Generally an undesirable oscillation at or near the required setpoint. Hunting typically occurs when the demands on the system performance are high and possibly exceed the system capabilities. The output of the controller can be overcontrolled due to the resolution of accuracy limitations.

***Hysteresis***

The accuracy of the device is dependent on the previous value and the direction of variation. Hysteresis causes a device to show an inaccuracy from the correct value, as it is affected by the previous measurement.

***Ramp***

Defines the delayed and accumulated response of the output for a sudden change in the input.

***Range***

The region between the specified upper and lower limits where a value or device is defined and operated.

***Reliability***

The probability that a device will perform within its specifications for the number of operations or time period specified.

***Repeatability***

The closeness of repeated samples under exact operating conditions.

***Reproducibility***

The similarity of one measurement to another over time, where the operating conditions have varied within the time span, but the input is restored.

***Resolution***

The smallest interval that can be identified as a measurement varies.

***Resonance***

The frequency of oscillation that is maintained due to the natural dynamics of the system.

***Response***

Defines the behaviour over time of the output as a function of the input. The output is the response or effect, with the input usually noted as the cause.

***Self Heating***

The internal heating caused within a device due to the electrical excitation. Self-heating is primarily due to the current draw and not the voltage applied, and is typically shown by the voltage drop as a result of power ( $I^2R$ ) losses.

***Sensitivity***

This defines how much the output changes, for a specified change in the input to the device.

***Setpoint***

Used in closed loop control, the setpoint is the ideal process variable. It is represented in the units of the process variable and is used by the controller to determine the output to the process.

***Span Adjustment***

The difference between the maximum and minimum range values. When provided in an instrument, this changes the slope of the input-output curve.

***Steady state***

Used in closed loop control where the process no longer oscillates or changes and settles at some defined value.

***Stiction***

Shortened form of static friction, and defined as resistance to motion. More important is the force required (electrical or mechanical) to overcome such a resistance.

***Stiffness***

This is a measure of the force required to cause a deflection of an elastic object.

***Thermal shock***

An abrupt temperature change applied to an object or device.

***Time constant***

Typically a unit of measure which defines the response of a device or system. The time constant of a first order system is defined as the time taken for the output to reach 63.2% of the total change, when subjected to a step input change.

***Transducer***

An element or device that converts information from one form (usually physical, such as temperature or pressure) and converts it to another ( usually electrical, such as volts or millivolts or resistance change). A transducer can be considered to comprise a sensor at the front end (at the process) and a transmitter.

***Transient***

A sudden change in a variable which is neither a controlled response nor long lasting.

***Transmitter***

A device that converts from one form of energy to another. Usually from electrical to electrical for the purpose of signal integrity for transmission over longer distances and for suitability with control equipment.

***Variable***

Generally, this is some quantity of the system or process. The two main types of variables that exist in the system are the measured variable and the controlled variable. The measured variable is the measured quantity and is also referred to as the process variable as it measures process information. The controlled variable is the controller output which controls the process.

***Vibration***

This is the periodic motion (mechanical) or oscillation of an object.

***Zero adjustment***

The zero in an instrument is the output provided when no, or zero input is applied. The zero adjustment produces a parallel shift in the input-output curve.



## 1.5 P&ID (Process and Instrumentation Diagram) Symbols

Graphical symbols and identifying letters for Process measurement and control functions are listed below:

<b>First letter</b>		<b>Second letter</b>
A	Analysis	Alarm
B	Burner	
C	Conductivity	Control
D	Density	
E	Voltage	Primary element
F	Flow	
G	Gauging	Glass (sight tube)
H	Hand	
I	Current (electric)	Indicate
J	Power	
K	Time	Control station
L	Level	Light
M	Moisture	
O		Orifice
P	Pressure	Point
Q	Quantity	
R	Radioactivity	Record
S	Speed	Switch
T	Temperature	Transmit
U	Multivariable	Multifunction
V	Viscosity	Valve
W	Weight	Well
Y		Relay (transformation)
Z	Position	Drive

Some of the typical symbols used are indicated in the figures below.

Instrument Representation on Flow Diagrams

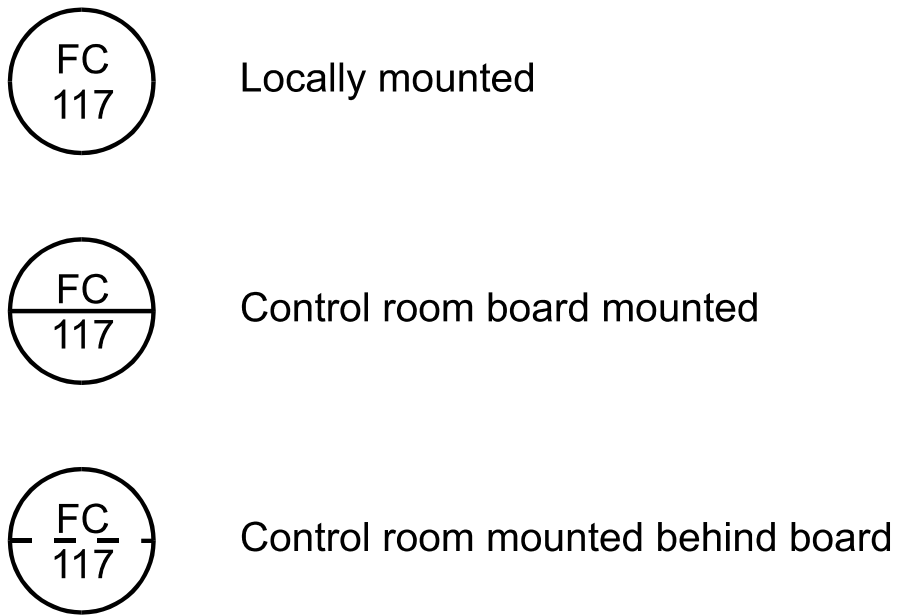
	Central Control Room		Auxillary Location		
	Accessible to Operator	Behind the panel or otherwise inaccessible to Operator	Accessible to Operator	Behind the panel or otherwise inaccessible to Operator	Feild Mounted Instrument
Discrete Instruments					
Shared Hardware Shared Display, Shared Control					
Software Computer Function					
Shared Logic Programmable Logic Control					

**Figure 1.6**  
*Instrument representation on flow diagrams (a).*

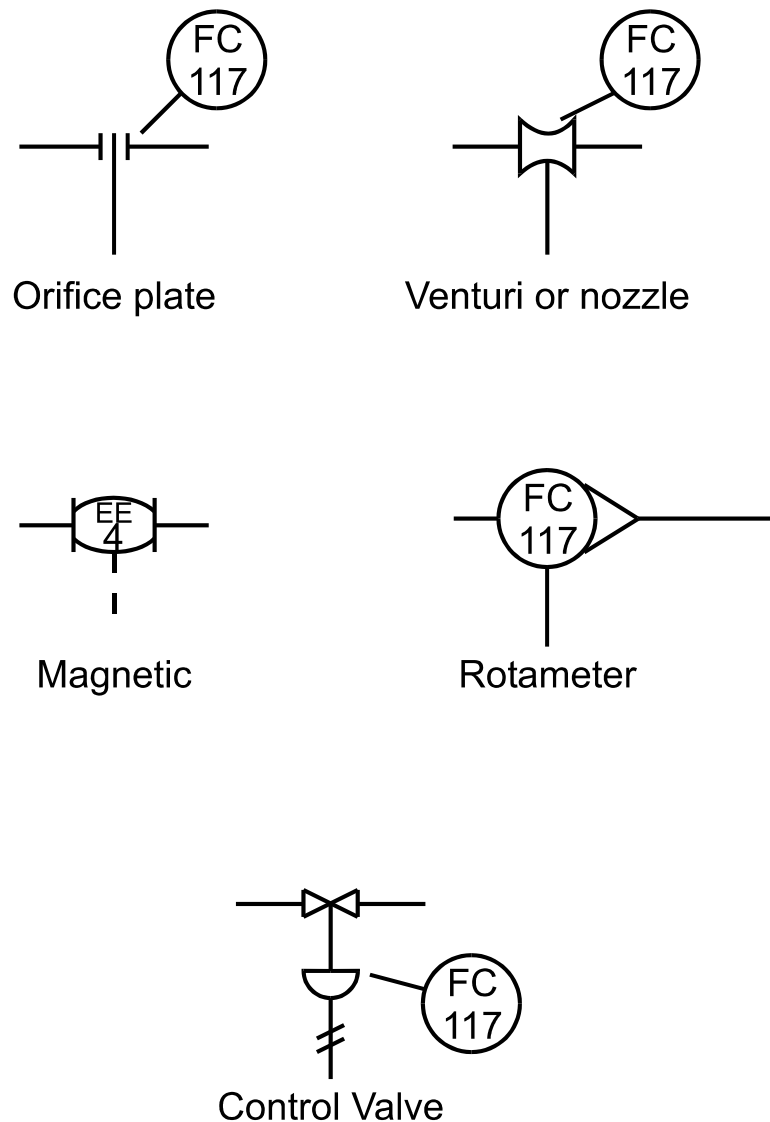
Instrument Line Symbols

- } Undefined Signal
- Pneumatic Signal
- Electric Signal
- Capillary Tubing (filled system)
- Hydraulic Signal

**Figure 1.7**  
*Instrument representation on flow diagrams (b)*



*Figure 1.8*  
*Letter codes and balloon symbols*



**Figure 1.9**  
*P&ID symbols for transducers and other elements.*

## 1.6 Effects of Selection Criteria

### 1.6.1 Advantages

#### Wide operating range

The range of operation not only determines the suitability of the device for a particular application, but can be chosen for a range of applications. This can reduce the inventory in a plant as the number of sensors and models decrease. This also increases system reliability as sensing equipment can be interchanged as the need arises.

An increased operating range also gives greater over and under-range protection, should the process perform outside of specifications.

Widening the operating range of the sensing equipment may be at the expense of resolution. Precautions also need to be made when changing the range of existing equipment. In the case of control systems, the dynamics of the control loop can be affected.

### ***Fast Response***

With a fast response, delays are not added into the system. In the case of continuous control, lags can accumulate with the various control components and result in poor or slow control of the process. In a point or alarming application, a fast speed of response can assist in triggering safety or shutdown procedures that can reduce the amount of equipment failure or product lost.

Often a fast response is achieved by sacrificing the mechanical protection of the transducer element.

### ***Good Sensitivity***

Improved sensitivity of a device means that more accurate measurements are possible. The sensitivity also defines the magnitude of change that occurs. High sensitivity in the measuring equipment means that the signal is easily read by a controller or other equipment.

### ***High Accuracy***

This is probably one of the most important selection criteria. The accuracy determines the suitability of the measuring equipment to the application, and is often a trade off with cost.

High accuracy means reduced errors in measurement; this also can improve the integrity and performance of a system.

### ***High Overrange Protection***

This is more a physical limitation on the protection of the equipment. In applications where the operating conditions are uncertain or prone to failure, it is good practice to 'build-in' suitable protection for the measuring equipment.

High overrange protection is different to having a wide operating range in that it does not measure when out of range. The range is kept small to allow sufficient resolution, with the overrange protection ensuring a longer operating life.

### ***Simple Design and Maintenance***

A simple design means that there are less "bits that can break". More robust designs are generally of simple manufacture.

Maintenance is reduced with less pieces to wear, replace or assemble. There are also savings in the time it takes to service, repair and replace, with the associated procedures being simplified.

**Cost**

Any application that requires a control solution or the interrogation of process information is driven by a budget. It therefore is no surprise that cost is an important selection criteria when choosing measurement equipment.

The cost of a device is generally increased by improvements in the following specifications:

- Accuracy
- Range of operation
- Operating environment (high temperature, pressure etc.)

The technology used and materials of construction do affect the cost, but are generally chosen based on the improvement of the other selection criteria (typically those listed above).

**Repeatability**

Good repeatability ensures measurements vary according to process changes and not due to the limitations of the sensing equipment. An error can still exist in the measurement, which is defined by the accuracy. However tighter control is still possible as the variations are minimised and the error can be overcome with a deadband.

**Size**

This mainly applies to applications requiring specifically sized devices and has a bearing on the cost.

Small devices have the added advantage of:

- Can be placed in tight spaces
- Limited obstruction to the process
- Very accurate location of the measurement required (point measurement)

Large devices have the added advantage of:

- Area measurements

**Stable**

If a device drifts or loses calibration over time then it is considered to be unstable. Drifting can occur over time, or on repeated operation of the device. In the case of thermocouples, it has been proven that drift is more extreme when the thermocouple is varied over a wide range quite often, typically in furnaces that are repeatedly heated to high temperatures from the ambient temperature.

Even though a device can be recalibrated, there are a number of factors that make it undesirable:

- Labour required
- Possible shutdown of process for access
- Accessibility

### ***Resolution***

Whereas the accuracy defines how close the measurement is to the actual value, the resolution is the smallest measurable difference between two consecutive measurements.

The resolution defines how much detail is in the measured value. The control or alarming is limited by the resolution.

### ***Robust***

This has the obvious advantage of being able to handle adverse conditions. However this can have the added limitation of bulk.

### ***Self Generated Signal***

This eliminates the need for supplying power to the device.

Most sensing devices are quite sensitive to electrical power variations, and therefore if power is required it generally needs to be conditioned.

### ***Temperature Corrected***

Ambient temperature variations often affect measuring devices. Temperature correction eliminates the problems associated with these changes.

### ***Intrinsic Safety***

Required for specific service applications. This requirement is typically used in environments where electrical or thermal energy can ignite the atmospheric mixture.

### ***Simple to Adjust***

This relates to the accessibility of the device. Helpful if the application is not proven and constant adjustments and alterations are required.

A typical application may be the transducer for ultrasonic level measurement. It is not uncommon to weld in brackets for mounting, only to find the transducer needs to be relocated.

### ***Suitable for Various Materials***

Selecting a device that is suitable for various materials not only ensures the suitability of the device for a particular application, but can it to be used for a range of applications. This can reduce the inventory in a plant as the number of sensors

and models are decreased. This also increases system reliability as sensing equipment can be interchanged as the need arises.

### ***Non Contact***

This is usually a requirement based on the type of material being sensed. Non-contact sensing is used in applications where the material causes build-up on the probe or sensing devices. Other applications are where the conditions are hazardous to the operation of the equipment. Such conditions may be high temperature, pressure or acidity.

### ***Reliable Performance***

This is an obvious advantage with any sensing device, but generally is at the expense of cost for very reliable and proven equipment. More expensive and reliable devices need to be weighed up against the cost of repair or replacement, and also the cost of loss of production should the device fail. The costs incurred should a device fail, are not only the loss of production (if applicable), but also the labour required to replace the equipment. This also may include travel costs or appropriately certified personnel for hazardous equipment or areas.

### ***Unaffected by Density***

Many applications measure process materials that may have variations in density. Large variations in the density can cause measurement problems unless accounted for. Measuring equipment that is unaffected by density provides a higher accuracy and is more versatile

### ***Unaffected by Moisture Content***

Applies primarily to applications where the moisture content can vary, and where precautions with sensing equipment are required. It is quite common for sensing equipment, especially electrical and capacitance, to be affected by moisture in the material.

The effect of moisture content can cause problems in both cases, ie. when a product goes from a dry state to wet, or when drying out from a wet state.

### ***Unaffected by Conductivity***

The conductivity of a process material can change due to a number of factors, and if not checked can cause erroneous measurements. Some of the factors affecting conductivity are:

- pH
- salinity
- temperature

### ***Mounting External to the Vessel***

This has the same advantages as non-contact sensing. However it is also possible to sense through the container housing, allowing for pressurised sensing. This permits maintenance and installation without affecting the operation of the process.



Another useful advantage with this form of measurement is that the detection obstructions in chutes or product in boxes can be performed unintrusively.

### ***High Pressure Applications***

Equipment that can be used in high pressure applications generally reduces error by not requiring any further transducer devices to retransmit the signal. However the cost is usually greater than an average sensor due to the higher pressure rating.

This is more a criteria that determines the suitability of the device for the application.

### ***High Temperature Applications***

This is very similar to the advantages of high pressure applications, and also determines the suitability of the device for the application.

### ***Dual Point Control***

This mainly applies to point control devices. With one device measuring two or even three process points, ON-OFF control can be performed simply with the one device. This is quite common in level control. This type of sensing also limits the number of tapping points required into the process.

### ***Polarity Insensitive***

Sensing equipment that is polarity insensitive generally protects against failure from incorrect installation.

### ***Small Spot or Area Sensing***

Selecting instrumentation for the specific purpose reduces the problems and errors in averaging multiple sensors over an area, or deducing the spot measurement from a crude reading.

Generally, spot sensing is done with smaller transducers, with area or average sensing being performed with large transducers.

### ***Remote Sensing***

Sensing from afar has the advantage of being non-intrusive and allowing higher temperature and pressure ratings. It can also avoid the problem of mounting and accessibility by locating sensing equipment at a more convenient location.

### ***Well Understood and Proven***

This, more than anything, reduces the stress involved when installing new equipment, both for its reliability and suitability.

### ***No Calibration Required***

Pre-calibrated equipment reduces the labour costs associated with installing new equipment and also the need for expensive calibration equipment.

### ***No Moving Parts***

The advantages are:

- Long operating life
- Reliable operation with no wear or blockages

If the instrument does not have any moving or wearing components, then this provides improved reliability and reduced maintenance.

Maintenance can be further reduced if there are no valves or manifolds to cause leakage problems. The absence of manifolds and valves results in a particularly safe installation; an important consideration when the process fluid is hazardous or toxic.

### ***Complete Unit Consisting of Probe and Mounting***

An integrated unit provides easy mounting and lowers the installation costs, although the cost of the equipment may be slightly higher.

## ***FLOW APPLICATIONS***

### ***Low Pressure Drop***

A device that has a low pressure drop presents less restriction to flow and also has less friction. Friction generates heat, which is to be avoided. Erosion (due to cavitation and flashing) is more likely in high pressure drop applications.

### ***Less Unrecoverable Pressure Drop***

If there are applications that require sufficient pressure downstream of the measuring and control devices, then the pressure drops across these devices needs to be taken into account to determine a suitable head pressure. If the pressure drops are significant, then it may require higher pressures. Equipment of higher pressure ratings (and higher cost) are then required.

Selecting equipment with low pressure losses results in safer operating pressures with a lower operating cost.

### ***High Velocity Applications***

It is possible in high velocity applications to increase the diameter of the section which gives the same quantity of flow, but at a reduced velocity. In these applications, because of the expanding and reducing sections, suitable straight pipe runs need to be arranged for suitable laminar flow.

### ***Operate in Higher Turbulence***

Devices that can operate with a higher level of turbulence are typically suited to applications where there are limited sections of straight length pipe.

### ***Fluids Containing Suspended Solids***

These devices are not prone to mechanical damage due to the solids in suspension, and can also account for the density variations.

***Require Less Straight Pipe Up and Downstream***

This is generally a requirement applied to equipment that can accommodate a higher level of turbulence. However the device may contain straightening vanes which assist in providing laminar flow.

***Price does not Increase Dramatically with Size***

This consideration applies when selecting suitable equipment, and selecting a larger instrument sized for a higher range of operation.

***Good Rangeability***

In cases where the process has considerable variations (in flow for example), and accuracy is important across the entire range of operation, the selecting of equipment with good rangeability is vital.

***Suitable for Very Low Flow Rates***

Very low flow rates provide very little energy (or force) and as such can be a problem with many flow devices. Detection of low flow rates requires particular consideration.

***Unaffected by Viscosity***

The viscosity generally changes with temperature, and even though the equipment may be rated for the range of temperature, problems may occur with the fluidity of the process material.

***No Obstructions***

This primarily means no pressure loss. It is also a useful criteria when avoiding equipment that requires maintenance due to wear, or when using abrasive process fluids.

***Installed on Existing Installations***

This can reduce installation costs, but more importantly can avoid the requirement of having the plant shutdown for the purpose or duration of the installation.

***Suitable for Large Diameter Pipes***

Various technologies do have limitations on pipe diameter, or the cost increases rapidly as the diameter increases.

**1.6.2 *Disadvantages***

The disadvantages are obviously the opposite of the advantages listed previously. The following is a discussion of effects of the disadvantages and reasons for the associated limitations.

***Hysteresis***

Hysteresis can cause significant errors. The errors are dependent on the magnitude of change and the direction of variation in the measurement.

One common cause of hysteresis is thermoelastic strain.

***Linearity***

This affects the resolution over the range of operation. For a unit change in the process conditions, there may be a 2% change at one end of the scale, with a 10% change at the other end of the scale. This change is effectively a change in the sensitivity or gain of the measuring device.

In point measuring applications this can affect the resolution and accuracy over the range. In continuous control applications where the device is included in the control loop, it can affect the dynamic performance of the system.

***Indication Only***

Devices that only perform indication are not suited for automated control systems as the information is not readily accessible. Errors are also more likely and less predictable as they are subject to operator interpretation.

These devices are also generally limited to localised measurement only and are isolated from other control and recording equipment.

***Sensitive to Temperature Variations***

Problems occur when equipment that is temperature sensitive is used in applications where the ambient temperature varies continuously. Although temperature compensation is generally available, these devices should be avoided with such applications.

***Shock and Vibration***

These effects not only cause errors but can reduce the working life of equipment, and cause premature failure.

***Transducer Work Hardened***

The physical movement and operation of a device may cause it to become harder to move. This particularly applies to pressure bellows, but some other devices do have similar problems.

If it is unavoidable to use such equipment, then periodic calibration needs to be considered as a maintenance requirement.

***Poor Overrange Protection***

Care needs to be taken to ensure that the process conditions do not exceed the operating specifications of the measuring equipment. Protection may need to be supplied with additional equipment.

Poor overrange protection in the device may not be a problem if the process is physically incapable of exceeding the operating conditions, even under extreme fault conditions.

***Unstable***

This generally relates to the accuracy of the device over time. However the accuracy can also change due to large variations in the operation of the device due to the process variations. Subsequently, unstable devices require repeated calibration over time or when operated frequently.

***Size***

Often the bulkiness of the equipment is a limitation. In applications requiring area or average measurements then too small a sensing device can be a disadvantage in that it does not “see” the full process value.

***Dynamic Sensing Only***

This mainly applies to shock and acceleration devices where the impact force is significant. Typical applications would involve piezoelectric devices.

***Special Cabling***

Measurement equipment requiring special cabling bears directly on the cost of the application. Another concern with cabling is that of noise and cable routing. Special conditions may also apply to the location of the cable in reference to high voltage, high current, high temperature, and other low power or signal cabling.

***Signal Conditioning***

Primarily used when transmitting signals over longer distances, particularly when the transducer signal requires amplification. This is also a requirement in noisy environments. As with cabling, this bears directly on the cost and also may require extra space for mounting.

***Stray Capacitance Problems***

This mainly applies to capacitive devices where special mounting equipment may be required, depending on the application and process environment.

***Maintenance***

High maintenance equipment increases the labour which become a periodic expense. Some typical maintenance requirements may include the following:

- Cleaning
- Removal/replacement
- Calibration

If the equipment is fragile then there is the risk of it being easily damaged due to repeated handling.

***Sampled Measurement Only***

Measurement equipment that requires periodic sampling of the process (as opposed to continual) generally relies on statistical probability for the accuracy. More pertinent in selecting such devices is the longer response and update times incurred in using such equipment.

Sampled measurement equipment is mainly used for quality control applications where specific samples are required and the quality does not change rapidly.

### ***Pressure Applications***

This applies to applications where the measuring equipment is mounted in a pressurised environment and accessibility is impaired. There are obvious limitations in installing and servicing such equipment. In addition are the procedures and experience required for personnel working in such environments.

### ***Access***

Access to the process and measuring equipment needs to be assessed for the purpose of:

- The initial installation
- Routine maintenance

The initial mounting of the measuring equipment may be remote from the final installation; as such the accessibility of the final location also needs to be considered. This may also have a bearing on the orientation required when mounting equipment.

### ***Requires Compressed Air***

Pneumatic equipment requires compressed air. It is quite common in plants with numerous demands for instrument air to have a common compressor with pneumatic hose supplying the devices.

The cost of the installation is greatly increased if no compressed air is available for such a purpose. More common is the requirement to tap into the existing supply, but this still requires the installation of air lines.

### ***Material Build-up***

Material build-up is primarily related to the type of process material being measured. This can cause significant errors, or degrade the operating efficiency of a device over time. There are a number of ways to avoid or rectify the problems associated with material build-up:

- Regular maintenance
- Location (or relocation) of sensing equipment
- Automated or self cleaning (water sprays)

***Constant Relative Density***

Measurement equipment that relies on a constant density of process material is limited in applications where the density varies. Variations in the density will not affect the continued operation of the equipment, but will cause increased errors in the measurement. A typical example would be level measurement using hydrostatic pressure.

***Radiation***

The use of radioactive materials such as Cobalt or Cesium often gives accurate measurements. However, problems arise from the hazards of using radioactive materials which require special safety measures. Precautions are required when housing such equipment, to ensure that it is suitably enclosed and installation safety requirements are also required for personal safety.

Licensing requirements may also apply with such material.

***Electrolytic Corrosion***

The application of a voltage to measuring equipment can cause chemical corrosion to the sensing transducer, typically a probe. Matching of the process materials and metals used for the housing and sensor can limit the effects; however in extreme mismatches, corrosion is quite rapid.

***Susceptible to Electrical Noise***

In selecting equipment, this should be seen as an extra cost and possibly more equipment or configuration time is required to eliminate noise problems.

***More Expensive to Test and Diagnose***

More difficult and expensive equipment can also require costly test and diagnosis equipment. For 'one-off' applications, this may prove an inhibiting factor. The added expense and availability of specialised services should also be considered.

***Not Easily Interchangeable***

In the event of failure or for inventory purposes, having interchangeable equipment can reduce costs and increase system availability. Any new equipment that is not easily replaced by anything already existing, could require an extra as a spare.

***High Resistance***

Devices that have a high resistance can pick up noise quite easily. Generally high resistance devices require good practice in terms of cable selection and grounding to minimise noise pickup.

***Accuracy Based on Technical Data***

The accuracy of a device can also be dependent on how well the technical data is obtained from the installation and data sheets. Applications requiring such calculations are often subject to interpretation.

***Requires Clean Liquid***

Measuring equipment requiring a clean fluid do so for a number of reasons:

- Constant density of process fluid
- Sensing equipment with holes can become easily clogged
- Solids cause interference with sensing technology

### ***Orientation Dependent***

Depending on the technology used, requirements may be imposed on the orientation when mounting the sensing transducer. This may involve extra work, labour and materials in the initial installation. A typical application for mounting an instrument vertically would be a variable area flowmeter.

### ***Uni-Directional Measurement Only***

This is mainly a disadvantage with flow measurement devices where flow can only be measured in the one direction. Although this may seem like a major limitation, few applications use bi-directional flows.

### ***Not Suitable with Partial Phase Change***

Phase change is where a fluid, due to pressure changes, reverts partly to a gas. This can cause major errors in measurements, as it is effectively a very large change in density.

For those technologies that sense through the process material, the phase change can result in reflections and possibly make the application unmeasurable.

### ***Viscosity Must be Known***

The viscosity of a fluid is gauged by the Reynolds number and does vary with temperature. In applications requiring the swirling of fluids and pressure changes there is usually an operating range of which the fluids viscosity is required to be within.

### ***Limited Life Due to Wear***

Non-critical service applications can afford measuring equipment with a limited operating life, or time to repair. In selecting such devices, consideration needs to be given to the accuracy of the measurement over time.

### ***Mechanical Failure***

Failure of mechanical equipment cannot be avoided; however the effects and consequences can be assessed in determining the suitable technology for the application. Flow is probably the best example of illustrating the problems caused if a measurement transducer should fail. If the device fails, and it is of such a construction that debris may block the line or a valve downstream, then this can make the process inoperative until shutdown and repaired.



***Filters***

There are two main disadvantages with filters:

- Maintenance and cleaning
- Pressure loss across filter

The pressure loss can be a process limitation, but from a control point of view can indicate that the filter is in need of cleaning or replacement.

***Flow Profile***

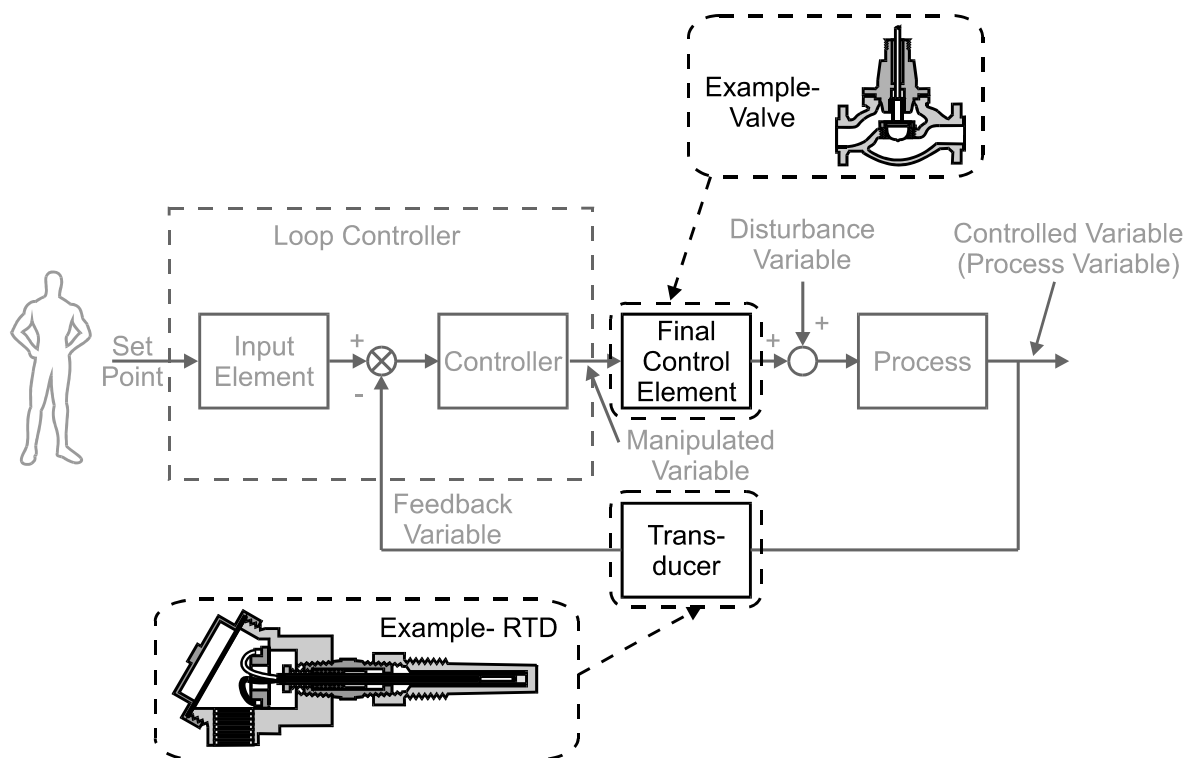
The flow profile may need to be of a significant form for selected measuring equipment. Note that the flow profile is dependent on viscosity and turbulence.

***Acoustically Transparent***

Measuring transducers requiring the reflection of acoustic energy are not suitable where the process material is acoustically transparent. These applications would generally require some contact means of measurement.

## **1.7 Measuring Instruments and Control Valves as part of the Overall Control System**

Below is a diagram outlining how instrument and control valves fit into the overall control system structure. The topic of controllers and tuning forms part of a separate workshop.



**Figure 1.10**  
*Instruments and control valves in the overall control system.*

## 1.8 Typical Applications

Some typical applications are listed below.

### *HVAC (Heating, ventilation and air conditioning) Applications*

- Heat transfer
- Billing
- Axial fans
- Climate control
- Hot and chilled water flows
- Forced air
- Fumehoods
- System balancing
- Pump operation and efficiency

***Petrochemical Applications***

- Co-generation
- Light oils
- Petroleum products
- Steam
- Hydrocarbon vapours
- Flare lines, stacks

***Natural Gas***

- Gas leak detection
- Compressor efficiency
- Fuel gas systems
- Bi-directional flows
- Mainline measurement
- Distribution lines measurement
- Jacket water systems
- Station yard piping

***Power Industry***

- Feed water
- Circulating water
- High pressure heaters
- Fuel oil
- Stacks
- Auxiliary steam lines
- Cooling tower measurement
- Low pressure heaters
- Reheat lines
- Combustion air

***Emissions Monitoring***

- Chemical incinerators
- Trash incinerators
- Refineries
- Stacks and rectangular ducts
- Flare lines

# Tips and Tricks



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# Tips and Tricks



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## **2**

# **Pressure Measurement**

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# Chapter 2

## Pressure Measurement

### 2.1 Principles of Pressure Measurement

#### 2.1.1 Bar and Pascal

Pressure is defined as a force per unit area, and can be measured in units such as psi (pounds per square inch), inches of water, millimetres of mercury, pascals (Pa, or  $\text{N}/\text{m}^2$ ) or bar. Until the introduction of SI units, the 'bar' was quite common.

The bar is equivalent to  $100,000 \text{ N}/\text{m}^2$ , which were the SI units for measurement. To simplify the units, the  $\text{N}/\text{m}^2$  was adopted with the name of Pascal, abbreviated to Pa. Pressure is quite commonly measured in kilopascals (kPa), which is 1000 Pascals and equivalent to 0.145psi.

#### 2.1.2 Absolute, Gauge and Differential Pressure

The Pascal is a means of measuring a quantity of pressure. When the pressure is measured in reference to an absolute vacuum (no atmospheric conditions), then the result will be in Pascal (Absolute). However when the pressure is measured relative to the atmospheric pressure, then the result will be termed Pascal (Gauge). If the gauge is used to measure the difference between two pressures, it then becomes Pascal (Differential).

Note 1: It is common practice to show gauge pressure without specifying the type, and to specify absolute or differential by stating 'absolute' or 'differential' for those pressures.

Note 2: Older measurement equipment may be in terms of psi (pounds per square inch) and as such represent gauge and absolute pressure as psig and psia respectively. Note that the 'g' and 'a' are not recognised in the SI unit symbols, and as such are no longer encouraged.

To determine differential in inches of mercury vacuum multiply psi by 2.036 (or approximately 2). Another common conversion is  $1 \text{ Bar} = 14.7 \text{ psi}$ .



<b>Conversion Factors (Rounded)</b>	
psi x 703.1 = mm/ H <sub>2</sub> O	
psi x 27.68 = in. H <sub>2</sub> O	
psi x 51/71 = mm/ H <sub>2</sub> O	
psi x 2.036 = in.Hg	
psi x .0703 = kg/cm <sup>2</sup>	
psi x .0689 = bar	
psi x 68.95 = mbar	
psi x 6895 = Pa	
psi x 6.895 = kPa	
<b>Note:</b>	psi – pounds per square inch (gauge)
	H <sub>2</sub> O at 39.2° F
	Hg at 32° F

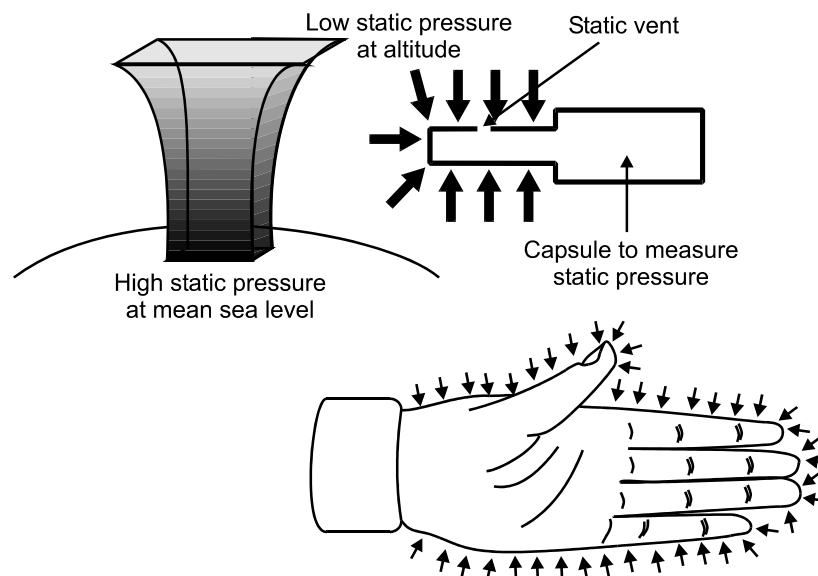
**Table 2.1**  
**Conversion Factors**

## 2.2 Pressure Sources

### 2.2.1 Static Pressure

In the atmosphere at any point, static pressure is exerted equally in all directions. Static pressure is the result of the weight of all the air molecules above that point pressing down.

Static pressure does not involve the relative movement of the air.



**Figure 2.1**  
**Static pressure**

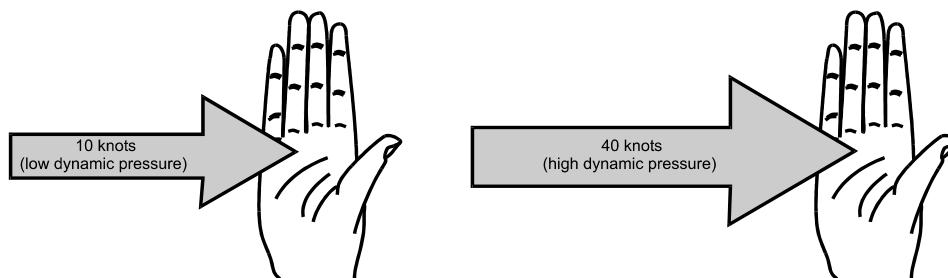
### 2.2.2 Dynamic Pressure

Quite simply, if you hold your hand up in a strong wind or out of the window of a moving car, then the extra wind pressure is felt due to the air impacting your hand.

This extra pressure is over and above the (always-present) static pressure, and is called the dynamic pressure. The dynamic pressure is due to relative movement. Dynamic pressure occurs when a body is moving through the air, or the air is flowing past the body.

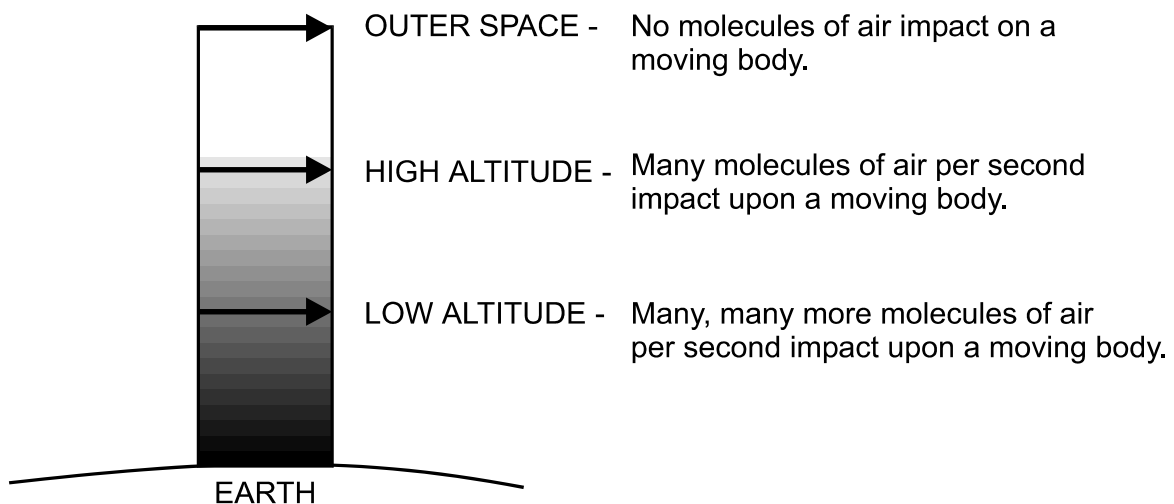
Dynamic pressure is dependent on two factors:

- The speed of the body relative to the flowstream. The faster the car moves or the stronger the wind blows, then the stronger the dynamic pressure that you feel on your hand. This is because of the greater number of air molecules that impact upon it per second.



**Figure 2.2**  
*Dynamic pressure increases with airspeed*

- The density of the air. The dynamic pressure depends also on the density of the air. If the flowrate was the same, and the air was less dense, then there would be less force and consequently a lower dynamic pressure.

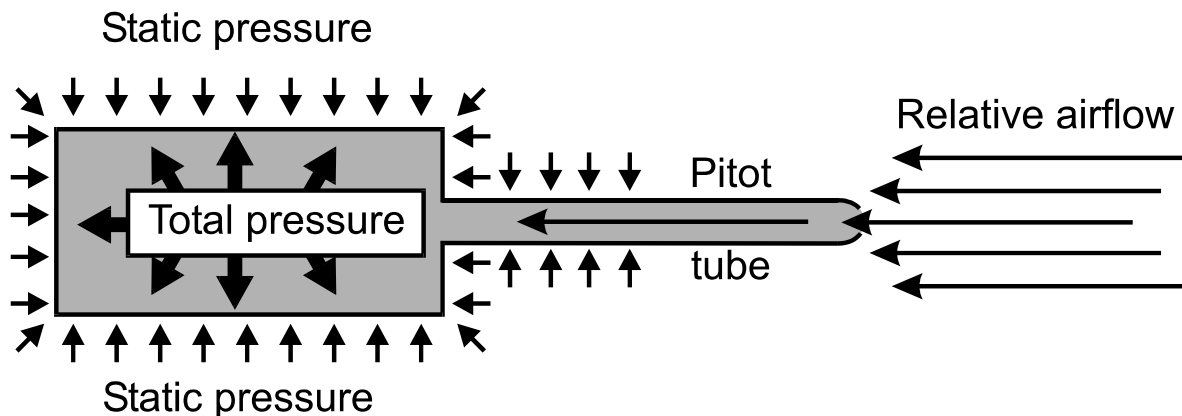


**Figure 2.3**  
*Dynamic pressure depends upon air density*

### 2.2.3 Total Pressure

In the atmosphere, some static pressure is always exerted, but for dynamic pressure to be exerted there must be motion of the body relative to the air. Total pressure is the sum of the static pressure and the dynamic pressure.

Total pressure is also known and referred to as impact pressure, pitot pressure or even ram pressure.



*Figure 2.4*  
Total pressure as measured by a pitot tube

## 2.3 Pressure transducers and elements - Mechanical

- Bourdon tube
- Helix and spiral tubes
- Spring and bellows
- Diaphragm
- Manometer
- Single and Double inverted bell

### 2.3.1 C-Bourdon Tube

The Bourdon tube works on a simple principle that a bent tube will change its shape when exposed to variations of internal and external pressure. As pressure is applied internally, the tube straightens and returns to its original form when the pressure is released.

The tip of the tube moves with the internal pressure change and is easily converted with a pointer onto a scale. A connector link is used to transfer the tip movement to the geared movement sector. The pointer is rotated through a toothed pinion by the geared sector.

This type of gauge may require vertical mounting (orientation dependent) for correct results. The element is subject to shock and vibration, which is also due to the mass of the tube. Because of this and the amount of movement with this type of sensing, they are prone to breakage, particularly at the base of the tube.

The main advantage with the Bourdon tube is that it has a wide operating (depending on the tube material). This type of pressure measurement can be used for positive or negative pressure ranges, although the accuracy is impaired when in a vacuum.

### **Selection and Sizing**

The type of duty is one of the main selection criteria when choosing Bourdon tubes for pressure measurement. For applications which have rapid cycling of the process pressure, such in ON/OFF controlled systems, then the measuring transducer requires an internal snubber. They are also prone to failure in these applications.

Liquid filled devices are one way to reduce the wear and tear on the tube element.

### **Advantages**

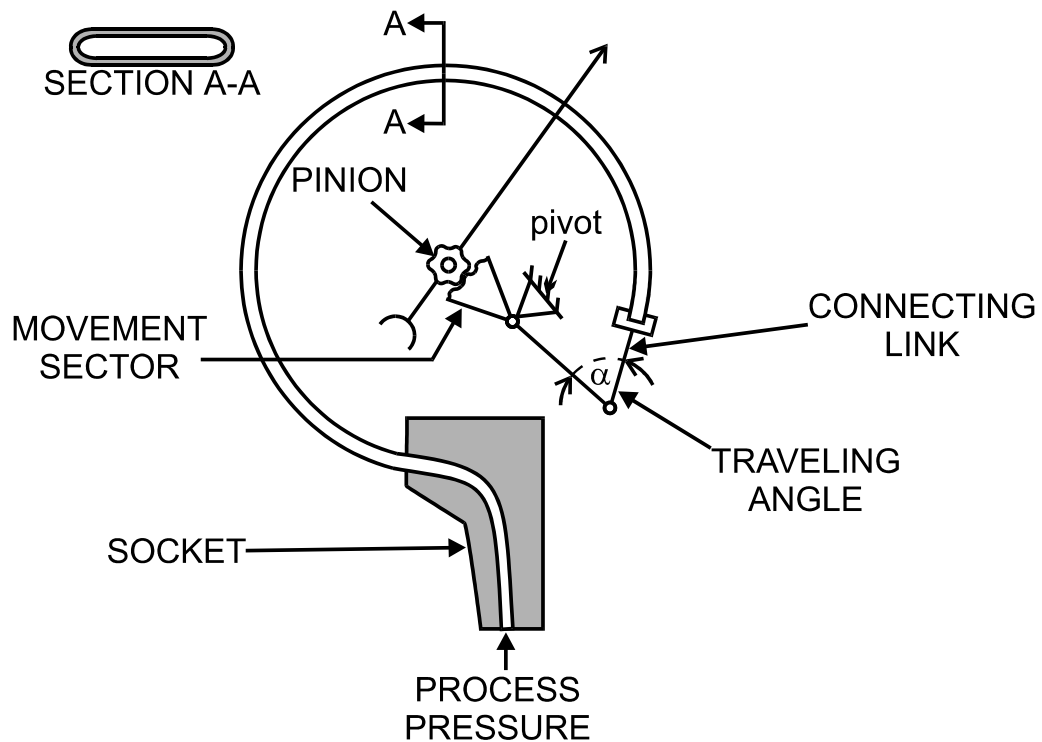
- Inexpensive
- Wide operating range
- Fast response
- Good sensitivity
- Direct pressure measurement

### **Disadvantages**

- Primarily intended for indication only
- Non linear transducer, linearised by gear mechanism
- Hysteresis on cycling
- Sensitive to temperature variations
- Limited life when subject to shock and vibration

### **Application Limitations**

These devices should be used in air if calibrated for air, and in liquid if calibrated for liquid. Special care is required for liquid applications in bleeding air from the liquid lines.



**Figure 2.5**  
**C-Bourdon pressure element**

This type of pressure measurement is limited in applications where there is input shock (a sudden surge of pressure), and in fast moving processes.

If the application is for the use of oxygen, then the device cannot be calibrated using oil. Lower ranges are usually calibrated in air. Higher ranges, usually 1000kPa, are calibrated with a dead weight tester (hydraulic oil).

### 2.3.2 Helix and Spiral Tubes

Helix and spiral tubes are fabricated from tubing into shapes as per their naming. With one end sealed, the pressure exerted on the tube causes the tube to straighten out. The amount of straightening or uncoiling is determined by the pressure applied.

These two approaches use the Bourdon principle. The uncoiling part of the tube is mechanically linked to a pointer which indicates the applied pressure on a scale. This has the added advantage over the C-Bourdon tube as there are no movement losses due to links and levers.

The Spiral tube is suitable for pressure ranges up to 28,000 kPa and the Helical tube for ranges up to 500,000 kPa. The pressure sensing elements vary depending on the range of operating pressure and type of process involved.

The choice of spiral or helical elements is based on the pressure ranges. The pressure level between spiral and helical tubes varies depending on the manufacturer. Low pressure elements have only two or three coils to sense the span of pressures required, however high pressure sensing may require up to 20 coils.

One difference and advantage of these is the dampening they have with fluids under pressure.

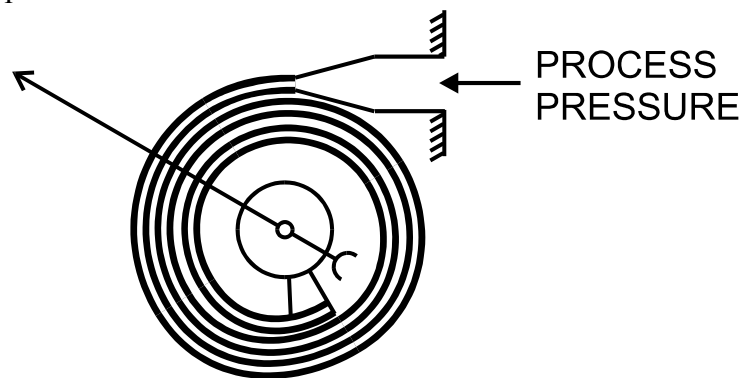
The advantages and disadvantages of this type of measurement are similar to the C-Bourdon tube with the following differences:

#### Advantages

- Increased accuracy and sensitivity
- Higher overrange protection

#### Disadvantages

- Very expensive



*Figure 2.6*  
*Spiral bourdon element*

#### Application Limitations

Process pressure changes cause problems with the increase in the coil size.

#### Summary

Very seldom used anymore.

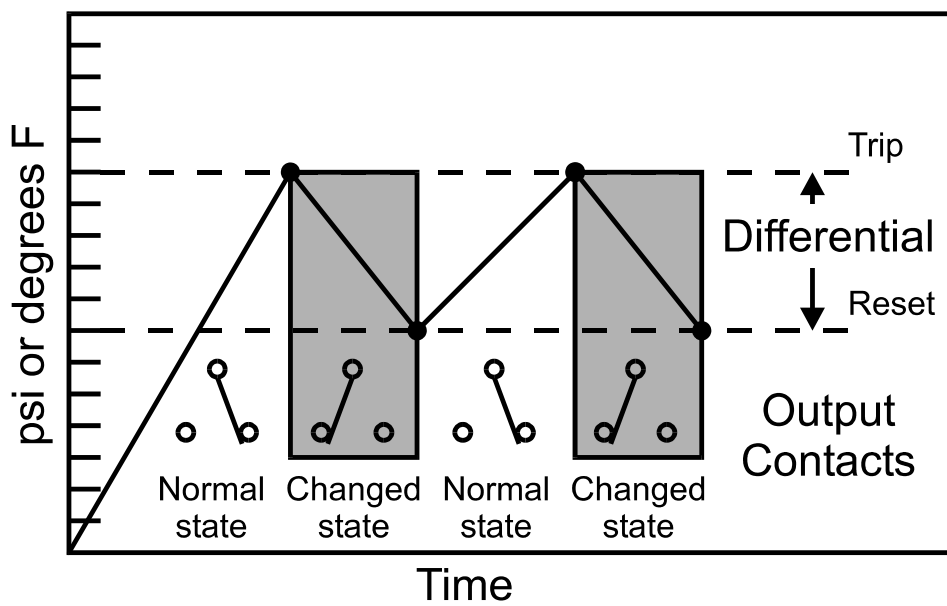
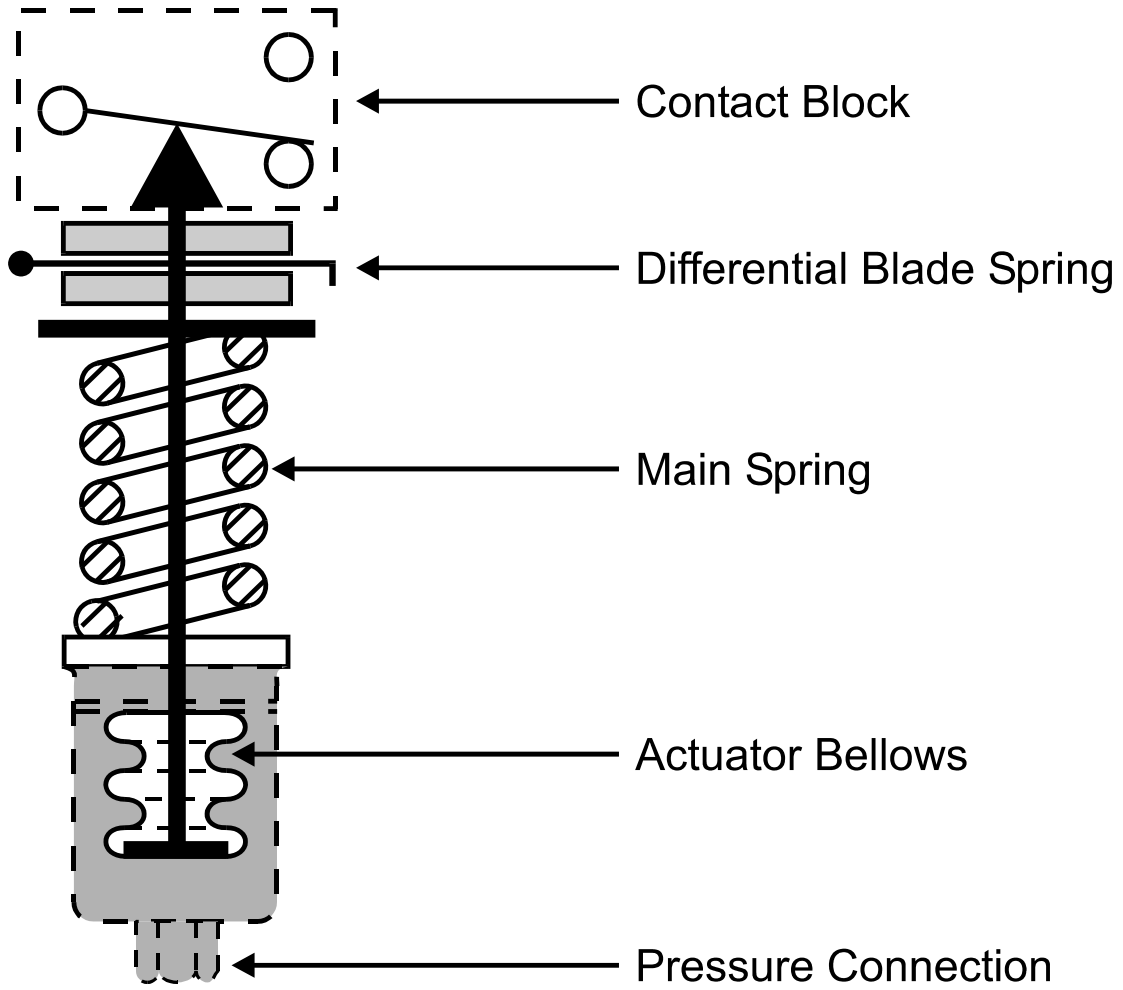
### 2.3.3 *Spring and Bellows*

A bellows is an expandable element and is made up of a series of folds which allow expansion. One end of the Bellows is fixed and the other moves in response to the applied pressure. A spring is used to oppose the applied force and a linkage connects the end of the bellows to a pointer for indication. Bellows type sensors are also

available which have the sensing pressure on the outside and the atmospheric conditions within.

The spring is added to the bellows for more accurate measurement. The elastic action of the bellows by themselves is insufficient to precisely measure the force of the applied pressure.

This type of pressure measurement is primarily used for ON/OFF control providing clean contacts for opening and closing electrical circuits. This form of sensing responds to changes in pneumatic or hydraulic pressure.



**Figure 2.7**  
**Basic mechanical structure**



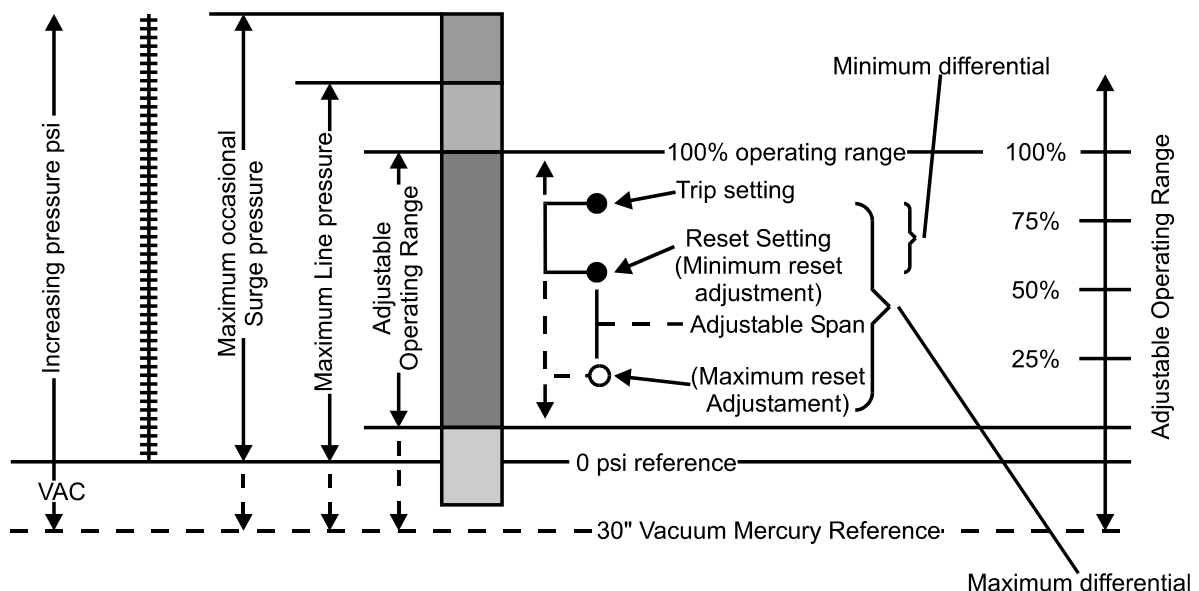
### Typical Application

The process pressure is connected to the sensor and is applied directly into the bellows. As the pressure increases, the bellows exert force on the main spring. When the threshold force of the main spring is overcome, the motion is transferred to the contact block causing the contacts to actuate. This is the Trip setting.

When the pressure decreases, the main spring will retract which causes the secondary differential blade spring to activate and reset the contacts. This is the Reset setting.

The force on the main spring is varied by turning the operating range adjustment screw. This determines where the contacts will trip.

The force on the secondary differential blade spring is varied by turning the differential adjustment screw. This determines where the contacts will reset.



**Figure 2.8**  
*Graphical illustration of technical terms*

Copper alloy bellows may be used on water or air. Other liquids and gases may be used if non-corrosive to this alloy. Use type 316 stainless steel for more corrosive liquids or gases.

### Diaphragm, bellows or piston?

The process pressure is applied to the actuator which can be either a diaphragm, bellows or piston type.

Piston controls are used for hydraulic fluids operating at high pressures. They are not intended for use with air or water as their accuracy is limited.

<b>Repeat Accuracy Table</b>	
<b>Type</b>	<b>Typical Characteristics (% of Maximum Range) ☆</b>
Diaphragm	± 1%
Bellows	± 1%
Piston with seal	± 5% Ⓟ
Piston without seal	± 3%
☆	Evaluation made from tests data and calculated using formula per NEMA ICS 2-225 Standards.
Ⓟ	Seal adds additional friction and value shown takes into consideration initial breakaway frictional force incurred during start-up or infrequent cycle operation. On continual cycle operation the repeat accuracy approaches ± 3%.

**Table 2.2**  
**Repeat Accuracy Table**

<b>Condition Sensing</b>					
<b>Bulletin 836T Pressure Controls</b>					
<b>Technical Data</b>					
<b>Bulletin Number</b>	<b>836T</b>	<b>836T</b>	<b>836T</b>	<b>836T</b>	<b>836T</b>
<b>Actuator Type</b>	<b>Diaphragm</b>	<b>Copper Alloy Bellows</b>	<b>Type 316 Stainless Steel Bellows</b>	<b>Piston Type without Seal</b>	<b>Piston Type with Seal</b>
Adjustable Operating Ranges	0 – 30” Hg Vac	3 to 650 psi	3 to 375 psi	40 to 5000 psi	80 to 5000 psi
Adjustable Differentials	5 to 20” Hg Vac	1.5 to 125 psi	1.5 to 90 psi	20 to 650 psi	40 to 650 psi
Maximum Line Pressures	15 psi	1300 psi	600 psi	-	-
Occasional Surge Pressures	15 psi	1600 psi	600 psi	15,000 psi	15,000 psi
<b>Pressure Media</b>					
Air	!	!	!		
Water	!	!	!		
Hydraulic Fluids	!	!	!	!	!
Liquids – Corrosive ☆			!		
- Non Corrosive	!	!	!		
Gases – Corrosive ☆			!		
- Non Corrosive	!	!	!		
<b>Enclosures</b>					
NEMA Type 1,4 & 13	!	!	!	!	!
NEMA Type 7 & 9	!	!	!	!	!
<b>Pipe Connections</b>					
Pressure connection	¼” NPTF Female Pipe Thread	¼” NPTF Female Pipe Thread	¼” NPTF Female Pipe Thread	3/8” NPTF Female Pipe Thread	3/8” NPTF Female Pipe Thread

☆ Corrosive liquids and gases must be compatible with Type 316 Stainless Steel Bellows.

Note: Pressure Difference Controls are supplied with either copper alloy or stainless steel bellows.

**Table 2.3**  
**Condition Sensing**

## **Refrigeration Applications**

Refrigeration controls are constructed with additional pulsation dampening to filter out the severe pulsations generated by reciprocating refrigeration compressors. Pressure controls not fitted with the added snubber function may result in reduced bellows life.

The reduced life results from pulsations severe enough to cause the bellows to squeal at the pump frequency or at the distorted harmonic wave generated at specific pump loading demands. Refrigeration controls are generally supplied as standard with the pulsation snubber built into the stem of the bellows.

## **Advantages**

- Simple construction
- Easily maintained
- Inexpensive

## **Disadvantages**

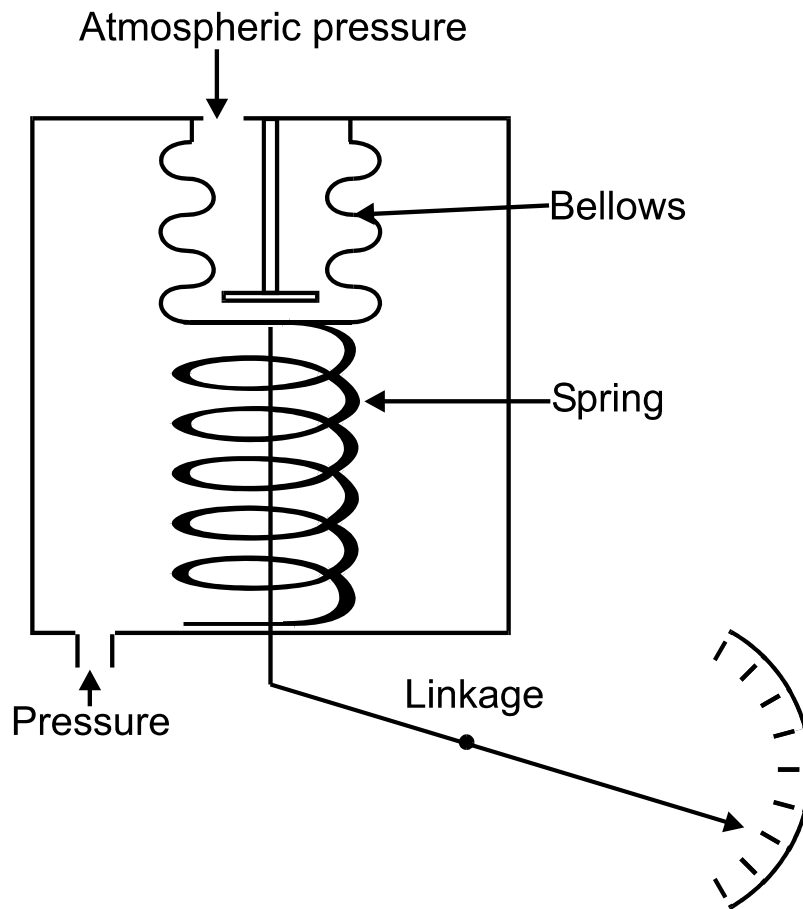
- Sensitive to temperature variations
- Work hardening of bellows
- Hysteresis
- Poor overrange protection

## **Application Limitations**

For applications where settings approach 0 psi, use a sensor that has a range that goes into vacuum.

Surges of pressure (transient pulses) can occur in a system prior to reaching the steady state condition. Generally, surge pressures within published values generated during start-up or shut-down of a machine or system (not exceeding 8 times in a 24 hour period), are negligible.

Bellows and fittings are specially prepared for oxygen and nitrous oxide service. The devices are tested with pure oxygen, bellows are plugged for protection from contamination, and a warning tag is generally applied to avoid contamination.



**Figure 2.9**  
**Spring and bellows gauge**

### Summary

Mainly used for barometric measurement, and are not so common in industrial control applications as they are fragile and have low overrange protection.

#### 2.3.4 Diaphragm

Many pressure sensors depend on the deflection of a diaphragm for measurement. The diaphragm is a flexible disc, which can be either flat or with concentric corrugations and is made from sheet metal with high tolerance dimensions.

The diaphragm can be used as a means of isolating the process fluids, or for high-pressure applications. It is also useful in providing pressure measurement with electrical transducers.

Diaphragms are well developed and proven. Modern designs have negligible hysteresis, friction and calibration problems when used with smart instrumentation.

They are used extensively on air conditioning plants and for ON/OFF switching applications.

### **Selection**

The selection of diaphragm materials is important, and are very much dependent on the application. Beryllium copper has good elastic qualities, where Ni-Span C has a very low temperature coefficient of elasticity.

Stainless steel and Inconel are used in extreme temperature applications, and are also suited for corrosive environments. For minimum hysteresis and drift, then Quartz is the best choice.

There are two main types of construction and operation of diaphragm sensors. They are:

- Motion Balanced
- Force Balanced

Motion balanced designs are used to control local, direct reading indicators. They are however more prone to hysteresis and friction errors.

Force balanced designs are used as transmitters for relaying information with a high accuracy, however they do not have direct indication capability.

### **Advantages**

- Provide isolation from process fluid
- Good for low pressure
- Inexpensive
- Wide range
- Reliable and proven
- Used to measure gauge, atmospheric and differential pressure

### **2.3.5 Manometer**

The simplest form of a manometer is that of a U-shaped tube filled with liquid. The reference pressure and the pressure to be measured are applied to the open ends of the tube. If there is a difference in pressure, then the heights of the liquid on the two sides of the tube will be different.

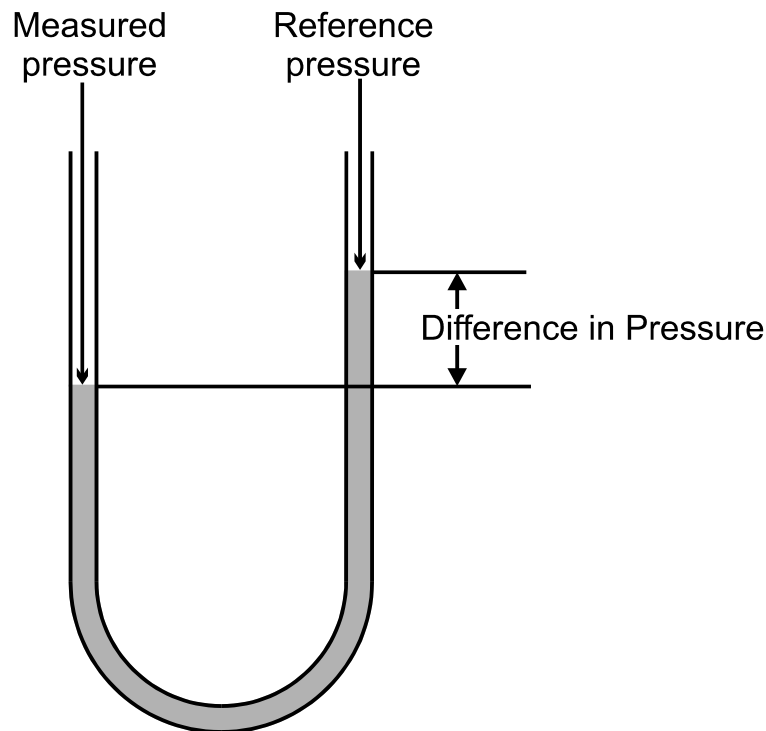
This difference in the heights is the process pressure in mm of water (or mm of mercury). The conversion into kPa is quite simple:

for water,  $Pa = \text{mm H}_2\text{O} \times 9.807$

for mercury,  $Pa = \text{mm Hg} \times 133.3$

## Typical Applications

This type of pressure measurement is mainly used for spot checks or for calibration. They are used for low range measurements, as higher measurements require mercury. Mercury is toxic and is therefore considered mildly hazardous.



*Figure 2.10*  
*Simplest form of manometer*

### Advantages

- Simple operation and construction
- Inexpensive

### Disadvantages

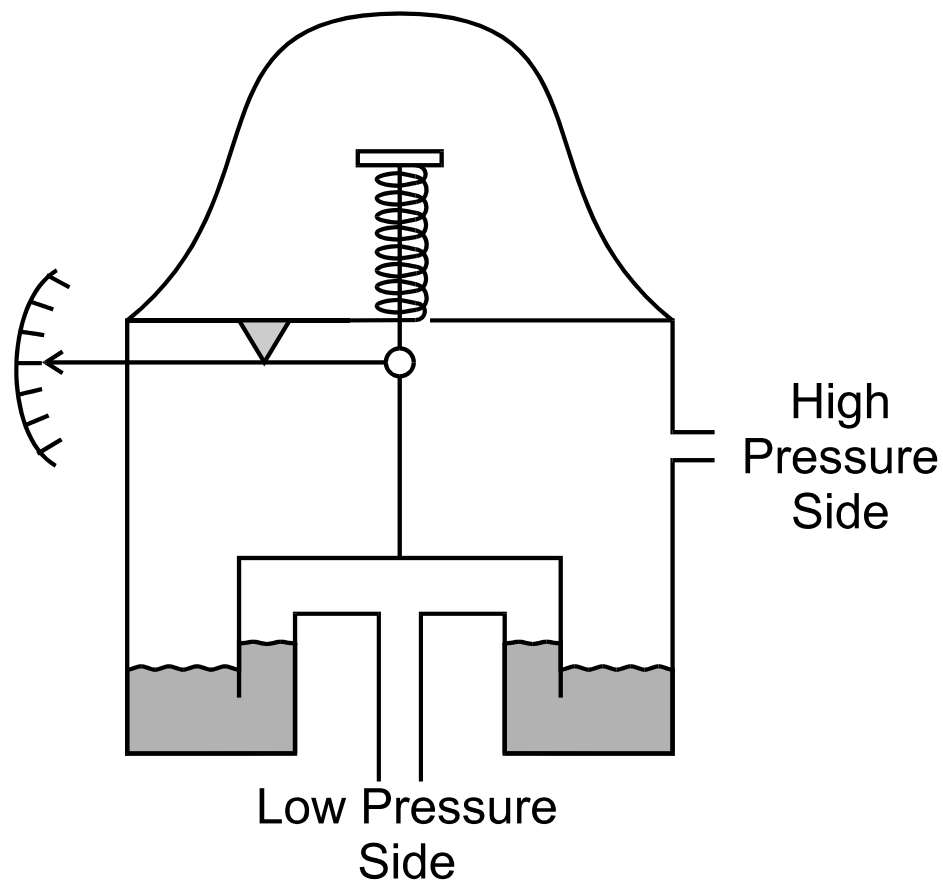
- Low pressure range (water)
- Higher pressure range requires mercury
- Readings are localised

### Application Limitations

Manometers are limited to a low range of operation due to size restrictions. They are also difficult to integrate into a continuous control system.

### 2.3.6 Single and Double Inverted Bell

The Bell instrument measures the pressure difference in a compartment on each side of a bell-shaped chamber. If the pressure to be measured is referenced to the surrounding conditions, then the lower compartment is vented to the atmosphere and gauge pressure is measured. If the lower compartment is evacuated to form a vacuum, then the pressure measured will be in absolute units. However, to measure differential pressure, the higher pressure is connected to the top of the chamber and the lower pressure to the bottom.



**Figure 2.11**  
**Inverted bell d/p detector**

The bell instrument is used in applications where very low pressures are required to be measured, typically in the order of 0 - 250 Pa.



## 2.4 Pressure Transducers and Elements - Electrical

The typical range of transducers here is:

- Strain gauge
- Vibrating wire
- Piezoelectric
- Capacitance
- Linear Variable Differential Transformer
- Optical

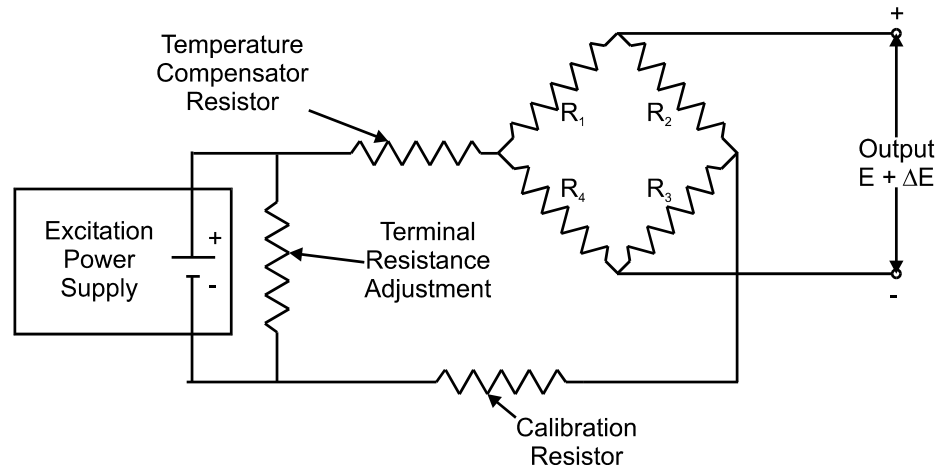
### 2.4.1 Strain Gauge

Strain gauge sensing uses a metal wire or semiconductor chip to measure changes in pressure. A change in pressure causes a change in resistance as the metal is deformed. This deformation is not permanent as the pressure (applied force) does not exceed the elastic limit of the metal. If the elastic limit is exceeded then permanent deformation will occur.

This is commonly used in a Wheatstone bridge arrangement where the change in pressure is detected as a change in the measured voltage.

Strain gauges in their infancy were metal wires supported by a frame. Advances in the technology of bonding materials mean that the wire can be adhered directly to the strained surface. Since the measurement of strain involves the deformation of metal, the strain material need not be limited to being a wire. As such, further developments also involve metal foil gauges. Bonded strain gauges are the more commonly used type.

As strain gauges are temperature sensitive, temperature compensation is required. One of the most common forms of temperature compensation is to use a wheatstone bridge. Apart from the sensing gauge, a dummy gauge is used which is not subjected to the forces but is also affected by temperature variations. In the bridge arrangement the dummy gauge cancels with the sensing gauge and eliminates temperature variations in the measurement.



**Figure 2.12**  
*Wheatstone circuit for strain gauges*

Strain gauges are mainly used due to their small size and fast response to load changes.

### Typical Application

Pressure is applied to an isolating diaphragm, where the force is transmitted to the polysilicon sensor by means of a silicone fill fluid. The reference side of the sensor is exposed to atmospheric pressure for gauge pressure transmitters. A sealed vacuum reference is used for absolute pressure transmitters.

When the process pressure is applied to the sensor, this creates a small deflection of the sensing diaphragm, which applies strain to the Wheatstone bridge circuit within the sensor. The change in resistance is sensed and converted to a digital signal for processing by the microprocessor.

### Selection and Sizing

There exists a very wide selection of strain gauge transducers, in range, accuracy and the associated cost.

### Advantages

- Wide range, 7.5kPa to 1400 Mpa
- Inaccuracy of 0.1%
- Small in size
- Stable devices with fast response
- Most have no moving parts
- Good over-range capability

**Disadvantages**

- Unstable due to bonding material
- Temperature sensitive
- Thermoelastic strain causes hysteresis

**Application Limitations**

All strain gauge applications require regulated power supplies for the excitation voltage, although this is commonly internal with the sensing circuits.

**2.4.2 Vibrating Wire**

This type of sensor consists of an electronic oscillator circuit which causes a wire to vibrate at its natural frequency when under tension. The principle is similar to that of a guitar string. The vibrating wire is located in a diaphragm. As the pressure changes on the diaphragm so does the tension on the wire which affects the frequency that the wire vibrates or resonates at. These frequency changes are a direct consequence of pressure changes and as such are detected and shown as pressure.

The frequency can be sensed as digital pulses from a electromagnetic pickup or sensing coil. An electronic transmitter would then convert this into an electrical signal suitable for transmission.

This type of pressure measurement can be used for differential, absolute or gauge installations. Absolute pressure measurement is achieved by evacuating the low-pressure diaphragm. A typical vacuum pressure for such a case would be about 0.5 Pa.

**Advantages**

- Good accuracy and repeatability
- Stable
- Low hysteresis
- high resolution
- Absolute, gauge or differential measurement

**Disadvantages**

- Temperature sensitive
- Affected by shock and vibration
- Non linear
- Physically large

### Application Limitations

Temperature variations require temperature compensation within the sensor, this problem limits the sensitivity of the device. The output generated is non-linear which can cause continuous control problems.

This technology is seldom used any more. Being older technology it is typically found with analogue control circuitry.

### 2.4.3 *Piezoelectric*

When pressure is applied to crystals, they are elastically deformed. Piezoelectric pressure sensing involves the measurement of such deformation. When a crystal is deformed, an electric charge is generated for only a few seconds. The electrical signal is proportional to the applied force.

Because these sensors can only measure for a short period, they are not suitable for static pressure measurement.

More suitable measurements are made of dynamic pressures caused from:

- shock
- vibration
- explosions
- pulsations
- engines
- compressors

This type of pressure sensing does not measure static pressure, and as such requires some means of identifying the pressure measured. As it measures dynamic pressure, the measurement needs to be referenced to the initial conditions before the impact of the pressure disturbance. The pressure can be expressed in relative pressure units, Pascal RELATIVE.

Quartz is commonly used as the sensing crystal as it is inexpensive, stable and insensitive to temperature variations. Tourmaline is an alternative which gives faster response speeds, typically in the order of microseconds.

### Advantages

- Accuracy 0.075%
- Very high pressure measurement, up to 70MPa
- small size
- robust
- fast response, < 1 nanosecond
- self-generated signal

**Disadvantages**

- Dynamic sensing only
- temperature sensitive

**Application Limitations**

Require special cabling and signal conditioning.

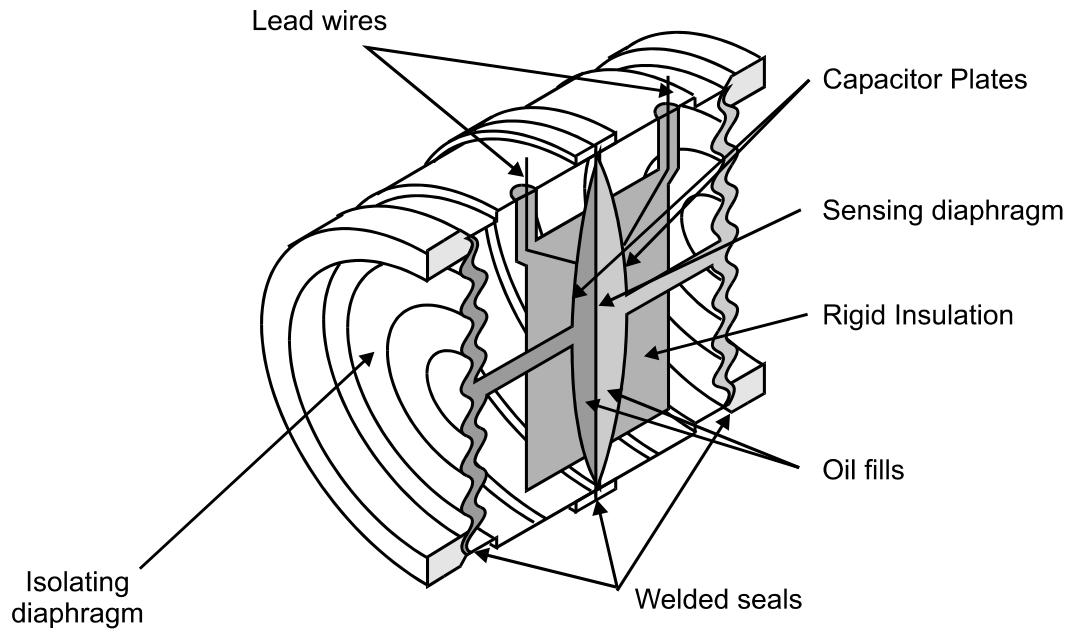
**2.4.4 Capacitance**

Capacitive pressure measurement involves sensing the change in capacitance that results from the movement of a diaphragm. The sensor is energised electrically with a high frequency oscillator. As the diaphragm is deflected due to pressure changes, the relative capacitance is measured by a bridge circuit.

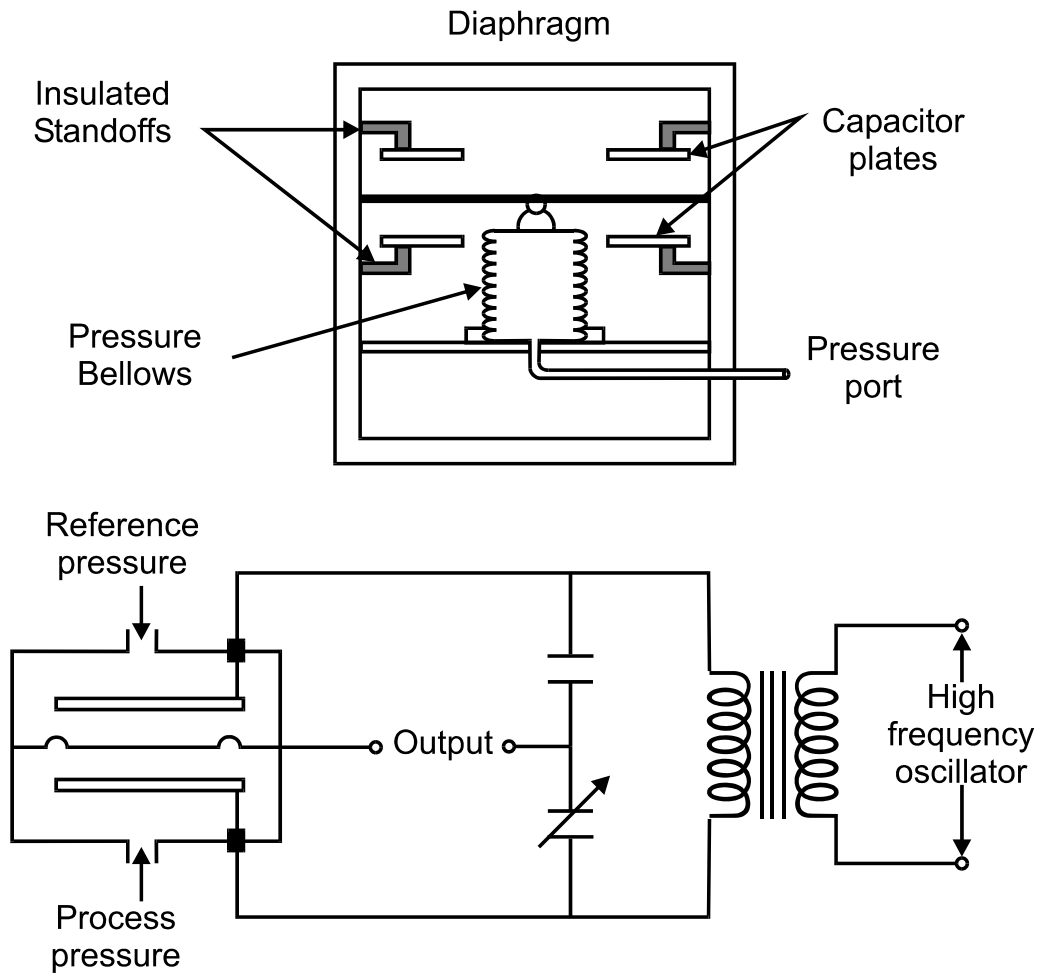
Two designs are quite common. The first is the two-plate design and is configured to operate in the balanced or unbalanced mode. The other is a single capacitor design.

The balanced mode is where the reference capacitor is varied to give zero voltage on the output. The unbalanced mode requires measuring the ratio of output to excitation voltage to determine pressure.

This type of pressure measurement is quite accurate and has a wide operating range. Capacitive pressure measurement is also quite common for determining the level in a tank or vessel.



**Figure 2.13**  
**Cross section of the Rosemount S-Cell™ Sensor**  
**(courtesy of Rosemount)**



**Figure 2.14**  
*Capacitance pressure detector*

### Advantages

- Inaccuracy 0.01 to 0.2%
- Range of 80Pa to 35MPa
- Linearity
- Fast response

### Disadvantages

- Temperature sensitive
- Stray capacitance problems
- Vibration
- Limited overpressure capability
- Cost

## Application Limitations

Many of the disadvantages above have been addressed and their problems reduced in newer designs. Temperature controlled sensors are available for applications requiring a high accuracy.

With strain gauges being the most popular form of pressure measurement, capacitance sensors are the next most common solution.

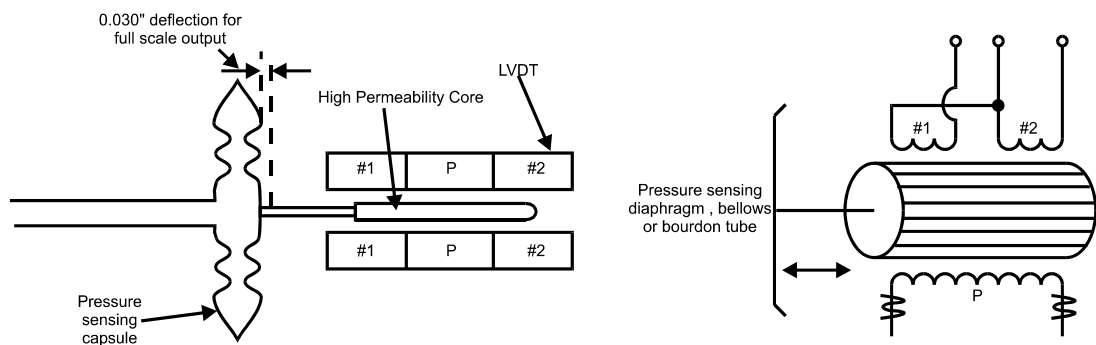
### 2.4.5 Linear Variable Differential Transformer

This type of pressure measurement relies on the movement of a high permeability core within transformer coils. The movement is transferred from the process medium to the core by use of a diaphragm, bellows or bourdon tube.

The LVDT operates on the inductance ratio between the coils. Three coils are wound onto the same insulating tube containing the high permeability iron core. The primary coil is located between the two secondary coils and is energised with an alternating current.

Equal voltages are induced in the secondary coils if the core is in the centre. The voltages are induced by the magnetic flux. When the core is moved from the centre position, the result of the voltages in the secondary windings will be different. The secondary coils are usually wired in series.

LVDT's are sensitive to vibration and are subject to mechanical wear.



**Figure 2.15**  
*Linear variable differential transformer*

## Disadvantages

- Mechanical wear
- Vibration



## Summary

This is an older technology, used before strain gauges were developed. Typically found on old weighframes or may be used for position control applications.

Very seldom used anymore.

### 2.4.6 *Optical*

Optical sensors can be used to measure the movement of a diaphragm due to pressure. An opaque vane is mounted to the diaphragm and moves in front of an infrared light beam. As the light is disturbed, the received light on the measuring diode indicates the position of the diaphragm.

A reference diode is used to compensate for the ageing of the light source. Also, by using a reference diode, the temperature effects are nulled as they affect the sensing and reference diodes in the same way.

#### **Advantages**

- Temperature corrected
- Good repeatability
- Negligible hysteresis

#### **Disadvantages**

- Expensive

#### **Summary**

Optical sensors require very little movement for accurate sensing. Because of this, optical pressure measurement provides very good repeatability with negligible hysteresis.

## 2.5 Installation Considerations

There are a number of points to consider in a pressure measurement application. All require some thought in both the planning and execution.

#### **Location of Process Connections**

Process connections should be located on the top of the process line for gases, and on the side of the lines for other fluids.

### **Isolation Valves**

Many pressure devices require tapping points into the process. Isolation valves should be considered between the process fluid and the measuring equipment if the device is required to be taken out of service for replacement or calibration.

### **Use of Impulse Tubing**

Impulse piping should be as short as possible. Instruments in gas applications should be self draining. Self draining can be achieved by sloping the lines towards the process to avoid trapping condensables and liquids.

Instruments used in liquid and condensable applications should be self-venting. Self-venting is performed by sloping the lines towards the instrument to avoid trapping gas.

If solids can accumulate in the impulse line, tees and plug fittings should be installed in the place of elbows to allow for “rodding” of plugged lines.

### **Test And Drain Valves**

Apart from the isolation valve at the process connection, the need for test and drain valves must be evaluated. If the fluid to be measured is toxic or corrosive, a blowdown valve line should be provided.

For maintenance reasons, all valves must be accessible from either the ground or suitable platforms.

### **Sensor Construction**

Depending on the environment in which the instrument is to be used, selection of the correct sensor should also involve physical conditions. The sensor may need to be isolated mechanically, electronically and thermally from the process medium and the external environment.

Mechanical and thermal isolation can be achieved by moving the sensor away from the process flange to a position in the neck of the electronics housing. Designs of this type relieve mechanical stress on the cell. This can result in improved static pressure performance and removes the sensor from direct heat.

Glass-sealed pressure transport tubes and insulated cell mountings provide electrical isolation. This improves performance and provides transient protection for the electronics.

## Temperature Effects

High temperatures and large temperature variations can affect pressure measuring equipment.

One of the most common forms of temperature compensation is to use a Wheatstone bridge. Apart from the primary sensor, a dummy sensor is used which is not subjected to the forces but is also affected by temperature variations. In the bridge arrangement the dummy sensor cancels the primary sensor's voltage and thus eliminates temperature variations in the measurement.

Temperature measurement and correction within the device is another form of compensation for thermal effects, but is the more expensive choice.

## Remote Diaphragm Seals

Remote diaphragm seals can be used to prevent the process medium from contacting the transmitter diaphragm while measuring process pressure.

Remote seal systems should be considered if:

- corrosion may cause a problem to the transmitter and pressure sensing element.
- the sensing fluid contains suspended solids or is sufficiently viscous to clog the piping.
- the process temperature is outside of the normal operating range of the transmitter.
- the process fluid may freeze or solidify in the transmitter or impulse piping.
- the process medium needs to be flushed out of the process connections when changing batches.
- maintaining sanitary or aseptic conditions.
- eliminating the maintenance required with wet leg applications.
- making density or other measurements.

## Precautions With Remote Diaphragm Seals

Although the benefits of using remote diaphragm seals are listed above, they can however have an effect on the overall transmitter response. By selecting the correct seals, capillaries and fill fluid, the effects of transmitter performance can be minimised while still achieving process requirements.

The following points can assist when selecting the different parts of a remote seal system:

- Larger diameter diaphragms minimise the temperature effects that are common with remote seals.
- Minimising the length of the capillary reduces temperature effects and also improves response time.
- In a two-seal system, the same diaphragm size, capillary length and fill fluid should be used on each side of the transmitter.
- Mount the transmitter at or below the lower tap for vacuum applications. Capillary length may be an inhibiting factor.
- The fill fluid should be selected to perform in the most extreme process conditions. The two critical criteria being highest temperature and lowest pressure.
- Select a fill fluid that is compatible with the process fluid, in case of contamination.

### **Process Flanges**

- Coplanar flange

These are becoming more standard for newer pressure transmitters. They are generally small and lightweight which makes for easier installation. They have a process operating temperature up to 120°C.

- Traditional flange

These are used in installations that require traditional biplanar configurations. An increased operating temperature at process connections, up to 150°C is possible.

- Level flange

This permits direct process mounting and is of a simple construction and low cost.

### **Additional Hardware**

If pulsation dampeners are required, the materials and fill fluid must be compatible with the process fluid being measured. In addition, siphons of the correct material are required for all vapours above 60°C, where condensation will occur.

If diaphragm seals are required, a flushing connection requirement must be assessed.

## **2.6 Impact on the Overall Control Loop**

Sensing devices that are situated in a control loop generally have an effect when the range of operation or response time changes.

With pressure measurement devices, problems occur due to:

- Material build-up on the sensing element causing a longer response
- Overranging causing incorrect readings

2.7 Selection Tables

Type of Design	mmHg absolute (1 mmHg = 133Pa)		"H <sub>2</sub> O = 250 Pa		PSIG (1 PSIG = 6.9 Pa)	
	10 <sup>-14</sup>	10 <sup>-10</sup>	10 <sup>-14</sup>	10 <sup>-10</sup>	10 <sup>-14</sup>	10 <sup>-10</sup>
Abs. Press. Motion Balance	✓	✓	✓	✓	✓	✓
Abs. Press. Force Balance	✓	✓	✓	✓	✓	✓
Abs. Press. Ref. Motion Bal.	✓	✓	✓	✓	✓	✓
Abs. Press. Ref. Force Bal.	✓	✓	✓	✓	✓	✓
Aneroid Manostats	✓	✓	✓	✓	✓	✓
C-Bourdon	✓	✓	✓	✓	✓	✓
Spiral Bourdon	✓	✓	✓	✓	✓	✓
Helical Bourdon	✓	✓	✓	✓	✓	✓
Quartz Helix	✓	✓	✓	✓	✓	✓
Abs. Press. Motion Balance	✓	✓	✓	✓	✓	✓
Abs. Press. Force Balance	✓	✓	✓	✓	✓	✓
Abs. Press. Ref. Motion Bal.	✓	✓	✓	✓	✓	✓
Abs. Press. Ref. Force Bal.	✓	✓	✓	✓	✓	✓
Strain Gauge	✓	✓	✓	✓	✓	✓
Capacitance Sensors	✓	✓	✓	✓	✓	✓
Potentiometric	✓	✓	✓	✓	✓	✓
Resonant Wire	✓	✓	✓	✓	✓	✓
Piezoelectric	✓	✓	✓	✓	✓	✓
Magnetic	✓	✓	✓	✓	✓	✓
Optical	✓	✓	✓	✓	✓	✓

Table 2.4 Selection table.

Type of Design	Features	mmHg absolute (1 mmHg = 133Pa)	"H <sub>2</sub> O (1 "H <sub>2</sub> O = 250 Pa)	PSIG (1 PSIG = 6.9 Pa)
Hi-Press. Sensors	Online Device			
Dead Weight Piston Gauge	Remote Readout Trans.			
Bulk Modulus Cell	Local Readout (Gauge)			
Manganin Cell	Plant Device			
Inverted Bell	Laboratory or Pilot			
Ring Balance	Smart Units Available			
Float Manometer				
Barometers				
Visual Manometers				
Micromanometers				
D/P Cell				
Std. Diaphragm				
Button Diaphragm				
Hot Cathode				
Cold Cathode				
Thermocouple				
Thermopile				
Resistance Wire-Pirani				
Convection				
Quartz Helix				
McLeod				
Molecular Momentum				
Capacitance				
Spinning Ball				

Table 2.5  
Selection Table

## **2.8 Future Technologies**

### **Sensor Characterisation**

Sensors show slightly different characteristics depending on the pressure and temperature ranges they operate at. By running sensors through pressure and temperature cycles over their full operating range, it is possible to gather enough data to generate correction coefficients. This information is stored in the sensor module and ensures precise signal correction during normal operation.

Errors due to hysteresis and non-linearity can be improved upon with the use of smart instruments. The microprocessor does not eliminate the nonlinearity, but it does memorise the amount of nonlinearity and electronically corrects for it.

Smart pressure transmitters provide two main functions:

- Maximise accuracy and rangeability.
- Easily interfaced between field sensors and main control system.

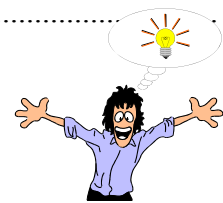


# Tips and Tricks



A series of horizontal dotted lines providing a template for writing notes or tips.

# Tips and Tricks



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# **3**

## **Level Measurement**

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# Chapter 3

## Level Measurement

### 3.1 Principles of Level Measurement

#### *Continuous Measurement*

The units of level are generally metres (m). However, there are numerous ways to measure level that require different technologies and various units of measurement.

Such means may be:

- Ultrasonic, transit time
- Pulse echo
- Pulse radar
- Pressure, hydrostatic
- Weight, strain gauge
- Conductivity
- Capacitive

For continuous measurement, the level is detected and converted into a signal that is proportional to the level. Microprocessor based devices can indicate level or volume.

Different techniques also have different requirements. For example, when detecting the level from the top of a tank, the shape of the tank is required to deduce volume.

When using hydrostatic means, which detects the pressure from the bottom of the tank, then the density must be known and remain constant.

#### *Point Detection*

Point detection can also be provided for all liquids and solids. Some of the more common types are:

- Capacitive
- Microwave
- Radioactive
- Vibration
- Conductive

The ON/OFF switching action is typically used for stopping, starting or alarming. They may also be used as process or safety protection devices in conjunction with continuous measuring equipment.

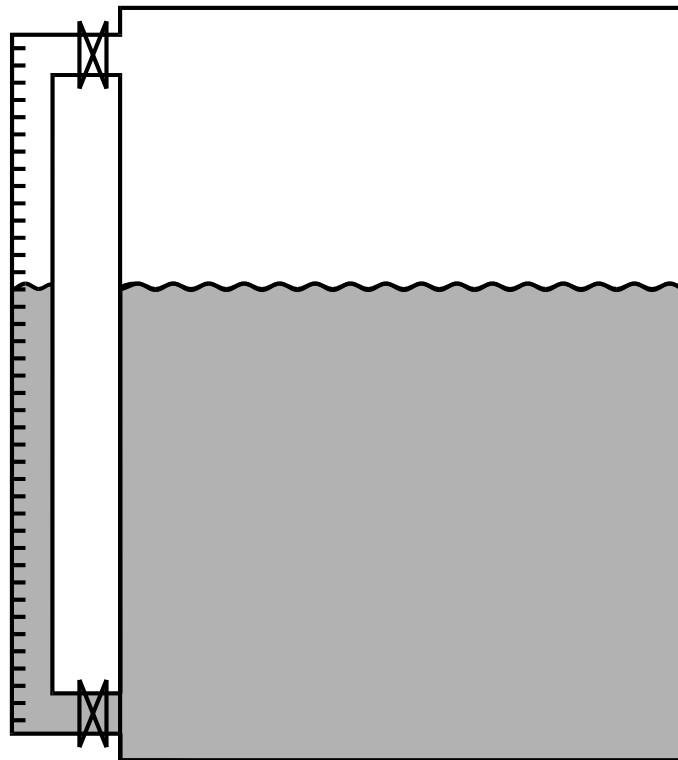
Overfill or empty protection can be a statutory requirement with some process materials, and this may have limitations on the technology used and the interface to associated circuits, which often are required to be hard-wired.

A level measuring system often consists of the sensor and a separate signal conditioning instrument. This combination is often chosen when multiple outputs (continuous and switched) are required and parameters may need to be altered.

## 3.2 Simple Sight Glasses and Gauging Rod

### 3.2.1 Simple Sight Glasses

A visual indication of the level can be obtained when part of the vessel is constructed from transparent material or the liquid in a vessel is bypassed through a transparent tube. The advantage of using stop valves with the use of a bypass pipe, is the ease in removal for cleaning.



Level by Visual Inspection

*Figure 3.1*  
*Level by Visual Inspection*

### **Advantages**

- Very simple
- Inexpensive

### **Disadvantages**

- Not suitable for automated control.
- Maintenance - requires cleaning
- Fragile - easily damaged

### **Applications/Limitations**

These are not highly suited for industrial applications as manual viewing and transmission of information is required by the operator.

Applications of such level measuring devices can be seen in tanks for the storage of lubricating oils or water. They provide a very simple means of accessing level information and can simplify the task of physically viewing or dipping a tank. They are, however, generally limited to operator inspection.

Sight glasses are also not suitable for dark or dirty liquids. This type should not be used when measuring hazardous liquids as the glass-tube is easily damaged or broken. In installations where the gauge is at a lower temperature than the process condensation can occur outside the gauge, impairing the accuracy of the reading.

### **Summary**

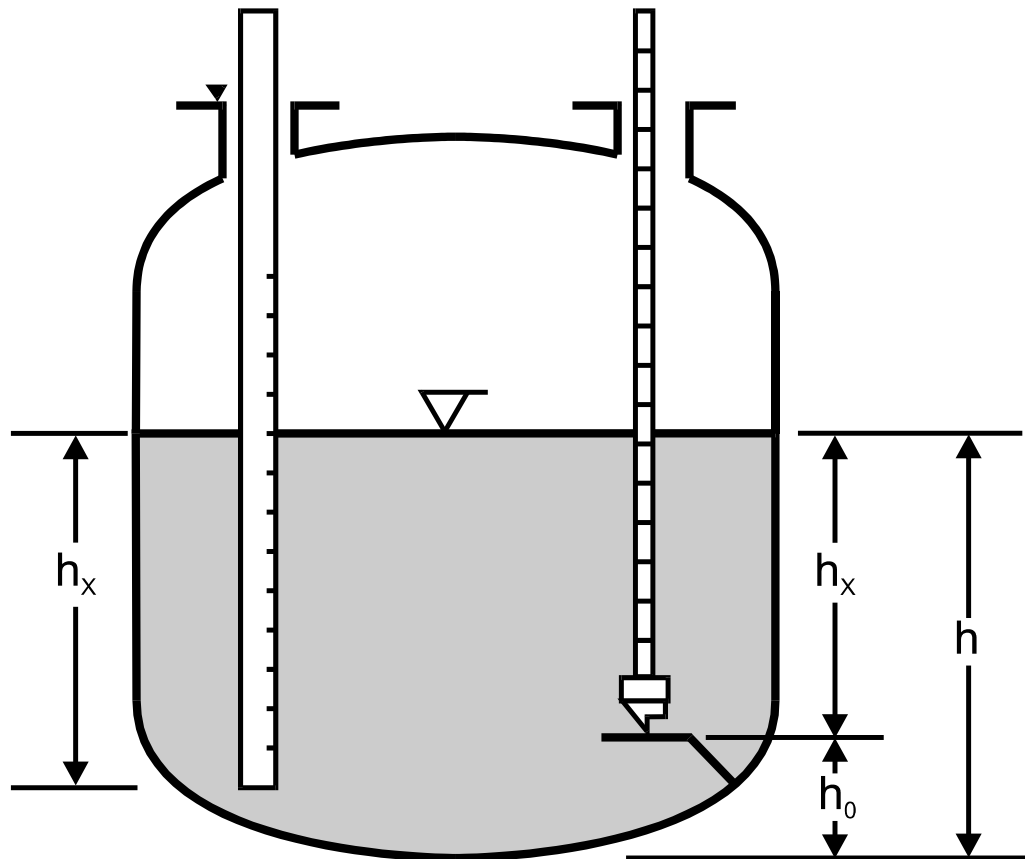
Simple sight glasses are an older technology and are very seldom used for automatic control applications. They are typically found on old urns!

### **3.2.2 Gauging Rod Method**

This requires a little more manual effort than the sight glass, but is another very simple and cheap method of accounting for level. This method can be applied to liquids and bulk materials, and weighted steel tapes can be used in very tall silos. Service stations use this method for 'dipping' their tanks, which use a notched dipping rod. A common example is the oil level 'dip stick' in a motor vehicle.

This method is primarily designed for atmospheric conditions. Slip tubes can be used for pressurised vessels, but require the venting of process gas or fluid into the atmosphere. These devices are hazardous to personnel and should not be used in designated safe areas or for control as part of an automated process.





**Figure 3.2**  
**Gauging rod**

*Note from the figure that the measurement is read from where the dipping rod contacts the bottom of the vessel.*

#### **Advantages**

- Simple and inexpensive.

#### **Disadvantages**

- Sampled measurement only
- Hazards associated with pressurised measurement
- Limited accuracy

#### **Application Limitations**

This is not suitable for industrial processes requiring continuous measurement. This type of measurement is top access only and in some cases may require the use of step ladders to access the sensing equipment. Applications are limited, especially for pressurised vessels.

This method is prone to errors due to operator interpretation and readability of the gradations on the measuring rod. It is also limited to the resolution of the gradations. The resolution or best accuracy can be assumed to be one half of the smallest marked division.

### 3.3 Buoyancy Tape Systems

There are two main types of buoyancy tape systems available:

- Float and tape systems
- Wire guided float detectors

#### 3.3.1 *Float and Tape Systems*

One common form of level measuring system uses a tape or servo motor which is connected to a float. The height can be read as the float moves with liquid level.

Other systems use the float method by sensing the position of the float magnetically or electrically.

Float systems can also be used when measuring granular solids as well as liquids.

#### **Disadvantages**

- High maintenance
- Expensive

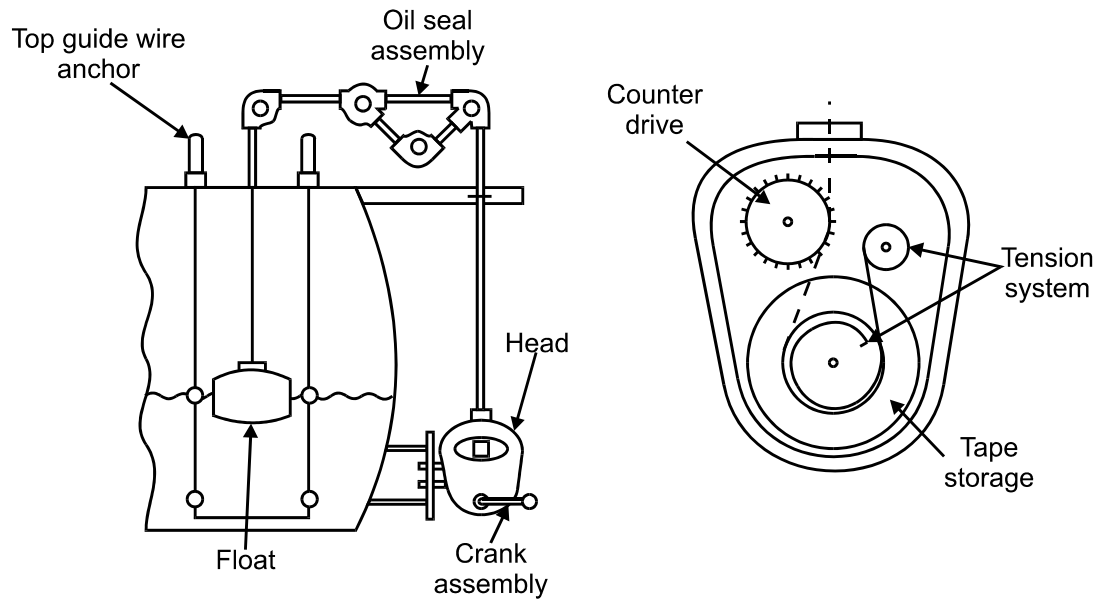
#### 3.3.2 *Wire Guided Float Detectors*

For large level measurements (ie. 20m), wire-guided float detectors can be used. The guide wires are connected to top and bottom anchors and assist in positioning the float as it moves with the fluid level. The tape is connected to the top of the float and runs directly up and over pulleys then down to the gauging head which is outside the tank at a suitable level for viewing.

The perforated tape is received in the gauge head by a sprocketed counter drive. Any slackness in the tape is taken up by the tape storage reel which is tensioned. Tensioning of the tape storage reel is sufficient to ensure correct measurement, while not affecting the position of the float.

The shaft on the counter drive rotates as the float moves the perforated tape up and down. The rotary motion of the shaft is used to give a metric readout.

In atmospheric conditions, a seal is used to protect the sensing head from the process fluid. However in pressurised applications, it is better to fill the head with the sensing fluid, particularly if the fluid is clean and lubricating.



**Figure 3.3**  
*Wire-guided float detectors and details of head*

### Typical Applications

This type of level measurement usually finds itself applied to large fuel farms, especially when intrinsic safety is significant.

### Advantages

- Large level measurement
- Intrinsically safe

### Disadvantages

- Installation costs
- Mechanical wear

### Application Limitations

Float and tape systems have a common problem with the tape hanging up. This often occurs if the long guide pipes are not perfectly vertical, where the tape rubs against the inside of the pipes.

Another common problem is with corrosion or dirt, where the tape can be held in place while the float is moving. These problems are more likely to result in a lower than actual reading.

The force from the float weight is usually great enough to overcome the friction of the tape against the impurities, whereas the force of the take-up device may not. Tanks controlled using tape level gauges will often overflow when the tape is stuck.

This problem can be protected against by the use of a separate high level switch.

More advanced controllers are available that monitor tank capacity and pumping rates to check the actual level, rate of change and direction of change.

### Summary

One of the main limitations is the high maintenance required in order to keep the tape clean and prevent it from gumming up. This is old technology and is seldom used.

## 3.4 Hydrostatic Pressure

Some of the different types of level measurement with pressure are:

- Static pressure
- Differential pressure
- Bubble tube method
- Diaphragm Box
- Weighing

### 3.4.1 Static Pressure

The basis of hydrostatic pressure measurement for level is such that the measured pressure is proportional to the height of liquid in the tank, irrespective of volume. The pressure is related to the height by the following:

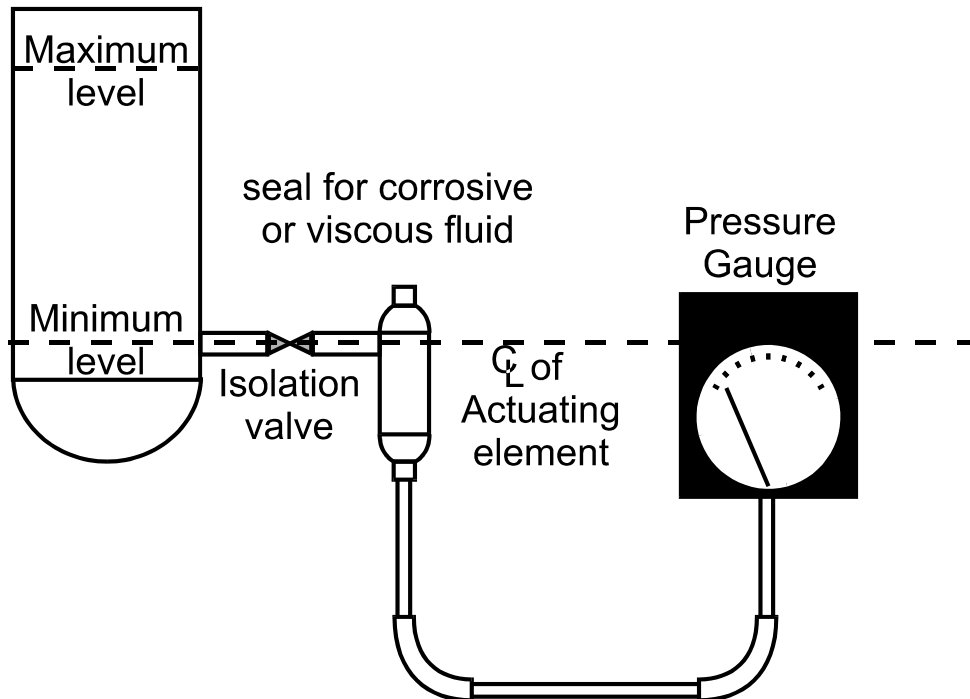
$$P = h \cdot \rho \cdot g$$

where: P = pressure  
h = height  
 $\rho$  = relative density of fluid  
g = acceleration due to gravity

For constant density, the only variable that changes is the height. In fact, any instrument that can measure pressure can be calibrated to read height of a given liquid, and can be used to measure liquid level in vessels under atmospheric conditions.

Most pressure sensors compensate for atmospheric conditions, so the pressure on the surface of liquids open to the atmosphere will be zero. The measuring units are generally in Pascals, but note that 1 Pa is equivalent to 1 m head of water.

Hydrostatic pressure transducers always consist of a membrane which is connected either mechanically or hydraulically to a transducer element. The transducer element can be based on such technologies as inductance, capacitance, strain gauge or even semiconductor.



**Figure 3.4**

*A pressure gauge used to measure the height of a liquid in an open tank*

The pressure transducer can be mounted in many types of pressure sensor so that the application can be quite specific to the requirement of the process conditions. Since the movement of the membrane is only a few microns, the semiconductor transducer is extremely insensitive to dirt or product build-up. This makes this type of measurement useful for such applications as sewage water, sludge, paint and oils. A seal is required for corrosive or viscous liquids, or in the case where a pipe is used to hydraulically transmit the pressure to a gauge.

Since there is no application of movement, there is no relaxing force to cause hysteresis.

A pressure sensor is exposed to the pressure of the system, and therefore needs to be mounted at or near the bottom of the vessel. In situations where it is not possible to mount the sensor directly in the side of the vessel at the appropriate depth, it can be mounted from the top of the vessel and lowered into the fluid on the end of a rod or cable. This method is commonly used for applications in reservoirs and deepwells.

If the use of extension nozzles or long pipes is unavoidable, precautions are required to ensure the fluid will not harden or congeal in the pipe. If this occurs, then the pressure detected will no longer be accurate. Different mounting systems or pipe heaters could be used to prevent this. to ensure

It is a requirement of this type of measurement that static pressure is measured. The sensor therefore, should not be mounted directly in the product stream as the pressure measured will be too high and the level reading inaccurate. For similar reasons, a pressure sensor should not be mounted in the discharge outlet of a vessel as the pressure measurement will be incorrectly low during discharge.

### **Advantages**

- Level or volume measurement
- Simple to assemble and install
- Simple to adjust
- Reasonably accurate

### **Disadvantages**

- Dependent on relative density of material
- More expensive than simpler types
- Expensive for high accuracy applications

### **Application Limitations**

Level measurement can be made using the hydrostatic principle in open tanks when the density of the material is constant. The sensor needs to be mounted in an open tank to ensure that the liquid, even at the minimum level always covers the process diaphragm.

Since the sensor is measuring pressure, it is therefore sensitive to sludge and dirt on the bottom of the tank. Build-up can often occur around or in the flange where the sensor is mounted. Bore water can also cause calcium build-up.

It is also critical that the pressure measurement is referenced to atmospheric conditions.

### **Level Measurement With Changing Product Density**

If the material being measured is of varying densities, then accurate level measurement is impaired. However, sensors are available that compensate for various densities. In such sensors, mounting an external limit switch at a known height above the sensor makes corrections. When the switch status changes, the sensor uses the current measured value to automatically compensate for any density change.

It is optimal to mount the external limit switch for this compensation at the point where the level increases or decreases. This correction for density changes is best when the distance between the limit switch and the sensor is made as large as possible.

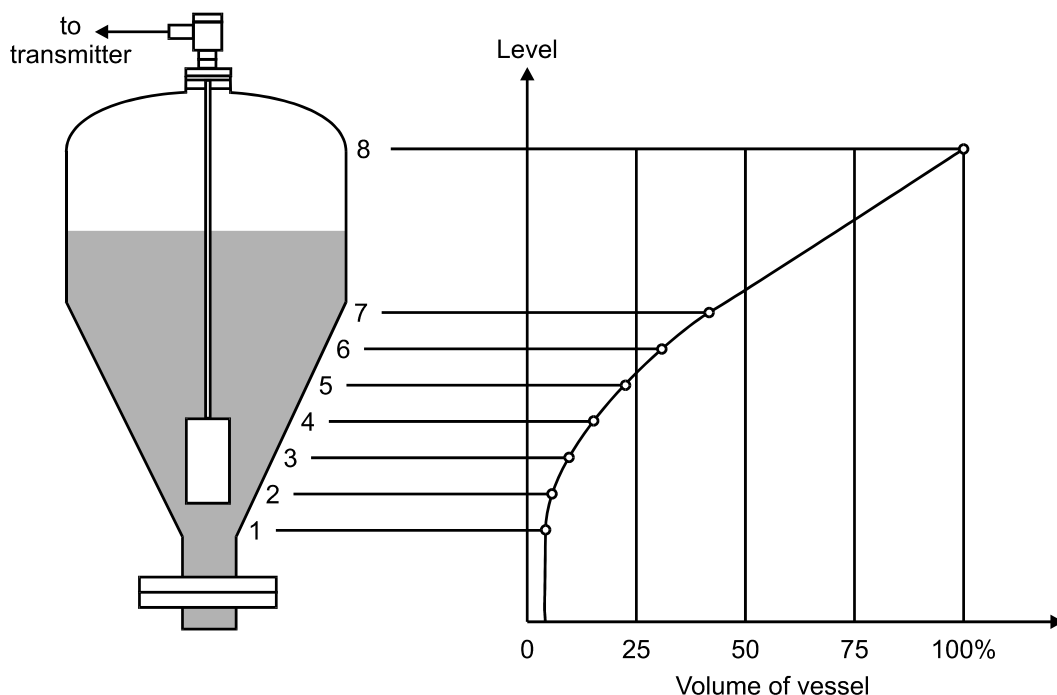
Variations in the temperature also affect the density of the fluid. Wax is a big problem where the pipes are heated with even slight variations in temperature cause noticeable changes in the density.

### Volume Measurement For Different Vessel Shapes

Level measurement is easily obtained by hydrostatic pressure; however the volume of fluid within a vessel relies on the shape of the vessel. If the shape of the vessel does not change for increasing height then the volume is simply the level multiplied by the cross-sectional area. But, if the shape (or contour) of the vessel changes for increasing height, then the relationship between the height and the volume is not so simple.

To accurately describe the volume in a vessel, a characteristic curve is used to describe the functional relationship between the height (h) and the volume (V) of the vessel. The curve for a horizontal cylinder is of the simplest type and is often a standard characteristic offered by most suppliers. Depending on the sophistication of the manufacturers sensors, other curves for various vessel shapes can also be entered.

The output of the sensor can be linearised using characteristic curves which are described by up to 100 reference points and determined either by filling the vessel or from data supplied by the manufacturer.

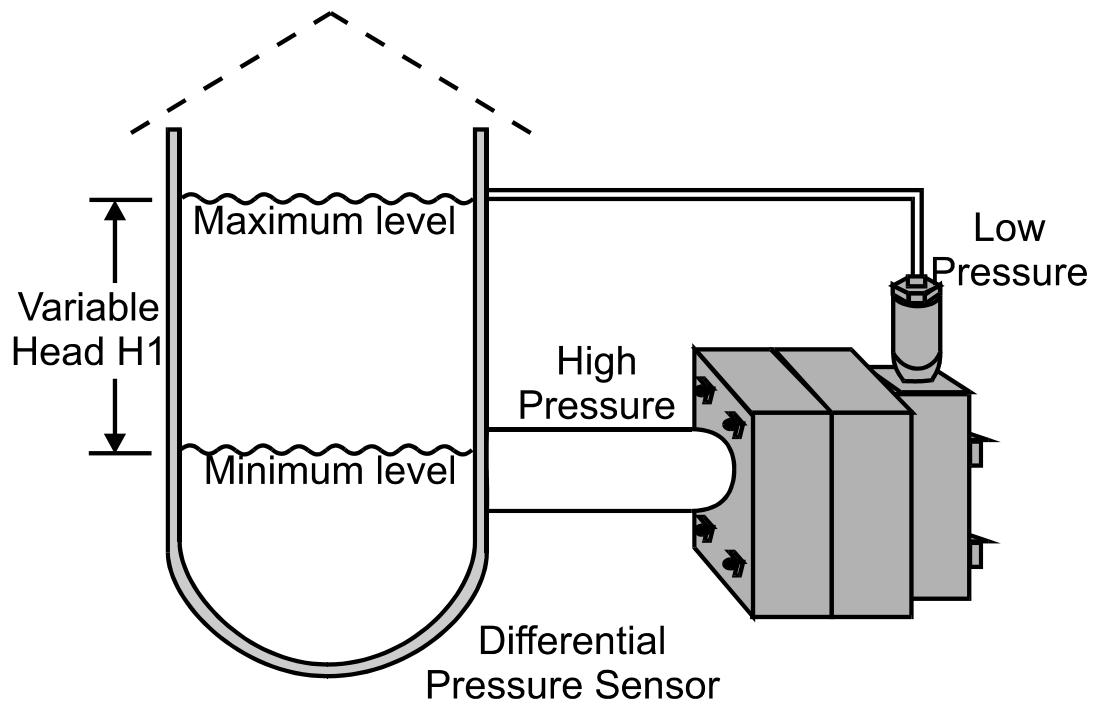


**Figure 3.5**  
*Volume measurement: entering a characteristic curve*

### 3.4.2 Differential

When the surface pressure on the liquid is greater (as may be the case of a pressurised tank) or different to the atmospheric pressure, then a differential pressure sensor is required. This is because the total pressure will be greater than the head of liquid pressure. With the differential pressure sensor, the pressure on the surface of the liquid will be subtracted from the total pressure, resulting in a measurement of the pressure due to the height of the liquid.

In applying this method of measurement, the LP (low-pressure) side of the transmitter is connected to the vessel above the maximum liquid level. This connection is called the dry leg. The pressure above the liquid is exerted on both the LP and HP (high-pressure) sides of the transmitter, and changes in this pressure do not affect the measured level.



**Figure 3.6**

*For a pressurised tank, the level is measured using differential pressure methods*

#### Installation Techniques

When using differential pressure sensors for this purpose, it is quite common for the liquid being measured to find its way into the dry leg. This can result from condensation or splash over. Changes in head pressure are then, usually on the low-pressure side of the transmitter. Liquid in the dry leg can cause a zero shift in the measurement. A common solution to this problem is to fill the previously dry reference leg with either the liquid used in the vessel or a sealing liquid. This wet leg ensures a constant reference pressure.



Because it has a higher pressure, changes to the dry reference leg reverses the LP and HP connections to the transmitter. The height of the liquid in the reference leg needs to be equal to or greater than the maximum level in the vessel. As the level increases, the pressure on the sensor at the base of the vessel will increase, and the differential pressure on the transmitter decreases. When the tank is full, the liquid pressure will be equal to the reference pressure and the differential pressure will be recorded as zero.

Correction of this is simple and involves reversing the HP and LP or the electrical output from the transmitter. The biasing is also used to allow for the HP reference.

### **Using DP for filters:**

Differential pressure measurement for level in pressurised tanks is also used in filters to indicate the amount of contamination of a filter. If the filter remains clean, there is no significant pressure difference across the filter. As the filter becomes contaminated, the pressure on the upstream side of the filter will become greater than on the downstream side.

### **Advantages**

- Level measurement in pressurised or evacuated tank
- Simple to adjust
- Reasonably accurate

### **Disadvantages**

- Dependent on relative density of material
- Quite expensive for differential pressure measurement
- Inaccuracies due to build-up
- Maintenance intensive

### **Application Limitations**

The density of the fluid affects the accuracy of the measurement. DP instruments should be used for liquids with relatively fixed specific gravity. Also the process connections are susceptible to plugging from debris, and the wet leg of the process connection may be susceptible to freezing.

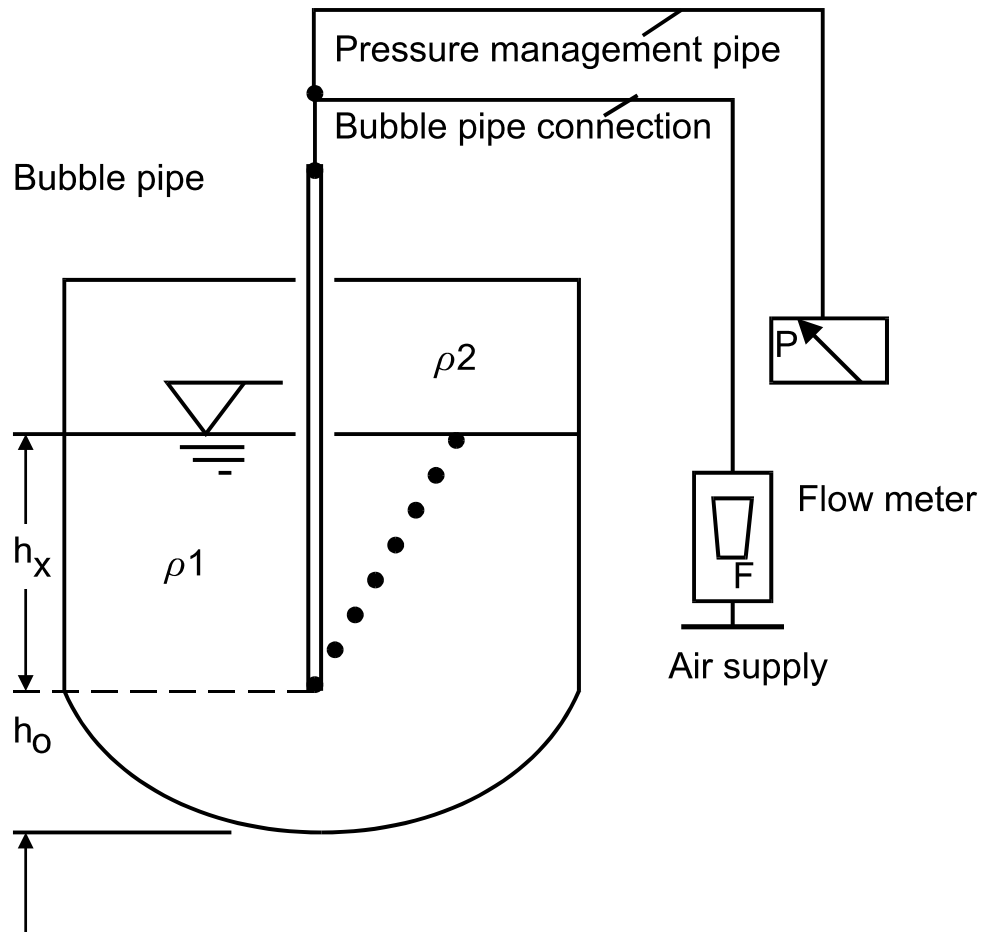
### **3.4.3 Bubble Tube Method**

In the bubble type system, liquid level is determined by measuring the pressure required to force a gas into a liquid at a point beneath the surface.

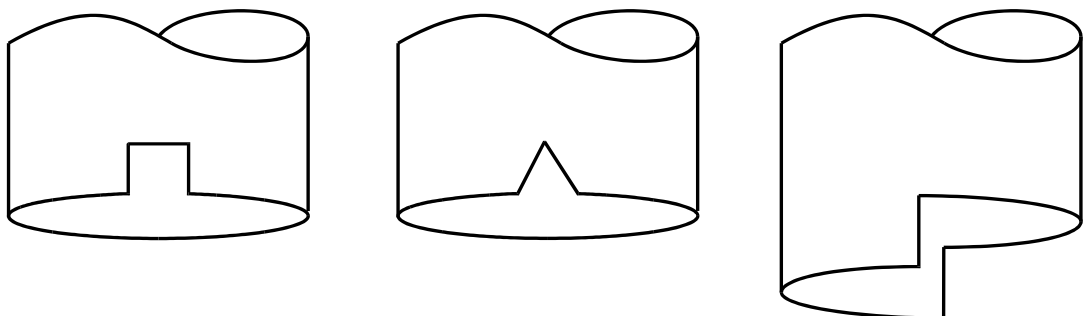
This method uses a source of clean air or gas and is connected through a restriction to a bubble tube immersed at a fixed depth into the vessel. The restriction reduces the airflow to a very small amount. As the pressure builds, bubbles are released from

the end of the bubble tube. Pressure is maintained as air bubbles escape through the liquid. Changes in the liquid level cause the air pressure in the bubble tube to vary. At the top of the bubble tube is where a pressure sensor detects differences in pressure as the level changes.

Most tubes use a small V-notch at the bottom to assist with the release of a constant stream of bubbles. This is preferable for consistent measurement rather than intermittent large bubbles.



**Figure 3.7**  
**Bubble tube method**



**Figure 3.8**  
***Air bubbler tube notch variations***

Bubblers are simple and inexpensive, but not extremely accurate. They have a typical accuracy of about 1-2%. One definite advantage is that corrosive liquids or liquids with solids can only do damage to the inexpensive and easily replaced pipe. They do however introduce a foreign substance into the fluid.

Although the level can be obtained without the liquid entering the piping, it is still possible to have blockages. However, blockages can be minimised by keeping the pipe tip 75mm from the bottom of the tank.

**Advantages**

- Simple assembly
- Suitable for use with corrosive fluids.
- Intrinsically safe
- High temp applications

**Disadvantages**

- Requires compressed air and installation of air lines
- Build-up of material on bubble tube not permissible
- Not suited to pressurised vessels
- Mechanical wear

**Application Limitations**

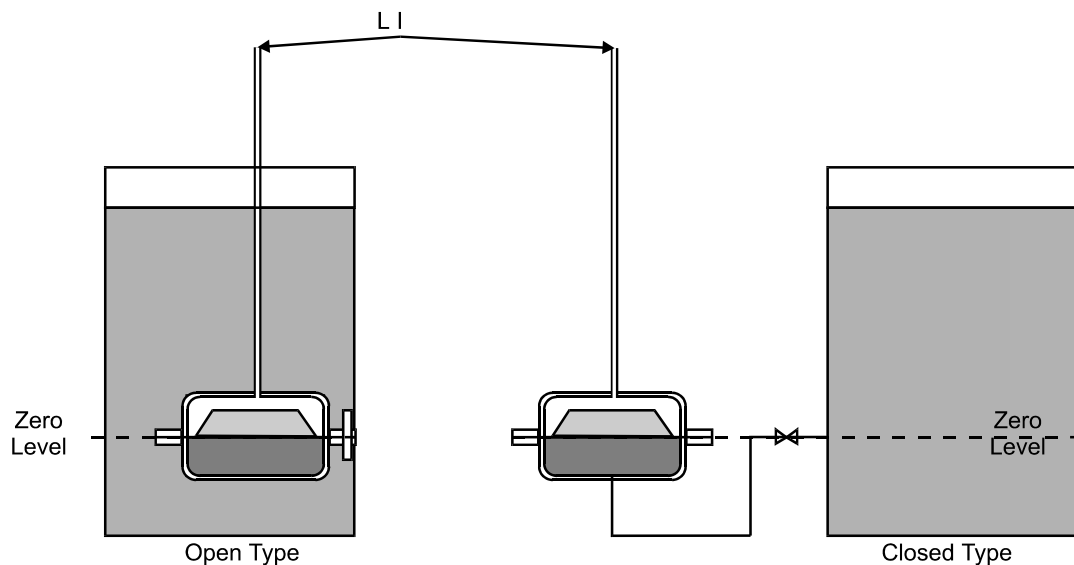
Bubble tube devices are susceptible to density variations, freezing and plugging or coating by the process fluid or debris. The gas that is used can introduce unwanted materials into the process as it is purged. Also the device must be capable of withstanding the maximum air pressure imposed if the pipe should become blocked. Rodding to clean the pipe is assisted by installing a tee section.

### 3.4.4 Diaphragm Box

The diaphragm box is primarily used for water level measurement in open vessels. The box contains a large amount of air, which is kept within a flexible diaphragm. A tube connects the diaphragm box to a pressure gauge.

The pressure exerted by the liquid against the volume of air within the box represents the fluid pressure at that level. The pressure gauge measures the air pressure and relates the value to fluid level.

There are two common types of diaphragm boxes – open and closed. The open diaphragm box is immersed in the fluid within the vessel. The closed diaphragm box is mounted externally from the vessel and is connected by a short length of piping. The open box is suitable in applications where there may be some suspended material, and the closed type is best suited to clean liquids only.



**Figure 3.9**  
**Diaphragm box measurements**

There are also distance limitations depending on the location of the gauge.

#### Advantages

Relatively simple, suitable for various materials and very accurate

#### Disadvantages

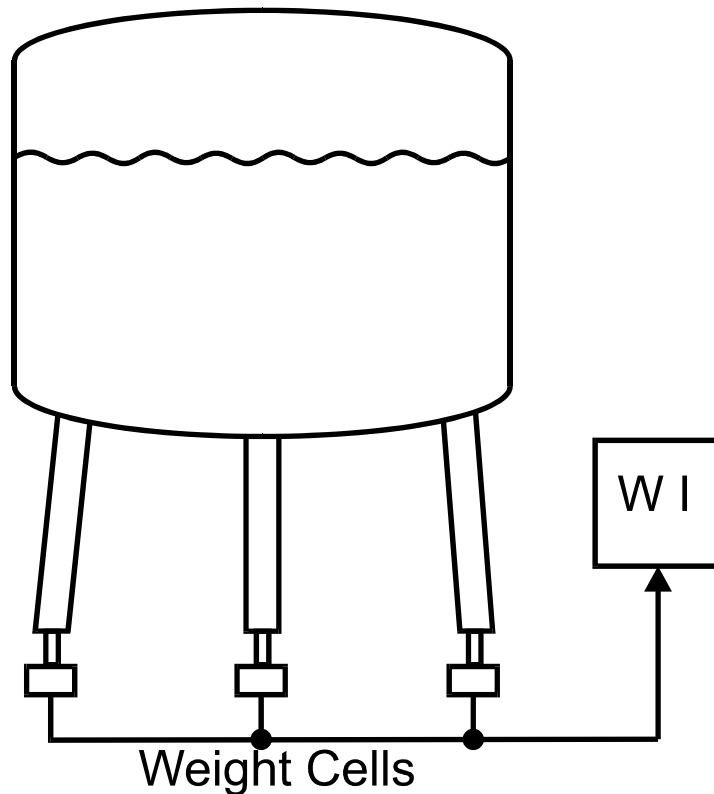
Requires more mechanical equipment, particularly with pressure vessels.

#### Summary

Very seldom used.

### 3.4.5 Weighing Method

This indirect type of level measurement is suited for liquids and bulk solids. Application involves using load cells to measure the weight of the vessel. With knowledge of the relative density and shape of the storage bin, the level is easy to calculate.



*Figure 3.10*  
*Level Measurement Using Weight*

#### Installation Techniques

Strain gauges can be mounted on the steel supports of a vessel or bin. Calibration is done quite simply by measuring the output when the tank is empty and again when full.

#### Advantages

- Very accurate level measurement for material of constant relative density

#### Disadvantages

- Requires a large amount of mechanical equipment
- Very costly
- Relies on consistent relative density of material

### **Application Limitations**

A large amount of mechanical equipment is required for the framework, and is also needed to stabilise the bin.

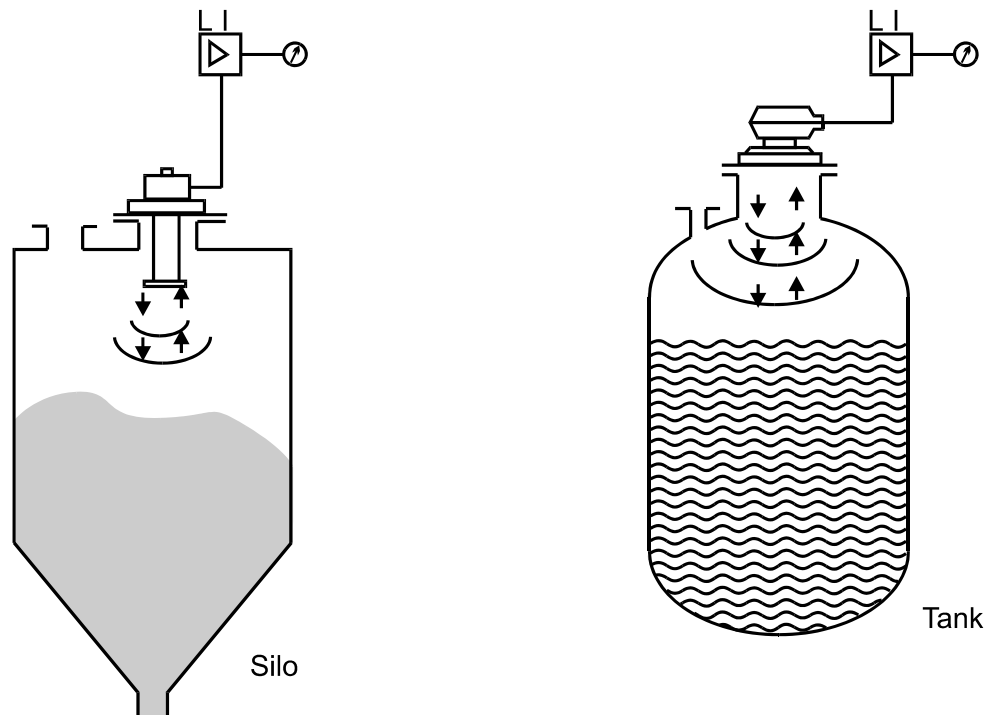
Measurement resolution is reduced because priority is given to the accuracy of the overall weight. Unstable readings occur when the bin is being filled or emptied. Because the overall weight is the sum of both the product and container weights wind loading can cause significant problems. For these reasons most installations use a four-load cell configuration.

## **3.5 Ultrasonic Measurement**

### **3.5.1 Principle of Operation**

Ultrasonic level sensors work by sending sound waves in the direction of the level and measuring the time taken for the sound wave to be returned. As the speed of sound is known, the transit time is measured and the distance can be calculated.

Ultrasonic measurement generally measures the distance between the contents and the top of the vessel. The height from the bottom is deduced as the difference between this reading and the total height of the vessel. Ultrasonic measurement systems are available that can measure from the bottom of the vessel when using liquid.



**Figure 3.11**  
**Ultrasonic measurement**

The original sound wave pulse has a transmission frequency between 5 and 40 kHz; this depends on the type of transducer used. The transducer and sensor consist of one or more piezo-electric crystals for the transmission and reception of the sound signal. When electrical energy is applied to the piezo-electric crystals, they move to produce a sound signal. When the sound wave is reflected back, the movement of the reflected sound wave generates an electrical signal, this is detected as the return pulse. The transit time is measured as the time between the transmitted and return signals.

### 3.5.2 Selection and Sizing

Below are listed some typical manufacturer's options.

#### Automatic Frequency Adaption

Optimum transmission relies on a certain resonance frequency which is dependent on the transmitter and application. This resonant frequency is also dependent on the build-up of dust, condensation or even changes in temperature.

The sensor electronics can measure the free resonant frequency during the current ringing of the membrane and changes the frequency of the next transmitted pulse to achieve an optimum efficiency.

Exact design specifications depend upon the manufacturer. Some manufacturers may vary the pulse rate and/or the gain (power).

As a guide, the transducer frequency should be chosen so that the acoustic wavelength exceeds the granule size (median diameter) by at least a factor of four.

#### Acoustic Wavelength in Air vs Frequency, Temperature

Frequency (kHz)	Wavelength (mm) at 0°C	Wavelength (mm) at 100°C
5	66	77
10	33	39
20	17	19
30	11	13
40	8	10

Table 3.1

#### Spurious Echo Suppression

Although ultrasonics can produce a good signal for level, they also detect other surfaces within a vessel. Other objects that can reflect a signal can be inlets, reinforcement beams or welding seams. To prevent the device reading these objects as a level, this information can be suppressed. Even though a signal may be reflected from these objects, their characteristics will be different. Suppression of these false signals is based on modifying the detection threshold.

Most suppliers have models that map the bin and the digital data is stored in memory. The reading is adjusted accordingly when a false echo is detected.

#### Volume Measurement

Most modern ultrasonic measurement devices also calculate volume. This is quite simple if the vessel has a constant cross sectional area. More complex, varying cross sectional area vessels require shapes of known geometry to calculate vessel volume. Conical or square shapes with tapering near the bottom are not uncommon.

#### 3.5.3 Selection Considerations

- Distance to be measured

The type of ultrasonic device must be able to cover the distance required. This is usually included in its specification sheets. Note that the general specifications are for clean air and a flat surface. The reason for variation in range is simply that a system designed for high accuracy and short distances will not be powerful enough for longer distances. Similarly a more powerful system may be too strong for short distances and cause too much echo and induced noise. It should be noted that new systems do have automatic variable gain to compensate for this. Temperature changes or dust, dirt and condensation on the sensor hamper the operation of the device.

- Surface of material



It is a fundamental requirement in this type of measuring system that part of the transmitted signal is reflected back from the surface of the product to be measured. The more distinct the measuring surface, then the more accurate and reliable the measured value.

The clarity of the surface can be obscured by:

- layer of foam on a liquid surface
- fine granules on bulk material
- excessive dust cloud with ore transfer

In the case of liquid, options can include measuring from the bottom of the vessel, to installing a mechanical form of foam removal. Dust extraction or a settling time may be required for the case or solids transfer where clouds are a problem. Small occurrences of either condition generally do not affect the measurement.

- Environmental conditions

Since the ultrasonic signal must pass through the air where it is installed, such factors as dust, steam, pressure, temperature and gas need to be considered.

- Acoustic noise

A common form of acoustic noise occurs when a truck tips a load of ore into a storage bin or hopper. The noise generated from the transfer of ore can affect and degrade the return signal quality.

- Pressure

In general, ultrasonic measurement systems are not affected by pressure variations. The only limitations that are imposed are due to the mechanical constraints of the equipment, and in the case of low pressure, the ability to transmit sound energy.

One limitation with pressurised vessels are that since they are fully enclosed there may be a problem with second or repeated echos.

- Temperature

Changes in temperature affect the speed of the sound wave and ultimately the transit time. The temperature sensor makes corrective adjustments. Errors can occur in situations where there is a varying temperature gradient over the distance of the measurement.

Operation of ultrasonic equipment can be up to 170°C, with the limitation being due to the transducer construction housing.

- Gas

As mentioned previously, this type of measurement is dependent on the speed of sound. The speed of sound not only varies with changes in temperature, but also with different media. Consequently, the speed of sound varies for different gases or vapours. The main recommendation is to consider the use of separate temperature sensors in the case of highly variable temperatures, which form in warm to hot liquids.

Gas	Speed of sound (m/sec) at 0°C
Air	331
Ammonia	415
Carbon Dioxide	259
Ethylene	317
Helium	965
Hydrogen Chloride	206
Methane	430
Nitrogen	334
Oxygen	316
Sulphur Dioxide	213

**Table 3.2**  
**Speed of sound in various gases**

- Mounting

Since the ultrasonic device is intended to measure the level, it requires an unobstructed path so that the only signal reflected is that of the material to be measured. The path of falling product, and reflections from surfaces of the holding vessel should be avoided. The bottom surface needs to be angled so that the reflected signal is directly back to the transmitter for a valid measurement. If the bottom of the vessel is at an angle so that the signal is reflected from a number of walls, the output from the device can be unpredictable.

The ultrasonic beam cannot be narrowed but a focalising cone can be used. All sensors have a dead zone, or blanking distance at which length they cannot sense any sound waves. This distance corresponds to the length of the transmitted signal and prevents the transmitted signal being detected as a return signal.

- Self-cleaning

In applications where splashing can occur, self cleaning probes may be required. Condensation, liquid and dust are atomised on contact with the highly active transducer face. This makes self cleaning probes resilient to build up reducing routine maintenance.

Transducer	Beam diameter	Blanking distance	Process material
10kHz	6°	1000mm	Liquids/dusty solids/powder/steam
20kHz	8°	600mm	Liquids/clean solids
30kHz	7.5°	300mm	liquids

**Table 3.3**  
**Transducer Selections**

With dual systems, both the transducer frequencies must be the same. The blanking distance also varies with the application.

#### 3.5.4 Installation Techniques

When measuring through dust, the transmitted signal is greatly attenuated and the sensing equipment has trouble in determining the level. There are two main components of an ultrasonic signal, the signal power and its frequency. It should be noted that although lower frequency sound is less attenuated by dust, it reverberates within the vessel creating a poor echo. A solution to measuring this type of process is to use a high frequency signal with high acoustic power.

Repositioning of the sensor is quite common for solving ultrasonic measuring problems.

#### 3.5.5 Advantages

- Non contact with product
- Suitable for wide range of liquids and bulk products
- Reliable performance in difficult service
- No moving parts
- Measurement without physical contact
- Unaffected by density, moisture content or conductivity
- Accuracy of 0.25% with temperature compensation and self-calibration

### **3.5.6 Disadvantages**

- Product must give a good reflection and not absorb sound
- Product must have a good distinct layer of measurement and not be obscured by foam or bubbling.
- Not suitable for higher pressures or in a vacuum
- Special cable is required between the transducer and electronics
- The temperature is limited to 170°C

### **3.5.7 Application Limitations**

The performance of an ultrasonic level transmitter is highly dependent on the echo it receives. The echo may be weak due to dispersion and absorption. Dispersion may be a problem on taller vessels and can be reduced by using a focalising cone.

In the case of sound absorbing materials, the echo signal can be greatly reduced, in which case higher energy systems may be required.

In applying ultrasonic level measuring equipment for more difficult applications, suitability may rely on past experience or require testing before permanent installation is carried out.

### **3.5.8 Summary**

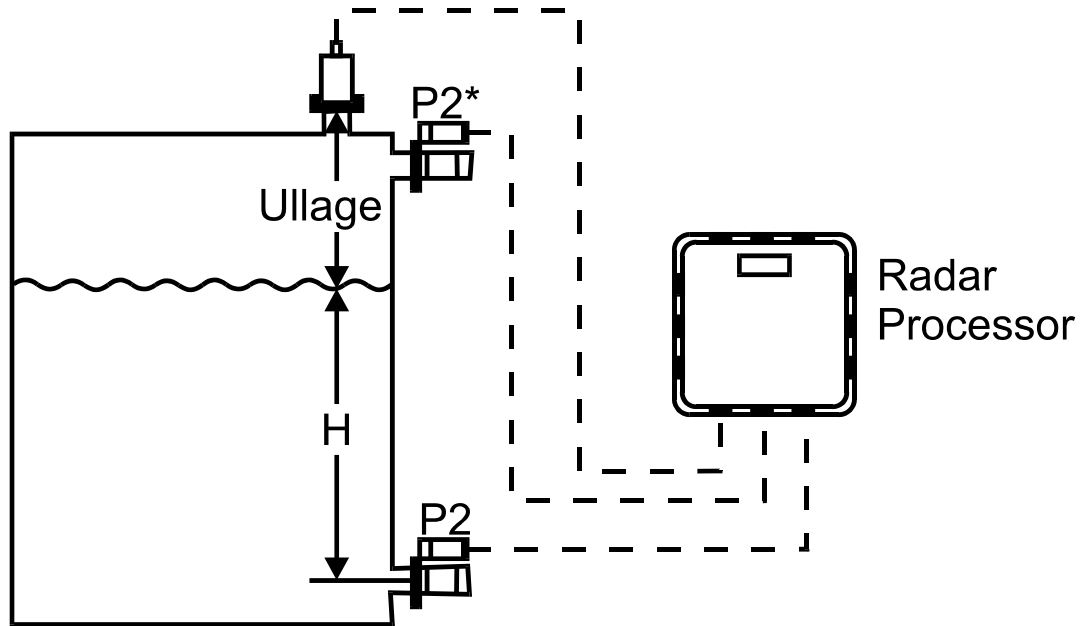
This type of level measurement has excellent reliability and very good accuracy. The other main advantage is that it is a non-contact technology, which limits corrosion and contamination with the contents of the vessel.

The large number of frequency transmitters available allows this type of sensing to be customised for each application.

## **3.6 Radar Measurement**

Radar gauges differ from ultrasonic in that they use microwaves instead of sound waves. Like ultrasonic devices they measure from the top of the vessel to determine the product level.

Two examples of radar gauges are the 5.8GHz and 24GHz systems. The higher transmission frequency can be used to detect dry, non-conductive materials with very low bulk density.



\* P2 required only on pressurized tanks.

*Figure 3.12*  
*Radar differential pressure hybrid system*

#### Advantages

- Used on difficult 'hard-to-handle' applications
- High accuracy
- Non-contact
- Measure level through plastic tanks
- Monitor contents of boxes or other multi-media material
- Detect obstructions in chutes or presses

#### Disadvantages

- Sensitive to build-up on sensor face
- Very expensive, A\$6-15k, depending on accuracy

#### Application Limitations

Radar gauges are quite specific in their application of use. Radar level measurement should be avoided on solids due to the weak signal reflection that occurs.

Although radar sensors cannot measure all the applications that nuclear radiation can, radar sensors are used in preference to ultrasonic or laser technology in applications that contain large amounts of the following:

- sensor coating
- liquid turbulence
- foam

### **Summary**

Radar level measurement is mainly used where temperature and pressure is a problem.

## **3.7 Vibration Switches**

Vibration sensing is only suitable for point measurement. They consist of an oscillating or tuning fork which is made to resonate in air. The resonance frequency will be reduced when the fork is brought into contact with the product.

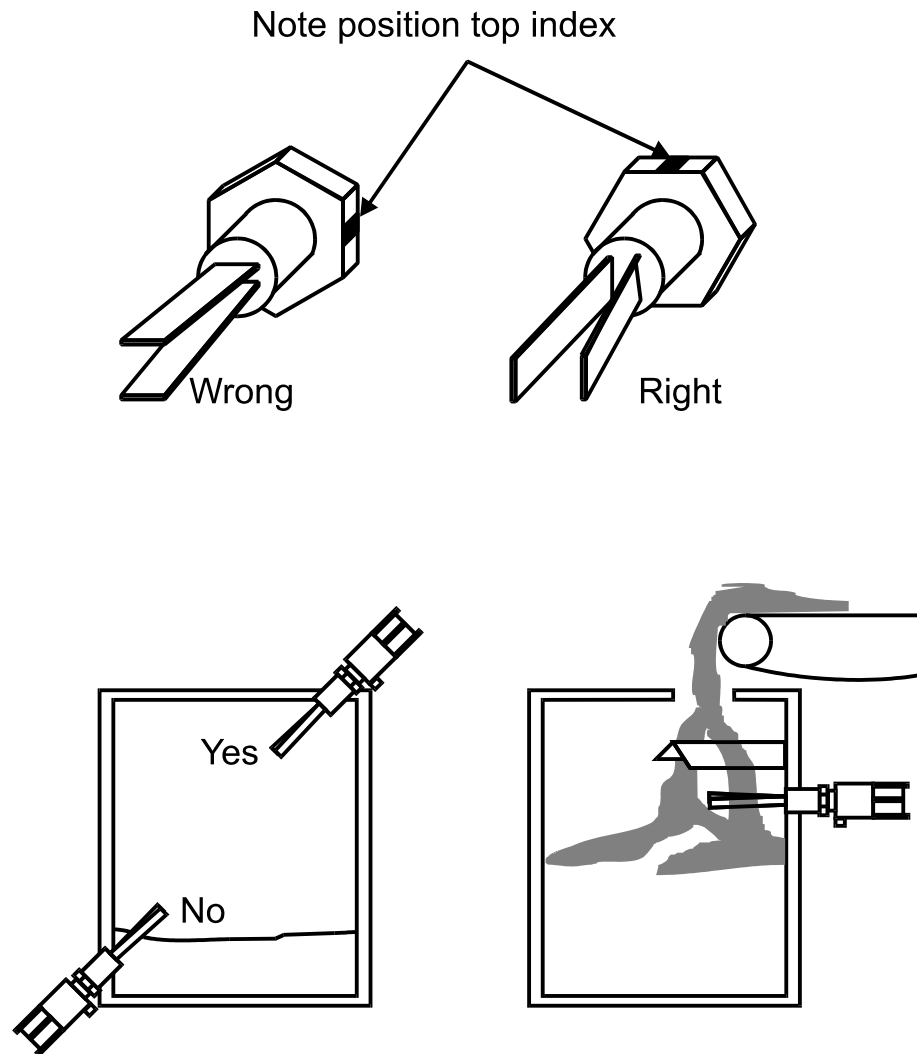
The type of fork used and its resonant frequency depends on the material to be measured. Their respective uses are listed as follows:

Tuning Fork:

- Bulk products in granular or powder form

Oscillating form:

- Liquids and slurries



**Figure 3.13**  
**Installation of tuning fork type level switches**  
*(courtesy of Endress & Hauser Inc.)*

#### Advantages

- Wide range of applications
- Inexpensive
- No adjustment or maintenance required

#### Disadvantages

- Grain limited to 10mm in size
- Same limitation for particles suspended in liquids

### **Application Limitations**

As previously mentioned, vibration level switches are limited to point or level detection.

## **3.8 Radiation Measurement**

Gamma radiation sources are chosen for use in level detecting equipment because gamma rays have great penetrating power and cannot be deflected.

Level measurement with radiation works on the principle of passing gamma radiation through the material to be measured. As the radiation passes through this material, the level can be determined by the amount of attenuation.

### **The Source**

The main component of this type of measuring device is the radioactive source. The two common types of radioactive sources are Caesium 137 (Cs 137) and Cobalt 60 (Co 60).

The activity of the radioactive substance decreases with time. The time taken for the activity of such a substance to halve is termed its half-life. Cobalt 60 has a half-life of 5.3 years while Caesium 137 on the other hand has a half-life of 32 years.

With Caesium 137 having such a long half-life, there is less need to apply any correction for the decreasing activity level. Cobalt 60, which decays a little more quickly requires a half-life correction factor to compensate for the decay in activity. Modern measurement equipment now have automatic half-life correction, and as such the choice of source is no longer a critical factor.

It should also be noted that although the source decays, the electromagnetic energy that is produced cannot induce other materials to become radioactive. This means that gamma sources can be used around such materials as food and also on food grade packaging materials.

### **Source Sizing**

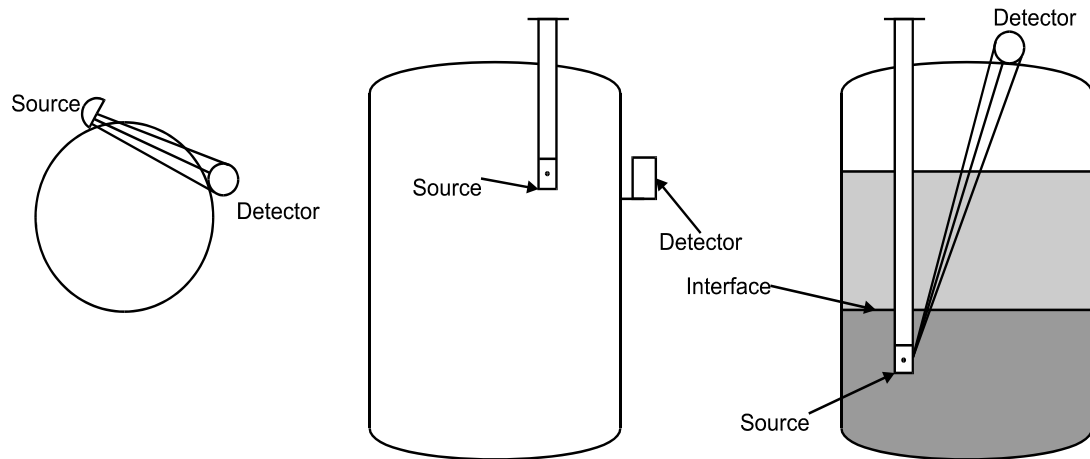
One of the advantages of this type of level measurement is that it can be mounted outside of the vessel of the material to be measured.

In such installations, the radiation of the source must penetrate substances other than air. There is a limit on the minimum radiation field intensity at the detector and therefore consideration of the attenuation of the source through the vessel walls and process material must be taken into account. This ensures that the radiation intensity does not go below the required sensing level at the detector.



This information involves numerous variables and is well researched and documented. However, sizing of the source is probably more easily and accurately obtained from the supplier when specifying and selecting the measuring equipment.

In large vessels which require a large source to overcome the attenuation through the material, the source size may inhibit the use of such a measurement technique. In such applications, a cord may be selected which reduces the amount of attenuation of the source due to the reduced area of material and therefore the source size is kept to a minimum.



**Figure 3.14**  
*Relative locations of radiation sources and detectors*

### The Strip Detector

The detector for continuous measurement is a type of scintillation counter and photomultiplier. This type of sensing has the advantage of high sensitivity of the scintillation crystals (compared to Geiger counters) coupled with the safety and economy of a point source.

The rod scintillation counter is a rod of optically pure perspex within which scintillation crystals are uniformly distributed. In the presence of gamma radiation, the scintillation crystals emit flashes of light which are then detected by a photomultiplier at the base of the rod and converted into electrical pulses.

A continuous series of reference flashes are generated by an LED onto a fibre optic link through the total length of the scintillator rod. This is done to monitor the critical optical link between the scintillation rod and the photo-multiplier. Irrespective of whether the rod is exposed to radiation, these reference flashes must be sensed by the photomultiplier. An alarm is activated if they are not received.

The level of radiation is converted into a PCM (Pulse Code Modulated) signal by the electronics mounted in the detector and transmitted to the measurement amplifier.

### **Point Level Measurement**

The detector is mounted adjacent to the source and is the measuring device. For level switching there are two commonly used types:

- The Geiger-Mueller (G-M) tube
- The Gas ionisation chamber

The G-M tube has a wire element anode in the centre of a cylindrical cathode. The area between the anode and cathode is filled with an inert gas and sealed. A voltage is applied across the terminals (250-300 V). When the gamma radiation ionises the inert gas, there is an electrical breakdown between the anode and cathode.

The frequency of the breakdowns is relative to the intensity of the gamma radiation. The field strength is determined by counting the pulses produced over a given time interval.

The other common detector is the gas ionisation chamber. The ionisation chamber is similar to the G-M tube in that it is filled with an inert gas and sealed.

The main difference is that instead of applying a breakdown voltage, a lower voltage (typically 6V) is applied across the terminals. When the chamber is exposed to gamma radiation, ionisation occurs and a continuous current is emitted from the detector. As the vessel fills, gamma energy is blocked from reaching the detector causing less ionisation producing a proportional change in the signal. A high level results in a low current output, with a low level producing a high output.

### **Continuous Level Measurement**

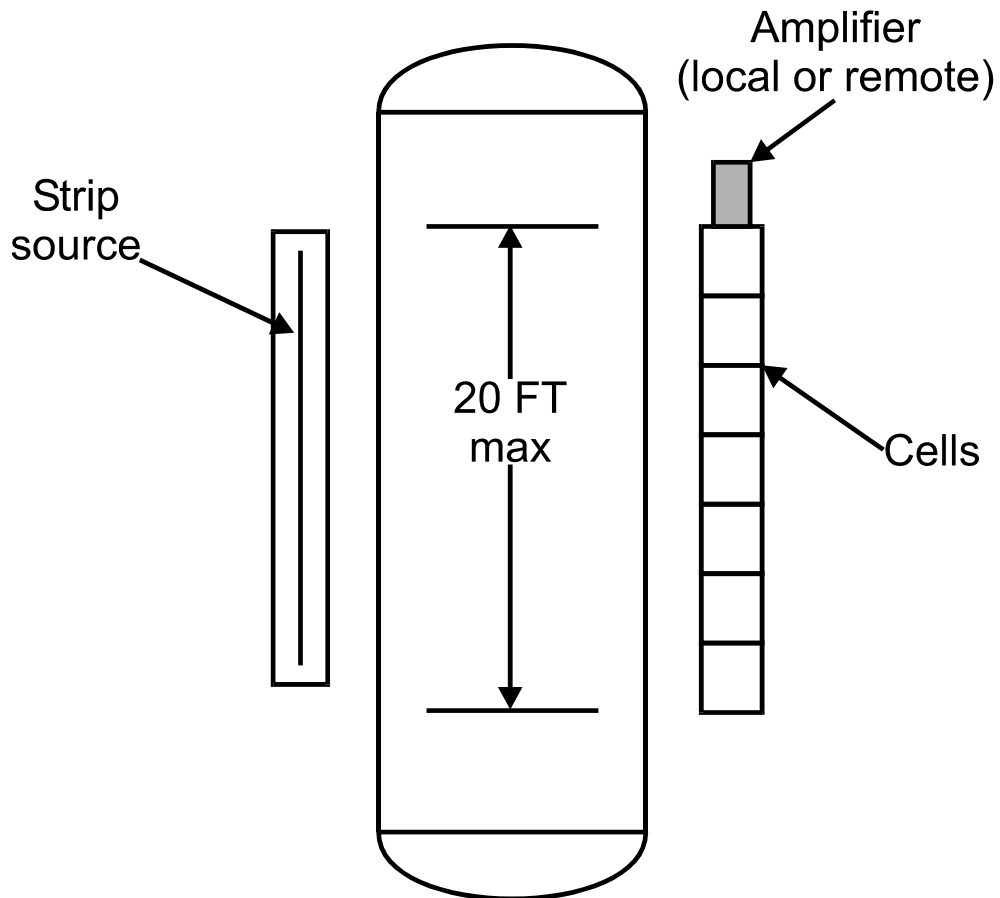
There are two common sources for continuous level measurement:

- Strip source
- Point source

Both of these methods use the strip detector.

The strip source is more accurate as it radiates a long, narrow, uniform beam in the direction of the detector. As the level changes, the detector is covered and protected from the source and the corresponding response changes. The response is uniform and linear over the entire span, producing a linear signal that corresponds with changes in level. Exceptions are at 0% and 100% where non-linear end effects occur.

Effects of density changes can be overcome by sizing the source for the lower density so that higher densities do not affect the reading on the detector.



**Figure 3.15**  
**Continuous level detection by use of strip source and electronic cell receivers**

The strip source is accurate and provides a good linear response, however it is the more expensive. The point source is a cheaper alternative.

The point source works in a similar way to the strip source system, in that the strip detector measures the radiation from the source. The radiation sensed by the detector is still attenuated with level, however the point source system produces a non-linear response with level change.

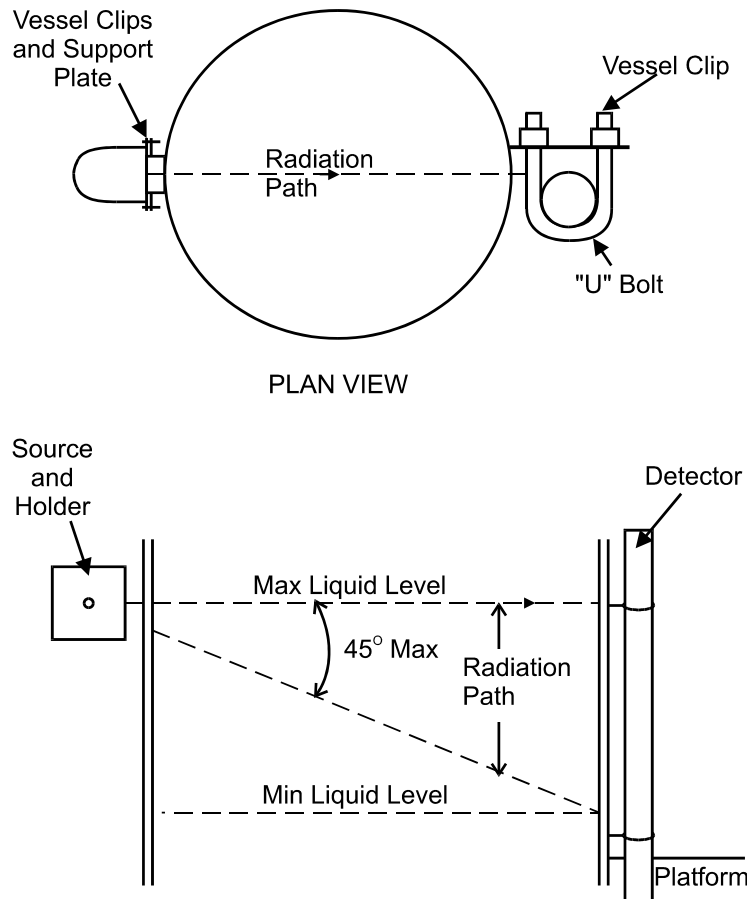
The source holder generally has an exit angle of 20 or 40 degrees. The radiation beam leaves the aperture directly and must be aimed by the mounting of the source holder. The angle of the source holder is half that of the radiation exit angle, allowing the source holder to be mounted at the highest measuring point.

Note that the low level gamma energy that is emitted from the source does so at a precise shape through the vessel wall. It is then measured on the other side with the detector.

There are a number of factors that change when the level rises and falls:

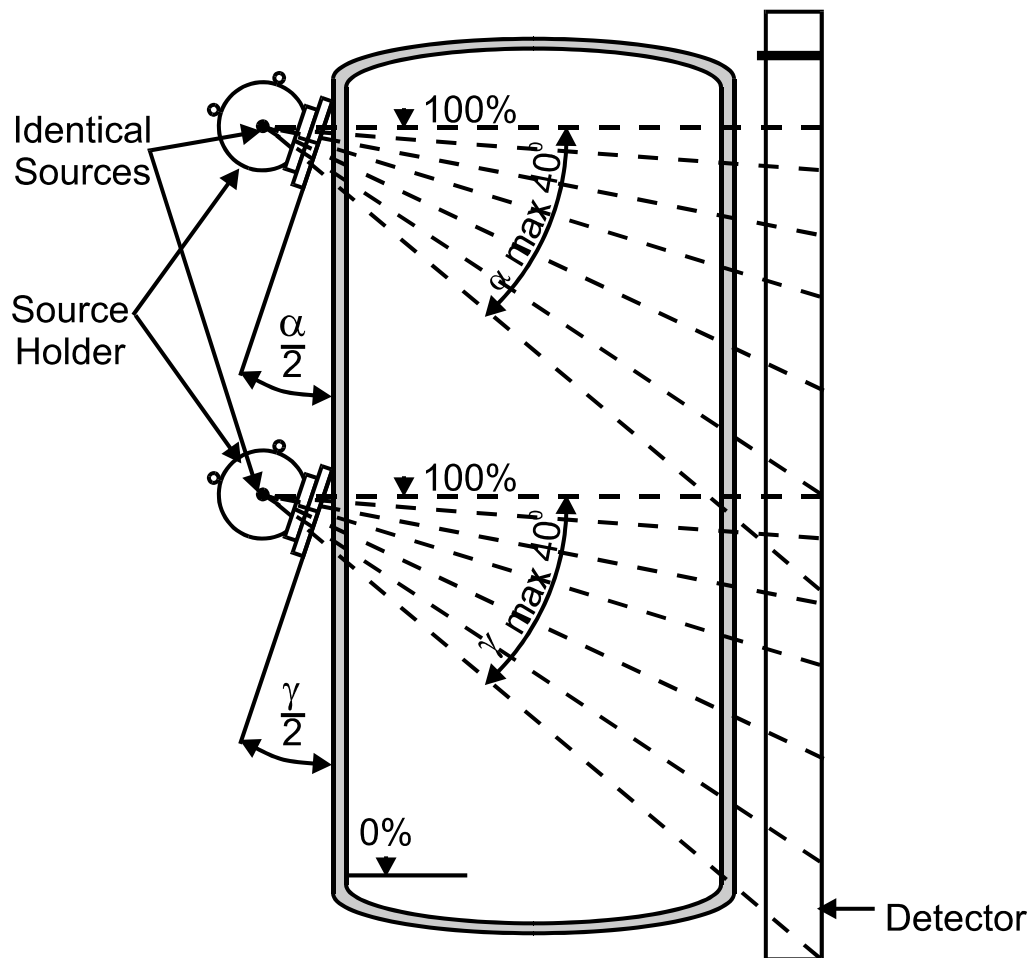
- thickness of material
- geometry of radiated source
- distance from the source to the detector
- free space

This system non-linearity can be rectified electronically in the receiver



**Figure 3.16**  
**Radiation instrument installation**

Ways to improve linearity and accuracy at the lower end is to use one strip detector and two or more point sources. Obviously cost may be an inhibiting factor.



**Figure 3.17**  
*Two point sources with a strip detector.*

### Troubleshooting

The method for testing and calibrating radiation level detectors is quite simple. Testing of 100% full is done by closing the source shutter, as if the vessel were full. To test or calibrate for the actual level, a portable Geiger counter is used. By running the Geiger counter down the wall between the vessel and the detector, the level is the point where the liquid screens off the source and the counter readings decrease rapidly.

### Advantages

- Suitable for a variety of products
- Mounted without obstruction
- Can be mounted external to the vessel

### **Disadvantages**

- Must always be mounted on the side of the vessel
- Special safety measures are required for the use of gamma radiation
- May also involve licensing requirements
- Expensive

### **Application Limitations**

The point source method of continuous level measurement is cheaper than the strip source. However, if not properly corrected, the non-linearity can cause problems with control systems performing continuous control. This is of particular concern if operating over a significant range, in which case changes in accuracy may become an issue.

The point source is highly suitable where varied alarm or indication levels are required and also provide an added advantage in terms of radiation safety.

Strip sources are limited to Co60 due to the weight of Cs137. Limitations also apply to the strip source of Co60, which is quite heavy, cumbersome and expensive.

### **Summary**

The advantage of this type of measurement is that it can be performed from outside the vessel. Such situations may be in the use of very coarse, abrasive, corrosive or extremely adhesive products. Applications with very high pressures or temperatures such as reactors or furnaces may also require external measurement techniques.

This type of measurement is very seldom used due to the expense and safety regulations that are required to operate radioactive equipment.

## **3.9 Electrical Measurement**

### **3.9.1 Conductive level detection**

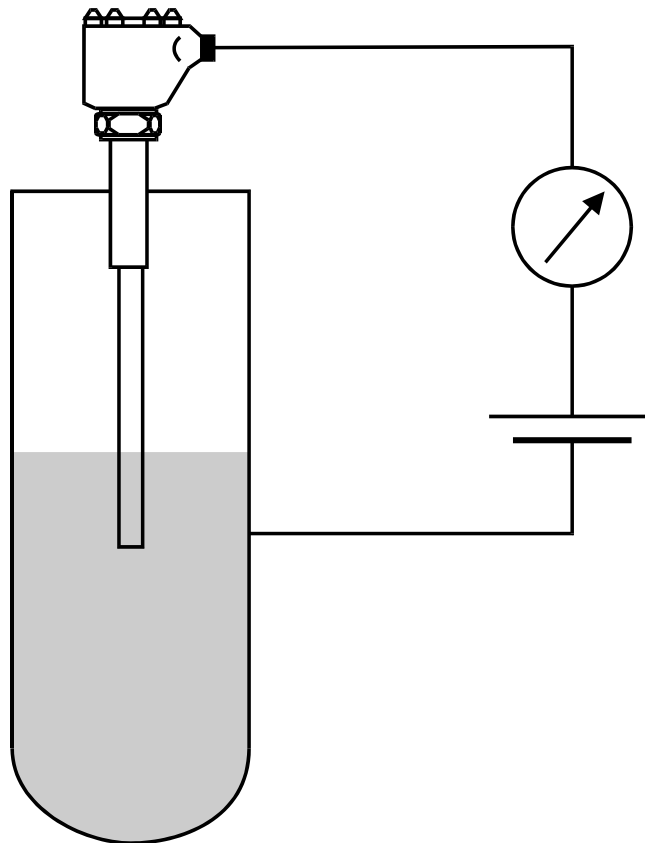
#### **Basis of Operation**

This form of level measurement is primarily used for high and low level detection. The electrode or conductivity probe uses the conductivity of a fluid to detect the presence of the fluid at the sensing location. The signal provided is either on or off.

When the fluid is not in contact with the probe, the electrical resistance between the probe and the vessel will be very high or even infinite. When the level of the fluid rises to cover the probe and complete the circuit between the probe and the vessel, the resistance in the circuit will be reduced.

Probes used on vessels constructed of a non-conductive material must have a good earth connection. The earth connection does not need to be an earthing wire – it could be a feed pipe, mounting bracket or a second probe.

Corrosion of the electrode can affect the performance of the probe. Direct current can cause oxidation as a result of electrolysis, although this can be minimised by using AC power.



**Figure 3.18**  
**Conductive level detection**

For level control, as opposed to level detection, two probes can be used.

There are many different types of probes available. In the case of liquids that leave a residual coat on the probe, a low resistance version is required. This version is capable of detecting the difference between the actual product when the probe is immersed and a residual resistance when the probe is exposed. Such applications for this type of sensor are products which froth, such as milk, beer or carbonated drinks.

Some of the disadvantages with conductivity switches are that they only work with conductive and non-adhesive fluids. Also in intrinsically safe applications, where sparking is not permissible, the sensors must operate at very low power.

Conductivity switches are low cost and simple in design.

They are a good indication for protection on pumps in the case of dry running detection.

### **Selection and Sizing**

In assessing the application for a conductivity probe, a small AC voltage from a transformer can be applied to a metal rod to simulate the probe and the vessel wall. For accuracy, this needs to be at the same position and distance from the wall as the probe. Then with about 50mm of the rod immersed in the fluid, the current can be measured and the resistance calculated:

$$R \text{ in ohms} = V \text{ in volts} / I \text{ in amps}$$

If the calculated resistance is less than that required for the instrument, then a conductivity probe and amplifier can be used. This is not a highly accurate means of determining the suitability, however it does give a reasonable indication. Problems with this test vary as it depends on the surface area of contact and the location of the probe.

### **Installation Techniques - Mounting in tanks**

Liquids causing build-up:

Vertical mounting in the tank from above is recommended when using liquids which leave a conductive deposit on the insulation. Lateral mounting in a tank is suitable if the liquid, after clearing the insulation, only leaves a layer which is a poor conductor.

Mounting point:

It must be ensured that the liquid does not touch the conductivity probes when the tank is filling. The probes should also not touch the metal walls or any other electrically conductive installations.

Mounting from above:

If mounting from above, it should be noted that the level at which the switch is triggered may be uncertain. The switch may activate with only a few millimetres of liquid covering the probes, or on less conductive material it may require the probe to be fully immersed.

Mounting from the side:

Probe lengths greater than 120mm are generally adequate for side mounting. If it is unavoidable and the probe has to be mounted in a tank where the liquid can cause build-up, then longer probes may be required. Longer probes have a higher contact resistance ratio between covered and free probes that have insulation with some conductivity. If the probe is to be mounted from the side, then it should be pointed slightly downwards to enable the liquid to drip off more easily. This can assist in reducing the conductive build-up on the insulation.



### **Installation Techniques - Mounting in pipes**

#### Selecting probe lengths:

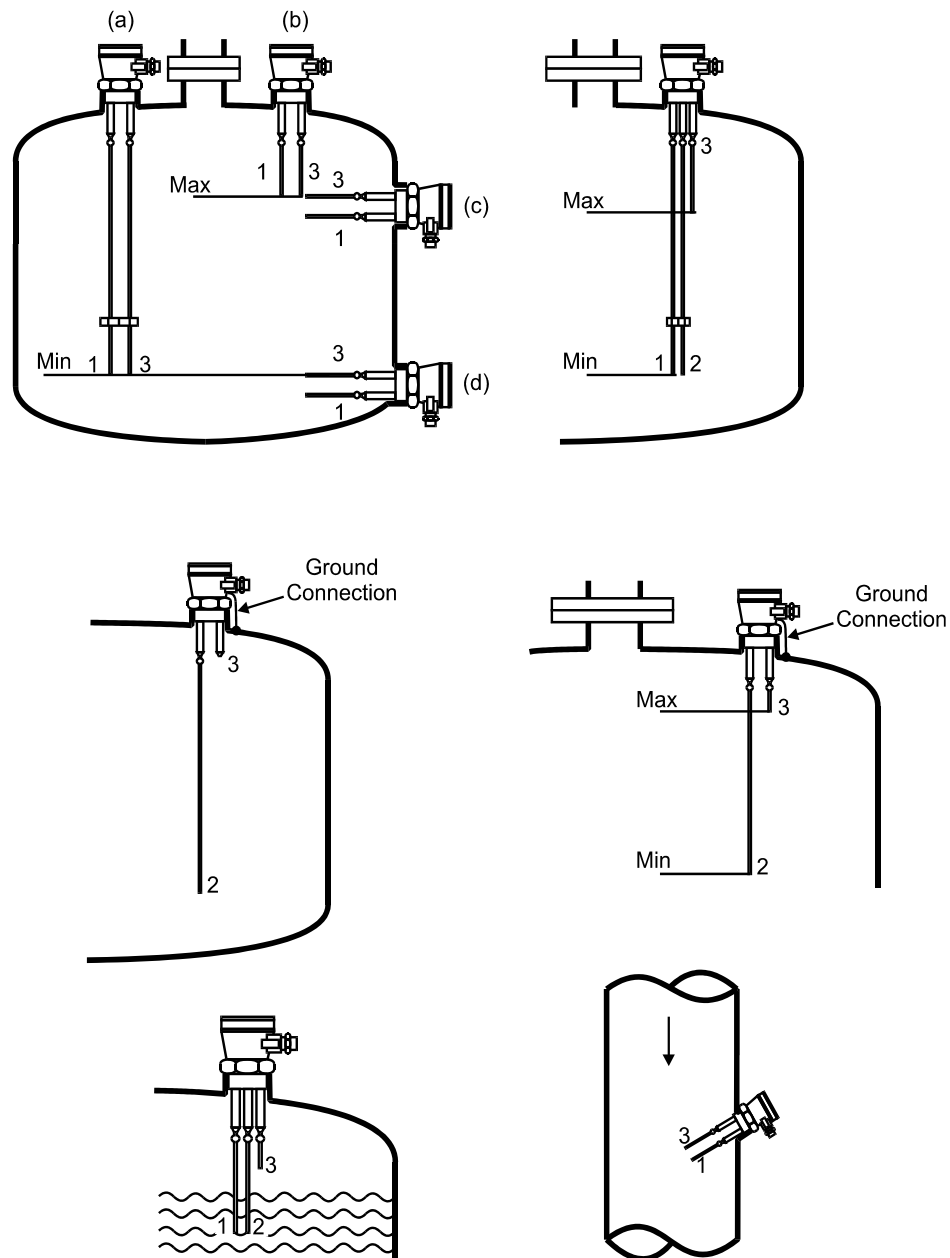
The shortest possible probe length should be used. This minimises the effects on the flow and also simplifies mounting.

#### Mounting point:

In flow applications, there can be considerable loading on the probe. When installing the probe, take into account the maximum lateral load of the probe. Mount the probe away from the flow by taking into account the flow velocity, viscosity and pipe diameter.

#### Contaminants:

Hard solid particles in the liquid can lead to wear of the insulation, this is particularly for flow applications. Another problem occurs when long and fibrous debris settles on the rod probes and produces errors in measurement.



**Figure 3.19**  
**Installation examples**

### Advantages

- Very simple and inexpensive
- No moving parts
- Good for dual point control (level switching control) in one instrument
- Good for high pressure applications

### **Disadvantages**

- Contamination of probe with adhering materials can affect results
- Limited application for products of varying conductivity
- Intrinsic safety designs need to be specified if required
- Restricted to conductive and non coating processes
- Possible electrolytic corrosion

### **Application Limitations**

One of the main limitations is that the liquid needs to be conductive. The manufacturer specifies the required conductivity level. A typical figure for effective operation would be below  $10^8$  ohm/cm resistivity.

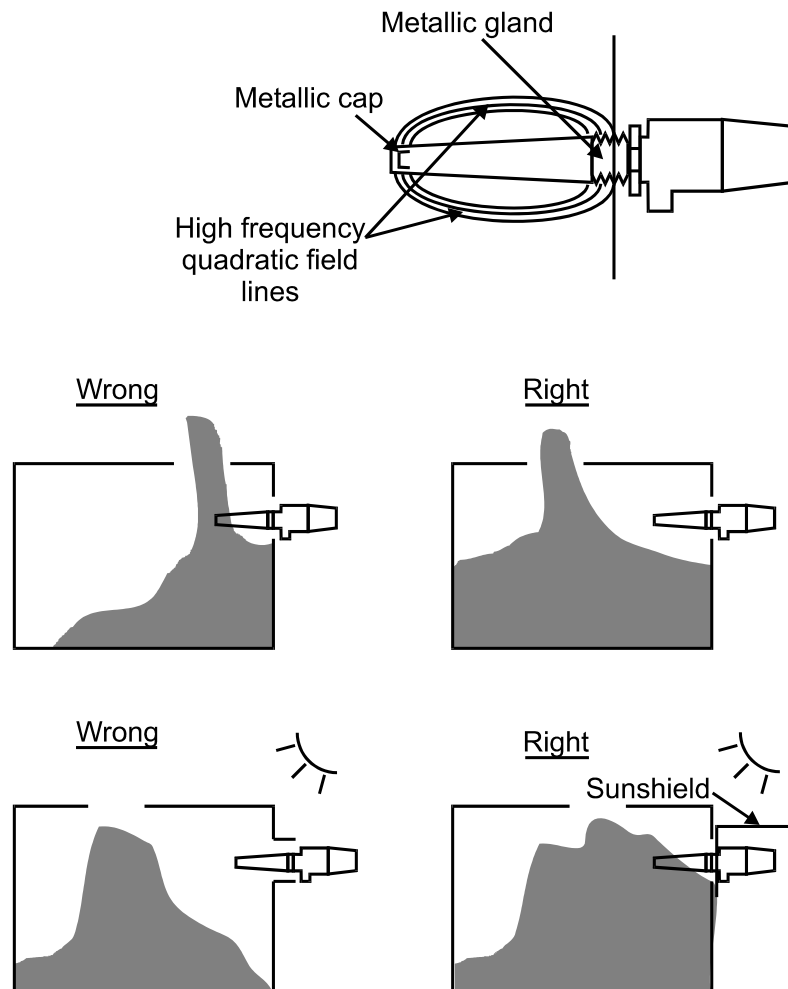
Problems may arise when detecting liquid that is being agitated or is turbulent. Due to the low cost of this type of measurement, it may be desirable to install two probes to detect the same level. Alternatively, a small vertical distance between the two probes can be used to provide a deadband or neutral zone. This can protect against cycling should splashing occur (a time delay serves the same purpose).

### **3.9.2 Field Effect Level Detection**

Whereas the conductive probe relies on the conductivity of the fluid, the field effect probe relies on the fluid (or material) having electrical properties different to air (or the void medium).

The field effect probe produces a field between the metallic cap and the metallic gland. The metallic cap is located at the end of the probe, with the gland about 200mm away at the mounting into the vessel.

When a liquid, slurry or even solid material breaks the field, the high frequency current increases and triggers the switch.



**Figure 3.20**  
**Field effect level switch and its installation**  
*(courtesy of Endress & Hauser Inc.)*

Advantages and disadvantages are similar to those for the conductivity probe with the following differences:

#### **Advantages**

- Suitable for conductive or non-conductive applications

#### **Disadvantages**

- Limited in high pressure and temperature applications

#### **Application Limitations**

Due to the added expense, with only a limited number of advantages, only a few manufacturers use this technology in their products.

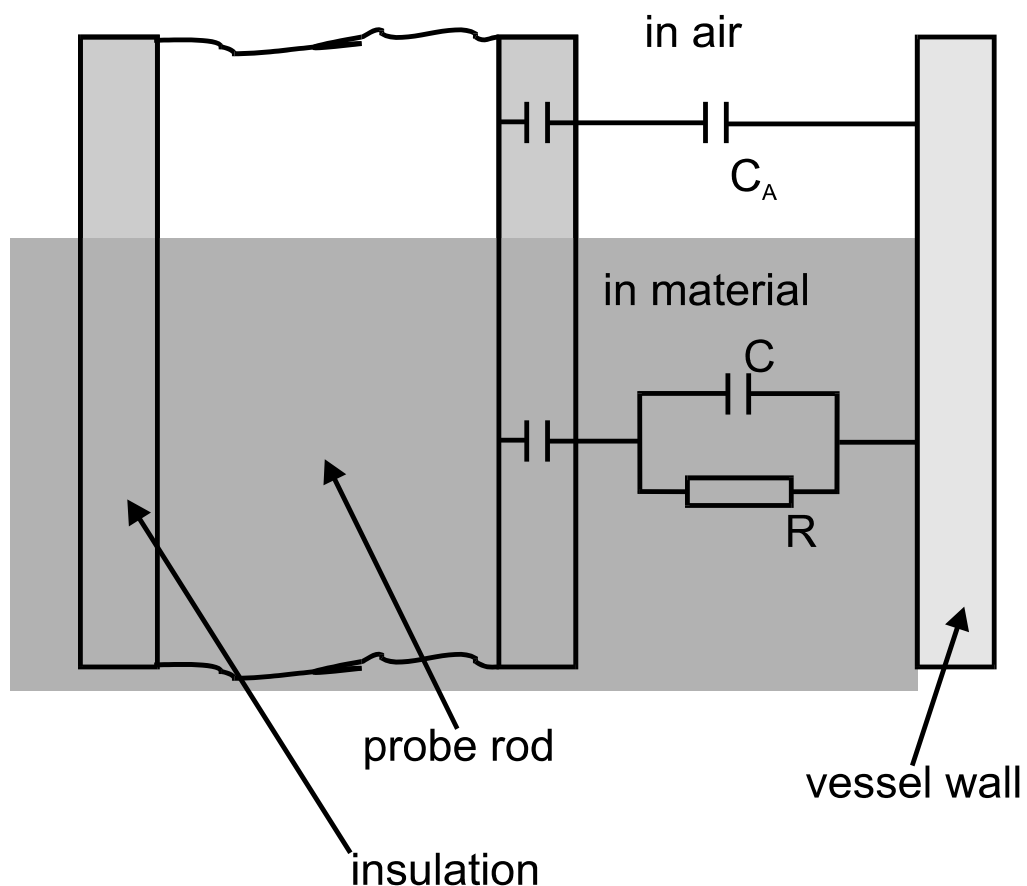
### 3.9.3 Capacitive Level Measurement

#### Basis of Operation - Non-conductive process material

Capacitive level measurement takes advantage of the dielectric constant in all materials to determine changes in level. The dielectric, in terms of capacitance, is the insulating material between the plates of the capacitor. The dielectric constant is a representation of a materials insulating ability.

Quite simply, a capacitor is no more than a pair of conductive electrodes with a fixed spacing and dielectric between them.

Capacitance is not limited to plates, and can be measured between probes or any other surface connected as an electrode. When a probe is installed in a vessel, a capacitor is formed between the probe and the wall of the vessel. The capacitance is well defined for many materials, and is quite low when the probe is in air. When the material covers the probe, a circuit is formed consisting of a much larger capacitance and a change in resistance. It is the changes in the dielectric constant that affects the capacitance and is ultimately what is measured.



*Figure 3.21*  
Simplified circuit diagram showing capacitance measurement  
with fully insulated probes

An alternative to this is the measurement of capacitance between two probes (electrodes).

### **Basis of Operation - Conductive process material**

Simple capacitive measurement is generally performed on non-conductive process material. In sizing an application for suitability, one of the concerns is the conductivity of the material. Problems arise when using a conductive material as this connects the plates together (an electrical short). As capacitance relies on the insulation (or dielectric), then the ability to measure capacitance is impaired.

In conductive applications, the process material is grounded by its contact with the vessel wall. The only insulation (or dielectric) is the insulation on the capacitive probe. As such, the rising process material does not increase the capacitance by inserting itself between the plates as in the case of a non-conductive material. However, it increases capacitance by bringing more of the ground plate in contact with the probe insulation.

The added advantage of this type of measurement, is that not only is the capacitance measurable, but also simplified because the measurement is independent of the dielectric constant of the process material.

### **Selection and Sizing**

Non-conductive process materials would include hydrocarbons, oils, alcohols, dry solids or similar. Process fluids that are water-based and acids can be considered as conductive.

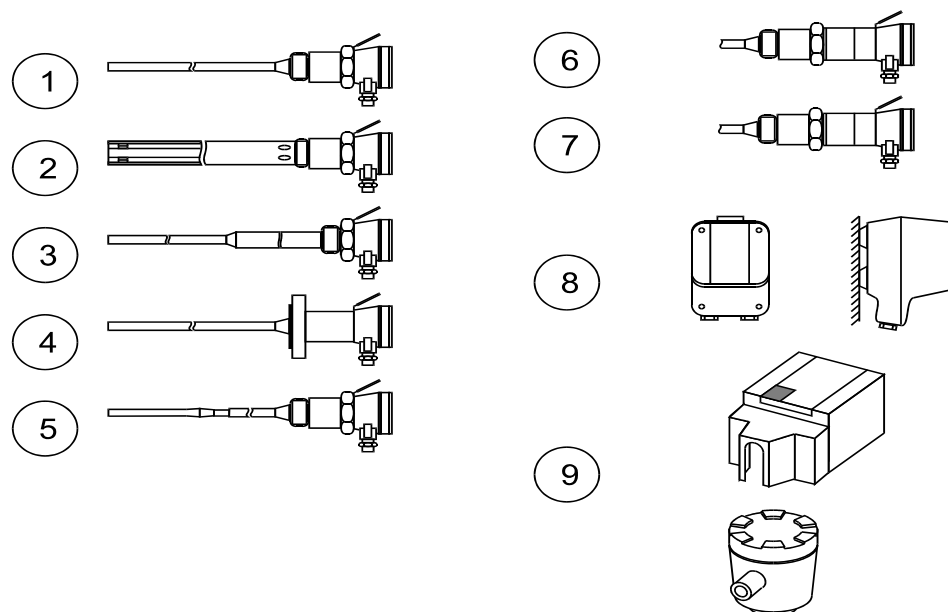
If the conductivity exceeds a specific low threshold, then any changes in the area between the probe and the wall will not be detected. A useful numerical criterion is that materials with a relative dielectric constant of 19 or more, or a conductivity of 20 micro ohms or more, may be considered conductive. If uncertain, the process material should be considered as being conductive.

For conductive applications, the capacitive probe will need to be insulated. This is typically done with Teflon.

Screening on the probe prevents build-up of material or condensation in the vicinity of the process connection. Probes that have active build-up compensation for limit switching cancel out the effects of builds-up on the probe.

There are a number of versions of probe designs that account for conductivity and build-up. Below is a list of some of the advantages when selecting a particular probe type:

- 1 - Probe without ground tube:
  - for conductive liquids
  - for high viscosity liquids
  - for bulk solids
- 2 - Probe with ground tube:
  - for non-conductive liquids
  - for use in agitator vessels
- 3 - Probe with screening:
  - for long nozzles
  - for condensation on the roof of the vessel
  - for build-up on the vessel wall
- 4 - Probe with fully insulated screening
  - extra protection especially for corrosive materials
- 5 - Probe with active build-up compensation for limit detection
  - for conductive build-up on the probe
- 6 - Probe with gas tight gland
  - for liquified gas tanks (if required)
  - prevents condensation forming in the probe under extreme temperature changes
- 7 - Probe with temperature spacer
  - for higher operating temperatures

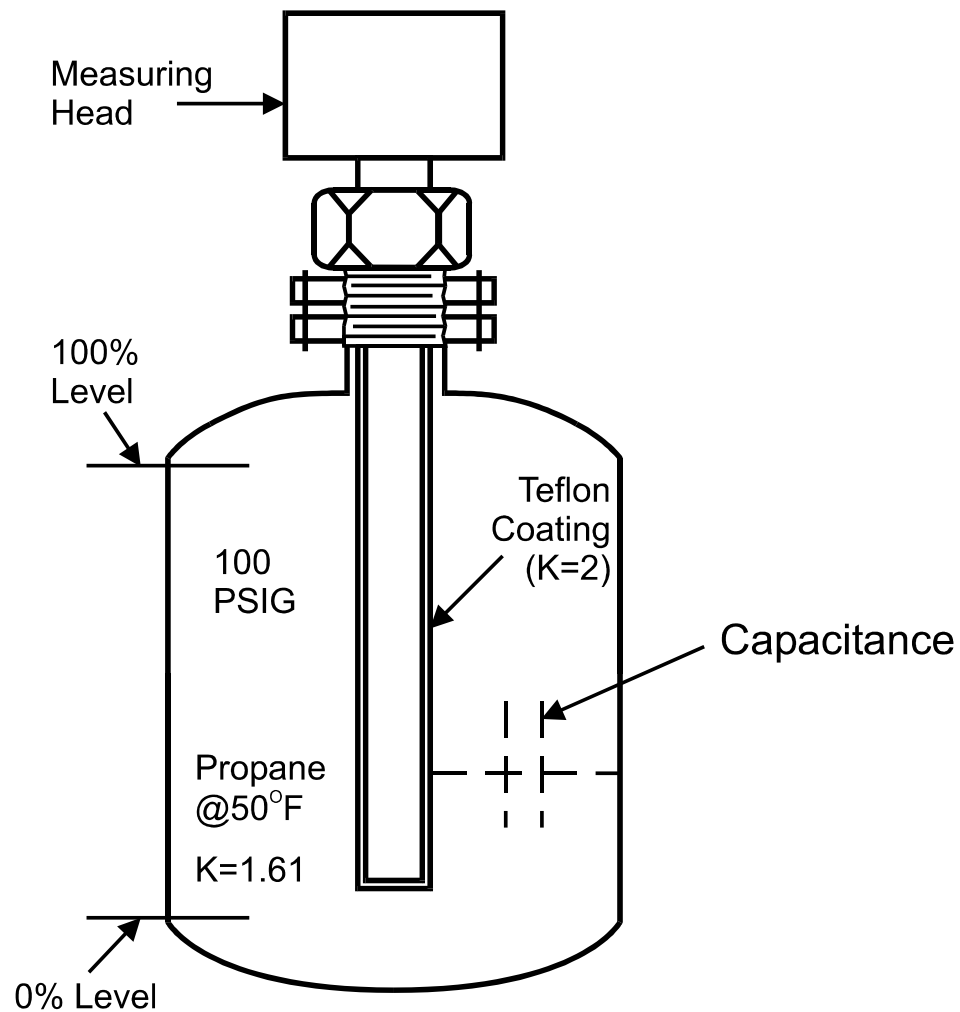


**Figure 3.22**  
**Probe versions**

## Installation Techniques

In practice for capacitive level measurement, the capacitor is formed from the wall of the vessel, and an insulated probe mounted in the wall. In the case of non-conductive walls (eg. reinforced concrete) iron reinforcement is adequate to act as one plate of the capacitor. For plastic tanks, a metal pipe or a grill placed around the probe or even a metal strip placed on the outside of the tank may be used.

In designing a capacitive measurement system, the three main areas for consideration are Mounting, Surface and Distance.



**Figure 3.23**  
*Typical capacitance probe installation*



### Mounting:

Nozzles are used in mounting the probe. These often have flanges and care needs to be taken to ensure that sediment cannot build-up in any voids around the flange. The chances of sediment being deposited in the nozzle are high. This is also exactly where the probe is most sensitive, as it is the closest area between the probe and the vessel.

Condensation is also a problem and can occur in voids much the same as the contaminants already mentioned.

Contamination of the nozzle can be avoided by projecting the probe into the vessel. One of the common methods is to replace the connection tube with a threaded socket, which is welded directly into the wall of the vessel. The screw connector of the probe fits directly into this, and the probe will then project directly into the vessel. This type of fitting is also less expensive.

Another method of avoiding contamination of the nozzle is by using a probe that is inactive along that part of the stem. In cases where it is not possible to modify an existing nozzle because of high pressure, then a probe with an inactive length can be used. In such a case, the active part of the probe is separated from the area most susceptible to condensation or contamination by the inactive section.

### Surface:

The change in capacitance can be quite small in applications that have a low dielectric constant or a short probe. To increase the change in capacitance and ultimately the sensitivity of the device, the capacitance can be increased. Increasing the surface area of the probe is an easy way to increase the capacitance. Because of their high relative permittivity, conductive liquids do not require an increased surface area.

### Distance:

The change in capacitance can also be increased by decreasing the distance between the two capacitor plates. The most common example of this is the use of a ground tube probe which eliminates the non-linear situation.

### Insulation:

The screw-in boss section or flange of a capacitance probe will always be insulated from the vessel but the probe rod itself can be either fully or partially insulated. In analogue level measurement, a fully insulated probe is always used to prevent capacitive short-circuiting. If a partially insulated probe is used for analogue measurement in a conductive material, then a reading of 100% occurs when the conductive material completes the circuit.

Level limit switches can use both fully insulated and partially insulated probes. Partially insulated probes are less expensive and give a larger change in capacitance. Again, for conductive fluids, only fully insulated probes are used. This also applies for materials that can contaminate the probe.

Capacitive level measurement is suitable for both limit detection and continuous level measurement of liquids, pastes and light bulk solids. Capacitive systems work reliably and accurately in extreme temperatures (both high and low), high pressure and vacuum, where there is build-up of material, explosion-hazardous areas and highly corrosive environments.

### **Typical Applications**

Capacitive level measuring instruments are used for level detection in silos, tanks and bunkers, for both limit detection and continuous measurement. These instruments are typically used in all areas of industry and are capable of measuring liquids as well as solid materials.

### **Advantages**

- Highly suitable for liquids and bulk solids
- No moving parts
- Suitable for highly corrosive media

### **Disadvantages**

- Limited in its application for products of changing electrical properties (especially moisture content)

### **Application Limitations**

Generally, capacitance level systems require calibration after installation, although some exceptions do exist.

They are limited in applications where levels of foam or other process materials with air bubbles occur.

## **3.10 Density Measurement**

Density is defined as the mass per unit volume. Specific gravity is a unitless measurement. It is the ratio of the density of a substance to the density of water, at a standard temperature. This term is also referred to as the relative density.

The measurement and control of liquid density can be quite critical in industrial processes. Density measurement gives useful information about composition, concentration of chemicals or of solids in suspension.

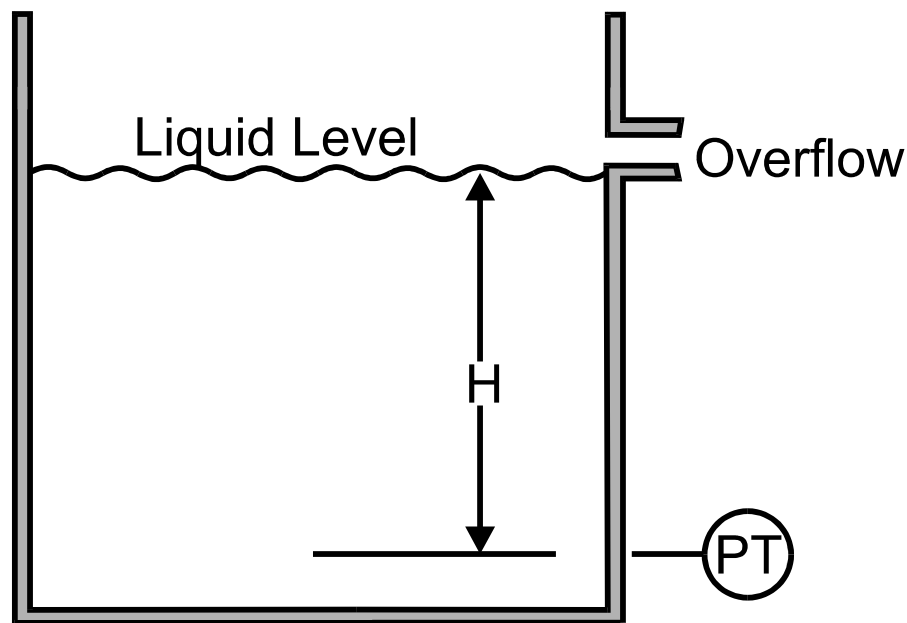
Density can be measured in a number of similar ways to level:

- Hydrostatic pressure
- Radiation
- Vibration
- Differential pressure

The Coriolis mass flowmeter is also capable of performing density measurement.

### 3.10.1 Hydrostatic Pressure

This type of density measurement relies on a constant height of liquid and measures the pressure differences. Since level may vary, the principle of operation works on the difference in pressure between any two fixed elevations below the surface. Because the height between these two points does not change, any change in pressure is due to density variations. The distance between these points is equal to the difference in liquid head pressure between these elevations.



*Figure 3.24*  
*Fixed heights of liquid for density measurement*

### 3.10.2 Radiation

Density measurement by radiation is based on the increased absorption of gamma radiation for an increase in specific gravity of the material being measured. The main components of such a system are a constant gamma source (usually radium) and a detector. Variations in radiation passing through a fixed volume of flowing liquid is converted into a proportional electrical signal by the detector.

This type of measurement is often used in dredging where the density of the mud indicates the effectiveness of the dredging vessel.

### 3.10.3 Vibration

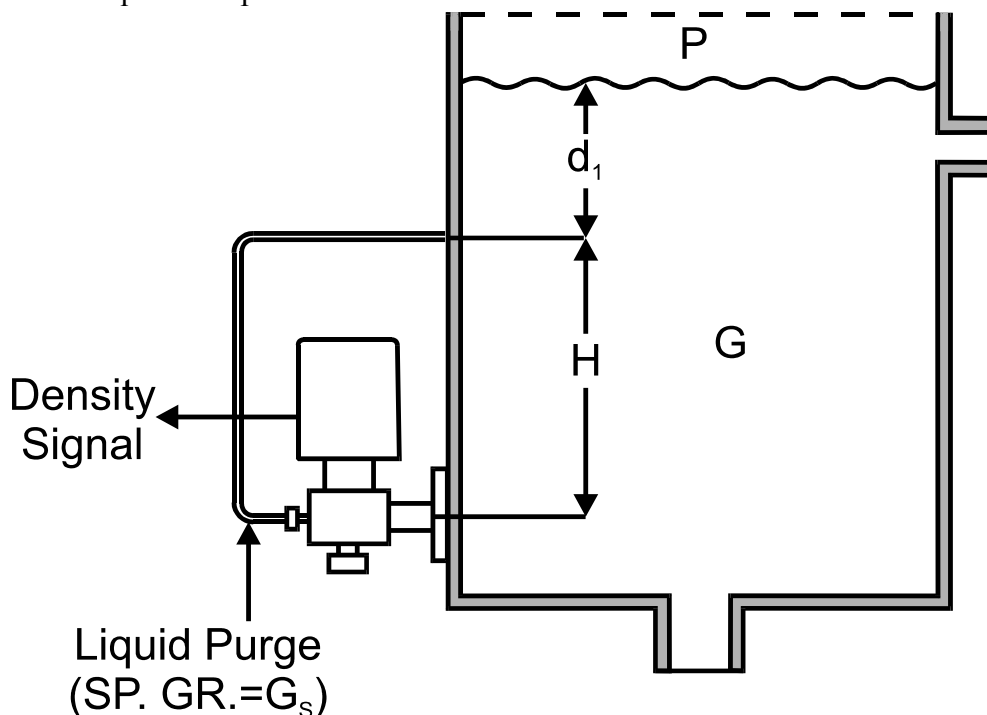
Damping of a vibrating object in a fluid will increase as the density of the fluid increases. An object is vibrated from an external energy source. The object may be an immersed reed or plate.

Density is measured from one of two procedures:

- 1 Changes in the natural frequency of vibration can be measured when the object is energised constantly.
- 2 Changes in the amplitude of vibration can be measured when the object is struck periodically, like a bell.

### 3.10.4 Differential Pressure

Constant level overflow tanks are the simplest for measuring as only one differential pressure transmitter is required. However applications with level or static pressure variations require compensation.



*Figure 3.25*

*In an open or closed tank with varying level or pressure, a wet leg can be filled with seal fluid heavier than the process liquid.*

## **Temperature Effects**

Increases in temperature cause expansion of a liquid, altering its density. Not all liquids expand at the same rate. A specific gravity measurement must be corrected for temperature effects in order to be completely accurate in terms of reference conditions for density and concentration, although in most cases this is not practical.

In applications where specific gravity is extremely critical, it is possible to control the temperature to a constant value. The necessary correction to the base temperature can then be included in the density instrument calibration.

## **3.11 Installation Considerations**

### **Atmospheric Vessels**

Most instruments involved with level detection can be easily removed from the vessel. Top mounting of the sensing device also eliminates the possibility of process fluid entering the transducer or sensor housing should the nozzle or probe corrode or break off.

Many level measurement devices have the added advantage that they can be manually gauged. This provides two important factors:

- Measurements are still possible in the event of equipment failure
- Calibration and point checks can provide vital operational information

One common installation criteria for point detection devices is that they must be mounted at the actuation level, presenting accessibility problems.

### **Pressurised Vessels**

Two main considerations apply with level measurement devices in pressurised vessels:

- Facilities for removal and installation while the vessel is pressurised.
- The pressure rating of the equipment for the service.

Pressurised vessels can also be used to prevent fugitive emissions, where an inert gas such as hydrogen pressurises the process materials. Compensation within the level device needs to also be accounted for as the head-pressure changes.

The accuracy of the measuring device may be dependent on the following:

- gravity variations
- temperature effects
- dielectric constant

Also the presence of foam, vapour or accumulated scum on the transducer affects the performance.

### **3.12 Impact on the Overall Control Loop**

Level sensing equipment is generally fast responding, and in terms of automated continuous control, does not add much lag to the system.

It is good practice though, to include any high and low switch limits into the control system. If the instrumentation does fail or goes out of calibration, then the process information can be acquired from the high and low limits. Apart from the hard wired safety circuits, it is good practice to incorporate this information into the control system.

3.13 Selection Tables

Type	Max Temperature (°F)	Available as Non-contact	Inaccuracy (1 in = 25.4 mm)	Cost			Available Designs			Applications								Limitations	
				Under \$1000	\$1000 - \$5000	Over \$5000	Switch	Local Indicator	Transmitter	Liquids				Solids					
										Clean	Viscous	Slurry / Sludge	Interface	Foam	Powder	Chunky	Sticky		
Air Bubblers	UL		1-2%FS	X			X	X	X	G	F	P	F						Introduces foreign substance into process; high maintenance
Capacitance	2000	X	1-2%FS	X	X		X			G	F-G	F	G-L	P	F	F	F	P	Interface between conductive layers and detection of foam is a problem.
Conductivity Switch	1800		1/8 in	X			X			F	P	F	L	L	L	L	L	P	Can detect interface only between conductive and non-conductive liquids. Field effect design for solids.
Diaphragm	350		0.5% FS	X	X		X		X	G	F	F			F	F	P		Switches only for solids service.
Differential Pressure	1200		1% FS	X	X		X	X	X	E	G-E	G	P						Only extended diaphragm seals or repeaters can eliminate plugging. Purging and sealing legs are also used.
Displacer	850		0.5 in	X	X		X		X	E	P	P	F-G						Not recommended for sludge or slurry service.
Float	500		1% FS	X			X	X	X	G	P	P	F						Moving parts limit most designs to clean service. Only preset density floats can follow interfaces.
Laser	UL		0.5 in			X			X	L	G	G		F	F	F	F		Limited to cloudy liquids or bright solids in tanks with transparent vapour spaces.
Level Gauges	700		0.25 in	X				X		G	F	P	F		G				Glass is not allowed in some processes.
Level Switch	400	X	0.5 in	X	X		X			G	G	F	G		F	G	F		Thick coating is a limitation.
Optical Switches	260	X	0.25 in	X	X		X		X	G	F	E	F-G	F	P	P	F		Refraction-type for clean liquids only; reflection type requires clean vapour space.
Radar	450	X	0.12 in			X				G	G	F	P		G	F	P		Interference from coating, agitator blades, spray or excessive turbulence.

Radiation	UL	X	0.25 in		X		X															Requires NRC licence.
Resistance Tape	225		0.5 in		X		X															Limited to liquids under near-atmospheric pressure and temperature conditions.
Rotating Paddle Switch	500		1 in		X																	Limited to detection of dry, non-corrosive, low-pressure solids.
Slip Tubes	200		0.5 in		X																	An unsafe manual device.
Tape Type	300		0.1 in		X							X										Only the inductively coupled float is suited for interface measurement. Float hangup is a potential problem with most designs.
Thermal	850		0.5 in		X							X										Foam and interface detection is limited by the thermal conduction involved.
TDR / PDS	221		3 in		X																	Limited performance on sticky process materials.
Ultrasonic	300	X	1% FS		X							X										Presence of dust, foam, dew in vapour space, sloping or fluffy process material interferes with performance.
Vibrating Switches	300		0.2 in		X							X										Excessive material build-up can prevent operation.

TDR = Time Domain Reflectometry  
PDS = Phase Difference Sensors

AS = in % of actual span  
E = Excellent

F = Fair  
FS = in % of full scale

G = Good  
L = Limited

P = Poor  
UL = Unlimited

Table 3.4  
Orientation Table for Level Detectors



### **3.14 Future Technologies**

The cost of sensing equipment is not a major consideration compared with the economics of controlling the process. There is therefore a growing demand for accuracy in level measuring equipment

Newer models incorporate better means of compensation, but not necessarily new technologies. For example, incorporating a temperature compensation detector in the pressure sensing diaphragm provides compensation and acts an alternative to remote pressure seals. This ensures the accuracy and stability of the measurement.

Greater demands in plant efficiency may require an improved accuracy of a device, not just for the actual measurement, but also to increase the range of operation. If the safety limits were set at 90% due to inaccuracies with the sensing device, then an increased range could be achieved by using more accurate equipment

Demands are also imposed on processes to conform to environmental regulations. Accurate accounting of materials assist in achieving this. Such technologies as RF admittance or ultrasonic minimise the expense of this environmental compliance.

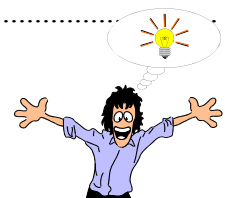
Problems occur in trying to sense level in existing vessels that may be non-metallic. RF flexible cable sensors have an integral ground element which eliminates the need for an external ground reference when using the sensor to measure the level of process materials in non-metallic vessels.

# Tips and Tricks



A series of horizontal dotted lines providing a template for writing tips and tricks.

# Tips and Tricks



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# **4**

## **Temperature Measurement**

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# Chapter 4

## Temperature Measurement

### 4.1 Principles of Temperature Measurement

Temperature measurement relies on the transfer of heat energy from the process material to the measuring device. The measuring device therefore needs to be temperature dependent.

There are two main industrial types of temperature sensors:

- Contact
- Non contact

#### *Contact*

Contact is the more common and widely used form of temperature measurement. The three main types are:

- Thermocouples
- Resistance Temperature Detectors (RTD's)
- Thermistors

These types of temperature devices all vary in electrical resistance for temperature change. The rate and proportion of change is different between the three types, and also different within the type classes.

Another less common device relies on the expansion of fluid up a capillary tube. This is where the bulk of the fluid is exposed to the process materials temperature.

#### *Non-Contact*

Temperature measurement by non-contact means is more specialised and can be performed with the following technologies:

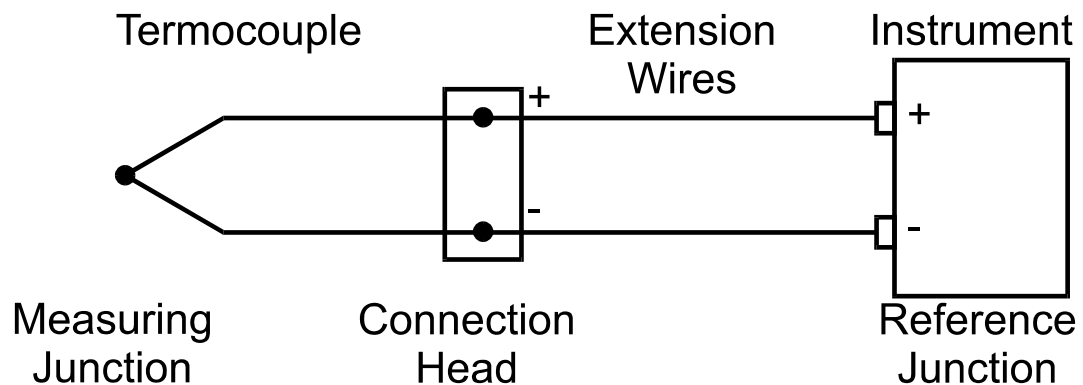
- Infrared
- Acoustic

## 4.2 Thermocouples

### 4.2.1 Basis of Operation

A Thermocouple consists of two wires of dissimilar metals, such as iron and constantan, electrically connected at one end. Applying heat to the junction of the two metals produces a voltage between the two wires. This voltage is called an emf (electro-motive force) and is proportional to temperature.

A thermocouple requires a reference junction, this is placed in series with the sensing junction. As the two junctions are at different temperatures a thermal emf is generated. The reference junction is used to correct the sensing junction measurement.



*Figure 4.1  
Typical thermocouple and extension leads*

The voltage across the thermocouple increases as the temperature rises and a suitably calibrated instrument, capable of measuring small voltages, can be used to measure the change. The process temperature is obtained from the voltage, either by reading from a graph or by using thermocouple tables. Thermocouple tables list the voltages corresponding to each temperature. A table is required for each thermocouple type.

The relationship between millivolts and temperature is not linear. In microprocessor based equipment, the conversion is done based on the data stored in the device.

*The Reference Junction:*

The sensing, or hot junction is inserted into the area where the temperature is to be measured. The reference, or cold junction is normally connected to the measuring instrument and held at 0 °C.

For accurate temperature measurement, the reference junction temperature must remain constant or suitable compensation provided if it should change. To reduce inaccuracies, most thermocouples are now installed with instruments that provide automatic reference compensation.

One of the most accurate ways of compensating for temperature change is to maintain the reference junction at 0 °C. This however is not that practical, and some form of compensation needs to be used. The technique of cold junction compensation measures the actual temperature and applies a correction to the thermocouple reading. The correction is made by adjusting the voltage by an amount equal to the difference between the actual temperature and 0 °C.

Another method of providing this compensation is to pass current through a temperature responsive resistor, which measures the variation in reference temperature and automatically provides the necessary correction by means of a voltage drop across the resistor.

Hardware compensation can be performed that uses electronic circuits that compensate for the ice-point reference. The main advantage over software compensation, is speed. The hardware response is not dependent on computation time. Hardware compensation is, however, only suited to a particular type of thermocouple. Hardware compensation is performed by using resistors whose combined temperature resistance coefficient curves match those of the voltage-temperature curves produced by the reference junctions.

#### *The Seebeck Effect:*

A thermocouple works on the Seebeck Effect. This is where (as previously mentioned) two wires of dissimilar metals are electrically connected at one end. When the junction is heated or cooled, a voltage is produced which is proportional to the temperature.

Note that the more technical term for voltage is emf, or Electro-motive force. This basically defines the electrical driving force.

#### *The Peltier Effect:*

The reverse of the Seebeck Effect is possible and can be useful. By applying a voltage and causing a current to flow between two wires of dissimilar metals, it is possible to generate a temperature difference. Because of the different electrothermal transport properties of the metals, it is found that one of the junctions will be heated and the other cooled. This process is referred to as the Peltier Effect.

Practical applications include cooling small electronic parts, or even to provide a 0°C reference junction for a thermocouple. Other applications using this principle are becoming increasingly popular for heating and refrigeration.



### 4.2.2 Selection and Sizing

#### *Isothermal Block:*

Problems can arise from a mismatch of metals when connecting a thermocouple circuit to measuring equipment. Copper, being a commonly used conductor, is often inserted into the circuit. An Isothermal block is used to change from the metal used in the thermocouple circuit to those, such as copper, used in the measuring equipment.

The law of intermediate metals states that the introduction of a third metal into a thermocouple circuit will have no effect on the voltage, so long as the junctions of the third metal with the other two are at the same temperature.

The isothermal block ensures that the connections to the measuring wires are at the same temperature, and as such, errors are avoided. The isothermal block can also include the reference junction. Appropriate temperature measurements can be made for compensation.

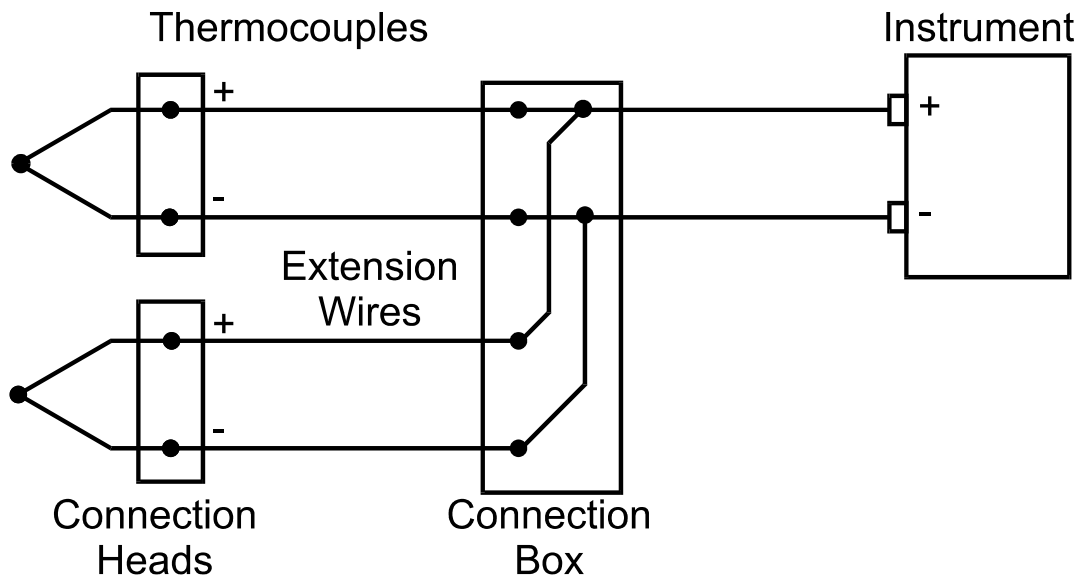
These are seldom used anymore.

#### *Extension cable and compensating cable:*

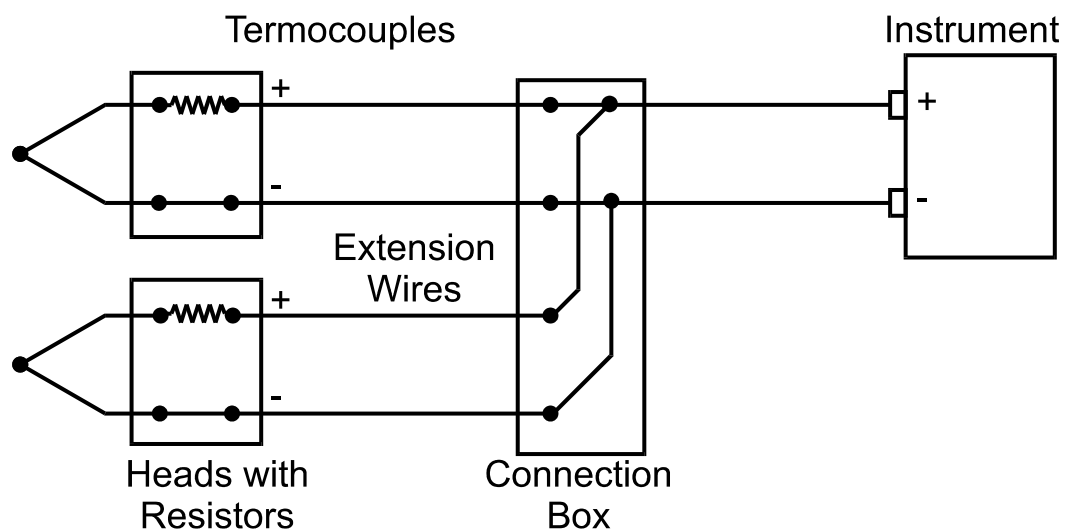
An extension cable for thermocouples consists of the same metals as the thermocouple junction; this has the advantage of no extra emf's generated, however the cable does prove to be quite costly. Compensating cable is a suitable and cheaper alternative, which uses copper in both conductors.

#### *Averaging temperatures:*

Thermocouples may be used in parallel when sensing an area of flow. The voltage developed at the instrument is an average of the thermocouples used. To maintain accuracy, the thermocouples need to be of the same type and extension wires should be identical.



**Figure 4.2**  
*Thermocouples in parallel for average temperature measurement*



**Figure 4.3**  
*Parallel thermocouples with swamping resistors*

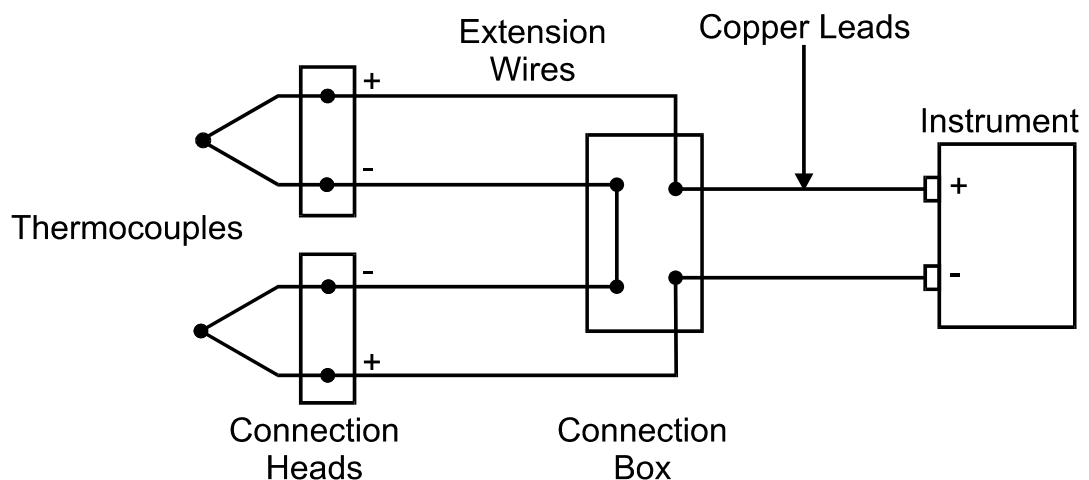
The advantage of using thermocouples in parallel for temperature averaging is that they can be used in the same way as a single thermocouple.

When used in series for averaging temperature, the circuit requires special reference junction compensation for the increased compensating voltage, and is dependent on the number of thermocouples in the circuit. The instrument also requires calibration for the total millivolt output for the number of thermocouples used in series.

Most thermocouples are grounded in the field. This presents a problem when using multiple thermocouples as the problems of a ground loop and shorting of signals exist.

#### *Differential temperatures:*

Two thermocouples can be used to measure the difference in temperature between two points. The thermocouples are connected together such that the voltages developed oppose each other. When measuring the same temperature, the net voltage will be zero. When a temperature difference does exist between the two points, this will be detected as a voltage and therefore the temperature measured.



**Figure 4.4**  
*Two thermocouples used to measure temperature difference*

#### 4.2.3 Construction

Thermocouples are fusion-welded to form a pure joint, which maintains the integrity of the circuit and also provides high accuracy. Grounded junctions provide good thermal contact with protection from the environment. Ungrounded and isolated junctions provide electrical isolation from the sensor sheath.

Thermocouples are usually encased in a protective metal sheath. The sheath material can be stainless steel which is good for temperatures up to 870 °C. For temperatures up to 1150 °C Inconel is used.

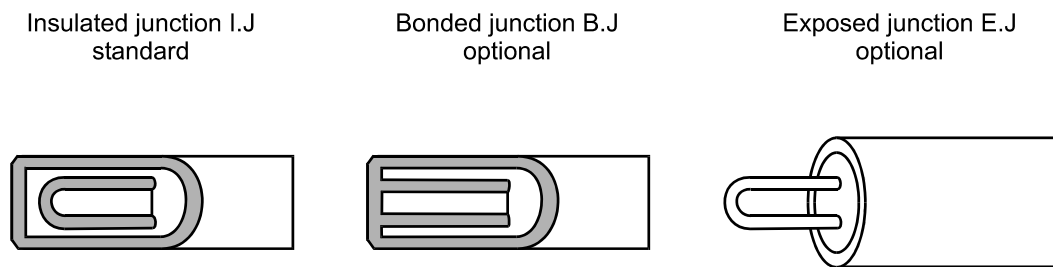
A metallic oxide can be compacted into the sheath. This provides mechanical support and also electrically insulates the thermocouple junction.

The metal sheathed mineral insulated thermocouple has become the accepted norm in most industries. They use a variety of temperature and corrosion resistant sheaths and have an extremely high purity (99.4%) of Magnesium oxide insulation.

Insert Table here (Thermocouple comparison)

<i>Thermocouple Comparison</i>									
ISA Type designation	Positive Wire	Negative Wire	$\mu\text{V}/^\circ\text{F}$	Recommended Temp limits $^\circ\text{F}$	Scale Linearity	Atmosphere recommended	Favourable Points	Unfavourable Points	
B	Pt70-Rh30	Pt94-Rh6	3-6	32 to 3380	Same as R type	Inert or slow oxidising			
E	Chromel	Constantan	15-42	-300 to 1800	Good	Oxidising	Highest emf/ $^\circ\text{F}$	Larger drift than other base metal couples	
J	Iron	Constantan	14-35	32 to 1500	Good; nearly linear from 300 to 800	Reducing	Most economical	Becomes brittle below 320 $^\circ\text{F}$	
K	Chromel	Alumel	9-24	-300 to 2300	Good; most linear of all T/Cs	Oxidising	Most linear	More expensive than T or J	
R	Pt87-Rh13	Platinum	3-8	32 to 3000	Good at high temps	Oxidising	Small size	More expensive	
S	Pt90-Th10	Platinum	3-7	32 to 3200	Same as R	Oxidising	Same as R	More expensive	
T	Copper	Constantan	8-35	-300 to 750	Good but crowded at low end	Oxidising but reducing	Resists corrosion from moisture	Limited temperature range	
Y	Iron	Constantan	22-33	-200 to 1800	About same as J	Reducing		Non-standard	
-	Tungsten	W74-Re26	1-12	0 to 4200	Same as R	Inert or vacuum	High temperature	Brittle; Expensive	
-	W94-Re6	W74-Re26	1-10	0 to 4200	Reasonable above 60K	Inert or vacuum	Same as above	Slightly less brittle than above	
-	Copper	Gold-cobalt	0.5-25	-450 to 0	Same as R		Good output at very low temp.	Expensive lab-type T/C	
-	Ir40-Rh60	Iridium	1-4	0 to 3800		Inert		Brittle; Expensive	

*Table 4.1  
Thermocouple comparison*



**Figure 4.5**  
**Mineral insulated thermocouples**

#### 4.2.4 Installation Techniques

##### *Extension leads:*

Care needs to be taken when extending or using long or joined leads when measuring with thermocouples. In theory, if dissimilar metals are used for connecting or extending thermocouples, and they are all at the same temperature, then no additional voltage is produced. So this should make it possible to connect a thermocouple to a measuring device as long as all components are at the same temperature.

In practice, this does not hold true. Especially with type J and T, which require extension leads of the same metal. The advantage in using consistent metals is the minimisation of effects from temperature variations as the leads pass through different thermal conditions in the plant.

The temperature variations within a thermocouple circuit are primarily dependent on the metals used and any temperature variations, and not on the length of the cable run or the diameter of the conductors.

Use the largest size thermocouple wire possible, and during installation, avoid stress and vibration. The wire length can be minimised by using transmitters that recondition the signal into a more robust and noise resistant form.

##### *Detecting thermocouple faults:*

Since thermocouples can be used in high temperature environments, it is possible that the extension wires be damaged by excessive heat. If a short develops in the wires, it may not be possible to detect. The sensing equipment will no longer be measuring the temperature at the sensing junction, but instead will measure the temperature at the short.

It should be noted, that thermocouples in this type of application are possibly used to detect high temperature fault conditions. If such a fault should occur, it is more likely to fail such that an alarm condition will not be detected. Techniques to measure the resistance continuously can be implemented to note any abrupt changes.

#### 4.2.5 *Application Details*

In a new installation, or in replacing failed equipment, it is possible to note a change in performance between the old and the new. In replacing thermocouples or RTD's there are a couple of common problems:

If the new thermocouple has been installed but does not make contact with the thermowell then an airgap is introduced which affects response time and can have a temperature variation from the actual temperature. A thermopaste can be used, and should only be applied at the tip where the temperature measurement occurs. The insertion depth is also a factor, as the deeper the insertion the more accurate the measurement. Thermopaste can make up for some shortness in length, but is limited if the shortfall is too great.

When replacing thermocouples in thermowells, it is important that the bore of the thermowell is cleaned. During the changeover or just over time, it is possible (and therefore probable!) that material may accumulate at the bottom of the well which can insulate the thermocouple from the sheath and prevent heat transfer.

Another problem is when the new thermocouple is of a different mass to the old one. This can affect the response time and, although it may not affect the accuracy, it can affect the stability in a closed loop system.

Grounding can be another problem, where the accuracy and response can differ between grounded and ungrounded devices.

Even though the thermocouple was replaced, the extension cable may require replacing also. Wear and tear or deterioration of the cable can affect accuracy. The contact with the terminals must also be considered as corrosion may be a problem.

Something that applies more to response time than accuracy is the type of junction. It may be possible that the original thermocouple had a bonded junction and the new thermocouple an insulated junction. Insulated junction thermocouples have twice the response time of bonded junction thermocouples.

#### 4.2.6 *Typical Applications*

Although R-type and B-type thermocouples are suitable in oxidising atmospheres, they are easily contaminated in other atmospheres.

T-type can be used in either oxidising or reducing atmospheres. This type of thermocouple has a high resistance to corrosion due to moisture. They also provide a relatively linear output and perform well from a medium to very low temperature range.

J-type can also be used in reducing atmospheres and provide a good near-linear output. They are also the least expensive of commercially available thermocouples.

K-type can be used in oxidising atmospheres, and are the most linear thermocouple for general use. These are the most widely used.

E-type are the most sensitive thermocouple available, and have the highest change in emf per temperature change, but they tend to drift more. They can be used in oxidising atmospheres.

#### **4.2.7 Advantages**

- Low cost
- Small size
- Robust
- Wide range of operation
- Reasonably stable
- Accurate for large temperature changes
- Provide fast response

#### **4.2.8 Disadvantages**

- Very weak output, millivolts
- Limited accuracy for small variations in temperature
- Sensitive to electrical noise
- Nonlinear
- Complicated conversion from emf to temperature

#### **4.2.9 Application Limitations**

Small temperature changes give a very small change in voltage. A platinum thermocouple, for example, will give a change of about 10microvolts for a 1 °C change in temperature.

It is because of the weak output signal from thermocouples that they are susceptible to electrical noise and are limited to applications requiring the measurement of large changes in temperature.

Thermocouples are not linear and the conversion from the generated emf to temperature is involved.

The calibration of thermocouples does change over time, and this is due to contamination, composition changes (possibly due to internal oxidation). Rapid changes in temperature may have an effect, but high temperatures definitely can affect the stability of the device. It is proven that when a K-type thermocouple is cycled to 1100°C it can vary by as much as 10%.

The integrity of the conductivity of a thermocouple has to be maintained and as such cannot be used exposed in conductive fluids.

#### **4.2.10 Summary**

Thermocouples are the most economical temperature measuring device available and also provide measurement of the highest temperatures. The emf that they generate is independent of the wire length and diameter, however noise can become a factor.

Thermocouples provide a wide range of temperature measurement but are not recommended for narrow span or small temperature difference measurement.

For critical temperature measurement, an accurate reference junction temperature needs to be measured and compensated for. This may require the use of an RTD.

If the process measurement can be performed with another device other than a thermocouple, then that should be considered. Thermocouples are low cost and suited for applications requiring a large temperature range.

#### 4.2.11 Technical Data - Thermocouple Tables

The output of a thermocouple is quite small, in the order of millivolts. Depending on the type of thermocouple, the range can vary from -11 to 75mV. The relationship between the temperature and voltage is not linear and calibration curves or formulae are used for the conversion.

<i>Orientation table for temperature sensors</i>								
Type	Temperature Range °F	Available Span	Accuracy % of span	Stability	Repeat-ability	Response Time	Sensit-ivity	Linear
T/Cs:								
Type T	-300 to 750	<100 to 1000	0.1	G	G	G	G	N
Type J	32 to 1500	<100 to >1000	0.1	G	G	G	G	N
Type K	-300 to 2300	<100 to >1000	0.1	G	G	G	G	-
Types R&S	32 to 3000	<1000 to >1000	0.1	G	G	E	E	N
RTDs:								
Pt	-400 to 1200	<100 to >1000	0.15	E	E	G	G,E	-
Nickel	-350 to 600	<100 to <1000	0.25	G,E	E	G	E	N
Thermistors	-100 to 500	<100 to <1000	0.2	F	G	E	E	N
Electronic	-350 to 325	<100 to <1000	0.2-2	G	G	G	E	-
Bimetallics	-100 to 1000	<100 to <1000	1-2	E	F	G	G	N
Filled:								
Liquid	-50 to 800	<100 to <1000	0.5-2	E	F	F	G	-
Vapour	0 to 600	<100 to <1000	0.5-2	E	F	G	F	N
Gas	-100 to 1800	<1000 to >1000	0.5-2	E	F	G	F	-
Mercury	-10 to 1000	<100 to >1000	0.5-2	E	F	F	G	-
Glass stem	-10 to 1000	<100 to <1000	0.1-2	E	E	F	G	-
Infrared	-10 to 6300	<1000 to >1000	1-2	F	F	E	G	N
Ultrasonic	1500 to 15000	<100 to >1000	5	G	F,G	E	E,G	N

**Table 4.2**  
**Orientation Table for Temperature Sensors**

Thermocouple tables are based on a reference junction of 0 °C. If the reference junction is not at 0 °C then a correction factor must be applied.

Thermocouple tables are provided in Appendix A.



*Calculating Temperature from Voltage (reference junction = 0 °C):*

1. Select the correct table for the thermocouple type in use. ie. J,S,T.
2. Locate the millivolt reading in the body of the table, and read from the margins the temperature value.

Note, that this only gives an accuracy to that of the increments on the scale, possibly 5 °C in this case. For more accurate measurement, a straight line approximation (or interpolation) can be made between two values. Interpolation takes into account the proportionate part of the difference between the two values read from the table.

$$T_M = T_L + \frac{(T_H - T_L)}{(V_H - V_L)} \cdot (V_M - V_L)$$

$V_M$  is the measured voltage

$V_H$  is the higher voltage read from the table

$V_L$  is the lower voltage read from the table

$T_M$  is the calculated temperature

$T_H$  is the higher temperature read from the table (corresponding to  $V_H$ )

$T_L$  is the lower temperature read from the table (corresponding to  $V_L$ )

3. Read the values of  $V_H$ ,  $V_L$ ,  $T_H$  and  $T_L$  from the table. From the above, interpolate the more precise temperature.

*Example:*

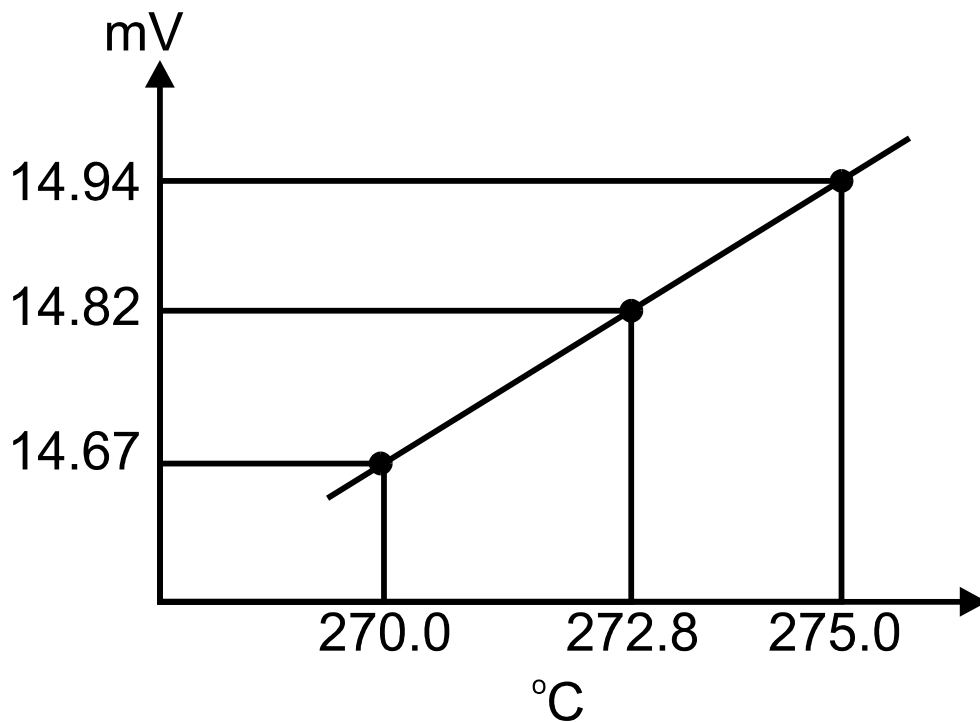
A voltage of 14.82 mV is measured with a type J thermocouple with a 0 °C reference temperature. Find the temperature of the sensing junction.

*Solution:*

From the table for J-type thermocouples, it is found that  $V_M = 14.82\text{mV}$  is between  $V_L = 14.67\text{mV}$  and  $V_H = 14.94\text{mV}$ . These voltages have corresponding temperatures of  $T_L = 270.0\text{ °C}$  and  $T_H = 275.0\text{ °C}$ .

$$T_M = 270.0\text{ °C} + \frac{(275.0\text{ °C} - 270.0\text{ °C})}{(14.94\text{mV} - 14.67\text{mV})} \cdot (14.82\text{mV} - 14.67\text{mV})$$

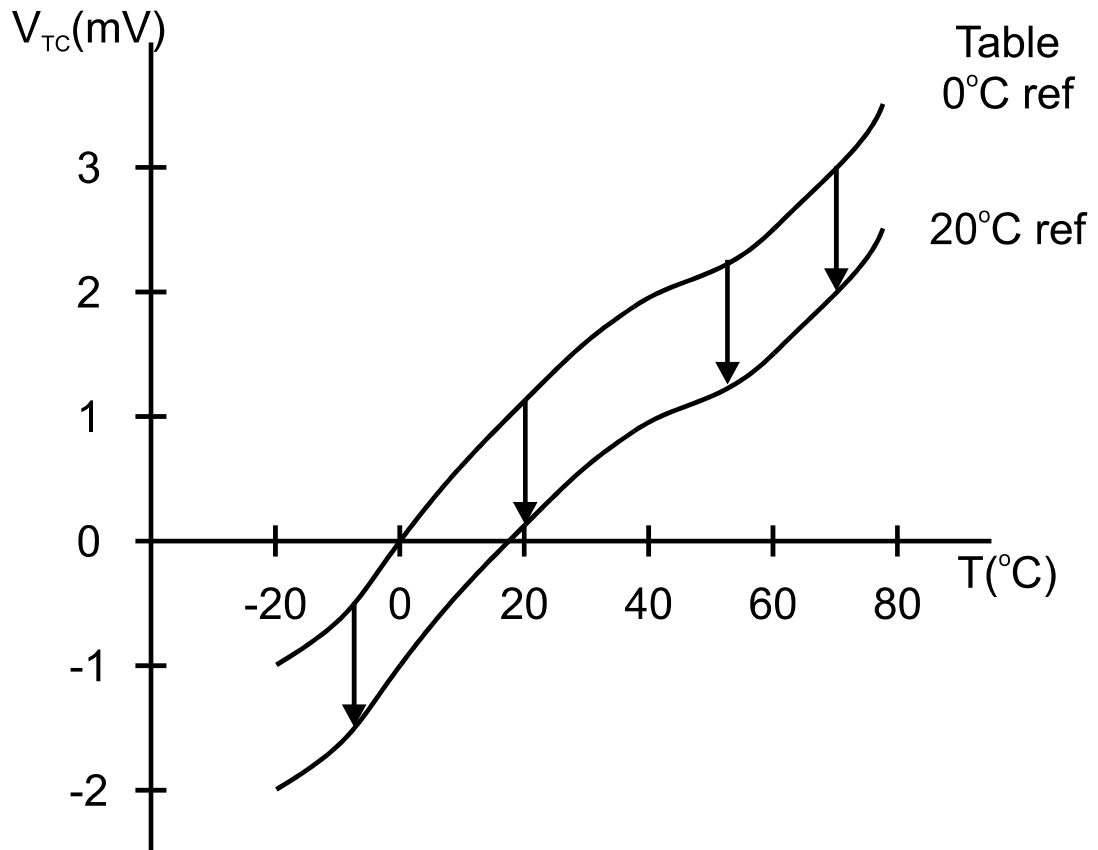
$$T_M = 272.8\text{ °C}$$



**Figure 4.6**  
**Thermocouple Interpolation**

*Calculating Temperature from Voltage (reference junction  $\neq 0^{\circ}\text{C}$ ):*

1. Select the correct table for the thermocouple type in use. ie. J,S,T.
2. Locate the millivolt reading for the REFERENCE junction in the body of the table, and read from the margins the temperature value.
3. ADD this millivolt reading to that measured by the instrument.
4. This corrected millivolt reading can be converted, using the table, into measured temperature.



**Figure 4.7**

*A change in reference from 0°C to 20V is equivalent to sliding the thermocouple curve down in voltage.*

*Example:*

A voltage of 3.444 mV is measured with a type S thermocouple with a 25.0 °C reference temperature. Find the temperature of the sensing junction.

*Solution:*

The voltage of the reference junction from the S-type table is 0.143 mV.

The measured voltage needs to be corrected such that the actual sensing voltage is the sum of the two:

$$0.143 + 3.444 = 3.587\text{mV}$$

From the S-type table, 3.587mV gives a temperature of 435 °C.

*Calculating Voltage from Temperature (reference junction = 0 °C):*

1. Select the correct table for the thermocouple type in use. ie. J,S,T.
2. Locate the temperature value from the margins and read the millivolt number in the body of the table.

Note, that this only gives an accuracy to that of the increments on the scale, possibly 5 °C in this case. For more accurate measurement, a straight line approximation (or interpolation) can be made between two values. Interpolation takes into account the proportionate part of the difference between the two values read from the table.

$$V_M = V_L + \frac{(V_H - V_L) \cdot (T_M - T_L)}{(T_H - T_L)}$$

$V_M$  is the measured voltage

$V_H$  is the higher voltage read from the table

$V_L$  is the lower voltage read from the table

$T_M$  is the calculated temperature

$T_H$  is the higher temperature read from the table (corresponding to  $V_H$ )

$T_L$  is the lower temperature read from the table (corresponding to  $V_L$ )

3. Read the values of  $V_H$ ,  $V_L$ ,  $T_H$  and  $T_L$  from the table. From the above, interpolate the more precise voltage.

*Example:*

A temperature of 272.8 °C is measured with a type J thermocouple with a 0 °C reference temperature. Find the output voltage for this temperature.

*Solution:*

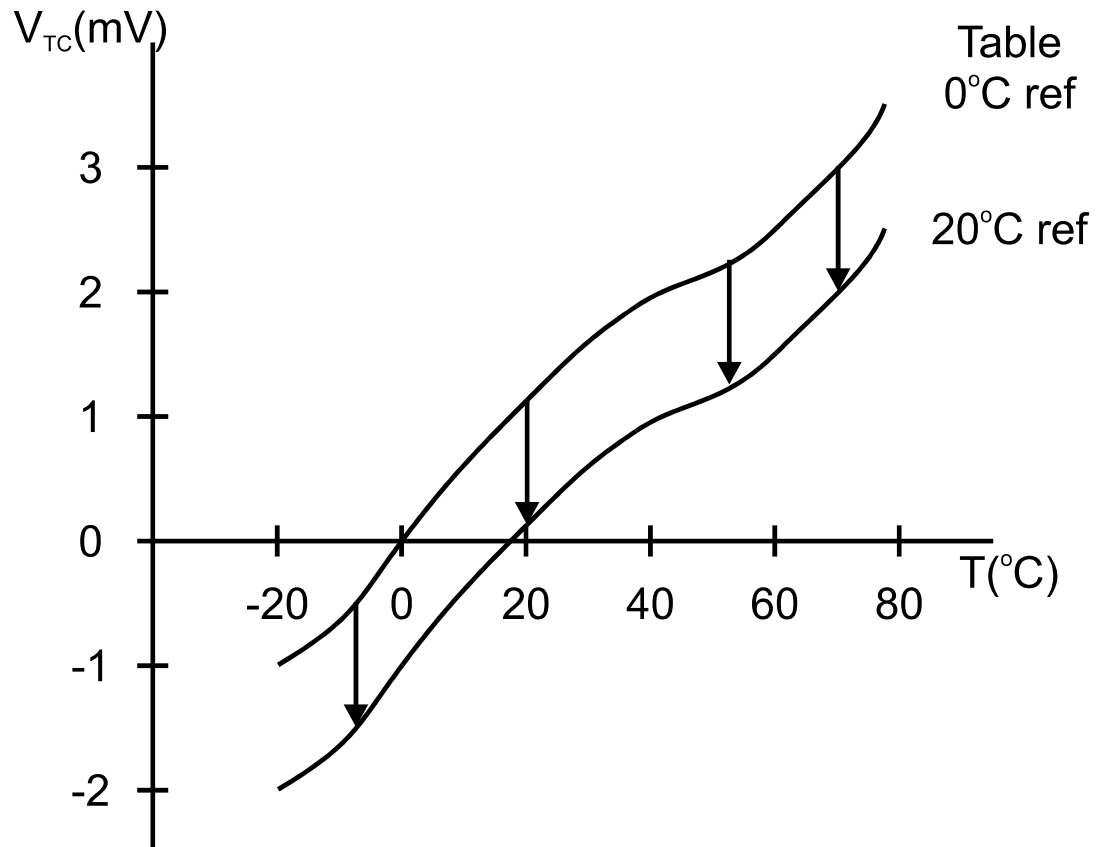
From the table for J-type thermocouples, it is found that  $T_M = 272.8$  °C is between  $T_L = 270.0$  °C and  $T_H = 275.0$  °C. These temperatures have corresponding voltages of  $V_L = 14.67$ mV and  $V_H = 14.94$ mV.

$$V_M = 14.67\text{mV} + \frac{(14.94\text{mV} - 14.67\text{mV}) \cdot (272.8\text{ °C} - 270.0\text{ °C})}{(275.0\text{ °C} - 270.0\text{ °C})}$$

$$V_M = 14.82\text{mV}$$

*Calculating Voltage from Temperature (reference junction  $\neq$  0 °C):*

1. Select the correct table for the thermocouple type in use. ie. J,S,T.
2. Determine the voltage of the actual temperature from the table based on 0 °C reference junction.
3. Determine the voltage of the reference junction temperature from the table.
4. Take the difference between the two voltages in the last two steps.



**Figure 4.8**

*A change in reference from 0°C to 20V is equivalent to sliding the thermocouple curve down in voltage.*

*Example:*

The calibration of an instrument is to be checked at 435 °C. This temperature is measured with a type S thermocouple with a 25.0 °C reference temperature. Calculate the millivolts expected at the instrument.

*Solution:*

The temperature of the reference junction is 25 °C, and from the S-type table is 0.143 mV.

The measured temperature should be 435 °C, and again from the S-type table would give a voltage of 3.587mV. Taking the reference voltage into account, the actual voltage that would need to be seen is:

$$3.587\text{mV} - 0.143\text{mV} = 3.444\text{mV}$$

For a temperature of 435 °C, with the reference at 25 °C, we would expect to see 3.444mV.

**Thermocouple Tables**

	British to BS 1843	American to ANSI/MC 96.1	German to Din 431710-4	French to NFE																
E	Brown <table border="1"><tr><td>Brown</td><td>+</td></tr><tr><td>Blue</td><td>-</td></tr></table>	Brown	+	Blue	-	Purple <table border="1"><tr><td>Purple</td><td>+</td></tr><tr><td>Red</td><td>-</td></tr></table>	Purple	+	Red	-										
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**Table 4.3**  
**Thermocouple table**

<b>Thermocouple Materials and Temperature Ranges</b>					
Thermocouple Type	Thermocouple Materials		Source of Data	Temperature Range	
	Positive wire	Negative wire		Calibrated range (given in the table)	Recommended practical range
B	Platinum with 30% Rhodium	Platinum with 6% Rhodium	Hoskins Manu. Co.	+32 to +3308°F 0 to + 1820°C	+32 to +3000°F 0 to +1700°
C	Tungsten with 5% Rhenium	Tungsten with 26% Rhenium	Hoskins Manu. Co.	+32 to +4200°F 0 to +2315°C	+ 32 to +3000°F 0 to +1700°C
N	Nicrosil	Nisil	Degussa Manu. Co.	-454 to +2372°F -270 to +1300°C	+32 to +2300°F 0 to 1250°C
E	Nickel Chromium alloy ("Chromel")	Copper-Nickel alloy ("Constantan")	NBS	-454 to +1832°F -270 to +1000°C	-300 to +850°F -200 to +450°C
G2	Tungsten	Tungsten with 26% Rhenium	Hoskins Manu. Co.	+32 to +4200°F 0 to +2315°C	+32 to +700°F 0 to +400°C
J	Iron	Copper-Nickel alloy ("Constantan" – SAMA version)	NBS	-346 to +2192°F -210 to 1200°C	+32 to +700°F 0 to +1000°C
K	Nickel-Chromium alloy ("Chromel")	Nickel-Aluminium alloy ("Alumel")	NBS	-454 to +2500°F -270 to +1372°C	-300 to 1600°F -200 to +900°C
PL2	"Platinel II" ** positive	"Platinel II" ** negative	Engelhard Industries	-454 to +2543°F -270 to +1395°C	+32 to +1800°F 0 to +1000°C
R	Platinum with 13% Rhodium	Platinum	NBS	-58 to 3213°F -50 to 1767°C	+32 to +2700°F 0 to +1500°C
S	Platinum with 10% Rhodium	Platinum	NBS	-58 to 3213°F -50 to 1767°C	+32 to +2700°F 0 to +1500°C
T	Copper	Copper-Nickel alloy ("Constantan")	NBS	-454 to +752°F -270 to +400°C	-450 to +400°F -270 to +200°C

**Table 4.4**  
**Thermocouple materials and temperature ranges**

## 4.3 Resistance Temperature Detectors (RTD's)

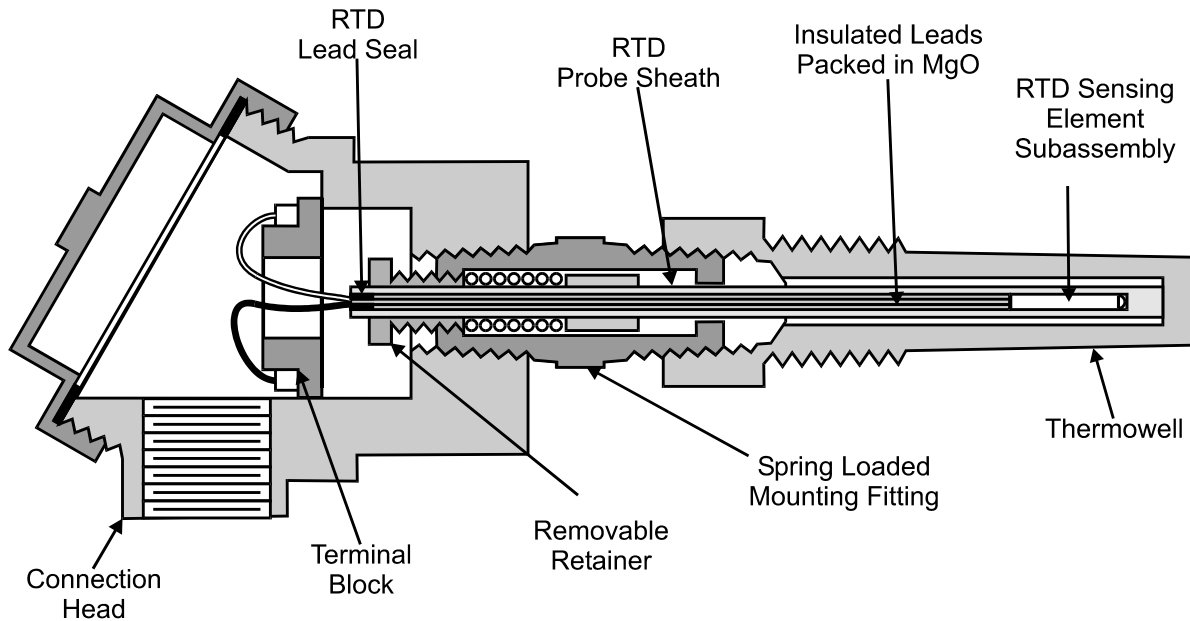
### 4.3.1 Basis of Operation

RTD's are built from selected metals (typically Platinum), which change resistance with temperature change.

The transducer is the temperature sensitive resistor itself, with the sensor being a combination of the transducer and electronics that measure the resistance of the device.

The resistance temperature detector (RTD) measures the electrical conductivity as it varies with temperature. The electrical resistance generally increases with temperature, and the device is defined as having a positive temperature coefficient. The magnitude of the temperature coefficient determines the sensitivity of the RTD.

Apart from Platinum, other metals are used for RTD's such as Copper and Nickel. Platinum is the most common and has the best linear characteristics of the three, although Nickel has a higher temperature coefficient giving it greater sensitivity.



**Figure 4.9**  
**Typical RTD and thermowell construction**

*Temperature Coefficient:*

The temperature coefficient defines how much the resistance will change for a change in temperature, and has units of ohms/ $^{\circ}\text{C}$ . The greater the temperature coefficient, the more the resistance will change for a given change in temperature. This ultimately defines how sensitive the device is.

RTD's are generally quite linear, however the temperature coefficient does vary over the range of operation. As an indication, the temperature coefficient for Platinum is averaged at 0.00385 over the range from  $0^{\circ}\text{C}$  to  $100^{\circ}\text{C}$ , but varies by about 2% over this range.



### 4.3.2 Selection and Sizing

There are two basic types of RTD's:

- PT100
- PT1000

#### *PT100*

The 'PT' defines that the metal is Platinum and the '100' is the resistance in ohms at ice point (or 0 °C). These are generally wire wound and are quite common.

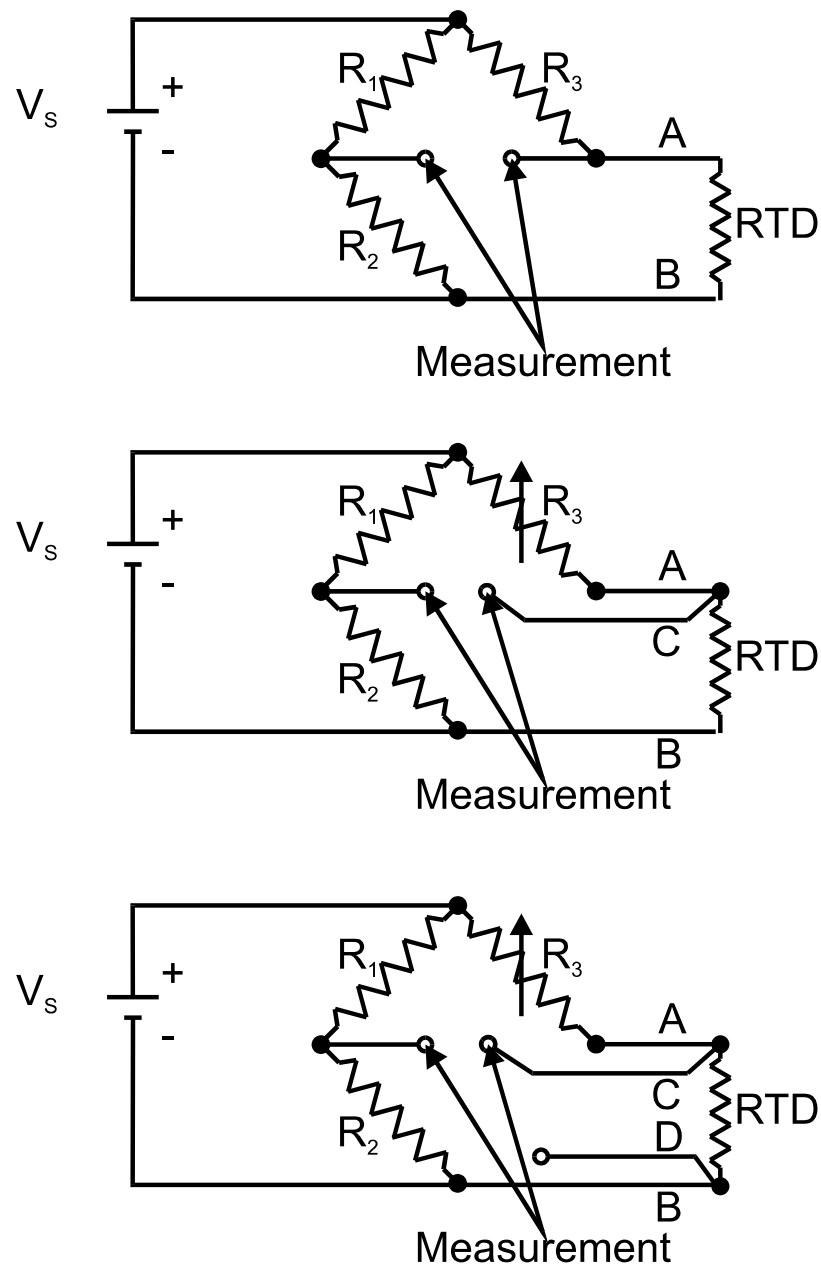
#### *PT1000*

Again, the 'PT' defines a Platinum metal as the sensing element, but a resistance of 1000 ohms can be measured at 0 °C. These are generally thin film devices and are more expensive.

200 and 500 ohm Platinum RTD's are available, but are more expensive and less common.

Platinum is most popular for RTD's, it has good calibrated accuracy, is quite stable and has good repeatability, but is quite expensive. They are, however, not as sensitive as the Nickel and Balco devices. Nickel is not quite as repeatable, but is less expensive.

The effective range of RTD's depends principally on the type of wire used as the active element. A Platinum RTD may have a range from -100 °C to 650 °C, whereas a Nickel RTD typically ranges from -180 °C to 300 °C.

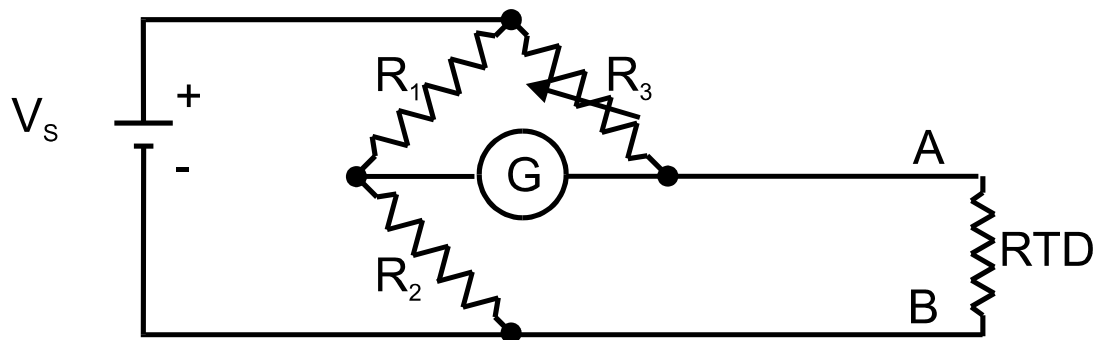


**Figure 4.10**  
**Two, three and four wire measurement**

*Measurement - THE WHEATSTONE BRIDGE:*

There are a number of ways to measure the RTD resistance. The most common way is to use a Wheatstone bridge.

The Wheatstone Bridge consists of a bridge of three resistors located in the instrument housing, with the fourth resistor being that of the RTD. In a balanced situation, the balancing resistor is adjusted to give zero voltage across the bridge. In an unbalanced configuration, the voltage is measured across the bridge.



*Figure 4.11*

*Null-balance – bridge – type two-wire RTD installation showing a galvanometric (G) readout in a balanced condition*

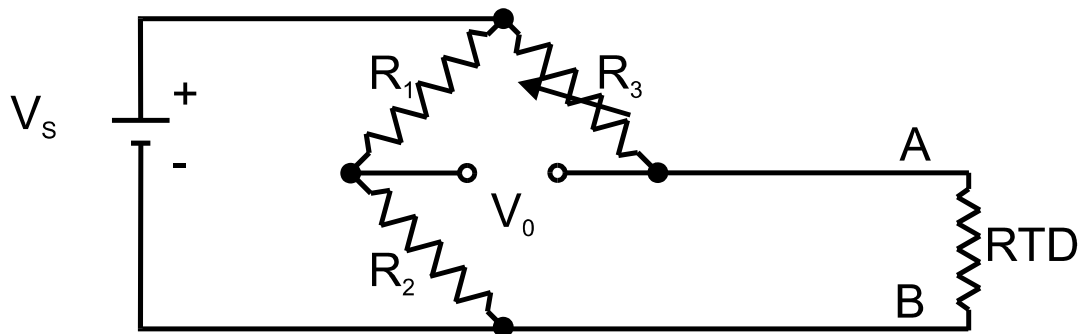
In a bridge arrangement, the measurement of the RTD also includes the resistance of the sensing leads. There are three ways to connect up the RTD to a Wheatstone bridge, with the more complex having greater success in overcoming lead resistance problems.

RTD connection to a Wheatstone Bridge:

- Two-wire
- Three-wire
- Four-wire

*Two-wire measurement:*

This is the most basic type of connection for an RTD device. It is used in very simple, cheap applications. They minimise cost at the expense of accuracy. The main problem with two wire measurement is that there is no accounting for the resistance, or even change of resistance in the sensing leads. The measuring device cannot differentiate between the RTD resistance and lead resistance.



**Figure 4.12**

***Null-balanced – bridge type two-wire RTD installation showing a digital voltmeter readout in an unbalanced condition where the DVM reads  $V_0$  volts.***

When the bridge is balanced,

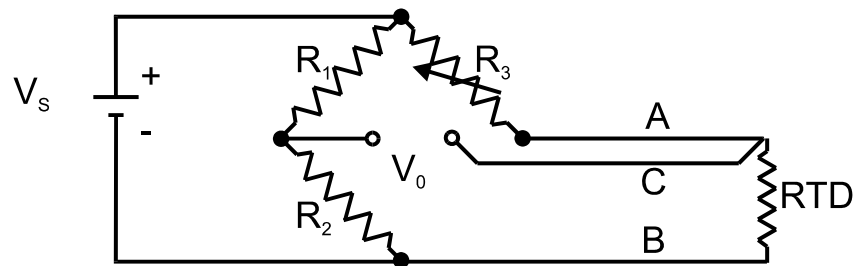
$$R_3 = A + B + \text{RTD}$$

Without the benefits of three-wire sensing, a two-wire element can be used with a three-wire transmitter. This can reduce inventory, but is mentioned here if the need arises for system standardisation and highlights the compatibility between two and three-wire sensors. This is of particular importance for installed equipment.

*Three-wire measurement:*

Three-wire measurement with an RTD device balances the resistances in the lead wires within the bridge. Even though this is a simple modification to the two-wire device, it has the added cost of requiring three wires to obtain the measurement.

The concept of operation is quite simple in that one lead is measured in the top half of the bridge, with the other lead in the bottom half. Since the sensing distance and other effects are the same, the lead resistance from both sensing leads cancel.



When bridge is balanced:  $R_1 + R_3 + A + C = R_2 + B + RTD + C$

If  $R_1 = R_2$  this becomes:  $R_3 = RTD + B - A = RTD$

**Figure 4.13**

***In three-wire null-balance bridge the lead-wire effect is reduced to the difference between the resistance of the two lead-wires (A - B)***

When the bridge is balanced,

$$R_3 + A + C = C + RTD + B$$

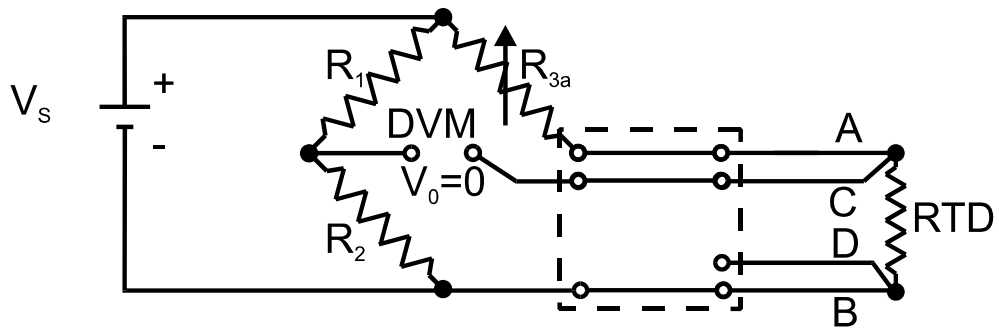
As A and B are identical for practical purposes,

$$R_3 = RTD$$

*Four-wire measurement - Switched:*

One of the limitations with the three-wire measurement, is that if the lead resistance is not the same or suffer different effects, then the measurement will be erroneous. The Four-wire measurement takes both sensing leads into account and alternates the leads into the upper part of the bridge.

By alternating, the lead resistance is effectively measured in both sensing leads, but is then cancelled out by taking the average of the two readings. This level of complexity does make four-wire sensing more expensive.

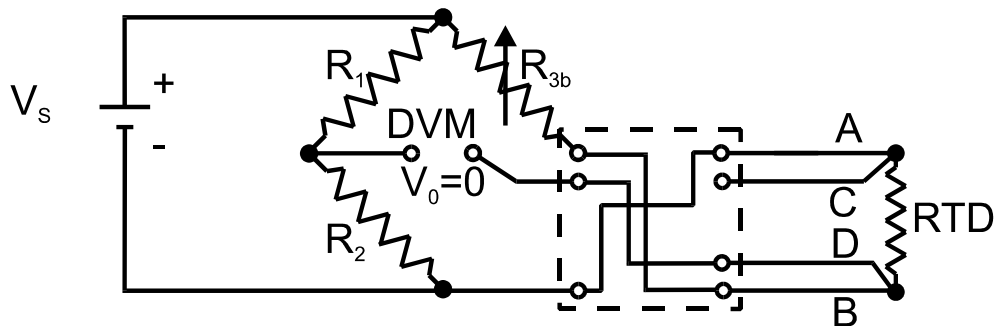


Switch in position "A"

$$R_1 + R_{3a} + A + C = R_2 + B + RTD + C$$

when  $R_1 = R_2$ :

$$R_{3a} + A = B + RTD$$



Switch in position "B"

$$R_1 + R_{3b} + B + D = R_2 + A + RTD + D$$

when  $R_1 = R_2$ :

$$R_{3b} + B = A + RTD$$

**Figure 4.14**

***If the leads of a four-wire null-balance bridge are switched as shown, and the resulting two equations are added up, the lead wire effects are eliminated and the resistance of RTD =  $(R_{3a} + R_{3b})/2$ .***

*Four-wire measurement - Constant Current:*

A simpler and more common way to eliminate errors due to lead resistance is to excite the RTD with a constant current. The main errors in sensing are due to the voltage drop caused by the excitation power in the excitation leads. The measurement of the voltage is performed by the other pair of leads which have very little current passed through them. The excitation power varies according to the manufacturers design, and is anywhere from 1 to 2mA.

The voltage drop in the power leads is defined by,

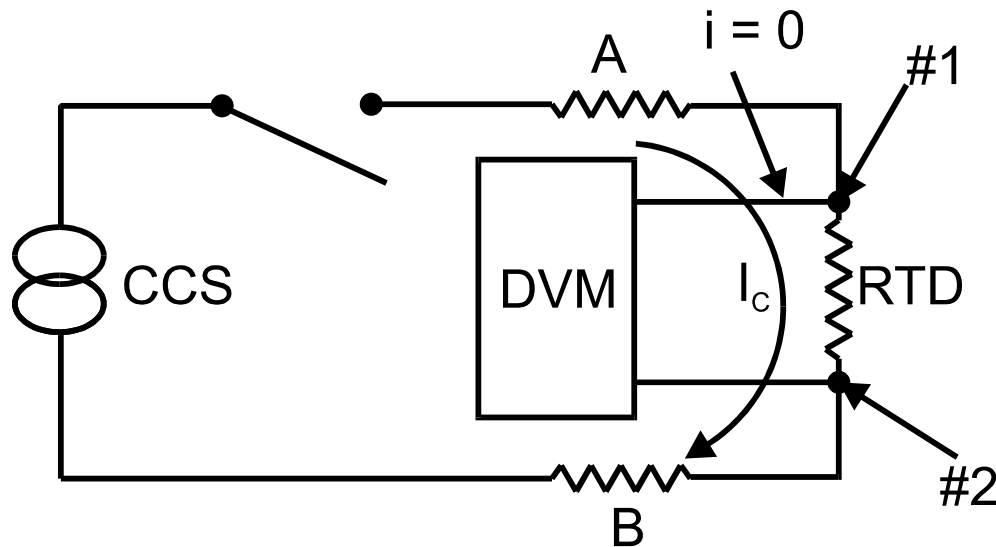
$$V = IR.$$

Power dissipation is defined by,

$$(P = I^2R).$$

As the sensing leads have very little current, there is negligible voltage drop.

Lower excitation power can be used to avoid self-heating errors.



*Figure 4.15*

*Offset compensated four-wire RTD measurement using constant voltage source and digital voltmeter as a readout (courtesy of Hewlett Packard)*

### 4.3.3 Installation Techniques

Most of the installation techniques are common between various temperature measurement equipment. It is detailed at the end of the chapter in Installation considerations.

### 4.3.4 Typical Applications

A thermometer generally consists of an insert containing a PT100 housed in an external protective pipe called a thermowell. The terminal head houses either the electrical connections, or a locally mounted transmitter.

Two-wire RTD's are generally used in HVAC applications, whereas three-wire RTD's are commonly found in industrial situations. Four-wire RTD's are used in high-precision services requiring extremely good accuracy.

#### 4.3.5 *Advantages*

- Good sensitivity
- Uses standard copper wire
- Copper RTD's minimise thermocouple effect

#### 4.3.6 *Disadvantages*

- Bulky in size and fragile
- Slow thermal response time due to bulk
- Self heating problems
- More susceptible to electrical noise
- More expensive to test and diagnose

#### 4.3.7 *Application Limitations*

RTD's can be quite bulky, which can inhibit their use in applications. Thin film designs overcome this limitation and make this device suitable for miniaturisation.

Self heating can be a problem with RTD's. The magnitude of the errors generated by self heating effects vary, but are dependent on the size and the resistance of the RTD. These errors can be reduced by heat transfer and by minimising the excitation current.

The response time of RTD's is typically anywhere from 0.5 sec to 5 seconds. The slowness of response is due primarily to the slowness of the thermal conductivity in bringing the device to the same temperature as the surrounds. The response time increases for increased sensor size, also the use of thermowells can double the response time.

For a 2.5 mm probe the response time is 1-2 seconds, this varies with an 8mm probe having a response time of 5-10 seconds.

#### 4.3.8 *Summary*

RTD's are a little more expensive but are quite stable. They are also very linear, which makes for an easier conversion between the sensing voltage and measured temperature.



<b>Comparison of RTD Types</b>				
<b>Evaluation criteria</b>	<b>Platinum RTD 100Ω wire wound and thin film</b>	<b>Platinum RTD 1000Ω thin film</b>	<b>Nickel RTD 1000Ω wire wound</b>	<b>Balco RTD 2000Ω wire wound</b>
Cost –OEM quantity	High	Low	Medium	Medium
Temperature range	Wide -400 to 1200°F (-240 to 649°C)	Wide -320 to 1000°F (-196 to 538°C)	Medium -350 to 600°F (-212 to 316°C)	Short -100 to 400°F (-73 to 204°C)
Interchangeability	Excellent	Excellent	Fair	Fair
Long term stability	Good	Good	Fair	Fair
Accuracy	High	High	Medium	Low
Repeatability	Excellent	Excellent	Good	Fair
Sensitivity (output)	Medium	High	High	Very high
Response	Medium	Medium to fast	Medium	Medium
Linearity	Good	Good	Fair	Fair
Self-heating	Very low to low	Medium	Medium	Medium
Point (end) sensitivity	Fair	Good	Poor	Poor
Lead effect	Medium	Low	Low	Low
Physical size / packaging	Small to medium	Small to large	Large	Large

**Table 4.5**  
**Comparison of RTD Types**

## **4.4 Thermistors**

### **4.4.1 Basis of Operation**

A thermistor is a semiconductor device formed from metal oxides. The principle of temperature measurement with a thermistor is that its resistance changes with temperature. Most thermistors differ from normal resistors in that they have a negative coefficient of resistance, this means that the resistance decreases with an increase in temperature. Negative (NTC) thermistors are the more common although positive (PTC) are also available.

Thermistors were traditionally quite unstable, and their performance was unpredictable. However, improvements in technology and the selection of oxides now means that thermistors are produced that have characteristics that are well defined.

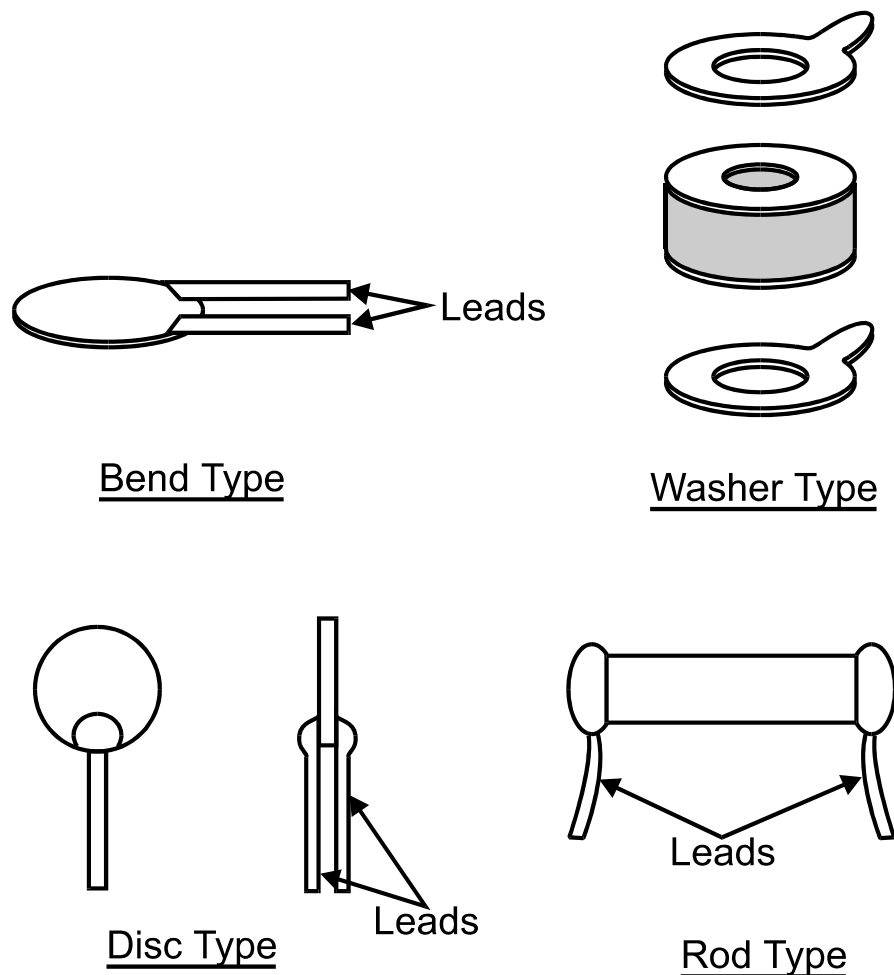
A thermistor is a bulk semiconductor device, and as such can be fabricated in many forms. The more common include discs, beads and rods. Size does vary from a bead

of 1mm to a disc of several centimetres in diameter and thickness. Wide ranges of thermistors (both resistance and temperature) are supplied by manufacturers. This is done by varying the doping and semiconductor materials.

#### 4.4.2 Selection and Sizing

Types of thermistors vary in a number of ways and one change is their response to temperature changes. Thermistors are not linear, and their response curves vary for the different types. Some thermistors have a near linear temperature resistance relationship, others are available with a sharp change in slope (sensitivity) at a particular characteristic temperature.

If the range of operation is suited, it is possible to replace an RTD with a thermistor, but problems lie in obtaining conversion units that fit the desired characteristic curve and meet the required accuracy.



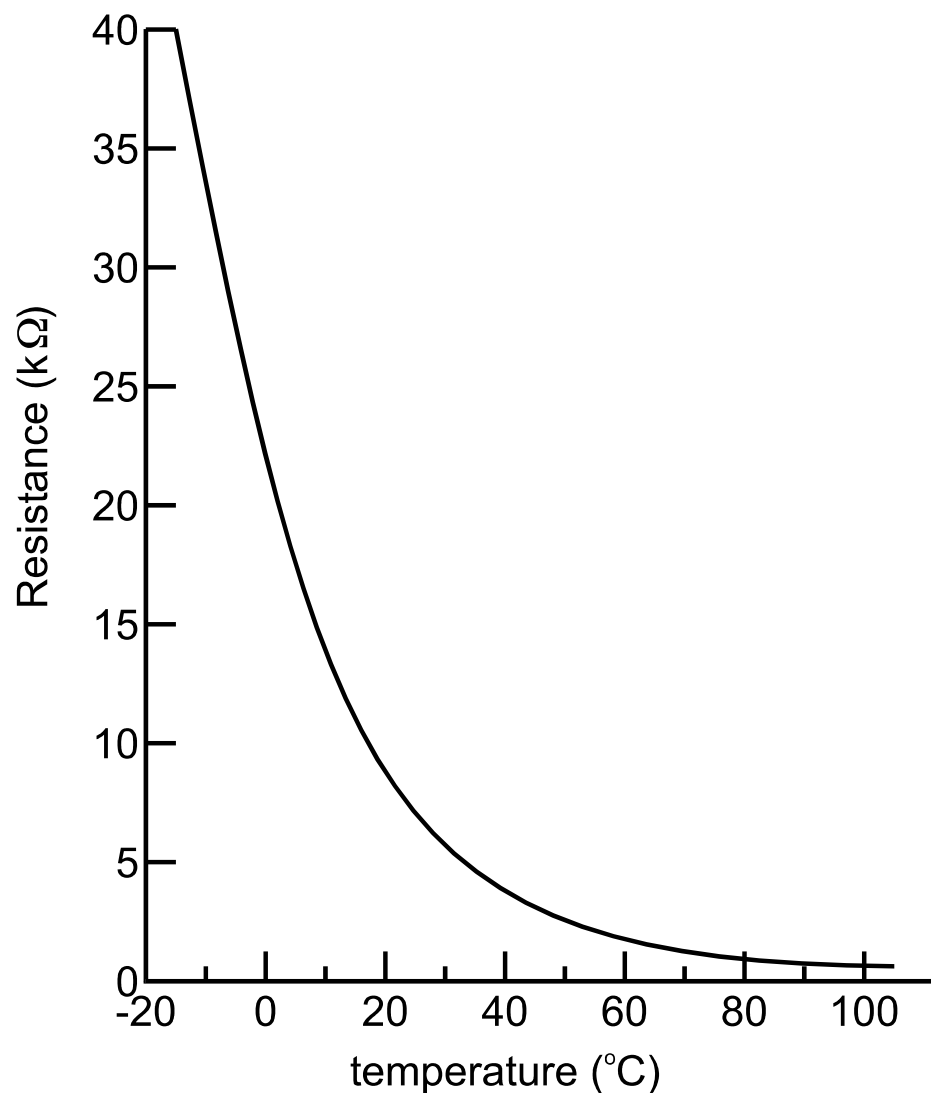
**Figure 4.16**  
*Variations in thermistor sensor packaging*

Thermistors have a much higher temperature coefficient than RTD's, so a small temperature change is easier to detect. However, thermistors do not have the accuracy of RTD's and this probably accounts for thermistors being limited in

process instrumentation. They are available in a large range of resistivities, with varying linearity.

Thermistors are available that perform temperature measurement from  $-73$  to  $316$  °C ( $-100$  to  $600$  °F). It should be noted that many have limited ranges and cannot be used above  $120$  °C ( $250$  °F).

Some thermistors have a large change in resistance for a change in temperature. Selecting these types makes for very good narrow span measurement, however they can cause problems for wide span applications.



**Figure 4.17**  
*Thermistor resistance versus temperature is highly non-linear and usually has a negative slope*

#### 4.4.3 Typical Applications

Due to their low cost, thermistors are used in many applications requiring information about process equipment for alarming and indication purposes. Such information, for example, would be the winding temperature of motors, or the temperature of bearings, or even the temperature of transformer windings.

In such applications, the actual temperature may not be of as much concern as the change or rapid increase in temperature. It is for this reason that thermistors give vital alarming information about the state of equipment in motion. In the examples of motor winding and bearings, both show a significant increase in temperature at the onset of the failure due to insulation breakdown in the windings or excessive friction in the bearings.

<i>Application</i>	<i>Cause of fault</i>	<i>Indication</i>
Motor winding temperature.	Breakdown of winding insulation due to moisture in windings or high motor currents (excessive starts)	Significant rise in temperature over time
Roller bearing	Excessive friction due to general wear over time, excessive loading or impulse loading	Sudden increase in temperature
Transformer windings	Breakdown of winding insulation	Significant rise in temperature over time

**Table 4.6**  
**Troubleshooting suggestions**

#### 4.4.4 Advantages

- Small size
- Fast response
- Very high sensitivity (Select range)
- No cold junction compensation
- Inexpensive
- Polarity insensitive
- Wide selection of sensors

#### 4.4.5 *Disadvantages*

- Unstable due to drift and decalibration (especially at high temperatures)
- Not easily interchangeable
- Non linear
- Narrow span
- Fragile
- High resistance, noise problems

#### 4.4.6 *Application Limitations*

For most applications, self-heating is not considered a problem as the thermistor currents used are relatively low. An adjustment in the form of an offset may be made for self-heating effects if a larger current is used, but only under fixed conditions. However, anything that affects the rate of heat dissipation will change the offset required. Such affects may be changes in flow or fluid composition.

The power dissipation from a thermistor can vary, and in industrial applications, a few degrees of self-heating can be expected for each milliwatt of resistive heating. As thermistors are made smaller to cater for increases in applications, their response times become faster as is required, however the problem of the effect of self-heating also rises.

Due to the high resistance of the thermistor, consideration is required to be given to cabling, filters and even the DC voltage supply.

##### *Range Limitations:*

The range of operation of the thermistor depends on the materials used to construct and protect the sensor. There are four main limitations that affect the range of effective operation:

- 1) Melting or deterioration of the semiconductor.

The semiconductor material may melt or deteriorate at higher temperatures. This condition generally limits the upper temperature to around 300 °C.

- 2) Deterioration of encapsulation material

It is quite common for the encapsulating material to be plastic, epoxy, Teflon or some other inert material. This is required as it protects the thermistor from the environment and adds mechanical strength, however the material may place an upper limit on the temperature at which the sensor can be used.

3) Insensitivity at higher temperatures

At higher temperature, the slope of the response curve is quite shallow, and possibly zero. This means that the device is physically not able to measure changes in temperature, because there is no change in resistance.

4) Difficulty in measurement at low temperatures.

As the temperature drops, the resistance of thermistors rise to quite high levels. It is because of these high resistances that low temperature limits are imposed due to the difficulty in measurement. The lower limit can be anywhere from  $-50\text{ }^{\circ}\text{C}$  to  $-100\text{ }^{\circ}\text{C}$ .

#### 4.4.7 Summary

It is the small size of thermistors that make this type of temperature measurement easy to implement. They are generally used for preventative maintenance applications, where the temperature goes into an alarm threshold.

Because of their non linearity and instability, thermistors are seldom used in continuous control applications.

The resistances of thermistors are a function of absolute temperature, which give the added advantage that they do not require cold junction compensation.

The stability of thermistors increases with age. Although they require recalibration due to drift, this becomes less of a problem over time as the amount of drift decreases. However, if a thermistor is operated at temperatures far below the maximum then it can remain a very stable device.

## 4.5 Liquid-In-Glass, Filled, Bimetallic

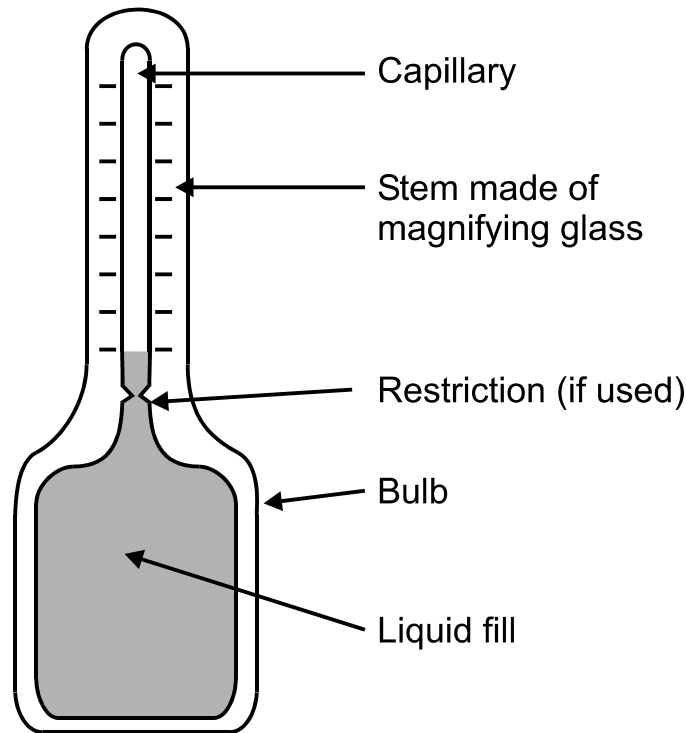
### 4.5.1 Glass-Stem Thermometers

The glass-stem thermometer is one of the oldest devices for measuring temperature. Either Mercury or alcohol is used to fill the glass bulb and extends into the capillary tube as it expands with temperature. The capillary tube where expansion occurs is evacuated, although in some applications it may be filled with nitrogen to increase the temperature range.

The material used in a glass-stem thermometer needs to remain a liquid over the full range of operation of the device. Mercury is quite common and has a large range of operation, typically  $-40\text{ }^{\circ}\text{C}$  to  $540\text{ }^{\circ}\text{C}$ .

Alcohol is used for lower temperatures. As alcohol is clear, colourfast dyes are used to increase the liquids visibility.

To increase the usability of these devices, they are mounted in metal thermowells for greater mechanical protection. All the limitations of using thermowells apply.



**Figure 4.18**  
**Liquid-in-glass thermometer**

#### **Advantages**

- Low cost
- Simplicity
- No recalibration required

#### **Disadvantages**

- Interpretation of measurement
- Localised measurement only
- Isolated from other control and recording equipment
- Fragile

#### **Summary**

Glass-stem thermometers are seldom used anymore because of the in-accessibility of the measurement information from a control system and also the toxicity of Mercury. They are a very cheap form of temperature indication and may still be found in older systems.

## 4.5.2 Filled Devices

### Basis of Operation

Filled thermal systems, consist of bulbs connected through capillary tubing to pressure or volume sensitive elements. They work on the expansion of a fluid with temperature. As the temperature increases, the fluid is pushed further along the capillary, and the pressure is increased. The Bourdon type is commonly used to measure the pressure.

### Selection and Sizing

In industrial applications, filled thermal systems not using glass are more common. These work on the same principle, where a bulb is filled with fluid which extends along a metal capillary tube. A pressure measuring device is used to detect the amount of expansion of the fluid.

Filled systems are classified on their expanding material, which can be a liquid, vapour, gas or mercury.

#### *Liquid filled systems (Class I):*

Liquid expansion systems have narrow spans, small sensors and give high accuracy. They also have the ability to provide temperature compensation using either an auxiliary capillary or bimetallic techniques. Fully compensated liquid expansion systems are expensive and complex.

Liquid filled systems have the advantage over Mercury in that the expansion of the fluid is about six times that of a Mercury systems. These also have the added advantage of using smaller bulbs.

The normal operating minimum for this type of sensing is from  $-75\text{ }^{\circ}\text{C}$  to  $-210\text{ }^{\circ}\text{C}$ , with the maximum being up to  $315\text{ }^{\circ}\text{C}$ .

Overrange protection is of particular concern in liquid filled systems, and is typically 100% over the normal operating range.

#### *Vapour filled systems (Class II):*

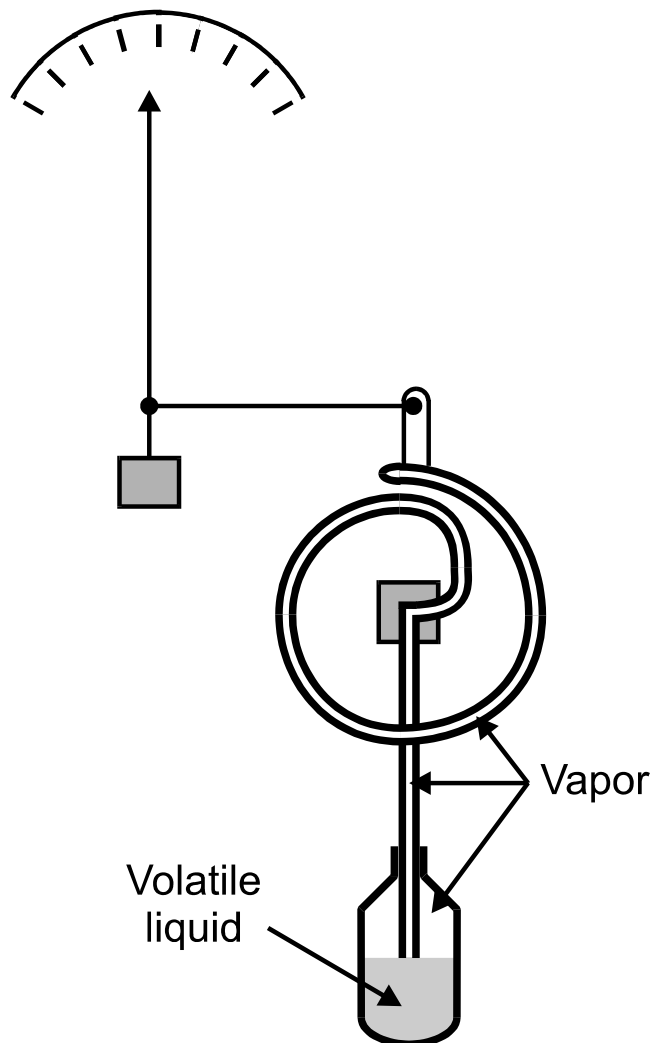
Vapour pressure systems are quite accurate and reliable. They also do not require any compensation for temperature effects. This form of measurement is based on the vapour-pressure curves of the fluid and measurement occurs at the transition between the liquid and vapour phases. This transition occurs in the bulb, and will move slightly with temperature, but it is the pressure that is affected and causes the measurement.



If the temperature is raised, more liquid will vaporise and the pressure will increase. A decrease in temperature will result in condensation of some of the vapour, and the pressure will decrease.

Different materials have different vapour pressure-temperature characteristics. Methyl chloride is quite commonly used in this type of sensor. Ethane is used for low temperature operation, typically from about  $-70\text{ }^{\circ}\text{C}$  to  $30\text{ }^{\circ}\text{C}$ . Whereas for high temperature applications, Ethyl Chloride can be used, with an effective operating range from  $40\text{ }^{\circ}\text{C}$  to  $175\text{ }^{\circ}\text{C}$ .

Vapour filled thermal systems are non-linear, and are generally more sensitive at the higher end of the scale. Selecting and sizing the application so that the range of operation is at the higher end can prove advantageous and provide better measurements. Overrange protection may become a problem as vapour filled systems have a low overrange limit.



**Figure 4.19**  
**Class IIB-type Vapour Filling**

*Gas filled systems (Class III):*

As the volume is kept constant, the pressure varies in direct proportion to the absolute temperature. This type of measurement is quite simple and low cost.

Nitrogen is quite commonly used as it doesn't react easily and is inexpensive, although it does have temperature limitations. At low temperatures and above 400 °C, helium should be considered.

The range of operation is determined by the initial filling pressure.

Gas filled systems do provide a faster response than other filled devices, and as it converts temperature directly into pressure it is particularly useful in pneumatic systems. This type of measurement also has the advantage that there are no moving parts and no electrical stimulation.

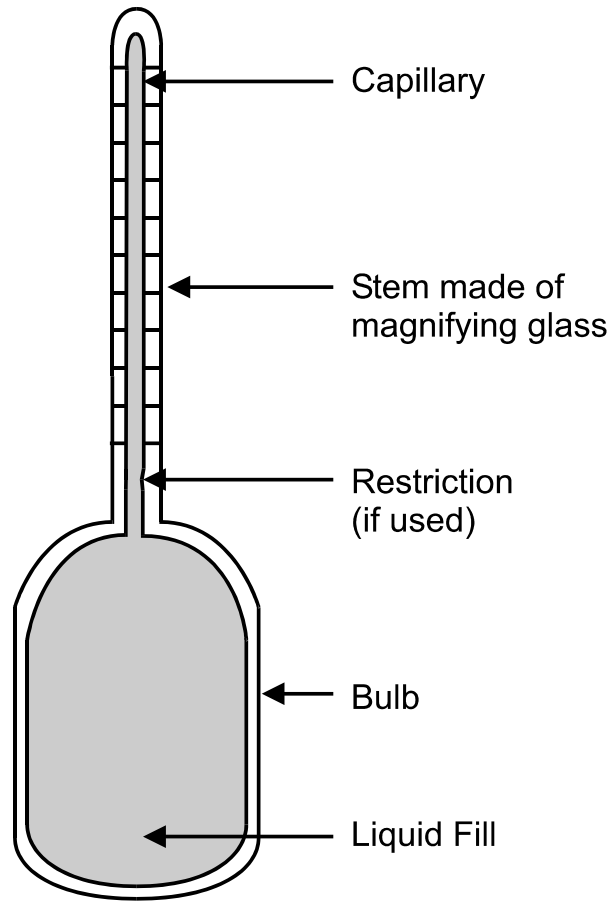
The size of the bulb is not critical and in fact can be sized quite large for averaging measurements in large volumes such as dryers and ovens.

*Mercury filled systems (Class V):*

Mercury expansion systems are different from other liquid filled systems because of the properties of the metal. Mercury is toxic and can affect some industrial processes and for this reason is used less in filled systems. The high liquid density also limits on the elevation difference between the sensor and instrument.

Mercury filled systems provide the widest range of operation, which range from the freezing to boiling point of the metal, ie from -40 °C to 650 °C.

Systems using this technology are simple, inexpensive and have fast responses. Typically they also have good overrange protection.



*Figure 4.20*  
*Liquid-in-glass thermometer*

<b>Instruments for Filled Thermal System Sensors</b>			
<b>Type Principle SAMA Class</b>	<b>Liquid Volume change I</b>	<b>Vapour (a) Pressure change II</b>	<b>Gas Pressure change III</b>
Fluids	Organic liquids (Hydro-carbons)	Organic liquids (Hydro-carbons), water	Pure gases
Lower range limit	-200°F (-130°C)	-425°F (-255°C)	-455°F (-270°C)
Upper range limit	+600°F (+315°C)	+600°F (+315°C)	+1,400°F (+760°C)
Narrowest span (b)	40°F (25°C)	70°F (40°C)	120°F (70°C)
Widest span	600°F (330°C)	400°F (215°C)	1,000°F (550°C)
Ambient temp.	IA full	Not required	
Compensation	IB case		IIIB case
Sensor size	Smallest	Medium	Largest
Typical sensor size for 100°C span	9.5mm (0.375 in) OD x 48mm (1.9in) long	9.5mm (0.375in.) OD x 50mm (2 in) long	22mm (7/8 in) OD x 70mm (6 in) long
Overrange capability	Medium	Least	Greatest
Sensor elevation effect	None	Class IIA, Yes Class IIB, None	None
Barometric pressure effect (altitude)	None	Slightly (greatest on small spans)	Slightly (greatest on small spans)
Scale uniformity	Uniform	Non-uniform	Uniform
Accuracy	±0.5 to ±1.0% of span	±0.5 to ±1.0% of span upper 2/3 of scale	±0.5 to ± 1.0% of span
Response (d) #1 Fastest #4 Slowest	#4	#1 – Class IIA #3 – Class IIB	#2
Cost	Highest	Lowest	Medium
Maximum standard	Class IA 30m or 100ft	30m or 100 ft	30m or 100 ft
Capillary length	Class IB 6, or 20ft		

**Table 4.7**  
**Instrument for filled thermal system sensors**

### Installation Techniques

To suit the differing applications, the temperature sensitive bulb is available in many different shapes and sizes. By using the largest bulb available for an application, this will limit temperature errors and allow smaller spans and longer capillaries.

A thermowell may need to be considered in adverse conditions and the associated problems need to be considered as the response time typically doubles when the thermowell is added. Response time is also affected by the size of the bulb, and doubles with the doubling of the bulb diameter.

Stainless steel is commonly used for the bulb material, due to the range of temperatures it can operate within. Protection of the thin fragile capillary needs to be considered. Typically this may be protected using flexible armoured stainless steel or PVC covered bronze tubing. Use of an extension neck to the bulb means that the tubing is greater protected from the process material.

### **Typical Applications**

#### **Advantages**

- Simple operation
- Robust
- Inexpensive
- No power source required
- Easily maintained
- Reasonably accurate

#### **Disadvantages**

- Bulky
- Slow response time
- Wide spans only
- Subject to gauge pressure problems
- Non linear

#### **Application Limitations**

The temperature that is displayed is a result of the pressure in the filled system. However the pressure in the system is a result of the temperature around the bulb and the temperature around the rest of the system.

Because the device is intended to measure process temperature only, temperature compensation may be required.

When the design is fully compensated for ambient temperature, the letter 'A' is added to the class distinction. If however only the case is compensated for, which may be sufficient, then the letter 'B' is added to the class distinction.

Vapour filled systems (Class II) do not require compensation as the liquid/vapour transition occurs within the bulb.

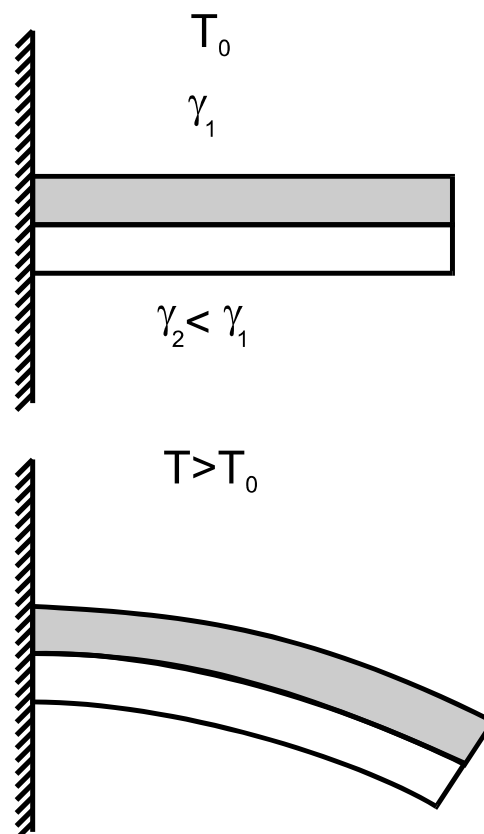
## Summary

This type of temperature measurement, as previously mentioned, relies on the measurement of pressure. As the pressure is referenced to the atmosphere, it is possible that atmospheric pressure changes can affect the pressure reading (also known as gauge pressure). This barometric change can cause an error of about 0.1% in the final measurement.

### 4.5.3 Bimetallic

#### Basis of Operation

Bimetallic temperature sensors work on the basis that different metals expand by different amounts. A bimetallic device consists of two metals bonded together which have different coefficients of expansion. Bending occurs as one metal expands more than the other. To amplify the mechanical movement of the deflection, the bimetallic device is generally wound into a spiral or helical form.



**Figure 4.21**

***A bimetal strip will curve when exposed to a temperature change because of the differential thermal expansion coefficients***

A bimetal strip will bend when exposed to a temperature variation. This is due to the different thermal coefficients of the two metals.

## **Selection and Sizing**

The operating ranges vary to cater for different applications, the lower range being from -70 °C to 50 °C, with a higher range available of up to 100 °C to 550 °C. Obviously, ranges are available between these extremes.

## **Installation Techniques**

Bimetallic thermometers can be used in a thermowell. A thermowell has the added advantages of allowing the removal or replacement of the device without opening up the process tank or piping.

They are typically in the helical form when used in thermowells.

Vibration and heat transfer can be a problem with some applications. However, selecting a unit that is completely sealed can overcome these limitations. A dry gas is generally used in the dial face portion of the assembly while silicone fluid fills the stem and surrounds the coil. Having fluid around the coil can assist in mechanical damping and heat transfer.

## **Advantages**

- Inexpensive
- Simple construction

## **Disadvantages**

- Limited accuracy
- Indication or simple switching only
- Localised measurement only
- Easily decalibrated due to mechanical shock
- Hysteresis

## **Application Limitations**

Primarily used for simple switching or indication on a dial. Use is generally restricted to local measurement only.

## **Summary**

Bimetallics are used in numerous applications because of their inexpensive and simple operation. Such applications range from household thermostats to HVAC equipment.

## 4.6 Non Contact Pyrometers

Pyrometric methods of temperature measurement use the electromagnetic radiation that is emitted from a material. The emitted radiation is proportional to the temperature.

There are two basic types of pyrometers:

- Infrared pyrometers
- Acoustic pyrometers

### 4.6.1 Infrared Pyrometers

#### Basis of Operation

Any object with a temperature above absolute zero will radiate electromagnetic energy. Infrared pyrometers measure the amount of energy radiated from an object in order to determine its temperature.

Infrared or radiation pyrometers use an optical system to focus the radiated energy onto a sensing device.

#### Selection & Sizing

Different materials transmit radiation of different wavelengths. In selecting an effective radiation pyrometer, a wavelength-band needs to be chosen that is not transmitted by the material. Also the selected wavelength-band cannot be absorbed by the environment.

The pyrometer wavelength needs to be sized for the process.

There are a number of different types of infrared pyrometers:

- Total radiation
- Single wavelength
- Dual wavelength

#### *Total radiation :*

This type of radiation thermometer measures all the energy, over a broad spectrum, emitted by the object. Because of the broad spectrum of sensing, this type of measurement is easily affected by any impurities or inconsistencies between the sensor and the object. Greater errors occur for materials with lower emissivity.



*Single wavelength :*

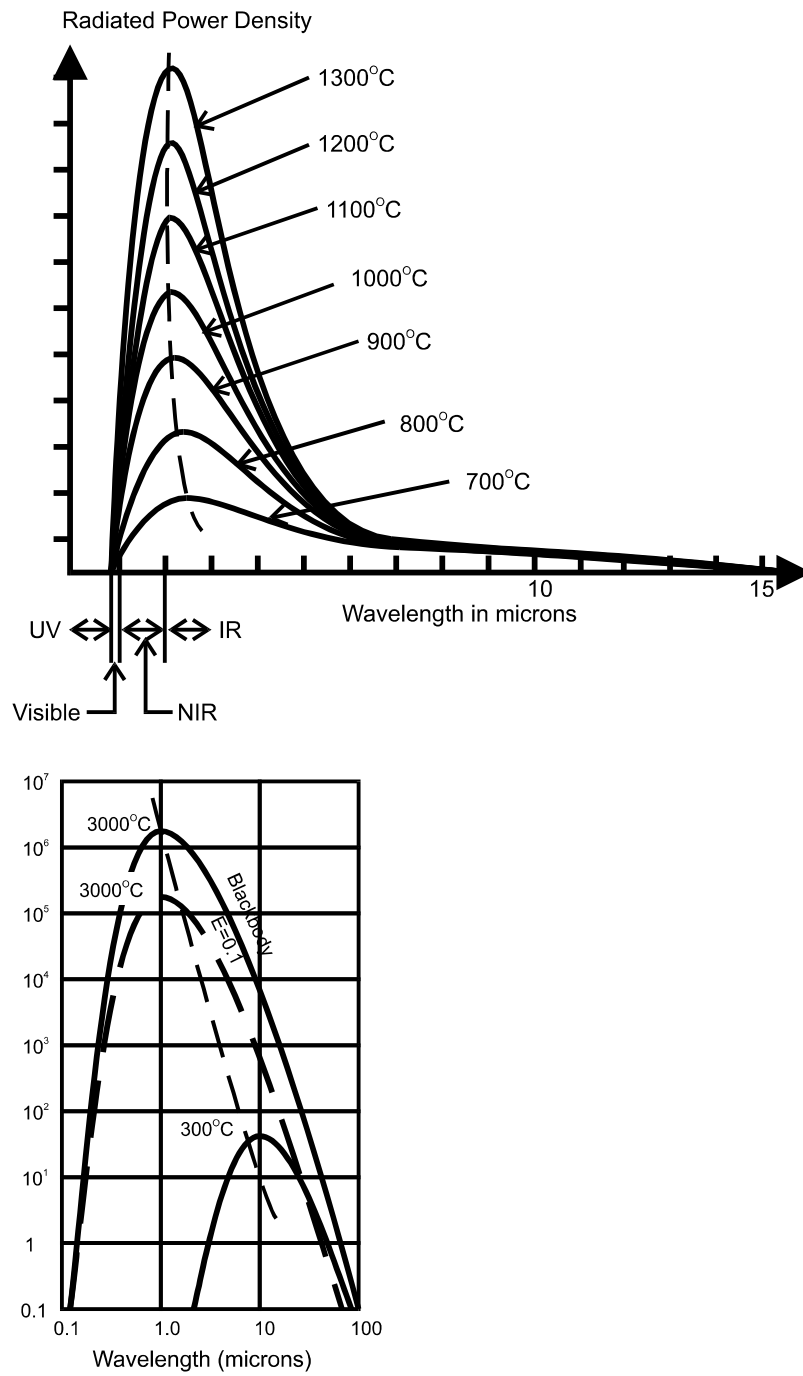
Unlike the broad spectrum, this type of radiation thermometer measures the magnitude of radiation at one wavelength. This optimises the accuracy of the device by selecting the wavelength best suited to the object being measured. This type of measurement provides good accuracy provided the emissivity is known.

*Dual wavelength :*

When the emissivity is low and hard to measure, or even variable, accuracy and reliability can be improved with a dual wavelength sensor. This type measures the magnitude of two wavelengths at the same time. The temperature is calculated from the two readings.

**Typical Applications**

Pyrometers are used for measuring high temperatures and where contact with the object is not possible.



**Figure 4.22**

***Any object above absolute zero will radiate electromagnetic energy. As the temperature increases, the peak moves to shorter wavelengths.***

### **Advantages**

- Non contact measurement
- High temperature sensing
- Remote sensing
- Fast response and can sense objects in motion
- Sense small or area targets

### **Disadvantages**

- Expensive
- Non linear response
- Subject to emissivity of material
- Require wide range of operation

### **Application Limitations**

Radiation pyrometry relies on thermal radiation leaving the material being measured. This is dependent on both the temperature of the object and the emittance of the material.

The accuracy is affected by reflections, presence of gases in the radiation path and the surface emissivity of the object. The surface emissivity can vary with wavelength, temperature and also the chemical composition of the object being measured. Other factors include the surface of the material, which include its texture or roughness and oxidation.

## **4.6.2 Acoustic Pyrometers**

### **Basis of Operation**

Acoustic pyrometers work on the principle that the speed of sound in a gas is dependant on the nature of the gas and its temperature. The time of flight is used, and since the distance between points is known it is possible to measure any change in conditions. This principle is adapted for liquid and solid temperature measurement also.

### **Typical Applications**

Acoustic pyrometers are used when requiring an average temperature or the temperature over a large area or volume of gas.

Acoustic pyrometers are useful for measuring gas temperatures inside kilns and furnaces. They work over a very large temperature range and are useful for mapping thermal contours. Unfortunately cost is often prohibitive.

## 4.7 Humidity

The moisture content in gases is termed humidity and is expressed as either:

- Relative humidity
- Absolute humidity
- Dew point

There are a vast number of methods and technologies developed over the years to measure humidity. Following is a list of such, with this section only focusing on the current and commonly used types.

### Relative Humidity

- Mechanical
- Wet and dry bulb
- Surface resistivity devices
- Crystal frequency change

### Absolute Humidity

- Gravimetry
- Electrolysis
- Infrared
- Conductivity
- Capacitance
- Colour change
- Karl Fischer titration
- RF power absorption
- Neutron reflection
- Heat of absorption or desorption
- Nuclear magnetic resonance

### Dew Point Measurement

- Chilled mirror
- Lithium chloride
- Wet bulb thermometer

#### 4.7.1 Capacitive

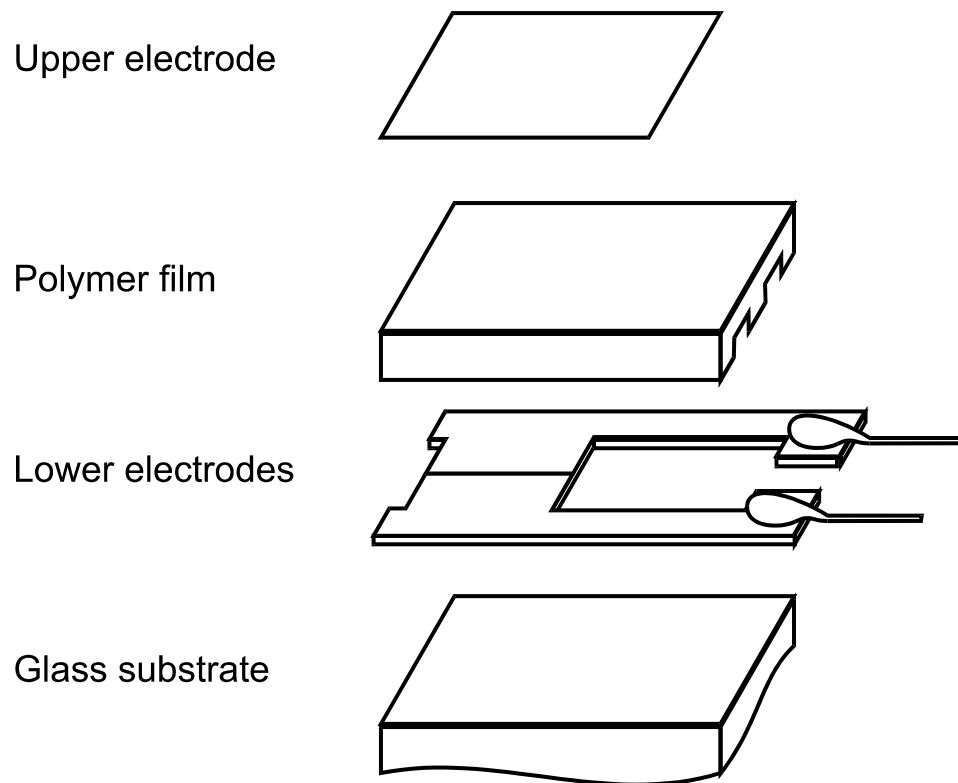
Capacitance is one of the most common forms of humidity measurement.

## Basis of Operation

Any type of capacitor requires two conductive plates separated by a dielectric. Humidity measurement is performed by exposing the dielectric to the moisture in the air. The moisture changes the relative capacitance between the two electrodes, which can be measured.

The metals used for the plates (or at least one plate) need to be porous in order for the dielectric to change in moisture content. The metals do vary as developments in technology progress.

The dielectric material is the single most important factor affecting the performance of capacitive humidity sensors. Other factors are the processing conditions, the sensor structure and the properties of the water permeable electrode or electrodes.



**Figure 4.23**  
**Structure of the Humicap® Sensor**

### *Water permeable top electrodes:*

The water permeable top electrode was originally thin gold film, but advances in technology have seen a cracked chromium film now used. Some of the advantages of the cracked chromium over the thin gold film are:

- Easier to manufacture
- Good corrosion resistance
- Good adhesion to polymer films
- Faster response times

Porous metal films is another emerging technology that only allows water to permeate the film, excluding alcohols. This feature improves the stability of the sensor particularly in applications involving vapours, other than water vapour. This technology also enables an ultra-fast response.

#### *Dielectric:*

Aluminium oxide is commonly used as the dielectric medium. Doping of the aluminium oxide may be done with lithium chloride to give a greater operating range, typically down to -70 °C. The use of lithium chloride also requires that the device be individually calibrated, and slows the response.

#### *Bottom electrode:*

A conductive aluminium base material is typically used as the bottom electrode.

### **Typical Applications**

Humidity sensors are typically used in building controls. The most effective location for a wall mounted sensor is near the return air duct, where the air leaving the room has the best averaged humidity.

### **Advantages**

- Wide range of sensing
- Small size

### **Disadvantages**

- Non linear
- Require periodic calibration
- Not highly accurate

### **Application Limitations**

Capacitive humidity devices that use an aluminium oxide moisture sensor are not very accurate and each sensor requires a separate calibration curve, which is non-linear.

Periodic calibration is necessary because of errors due to contamination and general ageing of the device.

## Summary

This type of sensing is generally used for HVAC applications due to their low cost and relatively small size. In these applications, accuracy is not critical and periodic calibration can be performed without disturbing the smooth operation of the process.

## 4.8 Installation Considerations

### 4.8.1 Location and Cabling

The best installation practice is to mount all electronics directly on top of the thermowell. This eliminates lead-wire and noise effects. If, for some reason this cannot be done, the lead wires need to be twisted and shielded to maximise protection from electrical interference. The wires should also not be stressed, either under tension or from tight bends. Large diameter cabling should be considered to minimise electrical resistance and increase mechanical robustness.

### 4.8.2 Thermowells

A thermowell has the added advantages of allowing the removal or replacement of the sensing device without opening up the process tank or piping.

Thermowells need to be considered when installing temperature sensing equipment. The length of the thermowell needs to be sized for the temperature probe.

Consideration of the thermal response needs to be taken into account. If a fast response is required, and the sensor probe already has adequate protection, then a thermowell may impede system performance and response time. Note that when a thermowell is used the response time is typically doubled.

Thermowells can provide added protection to the sensing equipment, and can also assist in maintenance and period calibration of equipment.

Thermopaste assists in the fast and effective transfer of thermal dynamics from the process to the sensing element. Application and maintenance of this material needs to be considered. Regular maintenance and condensation can affect the operation of the paste.

### 4.8.3 Effects of Self Heating

Any electrical temperature sensing device can be prone to self heating. In measuring the resistance of a device, a current must be passed through it. When current passes through a resistance, energy is lost or dissipated in the form of heat. When the current is kept low, this heat loss is minimised and the effects are minimal.

Other methods use the non-linear characteristics of the thermistors to rapidly switch the output for a temperature change. These thermistors can be used as thermostats for overheating protection.

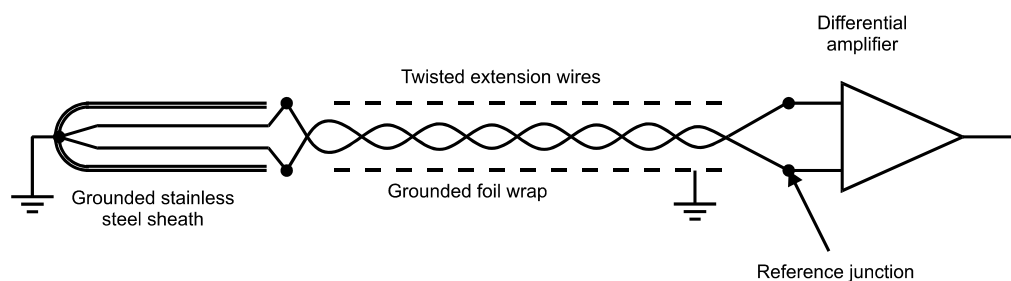
#### 4.8.4 Noise

One of the main problems, particularly with thermocouples, is their susceptibility to electrical noise. The voltages that are generated are in the order of a few millivolts. In an industrial environment it is not uncommon to have voltages of 100's of times greater of electrical noise generated by higher power equipment.

A thermocouple makes for an excellent antenna, as it picks up high frequency electromagnetic radiation.

The three most common noise reduction techniques are as follows:

1. Twist and shield (grounded foil sheath) the extension or lead wires from the thermocouple to the measurement system.
2. Ground the measurement junction at the point of measurement. The grounding is typically to the inside of the stainless steel sheath that covers the actual thermocouple.
3. Use a transmitter with very good common mode voltage rejection, and locate as close to the thermocouple as possible.



**Figure 4.24**  
**Protect the thermocouple signal against electrical noise by shielding, twisting and using a differential input.**

The advantage of grounding the measurement junction is that the electrical noise is distributed equally on each wire of the thermocouple.

## 4.9 Impact on the Overall Control Loop

The time response is how long it takes a system to come into thermal equilibrium with its surrounds. That is, how long it takes a sensor to read the actual temperature.

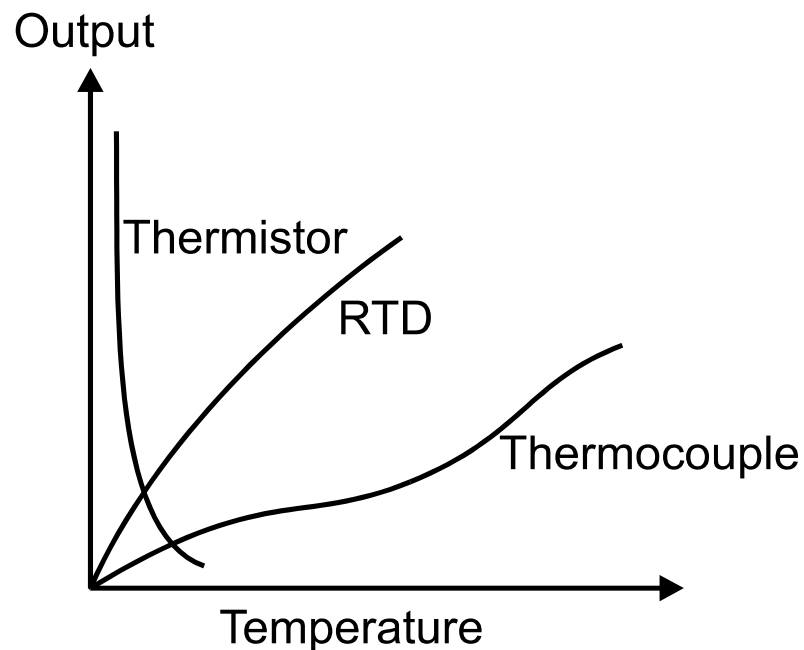


The response of a thermocouple is related to the size of the wire and any protective material used with the sensor. Many industrial thermocouples use thick wire or are encased in stainless steel sheathing, and may have time constants as high as 10 to 20 seconds. Conversely, thermocouples made from very small gauge wire can have time constants as small as 10 to 20 milliseconds.

The response time can be specified under conditions of good and poor thermal contact, so the application environment can be accounted for.

#### 4.10 Selection Tables

The figure below highlights the different responses between thermocouples, RTD's and thermistors.



*Figure 4.25*  
*Thermistor versus RTD's versus Thermocouples*

<b>Orientation table for temperature sensors</b>								
Type	Temperature Range °F	Available Span	Accuracy % of span	Stability	Repeat-ability	Response Time	Sensit-ivity	Linear
T/Cs:								
Type T	-300 to 750	<100 to 1000	0.1	G	G	G	G	N
Type J	32 to 1500	<100 to >1000	0.1	G	G	G	G	N
Type K	-300 to 2300	<100 to >1000	0.1	G	G	G	G	-
Types R&S	32 to 3000	<1000 to >1000	0.1	G	G	E	E	N
RTDs:								
Pt	-400 to 1200	<100 to >1000	0.15	E	E	G	G,E	-
Nickel	-350 to 600	<100 to <1000	0.25	G,E	E	G	E	N
Thermistors	-100 to 500	<100 to <1000	0.2	F	G	E	E	N
Electronic	-350 to 325	<100 to <1000	0.2-2	G	G	G	E	-
Bimetallics	-100 to 1000	<100 to <1000	1-2	E	F	G	G	N
Filled:								
Liquid	-50 to 800	<100 to <1000	0.5-2	E	F	F	G	-
Vapour	0 to 600	<100 to <1000	0.5-2	E	F	G	F	N
Gas	-100 to 1800	<1000 to >1000	0.5-2	E	F	G	F	-
Mercury	-10 to 1000	<100 to >1000	0.5-2	E	F	F	G	-
Glass stem	-10 to 1000	<100 to <1000	0.1-2	E	E	F	G	-
Infrared	-10 to 6300	<1000 to >1000	1-2	F	F	E	G	N
Ultrasonic	1500 to 15000	<100 to >1000	5	G	F,G	E	E,G	N

**Table 4.8**  
**Orientation table for temperature sensors**

## 4.11 Future Technologies

### *Electronic Temperature Sensors*

Transistors or diodes can be used for temperature measurement. The output of such a device is very linear and is good for a temperature range of -55 to 150°C. These electronic devices are not as accurate as other devices, however they are inexpensive.

### *Sensor Size*

Newer sensors use miniaturisation to maximise the number of applications and uses. This is not new. The miniaturisation of non-contact sensors is becoming more common with cost and specifications making them suitable in applications where contact sensors were previously used.

The development of smaller infrared sensors means that they have become more economical and maintain:

- calibrated accuracy
- minimal thermal drift
- stability

Applications of noncontact measurement is expanded with the use of fibre-optics, which does not require the need for miniaturisation. The fibre acts as a carrier for the

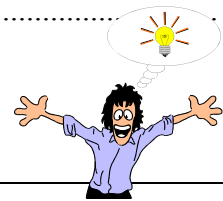
radiated energy. These have the added advantage of isolation of the components from direct heat or other hazardous surrounds.

# Tips and Tricks



A series of horizontal dotted lines providing a template for writing notes or tips.

# Tips and Tricks





<b>Thermocouple Comparison</b>								
<b>ISA Type designation</b>	<b>Positive wire</b>	<b>Negative wire</b>	<b><math>\mu\text{V}/^\circ\text{F}</math></b>	<b>Recommended Temp limits <math>^\circ\text{F}</math></b>	<b>Scale linearity</b>	<b>Atmosphere recommended</b>	<b>Favourable points</b>	<b>Unfavourable points</b>
B	Pt70-Rh30	Pt70-Rh6	3-6	32 to 3380	Same as type R	Inert or slow oxidising		
E	Chromel	Constantan	15-42	-300 to 1800	Good	Oxidising	Highest emf/ $^\circ\text{F}$	Larger drift than other base metal couples
J	Iron	Constantan	14-35	32 to 1500	Good; nearly linear from 300 to 800	Reducing	Most economical	Becomes brittle below $32^\circ\text{F}$
K	Chromel	Alumel	9-24	-300 to 2300	Good; most linear of all T/Cs	Oxidising	Most linear	More expensive than T or J
R	Pt87	Platinum	3-8	32 to 3000	Good at high temps	Oxidising	Small size	More expensive
S	Pt90-Th10	Platinum	3-7	32 to 3200	Same as R	Oxidising	Same as R	More expensive
T	Copper	Constantan	8-35	-300 to 750	Good but crowded at low end	Oxidising but reducing	Resists corrosion from moisture	Limited temperature range
Y	Iron	Constantan	22-33	-200 to 1800	About same as J	Reducing		Nonstandard
-	Tungsten	W74-Re26	1-12	0 to 4200	Same as R	Inert or vacuum	High temperature	Brittle; expensive
-	W94-Re6	W74-Re26	1-10	0 to 4200	Same as R	Inert or vacuum	Same as above	Slightly less brittle than above
-	Copper	Gold-cobalt	0.5-25	-450 to 0	Reasonable above $60^\circ\text{K}$		Good output at very low temp	Expensive lab-type T/C
-	Ir40-Rh60	Iridium	1-4	0 to 3800	Same as R	Inert		Brittle; expensive



# **5**

## **Flow Measurement**

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# Chapter 5

## Flow Measurement

### 5.1 Principles of Flow Measurement

#### 5.1.1 Types of Flow

There are four main types of liquid flow:

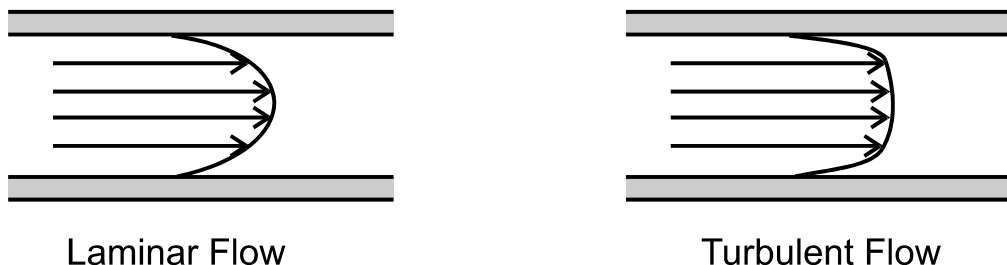
Type of flow	Notable Characteristics	Process material
General	Thin, clean liquids	Water, light oils and solvents
Two-phase flow	Liquids with bubbles	Beer, wet steam, unrefined petroleum
Slurry	Dirty liquids	Water and sand
Non-Newtonian	Heavy thick liquids	Grease, Paint, honey

*Table 5.1  
Main types of liquid flow*

#### 5.1.2 Basic Terms and Concepts

##### *Laminar vs Turbulent flow*

In laminar flow, the fluid moves smoothly in orderly layers, with little or no mixing of the fluid across the flow stream. With laminar flow, there can still exist changes in velocity as the friction of the wall slows the layers closest to the wall, while the flow in the centre of the pipe moves at a faster pace. This velocity change produces a parabolic streamlined flow profile.



*Figure 5.1  
Flow profile*

In turbulent flows, the laminar flow breaks down to produce intermixing between the layers. Turbulent flow is quite random, as smaller currents flow in all directions - these are also known as eddies. This type of flow has a flatter flow profile, such that the velocity of forward flow in the centre of the pipe is nearly the same as that near the walls of the pipe.

### *Swirl*

Swirl occurs with laminar flows as fluid passes through elbows or some other form of pipeline geometry. In a similar fashion to turbulent flows, they affect the measurements of many instruments and precautions should be taken to mount measuring devices well downstream from the swirling fluid. The effects of swirls can be minimised by the use of a flow conditioner, or straightener in the line upstream.

### *Reynolds number*

A Reynolds number defines the flow conditions at a particular point. It is a way of representing fluidity and is a useful indicator of laminar and turbulent flow. Laminar flow exists if the Reynolds number is less than 2000, and turbulence when the number is above 4000. There is not a clear transition between laminar and turbulent flows, which does complicate flow measurement in this range of operation.

The Reynolds number equation shown below shows the relationship between the density ( $\rho$ ), viscosity ( $u_{cp}$ ), pipe inside diameter ( $D$ ) and the flow rate ( $v$ ).

$$RD = \frac{K \times \rho \times v \times D}{u_{cp}}$$

### *Velocity*

This is the speed at which the fluid passes a point along the pipe. The velocity is used to calculate volume and mass flow rates.

### *Volumetric flow rate*

The volumetric flow rate represents that volume of fluid which passes through a pipe per unit of time. This form of measurement is most frequently achieved by measuring the velocity of a fluid with a DP sensor as it travels through a pipe of known cross sectional area.

### *Mass flow rates*

Mass flow is a measure of the actual amount of mass of the fluid that passes some point per unit of time

### *Totalized flow*

Totalized flow is an accumulation of the amount of fluid that has passed a point in a pipe. This is used in both volume or mass based systems generally for accounting purposes.

### *Viscosity*

The viscosity of a fluid defines the resistance which the fluid has against flowing. It is typically measured in units of poise or centipoise at a given temperature. Higher numbers indicate an increase in viscosity (which is a greater resistance to flow). As the temperature of most liquids increases, their viscosity decreases and they flow more readily.

### *Density*

The density of a fluid is the mass of the fluid per unit of volume. Density is affected by temperature and pressure variations. To avoid problems of pressure and temperature variation, mass flow measurements can be used. Although density can be of some use, it is usually more often used to infer composition, concentration of chemicals in solution or solids in suspension.

### *Specific Gravity*

The specific gravity is the unitless ratio, found by comparing the density of a substance to the density of water at a standard temperature.

### *Pulsation's*

In maintaining good measuring conditions, pulsations in the flow stream should be recognised and avoided if possible. Common causes of pulsating flows are from pumps, compressors and two-phase fluids.

### *Cavitation*

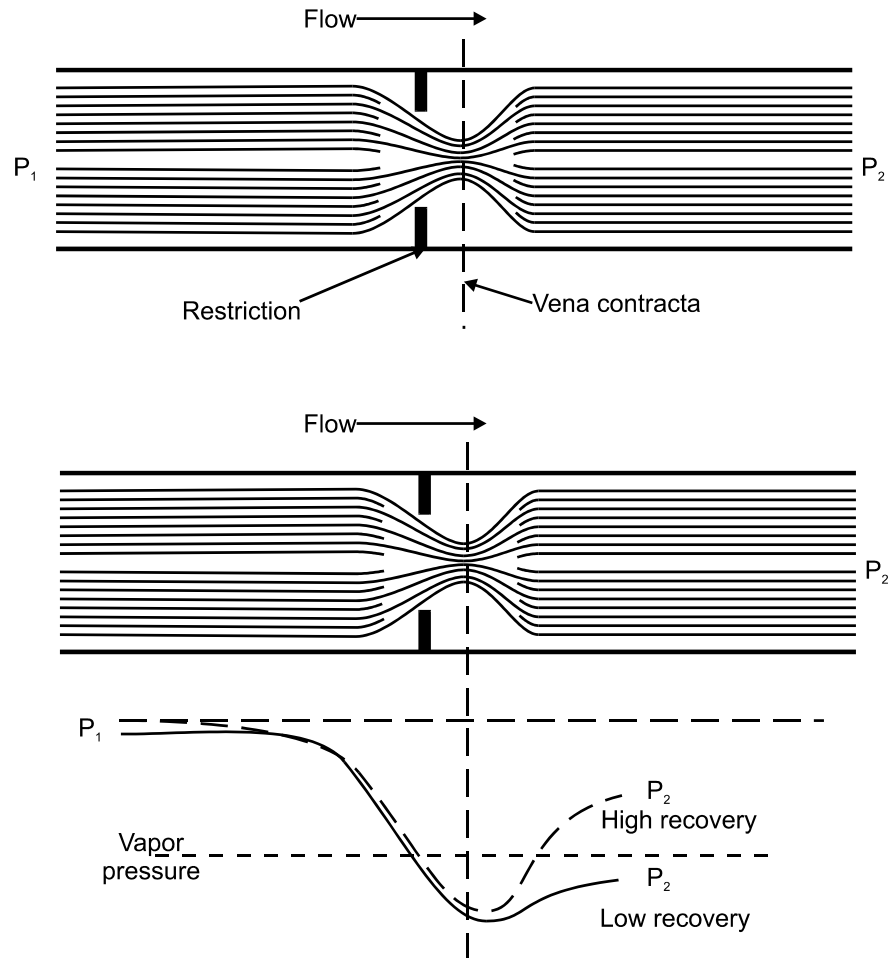
This condition occurs when the pressure is reduced below the vapour pressure of the liquid. This causes vapour cavities, or bubbles, to form. These bubbles can dissipate quickly causing damage to the piping system as well as the flowmeter, resulting in measurement errors. Maintaining sufficient pressure in the pipe commonly solves the problem. In applications where this is likely, measurement methods requiring a pressure drop should be avoided, such as differential pressure devices.

### *Non-Newtonian*

The normal behaviour of fluids is such that as temperature increases, viscosity decreases. There are fluids that do not abide by the standard rules of fluid dynamics. The so-called non-Newtonian fluids have viscosities that change with shear rate. Some products become thinner when agitated, whereas others stiffen when deformed.

### Vena Contracta

The cross-sectional area of a fluid decreases as it is forced through a restriction. With the inertia of the fluid, the cross-sectional area continues to decrease after the fluid has passed the restriction. Because of this, the fluid's minimum cross-sectional area, which also has the maximum velocity and lowest pressure, is located at some point downstream of the restriction. This point is called the vena-contracta.



**Figure 5.2**  
**Vena-Contracta**  
 (Courtesy of Fisher Controls International)

### Rangeability

Rangeability is the ratio of maximum to minimum flow. Rangeability is used to give a relative measure of the range of flows that can be controlled.

$$\text{Rangeability} = \frac{Q_{\max}}{Q_{\min}}$$

### 5.1.3 Flow Measurements

There are three main measurements that can be made with process flows:

- Velocity
- Volumetric flow
- Mass flow

Velocity is the speed at which the fluid moves. This by itself does not give any information about the quantity of fluid.

Volumetric flow is often deduced by knowing the cross sectional area of the fluid. Most volumetric flow equipment measures the velocity and calculates the volumetric flow based on a constant cross sectional area.

$$Q = v \cdot A$$

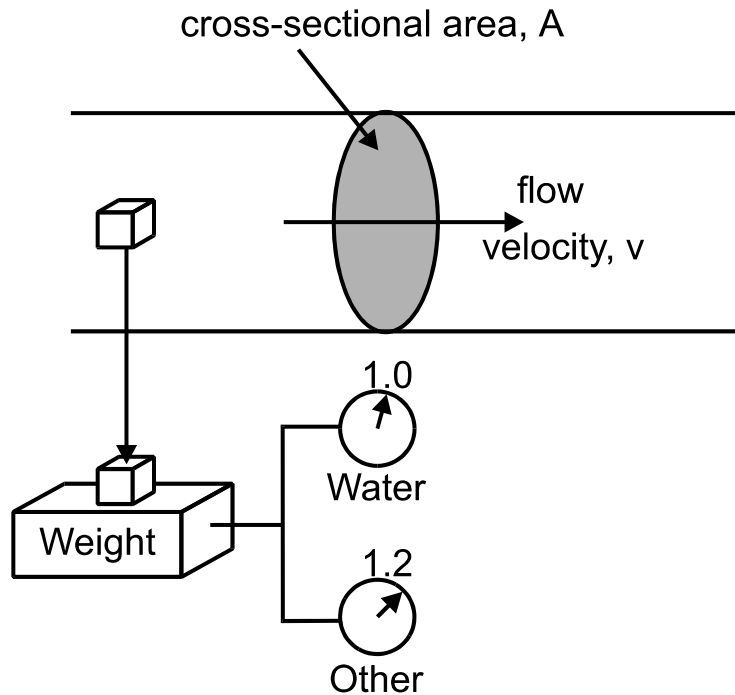
where:      v is the velocity  
              A is the cross sectional area  
              Q is the volumetric flow rate

Mass flow rate can only be calculated from the velocity or the volumetric flow rates if the density is constant. If the density is not constant, then mass flow measuring equipment is required for mass flow rate.

$$W = Q \cdot \rho$$

where:      Q is the volumetric flow rate  
              ρ is the density of the fluid  
              W is the mass flow rate

The flow of gases is normally measured in terms of mass per unit time. While most liquids are nearly incompressible, densities of gases vary with operating temperature and pressure. Some flowmeters, such as Coriolis meters, measure the mass flow directly. Volumetric flowmeters do not measure mass flow directly. Mass flow is calculated from the density and the volumetric flow as shown above. Some volumetric meters infer density based on the measured pressure and temperature of the fluid. This type of measurement is referred to as the inferred method of measuring mass flow.



**Figure 5.3**  
*Inferred method of measuring mass flow*

## 5.2 Differential Pressure Flowmeters

### 5.2.1 Basis of Operation

One of the most common methods of measuring flow is with a Differential Flowmeter. This technique requires the pressure to be measured on both sides of an imposed restriction in the path of normal flow. The flow rate of the material can be calculated from the change in pressure.

Before looking at the mathematics, some terms that best describe the response of imposing a restriction in a line need to be considered.

As an example, consider a garden hose with a spray nozzle. With the spray shut off (so that no water flows) the pressure in the hose can be felt. At this point, the hose has a lot of potential energy (or stored energy) - it has the ability to move the water if allowed to do so. When the spray nozzle is opened, energy is converted into a flow of water, ultimately converting the potential energy to a small amount of kinetic energy (or motion energy). If the nozzle is opened fully then most of the potential energy is converted to kinetic energy and the pressure on the hose drops considerably.

Differential pressure devices work on the principle of inducing a change in pressure by placing a restriction in the line. This effectively changes some potential energy kinetic energy - this is detected and measured as a change in pressure.

The principle of increasing kinetic energy by sacrificing potential energy when constricting the flow is described by mathematics (according to Bernoulli's streamline energy equation).

The restriction in the pipe is called the primary element. The secondary element is the differential pressure sensor and transmitter. This device can measure the and calculate the flow rate. Differential pressure or flow rate information can then be accessed from this device.

The velocity of flow is related to the square root of the differential pressure.

When the pressure differential is measured, the volumetric or mass flow rate can be calculated based on:

- fluid properties
- cross-sectional area
- shape of restriction
- adjacent piping

### 5.2.2 *Formulae*

The relationship between the flow rate and the change in pressure can be shown as:

$$V = k \cdot \sqrt{\frac{h}{\rho}}$$

$$Q = k \cdot A \cdot \sqrt{\frac{h}{\rho}}$$

$$W = k \cdot A \cdot \sqrt{h\rho}$$

where:

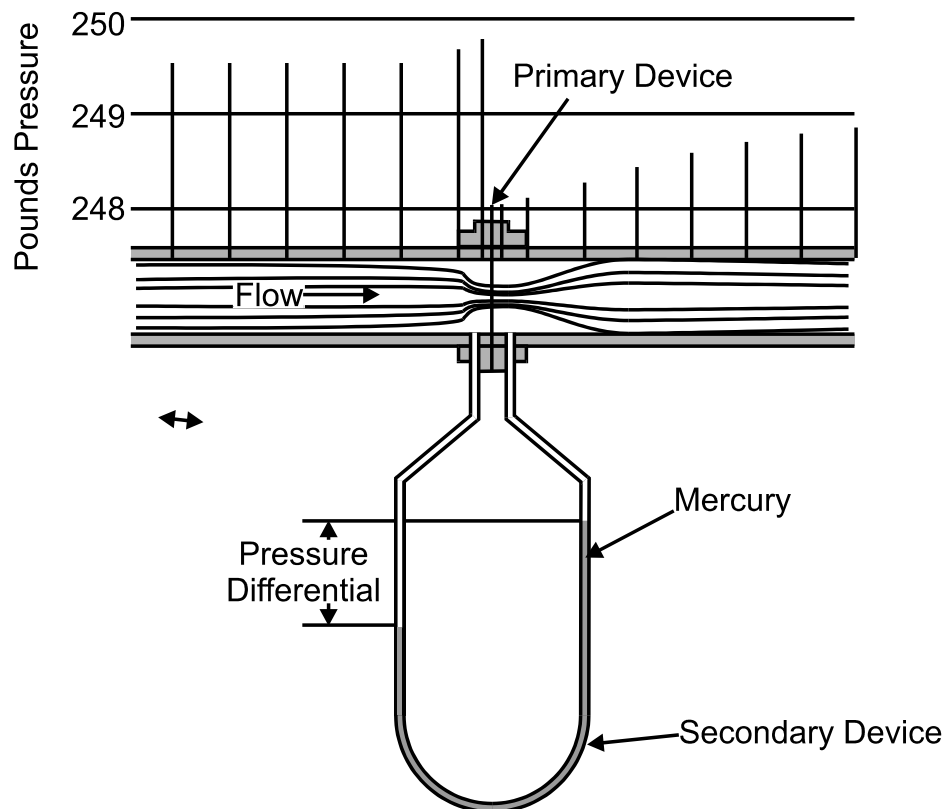
- v is the velocity
- Q is the volumetric flow rate
- W is the mass flow rate
- k is a constant
- h is the differential pressure
- $\rho$  is the density of the fluid
- A is the cross sectional area of the pipe



### 5.2.3 Primary Element

#### Orifice Plate

A standard orifice plate is simply a smooth disc with a round, sharp-edged inflow aperture and mounting rings. In the case of viscous liquids, the upstream edge of the bore can be rounded. The shape of the opening and its location do vary widely, and this is dependent on the material being measured. Most common are concentric orifice plates with a round opening in the centre. They produce the best results in turbulent flows when used with clean liquids and gases.



**Figure 5.4**  
**Differential pressure profile with orifice plate**

Options are available for unclean material or flows that contain liquid and gas of varying densities. When measuring liquids the bore can be positioned at the top of the pipeline to allow the passage of gases. The same applies when allowing suspended solids to pass, by positioning the bore at the bottom and gaining a more accurate liquid flow measurement. Half-circle bores are often used with light slurries or dirty gases.

The pressure removal holes or slits are located in the aperture and mounting rings. The location of these pressure taps depends on the type of tap being used. However, the taps are usually located in the adjacent flanges, or one diameter upstream and one-half diameter downstream.

Standard orifice meters are primarily used to measure gas and vapour flow. Measurement is relatively accurate. Because of the obstruction of flow there is a relatively high, residual permanent pressure loss. These meters are well understood, rugged and relatively inexpensive for large pipe sizes and are suited for most clean fluids and are not influenced by high temperatures.

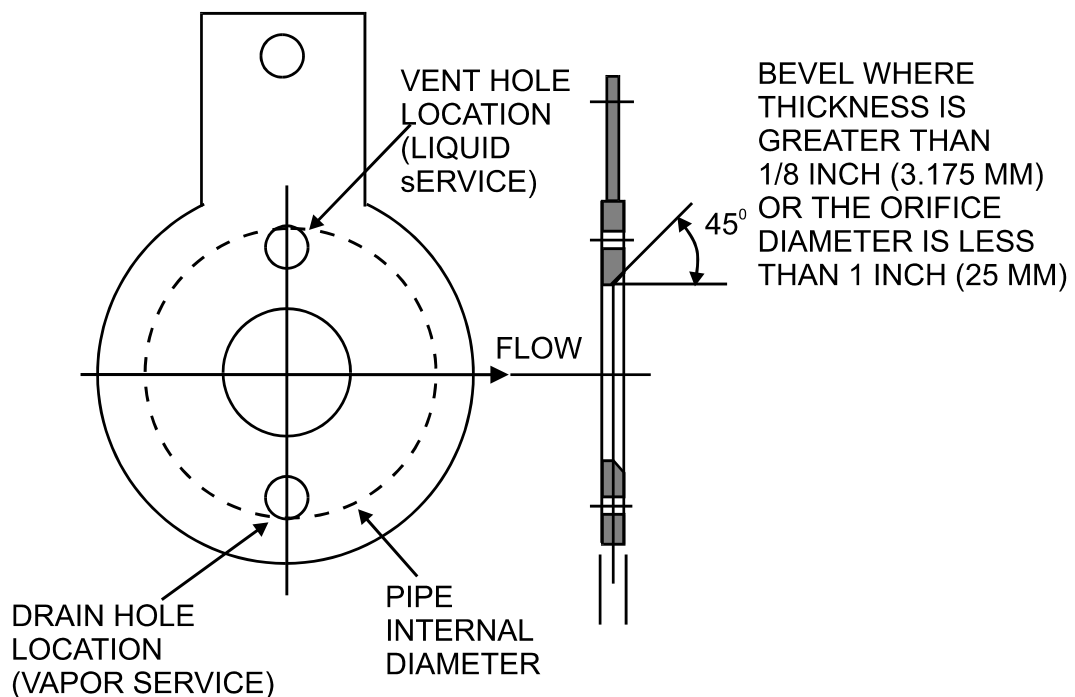
### ***Orifice Type***

There are two main types of orifices for various applications:

- Concentric, square edged
- Concentric, quadrant edged
- Eccentric or segmental square edged

### ***Concentric, square edged***

This is the most common and basic type of orifice meter. This device is typically a thin concentric sharp-edged orifice plate. Because of the simplicity, it is inexpensive to manufacture to very close tolerances. This also simplifies the ease in which it can be installed and replaced.



***Figure 5.5***  
***Concentric orifice plate***

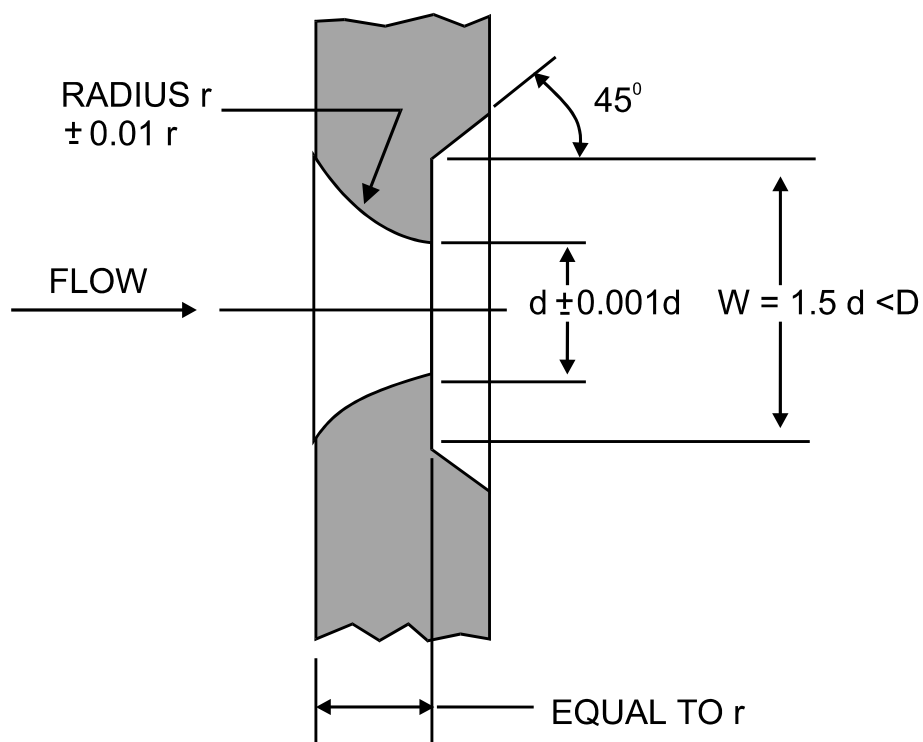
The thickness of the orifice plate depends on the following:

- Pipe size
- Flow temperature
- Differential pressure

***Concentric, quadrant edged***

This type of orifice plate is used to give increased stability in flow, and is about 10 times that for conventional plates.

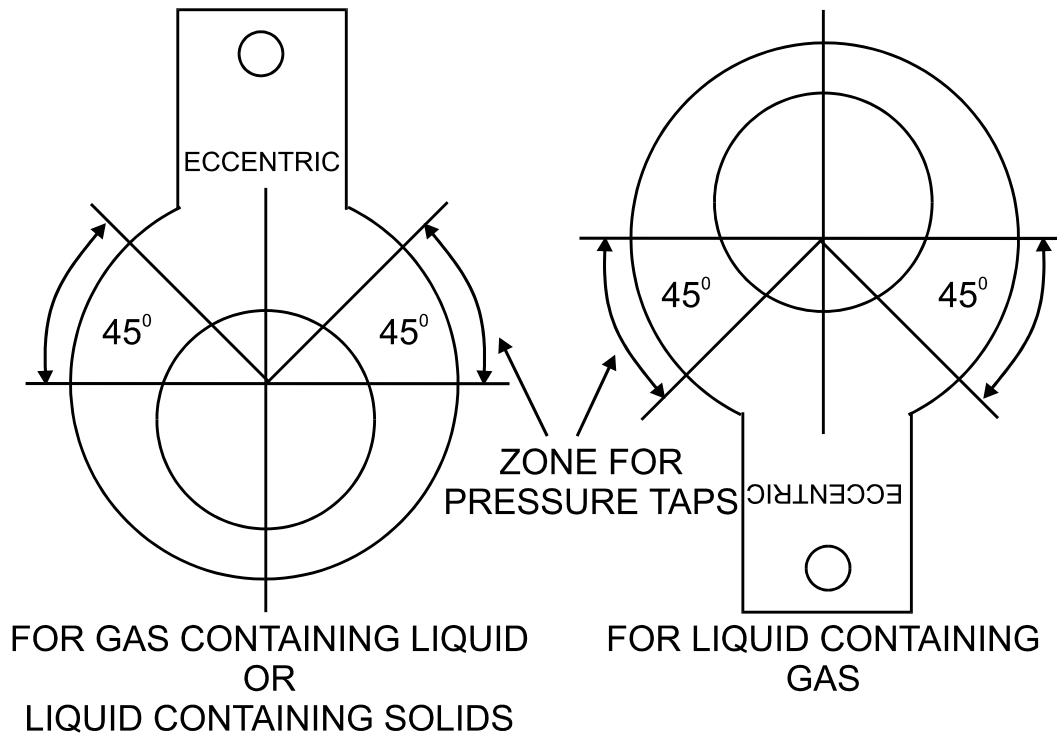
Flange taps are typically used with this type of primary element.



***Figure 5.6***  
***Quadrant edge orifice plate***

***Eccentric or segmental square edged***

These are generally used when the process material contains foreign matter that may block the orifice in the case of a concentric configuration.



**Figure 5.7**  
**Segmental orifice plate**

#### 5.2.4 Tap Locations

There are five common locations for differential pressure taps:

- Flange (>50mm)
- Vena contracta (>150mm)
- Radius
- Pipe (full flow)
- Corner taps (<50mm)

#### **Flange Taps**

Flange taps are quite common and are generally used for pipe sizes of 50mm and greater. Flange taps are a convenient alternative to drilling and tapping the main pipe for pressure connections.

Note that flow for several pipe diameters beyond the vena contracta is turbulent and does not provide suitable pressure measurements. It is for this reason that flange taps are not used for pipe diameters less than 50mm, as the vena contracta starts to become close to and possibly forward of the downstream tapping point.

### ***Vena contracta taps***

Vena contracta taps are limited to pipe sizes greater than 150mm. This limitation is mainly imposed to provide adequate clearance of the tap from the flange.

The vena contracta is where the fluid flow has the smallest cross-sectional area, and also has the lowest pressure. Vena contracta taps are designed around achieving the maximum differential pressure.

The vena contracta is dependent on the flow rate and pipe size, and can vary should either of these parameters change. The vena contracta taps will therefore be affected should the flow rate or pipe size change.

### ***Pipe Taps***

Pipe taps are located 2.5 pipe diameters upstream and 8 pipe diameters downstream of the orifice plate.

Pipe taps are used typically in existing installations, where radius and vena contracta taps cannot be used. They are also used in applications of greatly varying flow as the measurement is not affected by flowrate or orifice size.

Accuracy is reduced as they do not measure the maximum available pressure.

### ***Corner taps***

Corner taps measure the pressure in the corner between the orifice plate and the pipe wall. Uses for corner taps are found in installations with pipe diameters less than 50mm.

### ***Radius taps***

Radius taps are a modification on the vena contracta taps, where the downstream tap is located one-half pipe diameter from the orifice plate. This is to avoid the unstable region that occurs immediately after the orifice plate. Radius taps are generally preferred to vena contracta as the pressure tap location is simplified.

## **5.2.5 Selection and Sizing**

General sizing procedure:

1. First determine the equivalent flow rate corresponding to the process flow rate:

To convert liquids to equivalent water flow, use

$$q_{e, water} = (q_{lpm})(G_b) \sqrt{1/G_f}$$

where:

$q_{e, water}$	is the Equivalent liquid flow rate
$q_{lpm}$	Liquid flow rate in litres per minute
$G_b$	Liquid specific gravity at Base conditions
$G_f$	Liquid specific gravity at flowing conditions

2. Select the applicable graph based on fluid type, flow units and orifice bore size.
3. Find the calculated flow value on the horizontal axis of the graph. Follow the vertical line until it intersects with the desired orifice bore line. The horizontal line intersecting that point indicates the corresponding differential pressure.
4. Once the correct graph and line are chosen, any combination of equivalent flow rate and differential pressure can be found on the graph.

### 5.2.6 Advantages

- Simple construction.
- Inexpensive.
- Easily fitted between flanges.
- No moving parts.
- Large range of sizes and opening ratios.
- Suitable for most gases and liquids.
- Well understood and proven.
- Price does not increase dramatically with size.

### 5.2.7 Disadvantages

- Inaccuracy, typically 1%.
- Low Rangeability, typically 4:1.
- Accuracy is affected by density, pressure and viscosity fluctuations.
- Erosion and physical damage to the restriction affects measurement accuracy.
- Cause some unrecoverable pressure loss.
- Viscosity limits measuring range.
- Require straight pipe runs to ensure accuracy is maintained.
- Pipeline must be full (typically for liquids).

### 5.2.8 Application Limitations

The inaccuracy with orifice type measurement is due mainly to process conditions and temperature and pressure variations. Ambient conditions and upstream and

downstream piping also affect the accuracy because of changes to the pressure and continuity of flow.

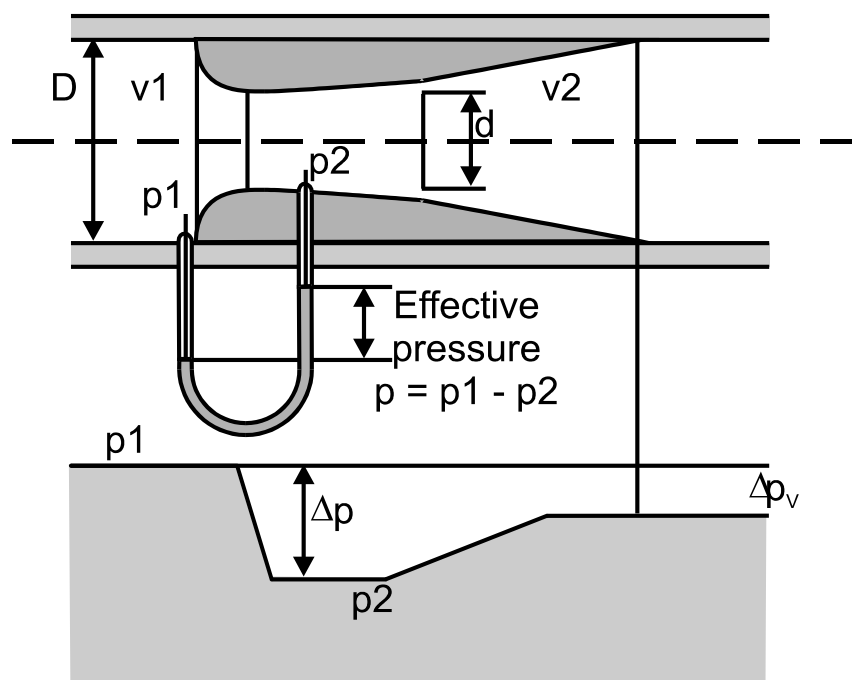
Standard concentric orifice plate devices should not be used for slurries and dirty fluids, or in applications where there is a high probability of solids accumulating near the plate. Half-circle or eccentric bores can be used for these applications.

### 5.2.9 Venturi Tube

In a venturi tube, the fluid is accelerated through a nozzle shaped inflow piece (converging cone) which induces a local pressure drop. After passing through the cylindrical restriction, it is released through an expanding section (diffuser) where it returns the flow to near its original pressure.

The Venturi Tube is often selected because pressure drop is not as significant as with the orifice plate and accuracy is better maintained.

Due to the relatively high cost of the Venturi Tube, applications are generally limited to high flow rate fluids, such as main steam lines.



**Figure 5.8**  
**Flow measurement with a restriction**

The advantages and disadvantages highlight any differences from the orifice meter and are over and above those listed for that device.

#### Advantages

- Less significant pressure drop across restriction.
- Less unrecoverable pressure loss.
- Requires less straight pipe up and downstream.

### Disadvantages

- More expensive.
- Bulky - requires large section for installation.

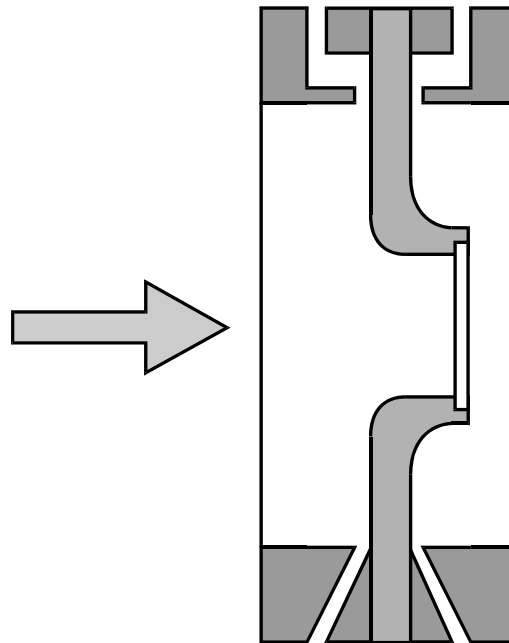
### 5.2.10 Flow Nozzles

The Flow Nozzle is similar to the venturi but are in the shape of an ellipse. They have a higher flow capacity than orifice plates. Another main difference between the flow nozzle and the venturi is that although they have similar inlet nozzles, the flow nozzle has no exit section.

Flow Nozzles can handle larger solids and be used for higher velocities, greater turbulence and high temperature applications. They are often used with fluid or steam applications containing some suspended solids, and in applications where the product is being discharged from service.

These devices are more cost effective, but as such they provide less accuracy than venturis, and have a higher unrecoverable pressure loss.

The advantages and disadvantages highlight any differences from the venturi tube and are over and above those listed for that device.



**Figure 5.9**

***The flow nozzle is preferable for high velocity applications***



### Advantages

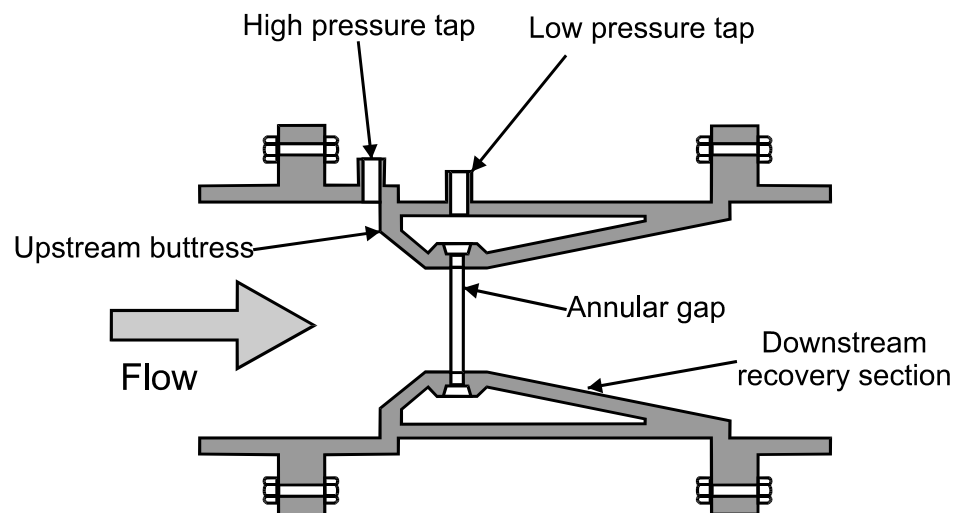
- High velocity applications.
- Operate in higher turbulence.
- Used with fluids containing suspended solids.
- More cost effective than venturis.
- Physically smaller than the venturi.

### Disadvantages

- More expensive than orifice plates.
- Higher unrecoverable pressure loss.

#### 5.2.11 Flow Tube

Flow tubes are more compact than the venturi tube, but provide a higher differential pressure for less unrecoverable pressure loss. They are primarily a low loss meter and the most common type would be the Dall tube.



**Figure 5.10**  
**The Dall tube low-loss meter**

### Advantages

- Shorter lay length.
- Lower unrecoverable pressure loss.

### Disadvantages

- More complex to manufacture.
- Sensitive to turbulence.
- Accuracy based on flow data.

## Application Limitations

It is recommended that when using this type of tube, it should be calibrated with the piping section in which it is to be used and over the full range of flows in which it will operate.

These types of flow devices do not necessarily conform to the wide range of conditions and extensive test data for orifice meters.

### 5.2.12 Pitot Tube

Refer to Chapter 2 for more information on this topic.

The Pitot tube measures flow based on differential pressure and is primarily used with gas flows.

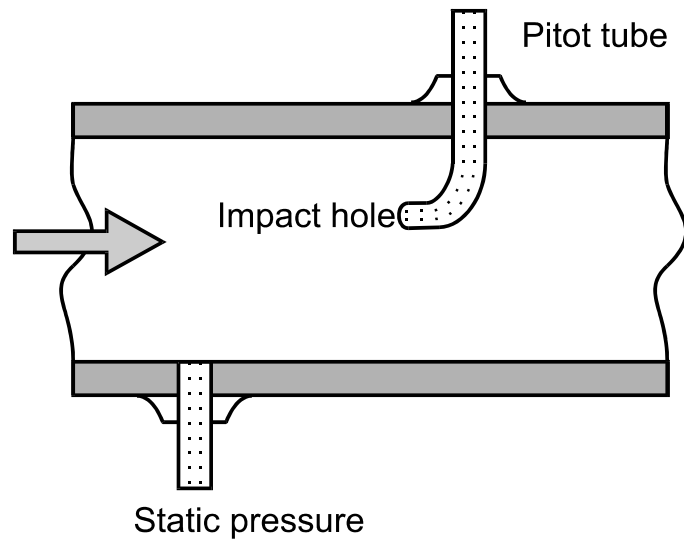
The Pitot tube is a small tube that is directed into the flowstream. This measures the total pressure (dynamic and static combined). A second measurement is required, being of static pressure. The difference between the two measurements gives a value for dynamic pressure. The flowrate, like other devices, is calculated from the square root of the pressure.

In calculating the flowrate from the pressure, the calculation is dependent on such factors as tube design and the location of the static tap. The Pitot-static probe incorporates the static holes in the tube system to eliminate this parameter.

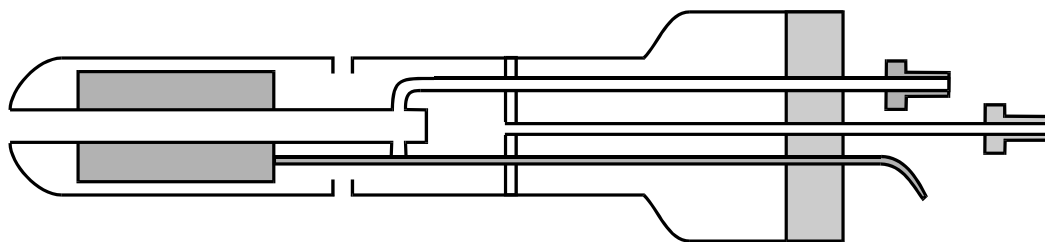
The Pitot tube is also used to determine the velocity profile in a pipe. This is done by measuring points at various distances from the pipe wall to construct a velocity profile.

The Pitot tube is the primary device. It has the advantage over orifice meters of practically no pressure drop. Its usefulness is limited to clean gases and liquids as the sensing element is a small orifice. Foreign materials tend to plug the openings in the tube, and the classical Pitot tube senses impact pressure at one point only, thus decreasing accuracy.

Pitot tubes develop a very low differential pressure, which can often be difficult to measure with the secondary element. Also the accuracy of the device is dependant on the velocity profile of the fluid. The velocity profile is also affected by turbulence in the flow stream.



**Figure 5.11**  
**Principle of operation of the Pitot tube**



**Figure 5.12**  
**Basic form of pitot-static tube**

### Advantages

- Low cost.
- Low permanent pressure loss.
- Ease of installation into existing systems.

### Disadvantages

- Low accuracy.
- Low Rangeability.
- Requires clean liquid, gas or vapour as holes are easily clogged.

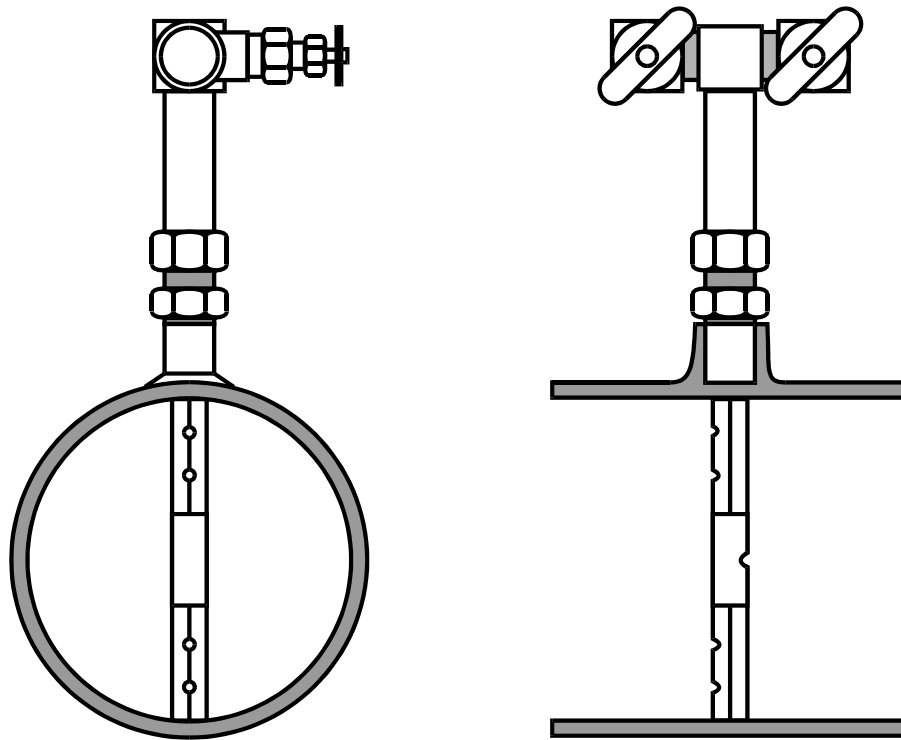
### 5.2.13 Multiport Pitot Averaging

An annubar tube is a multi-impact opening type and improves the accuracy of this type of measurement. In most industrial applications this type of multi-impact or averaging is used to compensate for changes in the velocity profile.

Annubar sensors are inserted perpendicular to the flowstream and extend the full diameter of the pipe. There is a very low obstruction to the flow, which causes minimal pressure loss.

Sensing ports are located on both upstream and downstream sides of the Annubar. These ports are connected to dual averaging plenums. The number of ports is proportional to the diameter of the pipe. The upstream ports produce an average impact (total) pressure and the downstream ports produce the average reference (static) pressure. The difference is an accurate and stable dynamic pressure that is easily converted into flowrate.

Annubars also provide good measurement when located in difficult piping. They can be located as close as two pipe diameters downstream of an elbow and still give accurate and repeatable measurements.



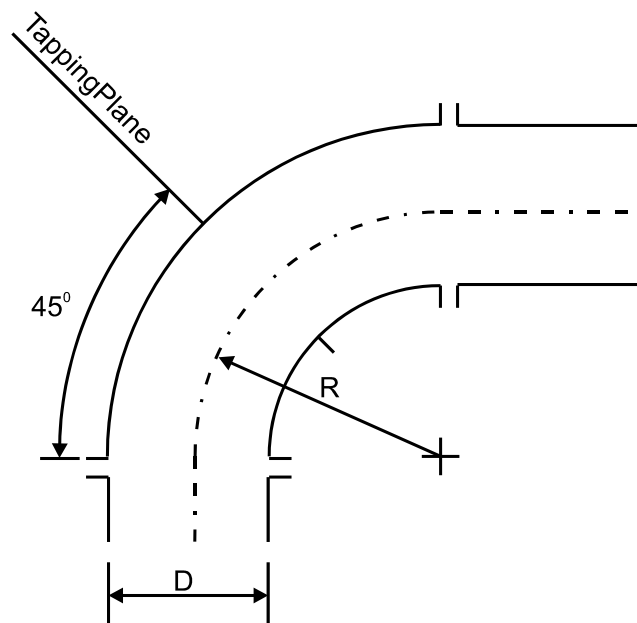
**Figure 5.13**  
**Multiport 'Annubar' Pitot averaging system**  
*(courtesy of Dieterich Standard)*

### 5.2.14 Elbow

A pipe elbow can be used as a primary device. Elbow taps have an advantage in that most piping systems have elbows that can be used. In applications where cost is a factor and additional pressure loss from an orifice plate is not permitted, the elbow meter is a viable differential pressure device.

If an existing elbow is used then no additional pressure drop occurs and the expense involved is minimal. They can also be produced in-situ from an existing bend, and are typically formed by two tapplings drilled at an angle of  $45^\circ$  through the bend. These tapplings provide the high and low pressure tapping points respectively.

Tapplings at  $22.5^\circ$  have shown to provide more stable and reliable readings and are less affected by upstream piping. However  $45^\circ$  tapplings are more suited to bi-directional flow measurement.



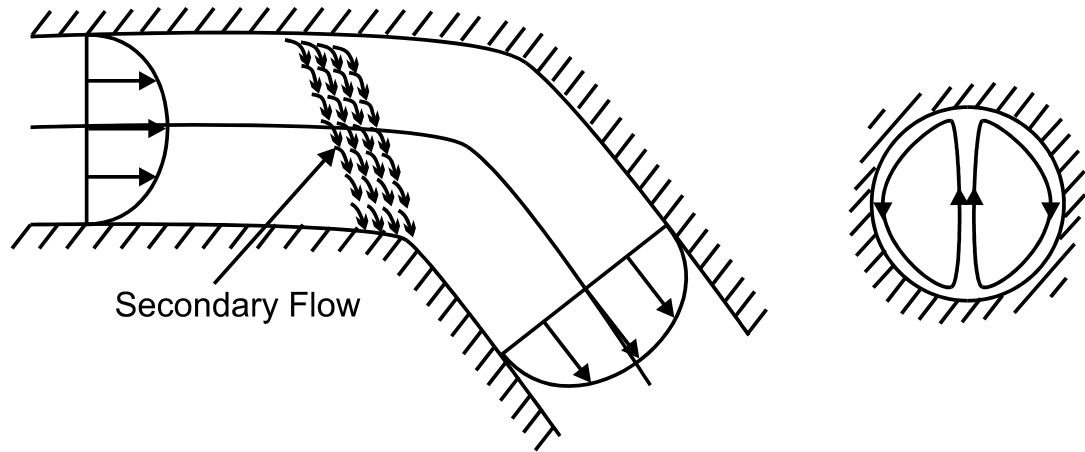
**Figure 5.14**  
**Elbow meter geometry**

A number of factors contribute to the differential pressure that is produced. Because of the number of variables, it is difficult to accurately predict the exact flowrate. Some of these factors are:

- Force of the flow onto the outer tapping.
- Turbulence generated due to cross-axial flow due to the bend
- Differing velocities between outer and inner radius of flow
- Pipe texture
- Relationship between elbow radius and pipe diameter

Apart from these factors, accuracy from tests means that a predicted accuracy of less than 5% is possible. On site tests can be performed for more accurate results, with the added advantage that repeatability is good for this type of measurement.

The disadvantages are that accuracy will be lacking (typically 5%) and dirty flows can plug the taps. At low-flow velocities, the differential produced is inadequate for good measurement, and is therefore only suitable for higher velocities.



**Figure 5.15**  
**Flow in a pipe band**

Although the elbow meter is not commonly used in industry, it is very much underrated. The low cost of the meter, together with its application after completion of pipework can be a major benefit for low accuracy flow metering applications.

Some suitable applications would include plant air conditioning, cooling water metering, site flow checkpoints possibly with local indicators, and check flow applications, where the cost of magmeters is prohibitive.

For installation, it is recommended that the elbow be installed with 25 pipe diameters of straight pipe upstream and at least 10 pipe diameters of straight pipe down stream.

#### **Advantages**

- Simplified installation.
- Inexpensive.

#### **Disadvantages**

- Low accuracy.

### 5.2.15 Primary element - overview

#### Advantages

- No moving parts.
- Large range of sizes and opening ratios.
- Suitable for most gases and liquids.
- Well understood and proven.
- Price does not increase dramatically with size.

#### Disadvantages

- Accuracy is affected by density, pressure and viscosity fluctuations.
- Erosion and physical damage to the restriction affects measurement accuracy.
- Cause some unrecoverable pressure loss.
- Viscosity limits measuring range.
- Require straight pipe runs for expected accuracies.

#### Application Limitations

- Limited accuracy in measurement.
- Low Rangeability of 4:1.

#### *Pressure loss:*

When obstructing the flow using the differential pressure method of sensing, note that they do cause some unrecoverable pressure loss in the line.

#### *Disturbances:*

Differential type instruments that cause a restriction are easily affected by disturbances to inflow and outflow. Apart from bends in the pipe, such fittings as T-pieces and valves can cause disturbances to the flow measurement and as such should be separated from the instrument by a significantly long straight pipe extension. The length of clean pipe should be greater than 5 x diameter on the upstream side and no less than 4 x diameter on the downstream side.

### 5.2.16 Secondary Element

The secondary element is a differential pressure transmitter. This device provides the electrical output signal for interfacing to other instrumentation or control equipment. The output from this device is proportional to either the differential pressure or the flow rate.

### 5.2.17 Troubleshooting

One of the most common inaccuracies induced in differential pressure flowmeters is not allowing enough straight pipe. When the flow material approaches and passes some change in the pipe small eddies are formed in the flow stream. These eddies are localised regions of high velocity and low pressure and can start to form upstream of the change and dissipate further downstream.

Flowmeter sensors detect these changes in pressure and consequently produce erratic or inaccurate readings for flow rate.

## 5.3 Open Channel Flow Measurement

The primary devices used in open channel flow measurements are weirs and flumes.

### 5.3.1 Weirs

Weirs are openings in the top of a dam or reservoir that allow for the flow of liquid, and enable measurement of the flow. With the characteristics of the weir known, the flow is generally determined by the height of the liquid in the weir.

There are two basic weirs - the rectangular and the V-notch.

#### Rectangular

There are three types of rectangular weirs:

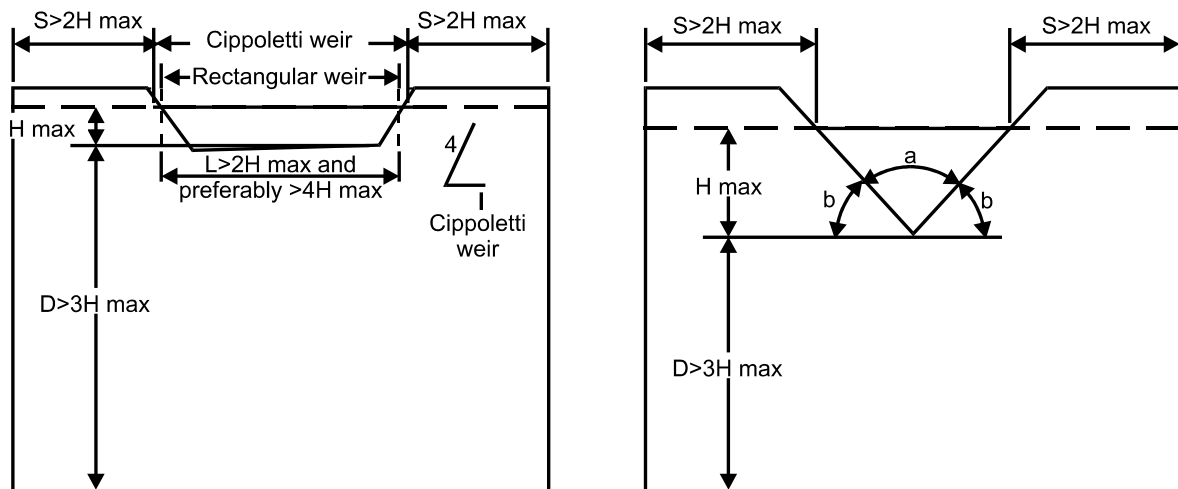
1. Vertical walls with a flat base to form a boxlike opening in the channel
2. Open weir which extends the width of the channel
3. Cipolletti weir, has the end contractions set at a 4:1 angle

#### V-Notch

V-notch weirs are generally metal plates that contain a V-shaped notch. The angle of the V can vary but the most common are for 30, 60 and 90 degrees.

V-notch weirs are used for lower flow rates than those that would be measured by a rectangular weir.





**Figure 5.16**  
**Rectangular, Cippoletti and V-notch weirs**

#### Advantages

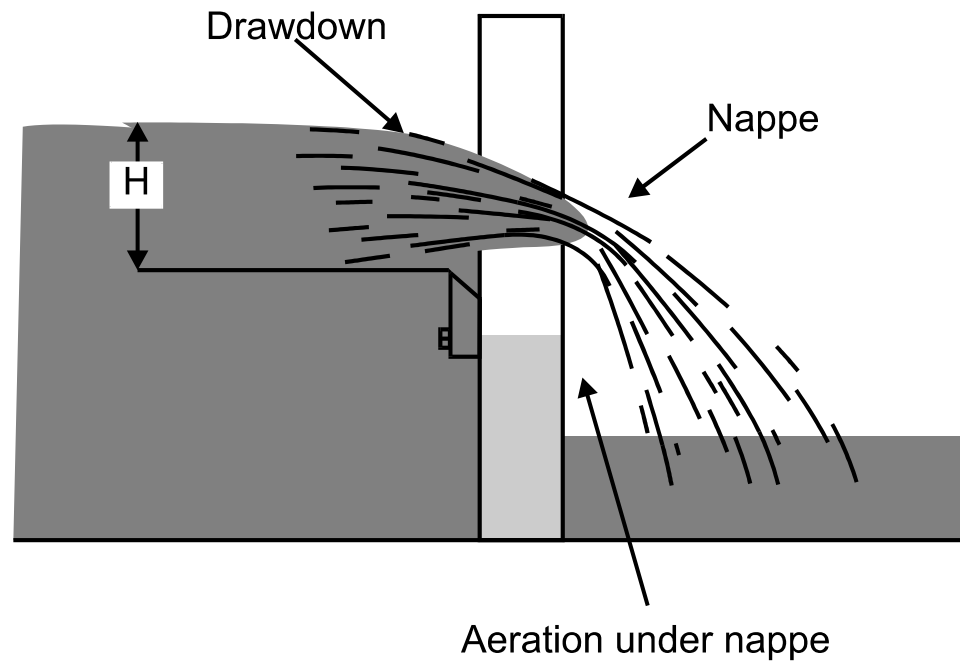
- Simple operation.
- Good Rangeability (for detecting high and low flow).

#### Disadvantages

- Pressure loss.
- Accuracy of about 2%.

#### Application Limitations

There is a high unrecoverable pressure loss with weirs, which may not be a problem in most applications. However with the operation of a weir, it is required that the flow clears the weir on departure. If the liquid is not free flowing and there is back pressure obstructing the free flow, then the level over the weir is affected and hence the level and flow measurement.



*Figure 5.17*  
*Flow over a weir*

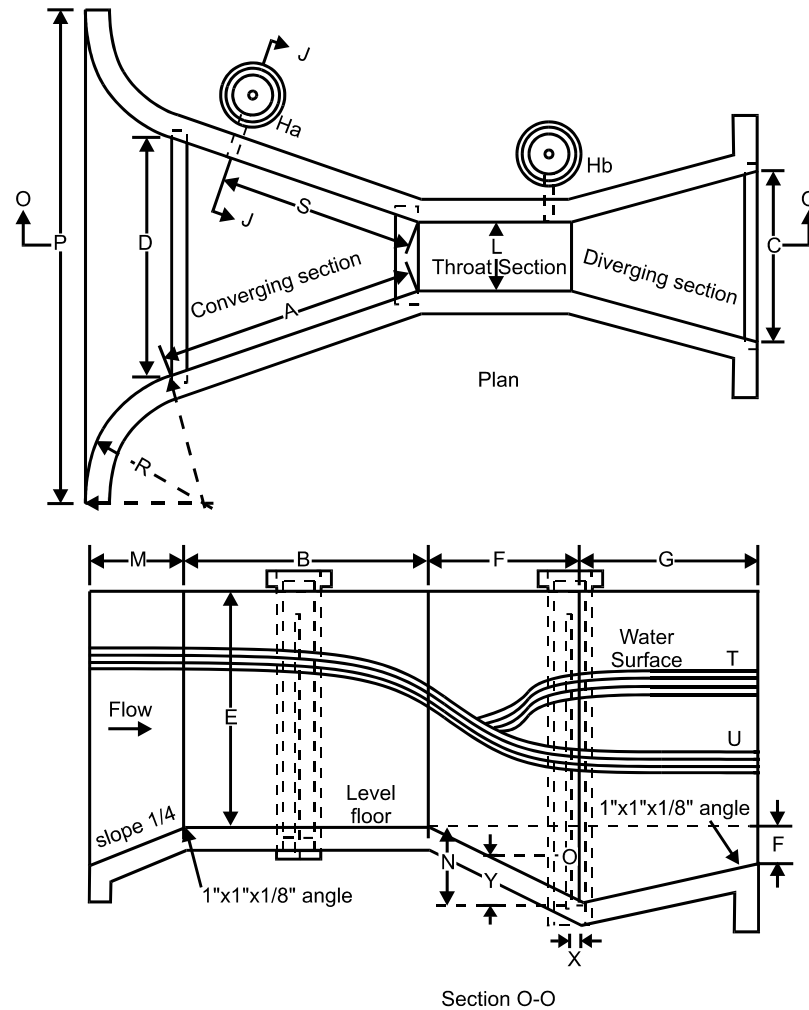
### Summary

In weir measurement, the fluid must not go over the side of the weir if accuracy is to be maintained. All weirs produce some head loss as the liquid falls free. A flume is a better choice when head loss is a problem

### 5.3.2 Flumes

Flumes are a modification to the weir where the section of flow is reduced to maintain head pressure. A flume forces the liquid into a narrower channel and in doing so only incurs a head pressure drop of about 1/4 of that for a weir of equal size. This process is similar in principle to a rectangular venturi tube.

Similar to the weir, the water level in the flume is a function of flow rate. The flume provides a little more accuracy by precisely channelling the flow. The flume is also independent of the velocity of the fluid as it enters, and as such the application does not require damming or a stilling basin.



**Figure 5.18**  
**Diagram and dimensions of Parshall Flume**

### Typical Applications

Flumes are typically used for applications involving larger scale irrigation systems, water supply, waste management and effluent treatment plants.

### Advantages

- Reliable and repeatable measurements.
- No erosion.
- Not sensitive to dirt and debris.
- Very low head pressure loss.
- Simple operation and maintenance.

### **Disadvantages**

- High installation costs.
- Low accuracy.
- Expensive electronics.

### **Application Limitations**

Small flumes may be purchased and installed whereas larger flumes are generally fabricated on site.

### **Summary**

The venturi flume has replaced the weir in most applications, and the Parshall flume is possibly the most accurate open channel flow measuring system at present.

### ***Primary Element***

#### **Installation and Selection Considerations**

Some of the factors to consider when selecting the primary element are:

- Probable flow range
- Acceptable head loss
- Accuracy and resolution
- Consistency of the fluid

This type of flow measurement will not function correctly if the weir or flume is overflowing. Minimum weir flows are also difficult to calculate because they depend on the nature of the weir. If the weir is sized too large then the readings will be negligible. A properly sized weir will produce a substantial, measurable amount of head over the weir for minimum flow.

### ***Secondary Element***

Measurement by weirs are very accurate under ideal conditions. However in the actual plant, measurement is affected by the velocity of approach factor and can have a typical error of 3 to 5 percent. The flow in an open channel system is related to the level and this is where the errors occur.

Also note that the equations for most open-channel primary devices are non-linear and extensive calculations would be required to convert head into flow rate. As such, the instrument best handles these calculations.

## Level Measurement

The head used for calculating the flow rate is measured using level sensing equipment. This is covered in Chapter 3, however some of the more common types for open channel flow measurement are:

- float and cable
- ball float
- air bubbles
- pressure sensing

In closed applications, and even in pipes, ultrasonics are often used to determine the level.

## 5.4 Variable Area Flowmeters

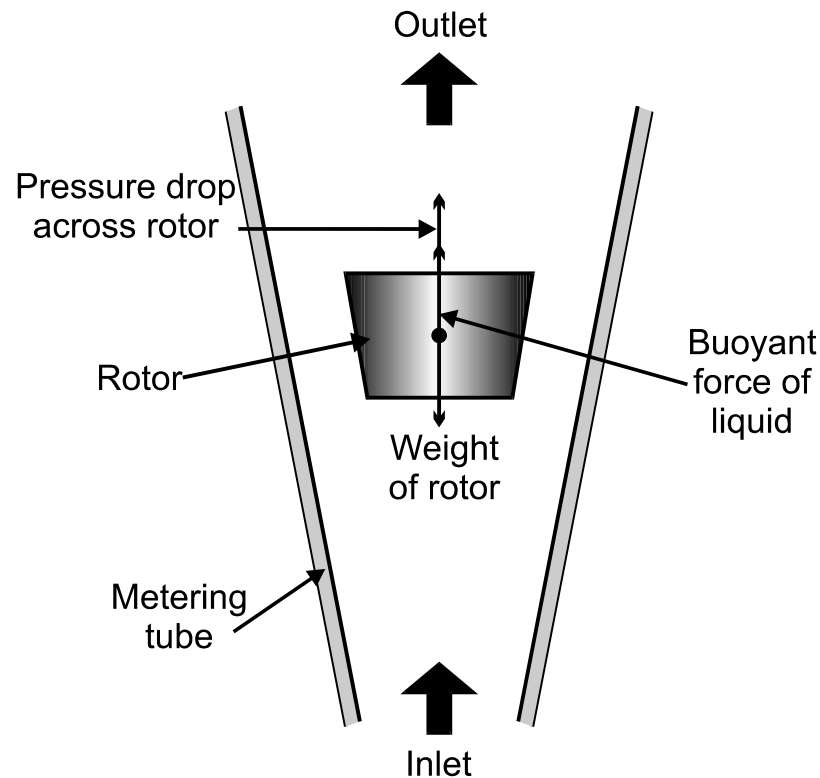
### 5.4.1 Principles of Operation

Variable Area flowmeters work with low viscous liquids at high velocities. The principle of operation is that the flow stream displaces a float placed in the stream. The rate of flow is related to the area produced by forcing the float up or down, and varying the area.

It is because of the low viscosity and high velocity that the frictional resistance of the flow is negligible compared to the resistance of the obstruction (float) placed in the flow stream.

The float in the early stages of development was slotted which caused the floats to rotate. This provided stability and centring of the float, and is where the designation of rotameter came from.

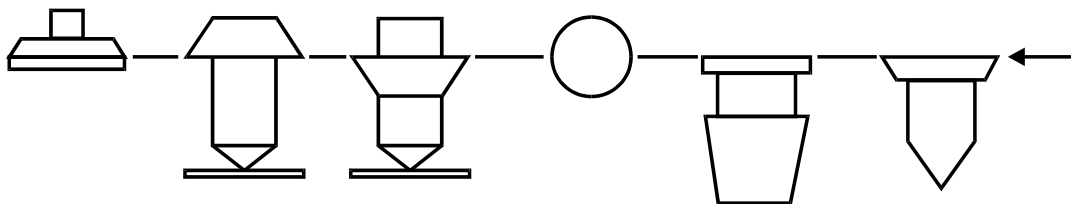
The rotameter consists of a tapered measuring tube and a float. This arrangement produces a resistance value (coefficient of resistance) for the float, which depends on its position in the measuring tube. A balance is achieved between the force of the flow stream and the weight of the float. The float positions itself vertically within the measuring tube such that the resistance value is balanced.



**Figure 5.19**  
**Variable area (Rotameter) flowmeter**

The inside of the measuring tube is conical and has guide strips for the float. For physical indication, there is a scale on the outside to indicate the flowrate. Metal versions are available that have a means of transmitting the float position. The measuring tube can be made from steel, stainless steel, plastics (polypropylene, teflon), glass or hard rubber.

Also a number of various floats are available. The rotating float is used for direct control. Another type that is available is unaffected by viscosity, and a modification of this is available that magnifies the sensitivity of the operating range by 30%, but is more sensitive to viscosity.



**Figure 5.20**  
**Viscosity limits of Rotameters depend on float shapes**  
**(Courtesy of Brooks Instrument Division of Rosemount)**

### 5.4.2 Selection and Sizing

In sizing a rotameter, it is required that the actual flow be converted into a standard flow. Capacity tables are based on the standard flow, this is where the density of the float is taken into account. To assist in the sizing, manufacturers provide slide rules or comparison tables specifically designed for rotameter sizing.

The rotameter is not affected by piping configurations. It can be installed with any form of upstream piping prior to the meter.

For a 25mm bore the cost is comparable to magmeter.

### 5.4.3 Typical Applications

High accuracy rotameters are generally used in laboratory and pilot scale testing applications.

### 5.4.4 Advantages

- Inexpensive
- Wide range of applications
- Very basic operation
- Easy installation and simple to replace

### 5.4.5 Disadvantages

- Limited accuracy
- Subject to density, viscosity and temperature
- Fluid must be clean, no solids content
- Erosion of device (wear and tear)
- Can be expensive for large diameters
- Operate in vertical position only
- Viscosity > 200cP

### 5.4.6 Application Limitations

Glass tubes provide the added limitations of visibility and also impose limitations relating to pressure and temperature ratings. Metal metering tubes are used in applications where glass is not permissible. The float position is determined by magnetic or electrical means.

## 5.5 Oscillatory Flow Measurement

Oscillatory flow equipment generally measures the velocity of flow (hence they are often referred to as velocity flowmeters) and the volumetric flow rate is calculated from the relationship:

$$Q = v \cdot A$$

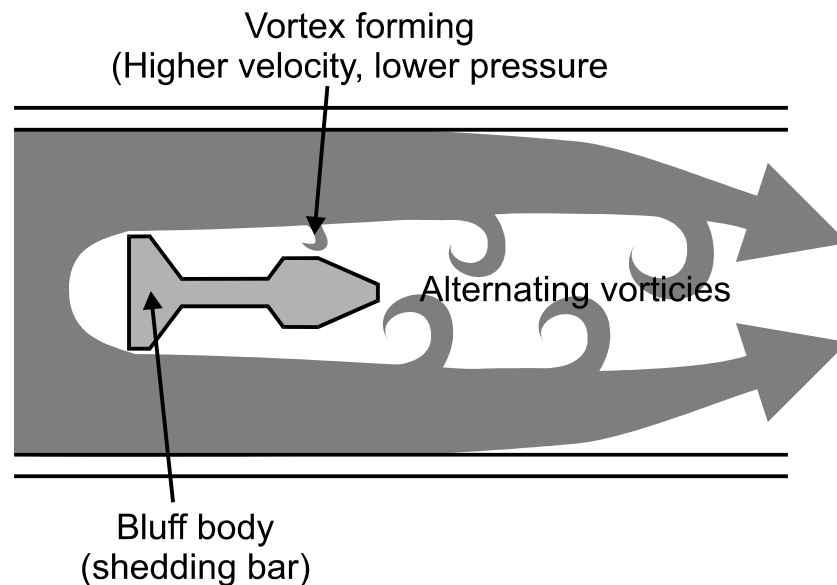
where: Q is the volumetric flow rate  
v is the velocity of the flow  
A is the cross sectional area

The primary device generates a signal that is proportional to fluid velocity. This eliminates the errors that are amplified in square root calculations.

Velocity flowmeters, in general can operate over a greater range of velocities and are less sensitive to the flow profile compared with differential pressure devices.

### 5.5.1 Vortex Flowmeters

Vortex flowmeters can measure liquid, gas or steam and use the principle of vortex shedding. Vortex shedding occurs when an obstruction is placed in the flowing stream. The obstruction is referred to as a bluff body and causes the formation of swirls, called vortices, downstream from the body.



**Figure 5.21**  
**Principle of operation of vortex meter**

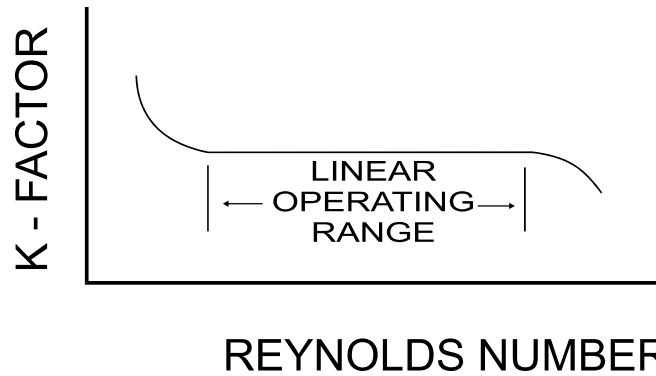
Differential pressure changes occur as the vortices are formed and shed. This pressure variation is used to actuate the sealed sensor at a frequency proportional to the vortex shedding. For continuous flow, a series of vortices generates electrical pulses with a frequency that is also proportional to the flow velocity. The velocity can then be converted to volumetric flow rate.

The output of a vortex flowmeter depends on the K-factor. The K-factor relates to the frequency of generated vortices to the fluid velocity.



$$\text{Fluid velocity} = \frac{\text{Vortex Frequency}}{K - \text{Factor}}$$

The K-factor varies with the Reynolds number, however it is virtually constant over a broad range of flows. Vortex flowmeters provide very linear flow rates when operated within the flat range.



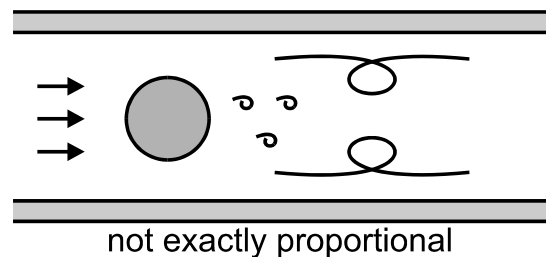
*Figure 5.22*

*Relationship between K-Factor and Reynolds number*

### **Primary Element - Bluff Bodies**

#### *Round Bluff Body*

The initial bluff bodies were cylindrical and it was found that the separating point of the vortex fluctuated depending on the flow velocity. It was because of this movement that the frequency of the vortices was not exactly proportional to velocity.

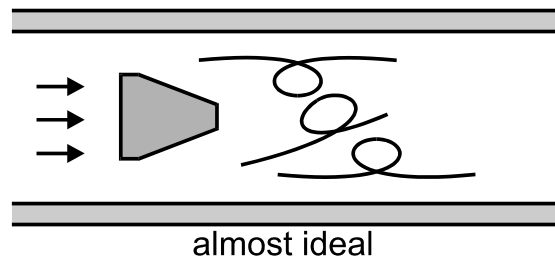


*Figure 5.23*

*Round bluff bodies*

#### *Delta-Shaped Bluff Body*

The Delta-shaped bluff body has been tested over many years and found to be ideal in terms of its linearity. Accuracy is not affected by pressure, viscosity or other fluid conditions. Many variations of the Delta shape exist and are in operation.



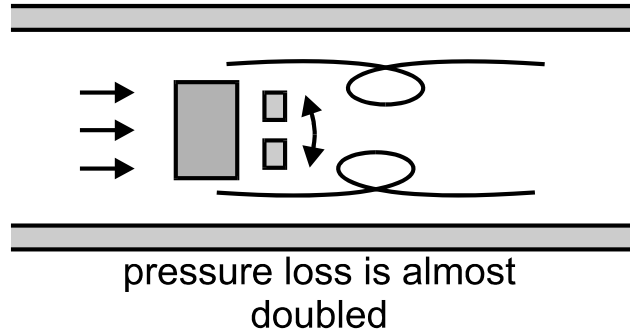
**Figure 5.24**  
**Delta shaped bluff bodies**

### *Two-Part Bluff Body*

Applications exist where a second bluff body is inserted behind the first. In this configuration, the first body is used to generate the vortices and the second body to measure them.

This method has the disadvantage of placing an extra obstruction in the stream. In such a case the pressure loss is almost doubled.

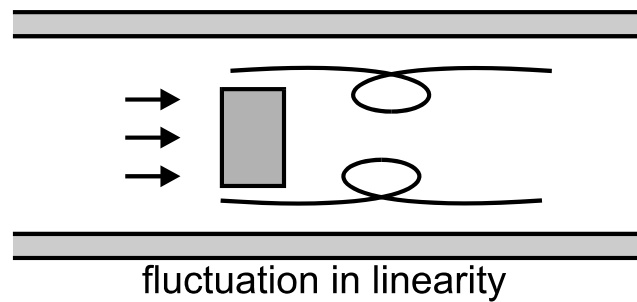
The advantage of this method is that a strong vortex is generated, which means that less complicated sensors and amplifiers may be used.



**Figure 5.25**  
**Two-part bluff body**

### *Rectangular Bluff Bodies*

One of the original bluff body designs was with a rectangular shape. This body style has been documented as unfavourable as they produces considerable fluctuations in linearity as the process density varies.



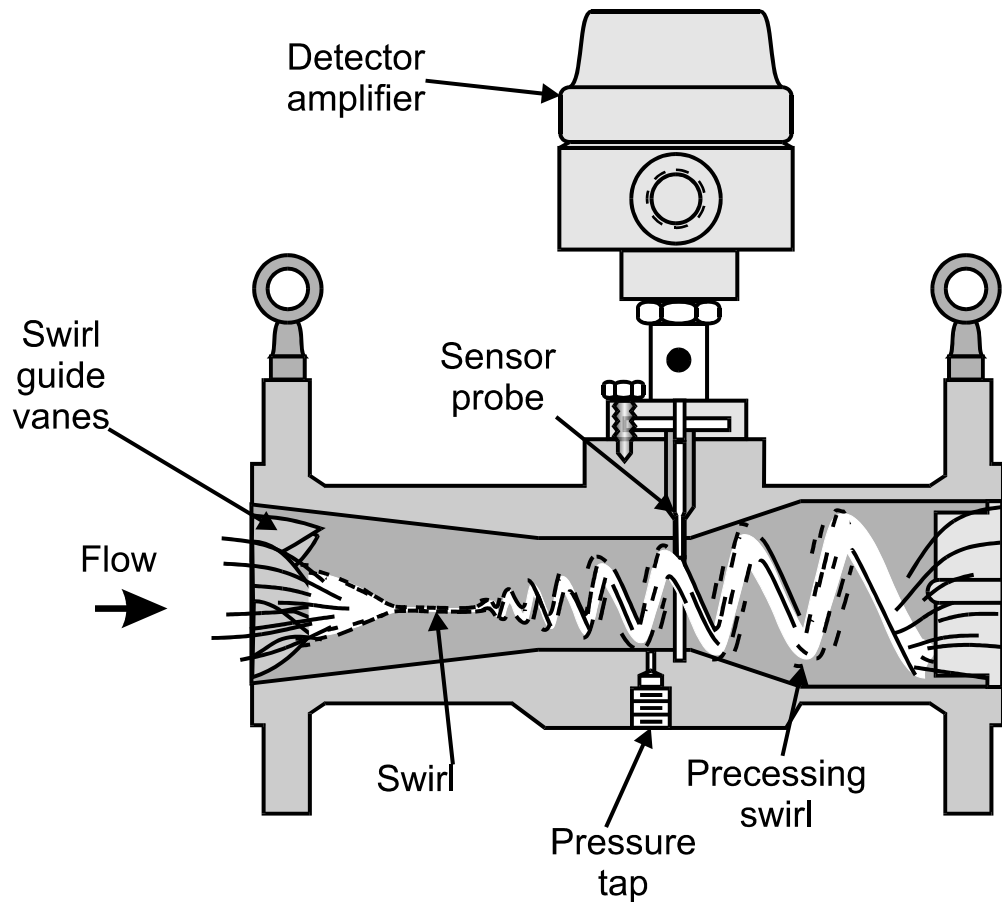
**Figure 5.26**  
**Rectangular bluff body**

### *Vortex Swirl Type*

A different type of vortex meter is that of the precession or swirl type. In this device, an internal vortex is forced into a helical path through the device. A thermistor is typically used to detect a change in temperature as the vortices pass. Again, the output signal is proportional to the flow rate.

A flow straightener is used at the outlet from the meter. This isolates the meter from any downstream piping effects that may affect the development of the vortex.

This type of measuring device has a Rangeability of about 10:1 and is used mainly with gases. Because of the higher tolerance in manufacture of this type of meter, it is more expensive than comparative meters.

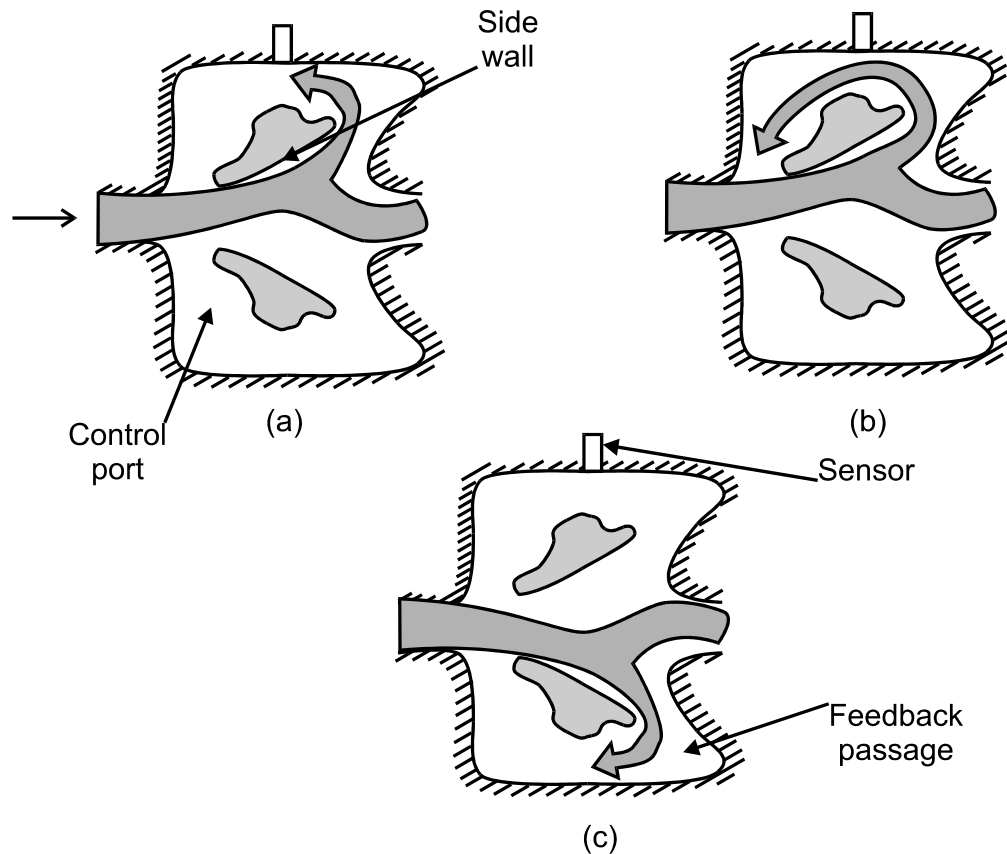


**Figure 5.27**  
**Construction of a typical vortex precession (swirl) meter**

#### *Coanda Flowmeter*

The Coanda flowmeter generates internal oscillations similar to that of an electronic oscillator. The oscillations are generated by feeding part of the mainstream flow back into itself. There are two ports for feedback on opposing sides of the flowstream. The sensor (typically a thermistor) measures the frequency of oscillation, which is proportional to the rate of flow.

This flowmeter has a Rangeability of up to 30:1 and is used mainly with liquids.



**Figure 5.28**  
**Diagram of the mode of operation of a feed back oscillator**

### **Secondary Element**

A number of devices can be used to measure the vortex frequency. The choice depends on the application, and more particularly the operating conditions.

- Thermistors
- Pressure sensors
- Magnetic pick-up
- Strain gauge
- Piezoelectric
- Capacitive

### **Thermistors**

Thermistors are heat sensitive, and generate an ac voltage signal due to the cooling from the vortices. These are used in clean gas applications.

### **Pressure Sensors**

As the vortices are generated and shed the pressure changes accordingly. A pressure sensor can be used where the pressure changes distort a diaphragm. A dielectric oil is used between the membrane and the insulated electrode and the change in

capacitance is measured. Other devices use a piezoelectric crystal and measure a change in voltage. Temperature limitations apply due to the diaphragm and they are generally insensitive in the lower range. Suitable for fluids and possibly gas and low pressure steam.

### *Magnetic Pick-Up*

A rather crude mechanical means of detecting the vortices is with a magnetic pick-up to sense a ball or disc which moves from side to side within the bluff body. Used for clean flows only as it can become blocked by dirt. Condensation problems can also occur when used in saturated steam, which can retard the action. Recommended for use with warm water, steam and low temperature liquids.

### *Strain Gauge*

A strain gauge can be mounted on the bluff body to sense the pressure changes. Strain gauges work on a change in resistance and this can be used to measure the frequency of the vortices. Temperature limitations apply to the strain gauge itself. In addition vibration can be a problem for larger diameter pipes where a heavier bluff body is used. Strain gauges are excellent for gases and liquids.

### *Piezoelectric*

A piezo device is a quartz crystal, which can be used in place of a strain gauge strip and can be mounted in the bluff body. The piezo device is more prone to failure, but is suitable for fluids, gases and steam.

### *Capacitive*

Capacitive measurement has the added advantage of being immune to effects of pipe vibration.

### ***Selection and Sizing***

The following tables should assist with the selection and sizing of flowmeters.

Line sizes (mm)	Reynolds number limitations
12 - 100	10,000 minimum
150	20,000 minimum
200	35,000 minimum

***Table 5.2***  
***Minimum measurable Reynolds Numbers***

	Minimum (m/sec)	Maximum (m/sec)
Liquids	$\text{SQRT}(54/\rho)$ or 0.22	$\text{SQRT}(134,000/\rho)$ or 7.6
Gases (12 - 25mm)	$\text{SQRT}(54/\rho)$ or 2.0	$\text{SQRT}(134,000/\rho)$ or 67
Gases (40 - 200mm)	$\text{SQRT}(54/\rho)$ or 2.0	$\text{SQRT}(134,000/\rho)$ or 76

**Table 5.3**  
**Minimum and maximum measurable velocities**

Line size, mm	K-factor, pulses/m <sup>3</sup>
15	430,300
25	80,190
40	20,660
50	9,520
80	2,850
100	1,233
150	363.9
200	156.8

**Table 5.4**  
**Nominal flowmeter K-factors**

Line size, mm	Minimum flow rate, m <sup>3</sup> /hr	Maximum flow rate, m <sup>3</sup> /hr
15	0.4	5.38
25	.61	15.3
40	1.09	35.9
50	1.81	59.4
80	4.00	130
100	6.86	225
150	23.6	512
200	54.5	885

**Table 5.5**  
**Minimum and maximum measurable flow rates - For Water at 25°C**

### Pressure Loss

The pressure loss varies depending on the manufacturers specifications. An example of the calculations required for determining the pressure loss for liquids and gases are provided below:

For Liquids:

$$DP = \frac{(0.425) \times \rho_f \times Q_{lpm}^2}{D^4}$$

For Gases:

$$DP = \frac{(118) \times \rho_f \times Q_{acmh}^2}{D^4}$$

where: DP = Pressure loss, kPa  
 $\rho_f$  = Density at operating conditions, kg/m<sup>3</sup>  
 D = Flowmeter bore diameter, mm  
 $Q_{lpm}$  = Actual volumetric flow rate, l/min  
 $Q_{acmh}$  = Actual volumetric flow rate, m<sup>3</sup>/hr

*Minimum back pressure - liquids only*

If there is too much of a pressure drop across the primary element, then cavitation can occur. By maintaining sufficient backpressure, this can be avoided. The minimum backpressure can be calculated as:

$$P = 2.9 DP + 1.3 \rho$$

where: P = Line pressure 5 diameters downstream of the meter  
 DP = Pressure loss across the meter  
 $\rho_v$  = Liquid vapour pressure at operating conditions

### ***Installation Techniques***

Laminar flow is required for good measurement. Long straight lengths of pipe are generally used to produce a laminar flow profile.

If it is not possible to have such a section of pipe, the meter should be installed upstream of any disturbance. Where there is a severe upstream disturbance, the resulting long straight lengths of pipe can be reduced by fitting a radial vane or bundle-of-tubes in the upstream pipework. This is also termed a flow-straightening element that reduces turbulence and produces a more laminar flow.



### **Advantages**

- Suitable for liquid, gas or steam.
- Used with non-conductive fluids.
- No moving parts, low maintenance.
- Sensors available to measure both gas and liquid.
- Not affected by viscosity, density, pressure or temperature.
- Low installation cost.
- Good accuracy.
- Linear response .

### **Disadvantages**

- Uni-directional measurement only.
- Clean fluids only.
- Not suitable with partial phase change.
- Not suitable for viscous liquids.
- Large unrecoverable pressure drop.
- Straight pipe runs required for installation.

### **Application Limitations**

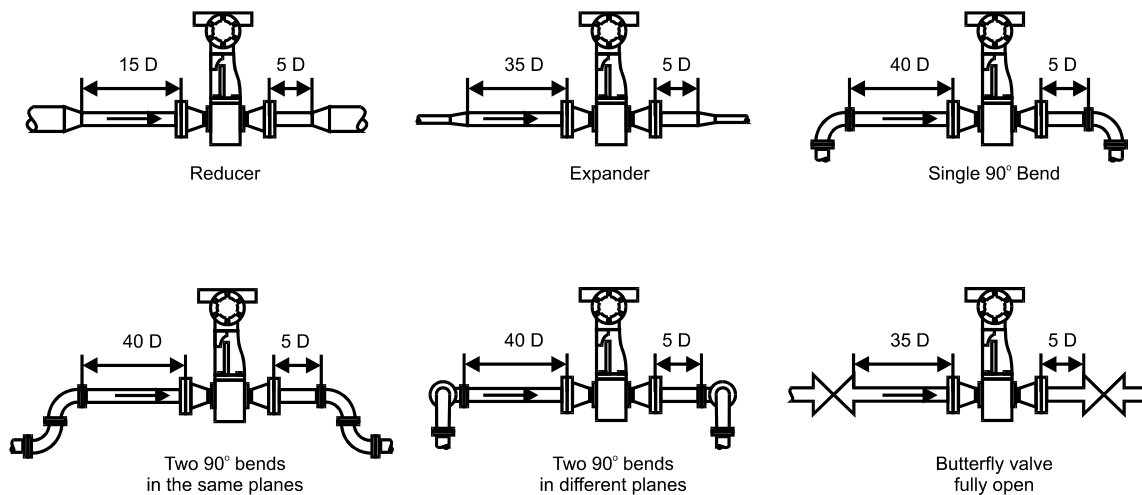
The upstream and downstream requirements of straight pipe vary according to a number of factors. A brief list of some of those factors is listed below:

- Severity and nature of disturbance upstream.
- Severity and nature of disturbance downstream.
- Type of vortex bluff body (the specific design of the meter).
- The accuracy required.

The nature of the disturbance can be any of the following:

- Elbow
- Regulating control valve
- Reducer
- Expander

The straight upstream and downstream lengths required for the various installations in order to meet stated accuracies varies between manufacturers and products. Below is a figure that shows the pipe length requirements for installations as marketed by a particular supplier.



**Figure 5.29**  
***Straight pipe-run requirements as a function of upstream disturbance***  
*(Courtesy of Endress & Hauser)*

Vortex flowmeters are not suitable where cavitation occurs and can be damaged, but will survive flashing conditions. Flashing conditions occur when some of the incoming liquid stream is permanently vaporised in the flowmeter.

### Summary

Combinations of the same or different secondary elements are available that give slightly different specifications depending on the manufacturers products.

The vortex flowmeter appears to be the best answer for flow measurement of non-conductive fluids. Orifice plates and other differential pressure technology are being replaced with vortex flowmeters for measuring liquids, gases and steam. Although vortex meters are most widely used for steam measurement.

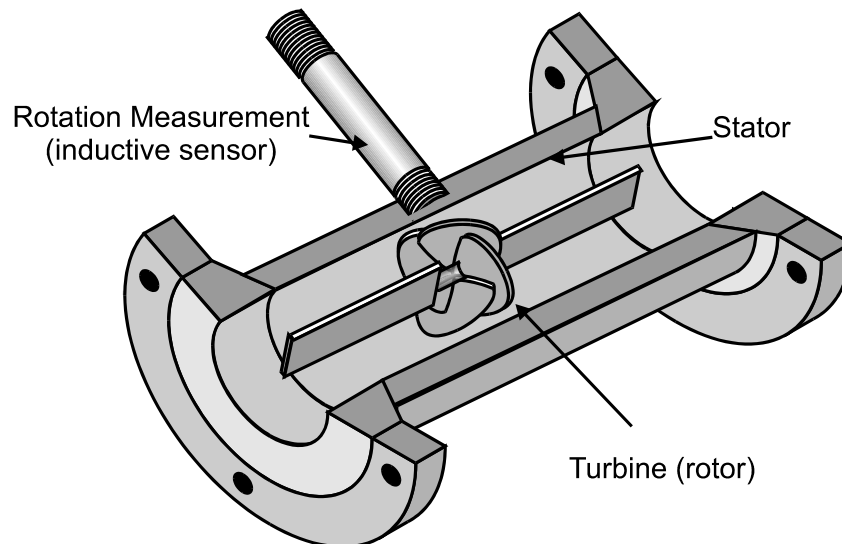
Vortex flowmeters generally have no moving parts and are unaffected by changes in temperature, pressure or density. They produce some unrecoverable pressure loss, but less than that for the same sized differential pressure flowmeter.

In general, the Rangeability is broad, and the meters can be used with liquids, gases or vapours simply by configuring the device.

Note: These devices work on the principle of generating vortices. Vortices are easily formed in high flow rates and low viscosities. Therefore these devices are not useful at very low flow rates, typically 0.3m/sec in liquid or 3m/sec in gases, or fluids with high viscosities. These devices produce a restriction in the line, and as such should not be used with erosive fluids, however they are more forgiving than orifice plates.

## 5.5.2 Turbine

### *Basis of Operation*



**Figure 5.30**  
***Turbine flowmeter***

Turbine meters have rotor-mounted blades that rotate when a fluid pushes against them. They work on the reverse concept to a propeller system. Whereas in a propeller system, the propeller drives the flow, in this case the flow drives and rotates the propeller. Since it is no longer propelling the fluid, it is now called a turbine.

The rotational speed of the turbine is proportional to the velocity of the fluid.

Different methods are used to convey rotational speed information. The usual method is by electrical means where a magnetic pick-up or inductive proximity switch detects the rotor blades as they turn. As each blade tip on the rotor passes the coil it changes the flux and produces a pulse. Pulse rate is directly proportional to the flowrate.

As the rotation of the turbine is measured by means of non-contact, no tapping points are required in the pipe. Pressure is therefore not a problem, and in fact pressures of up to 9300psi can be applied without any problem, but this of course does depend on pipe diameter and materials of construction.

Temperature limitations are only imposed by the limitations of the materials of construction. To reduce losses or changes in process temperature, turbine flowmeters are available which can be subjected to wide temperature variations.

Turbine meters require a good laminar flow. In fact 10 pipe diameters of straight line upstream and no less than 5 pipe diameters downstream from the meter are required. They are therefore not accurate with swirling flows.

They are not recommended for use with high viscosity fluids due to the high friction of the fluid which causes excessive losses as the turbine becomes too much of an obstruction. The viscosity of the liquid must be known for use of this type of meter.

They are also subject to erosion and damage. Each meter must be calibrated for its application.

### **Selection and Sizing**

Turbine meters are sized by volumetric flow rate, however the main factor that affects the meter is viscosity.

Typically, larger meters are less affected by viscosity than smaller meters. This may indicate that larger meters would be preferred; in fact the opposite is true. By using a smaller meter, operation is more likely to occur towards the maximum permitted flowrate, and away from the non-linear response at low flows.

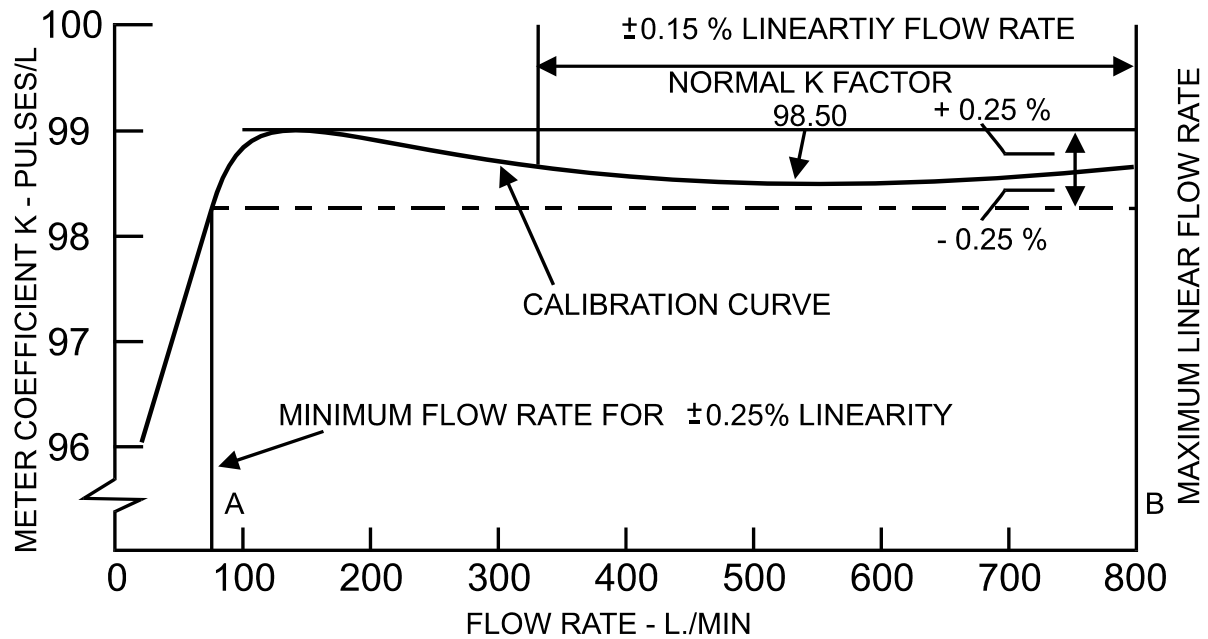
Turbine meters are specified with minimum and maximum linear flow rates that ensure the response is linear and the other specifications are met. For good Rangeability, it is recommended that the meter be sized such that the maximum flow rate of the application be about 70 to 80% of that of the meter.

Density changes have little effect on the meters' calibration.

### **K-Factor**

The turbine meter measures volumetric flow, however the pulses produced vary depending on the meter. The variation is accounted for by a K-factor.

The K-factor is the number of pulses per unit volume. It is primarily determined by the size and type of the turbine meter. Due to manufacturing tolerances, the actual K-factor can vary between similar models.



**Figure 5.31**  
*Typical calibration curve for a turbine meter*

### Advantages

- High accuracy, repeatability and Rangeability for a defined viscosity and measuring range.
- Temperature range of fluid measurement:  $-220^{\circ}\text{C}$  to  $+350^{\circ}\text{C}$ .
- Very high-pressure capability: 9300psi.
- Measurement of non-conductive liquids.
- Capability of heating measuring device..
- Suitable for very low flow rates.

### Disadvantages

- Not suitable for high viscous fluids.
- Viscosity must be known.
- 10 diameter upstream and 5 diameter downstream of straight pipe is required.
- Not effective with swirling fluids.
- Only suitable for clean liquids and gases.
- Pipe system must not vibrate.
- Specifications critical for measuring range and viscosity.

### Application Limitations

As turbine meters rely on the flow, they do absorb some pressure from the flow to propel the turbine. The pressure drop is typically around 20 to 30 kPa at the maximum flow rate and does vary depending on flow rate.

It is a requirement in operating turbine meters that sufficient line pressure be maintained to prevent liquid cavitation. The minimum pressure occurs at the rotor, however the pressure recovers substantially after the turbine.

If the backpressure is not sufficient, then it should be increased or a larger meter chosen to operate in a lower operating range. This does have the limitation of reducing the meter flow range and accuracy.

### **Summary**

Turbine meters provide excellent accuracy, repeatability and rangeability for a defined viscosity and measuring range, and are commonly used for custody transfer applications of clean liquids and gases.

## **5.6 Magnetic Flowmeters**

### **5.6.1 Basis of Operation**

Electromagnetic flowmeters, also known as magmeters, use Faradays' law of electromagnetic induction to sense the velocity of fluid flow.

Faradays law states that moving a conductive material at right angles through a magnetic field induces a voltage proportional to the velocity of the conductive material. The conductive material in the case of a magmeter is the conductive fluid.

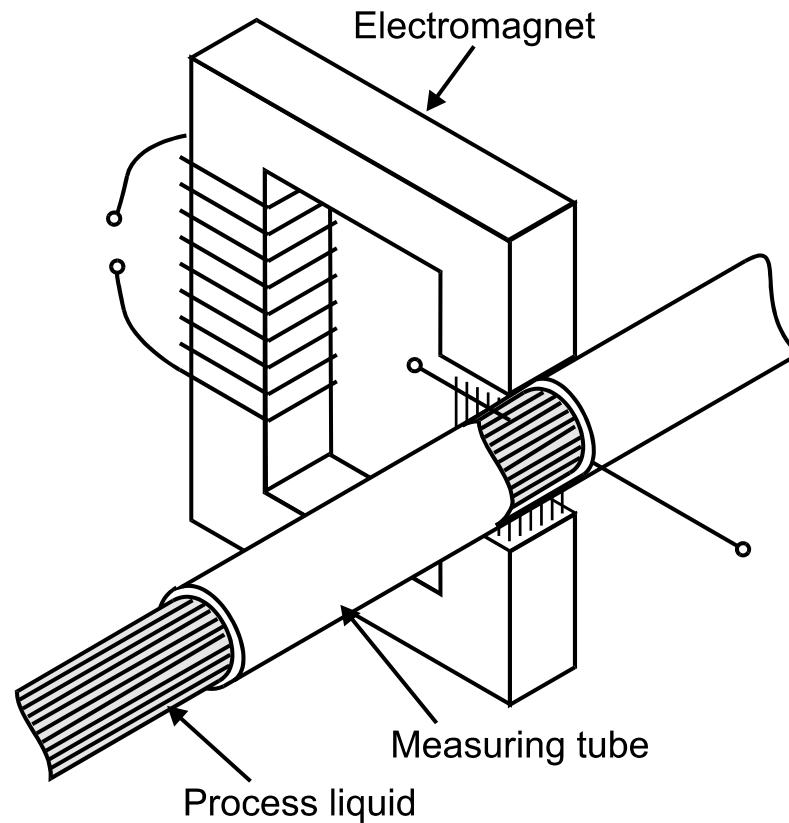
The fluid therefore must be electrically conductive, but not magnetic.

### **5.6.2 Power generators/magmeters - what's the connection?**

If we consider power generators or tachometers that are used for speed measurement, then these operate on the same principle. Electrically conductive process fluid is fundamentally the same as the rotor in a generator. The fluid passes through a magnetic field induced by coils that are positioned around a section of pipe.

The process fluid is electrically insulated from the pipe with a suitable lining, in the case of a metal pipe, so that the generated voltage is not dissipated through the pipeline. The electrodes are located in the pipe and a voltage is generated across these electrodes that is directly proportional to the average velocity of the liquid passing through the magnetic field.

The coils are energised with ac power or pulsed dc voltage, so consequently the magnetic field and resultant induced voltage responds accordingly. The generated voltage is protected from interference, amplified and converted into a dc current signal by the transmitter. Line voltage variations are accounted for by the sensing circuits.



**Figure 5.32**  
*Principle of the electromagnetic meter*

### 5.6.3 The Magmeter

The advantages of magnetic flowmeters are that they have no obstructions or restrictions to flow, and therefore no pressure drop and no moving parts to wear out. They can accommodate solids in suspension and have no pressure sensing points to block up. The magnetic flowmeter measures volume rate at the flowing temperature independent of the effects of viscosity, density, pressure or turbulence. Another advantage is that many magmeters are capable of measuring flow in either direction.

Most industrial liquids can be measured by magnetic flowmeters. These include acids, bases, water, and aqueous solutions. However, some exceptions are most organic chemicals and refinery products that have insufficient conductivity for measurement. Also pure substances, hydrocarbons and gases cannot be measured.

In general the pipeline must be full, although with the later models, level sensing takes this factor into account when calculating a flowrate.

Magnetic flowmeters are very accurate and have a linear relationship between the output and flowrate. Alternatively, the flow rate can be transmitted as a pulse per unit of volume or time.

The accuracy of most magnetic flowmeter systems is 1% of fullscale measurement. This takes into account both the meter itself and the secondary instrument. Because of its linearity, the accuracy at low flow rates exceeds that of such devices as the Venturi tube. The magnetic flowmeter can be calibrated to an accuracy of 0.5% of full scale and is linear throughout.

#### 5.6.4 Selection and Sizing - General

In most applications, the meter is sized to the pipe in which it is to be installed. Although this is probably the simplest approach, it is necessary to ensure that the meter meets the process requirements. The two main requirements are the maximum and minimum flows, although accuracy can be another deciding factor.

If these requirements cannot be achieved, then a meter of differing size to the pipeline is required. Under these conditions it is more common that the meter be downsized as the pipelines are often oversized.

Another reason for downsizing the meter is to increase the flowrate through the meter. In applications of liquids with a solids content, the flow velocity should be maintained above a certain level, typically 3 m/sec, to prevent build-up and deposits.

Sizing of magmeters is done from manufacturer's nomographs to determine suitable diameter meters for flow rates.

The conductivity of liquids can vary with temperature. Care should be taken to ensure the performance of the liquid in marginal conductivity applications is not affected by the operating temperatures. Most liquids do have a positive temperature coefficient of conductivity, however negative coefficients are possible in a few liquids.

Since the flowtube diameter determines the flow velocity, it becomes a very important consideration. The flowtube is sized to give a velocity between 0.3 and 9.1 m/sec.

<b>Application</b>	<b>Velocity range, m/sec</b>
Normal service	0.6 - 6.1
Abrasive slurries	0.9 - 3.1
Non-abrasive slurries	1.5 - 4.6

**Table 5.6**  
**Sizing guidelines for the type of application**



*Calculating velocity:*

Information is generally known about the required flow rate in the process, and from this the velocity needs to be determined. The manufacturer's specifications will give a Litres per minute factor for each size of meter.

$$\text{Velocity} = \frac{\text{Flowrate}}{\text{Factor}}$$

where:      Velocity      = speed of flow in m/sec  
               Flow rate      = the known volumetric flow in l/min  
               Factor         = obtained from the table below

Nominal size, mm	Litres per minute factor
15	11.834
25	33.657
40	79.297
50	130.67
80	287.88
100	495.73
150	1125.0
200	1948.3
250	3070.7
300	4437.2
350	5268.8
400	6881.5
450	8875.7
500	10826
600	15657
750	25036
900	36670

**Table 5.7**  
**Calculating flow rate**

**5.6.5 Selection and Sizing - Liners**

The principle of operation of the magmeter requires the generation of a magnetic field, and the detection of the voltage across the flow. If the pipe is made of a material with magnetic properties, then this will disrupt the magnetic field and this effectively short circuits the magnetic field. Similarly if the inside of the pipe is conductive, then this will short circuit the electrodes used to detect the voltage across the flow.

The meter piping must be manufactured from a non-magnetic material such as stainless steel in order to prevent short-circuiting of the magnetic field.

The lining of the meter piping must also be lined with an insulating material to prevent short-circuiting of the electric field.

The liner has to be chosen to suit the application, particularly the resistance it has to the following:

- chemical corrosion
- erosion
- abrasion
- pressure
- temperature

<b>Commonly used magnetic flowmeter liner materials</b>					
<b>Material</b>	<b>General</b>	<b>Corrosion resistance</b>	<b>Abrasion resistance</b>	<b>Temperature limit (°C)</b>	<b>Pressure limit (bar)</b>
Teflon PFA (PTFE)	Warm-deformable resin with excellent ant-stick properties and suitable for food and beverage	Excellent	Fair	220	40
Teflon PFA	Melt-processable resin with better shape accuracy, abrasion resistance and vacuum strength than PTFE	Excellent	Good	180	40
Polyurethane	Extreme resistance to wear and erosion but not suitable for strong acids or bases	Wide range	Excellent	40	250
Neoprene	Combines some of the resistance to chemical attack of PTFE with a good degree of abrasion resistance	Wide range	Good to excellent	80	100
Hard rubber	Inexpensive – finds its main application in the water and waste water industries	Fair to excellent	Fair	90	250
Soft rubber	Mainly used for slurries	Fair	Excellent	40	64
Fused aluminium oxide	Highly recommended for very abrasive and/or	Excellent	Excellent	180	40

**Table 5.8**  
**Commonly used magnetic flowmeter liner material**

A Summary of the characteristics of the various lines are:

*Teflon (PTFE):*

- Widely used due to its high temperature rating.
- Anti-stick properties reduce problems with build-up.
- Approved for food and beverage environments.
- Resistant to many acids and bases.

### *Neoprene*

- Good abrasion resistance.
- Good chemical resistance.

### *Soft Rubber*

- Relatively inexpensive.
- High resistance to abrasion.
- Used mainly for slurry applications.

### *Hard rubber*

- Inexpensive.
- General purpose applications.
- Used mainly for water and soft slurries.

### *Ceramic*

- High abrasion resistance.
- High corrosion resistance.
- High temperature rating.
- Less expensive to manufacture.
- Also suited to sanitary applications.
- Strong compressive strength, but poor tensile strength.
- Brittle.
- May crack with sudden temperature changes, especially downward.
- Cannot be used with oxidising acids or hot concentrated caustic.

## **5.6.6 Installation Techniques**

For correct operation of the magmeter, the pipeline must be full. This is generally done by maintaining sufficient backpressure from downstream piping and equipment. Meters are available that make allowances for this problem, but are more expensive and are specialised. This is mainly a problem in gravity feed systems.

Magmeters are not greatly affected by the profile of the flow, and are not affected by viscosity or the consistency of the liquid. It is however recommended that the meter be installed with 5 diameters of straight pipe upstream and 3 diameters of straight pipe downstream from the meter.

Applications requiring reduction in the pipe diameter for the meter installation, need to allow for the extra length of reducing pipe. It is also recommended that in those applications that the reducing angle not be greater than  $8^\circ$ , although manufacturers' data should be sought.

Grounding is another important aspect when installing magmeters, and manufacturers' recommendations should be adhered to. Such recommendations

would require the use of copper braid between the meter flange and pipe flange at both ends of the meter. These connections provide a path for stray currents and should also be grounded to a suitable grounding point. Magmeters with built in grounding electrodes eliminate this problem, as the grounding electrode is connected to the supply ground.

### **5.6.7 Typical Applications**

Magmeters are used in many applications as most liquids and slurries are suitable conductors. They are also the first to be considered in corrosive and abrasive applications. They can also be used for very low flow rates and small pipe diameters.

### **5.6.8 Advantages**

- No restrictions to flow.
- No pressure loss.
- No moving parts.
- Good resistance to erosion.
- Independent of viscosity, density, pressure and turbulence.
- Good accuracy.
- Bi-directional.
- Large range of flow rates and diameters.

### **5.6.9 Disadvantages**

- Expensive.
- Most require a full pipeline.
- Limited to conductive liquids.

### **5.6.10 Application Limitations**

As mentioned earlier, a magnetic flowmeter consists of either a lined metal tube, usually stainless steel because of its magnetic properties, or an unlined non-metallic tube. The problem can arise if the insulating liners and electrodes of the magnetic flowmeter become coated with conductive residues deposited by the flowing fluid. Erroneous voltages can be sensed if the lining becomes conductive.

Maintaining high flow rates reduces the chances of this happening. However, some manufacturers do provide magmeters with built in electrode cleaners.

Block valves are used on either side of ac-type magmeters to produce zero flow and maintain a full pipe to periodically check the zero calibration limit. Dc units do not have this requirement.

### **5.6.11 Summary**

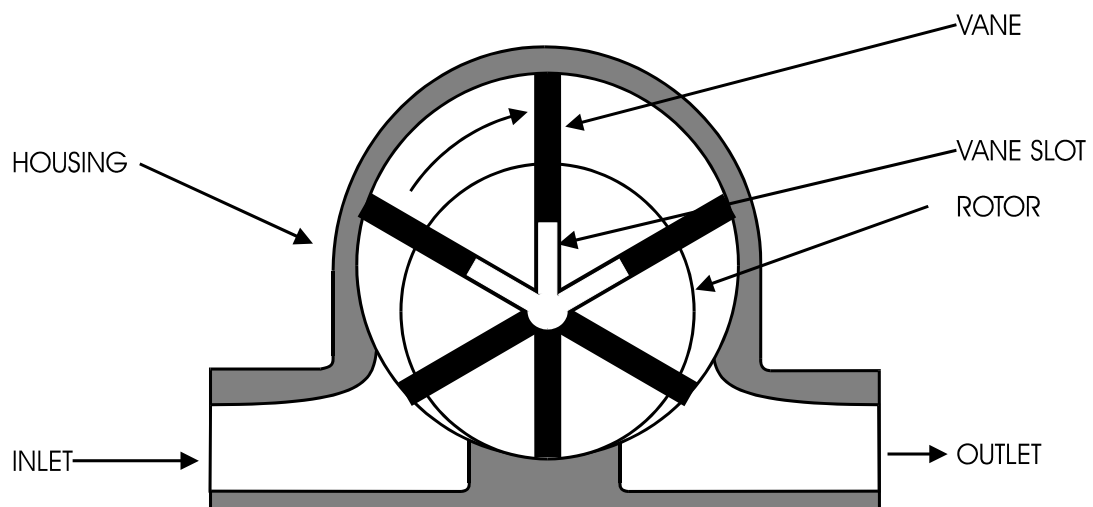
Magmeters are available with a ceramic lining and capable of measuring ultra-low conductivity fluids down to 0.01 uS/cm. Because of their electrode-less construction they are virtually immune to the effects of build-up and coating on the flowmeter liner.

## 5.7 Positive Displacement

Positive displacement meters measure flow rate by repeatedly passing a known quantity of fluid from the high to low pressure side of the device in a pipe. The number of times the known quantity is passed gives information about the totalised flow. The rate at which it is passed is the volumetric flow rate. Because they pass a known quantity, they are ideal for certain fluid batch, blending and custody transfer applications. They give very accurate information and are generally used for production and accounting purposes.

### 5.7.1 Rotary vane

Spring loaded vanes slide in and out of a channel in a rotor so that they make constant contact with the eccentric cylinder wall. When the rotor turns, a known volume of fluid is trapped between the two vanes and the outer wall. The flow rate is based on volume per revolution.



**Figure 5.33**  
**Rotating vane meter**

The piston type is suitable for accurately measuring small volumes and is not affected by viscosity. Limitations with this device are due to leakage and pressure loss.

### Typical Applications

This type of meter is used extensively in the petroleum industry for such liquids as gasoline and crude oil metering.

### Advantages

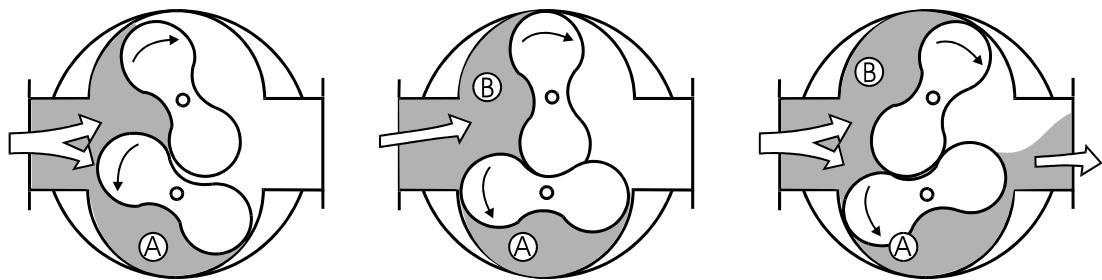
- Reasonable accuracy of 0.1%.
- Suitable for high temperature service, up to 180°C.
- Pressures up to 7Mpa.

### Disadvantages

- Suitable for clean liquids only.

### Lobed impeller

This type of meter uses two lobed impellers, which are geared and meshed to rotate at opposite directions within the enclosure. A known volume of fluid is transferred for each revolution.



**Figure 5.34**  
**Rotating lobe meter**

### Typical Applications

The lobed impeller meter is often used with gases.

### Advantages

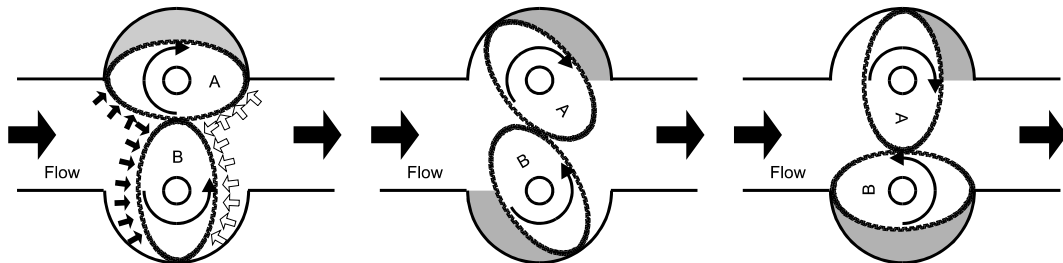
- High operating pressures, up to 8Mpa.
- High temperatures, up to 200°C.

### Disadvantages

- Poor accuracy at low flow rates.
- Bulky and heavy.
- Expensive.

### 5.7.2 Oval gear meters

Two oval gears are intermeshed and trap fluid between themselves and the outer walls of the device. The oval gears rotate due to the pressure from the fluid and a count of revolutions determines the volume of fluid moving through the device.



**Figure 5.35**

***Positive displacement meters measure volumetric flow rate directly by dividing a stream into distinct segments of known volume, counting segments and multiplying by the volume of each segment.***

The viscosity of the fluid can affect the leakage, or slip flow. If the meter is calibrated on a particular fluid, it will read marginally higher should the viscosity rise.

Newer designs of this type of meter use servomotors to drive the gears. This eliminates the pressure drop across the meter and also the force required to drive the gear. This eliminates the force, which causes the slip flow. This mainly applies to smaller sized meters and significantly increases the accuracy at low flows.

#### **Advantages**

- High accuracy of 0.25%
- High operating pressures, up to 10MPa
- High temperatures, up to 300°C
- Wide range of materials of construction

#### **Disadvantages**

- Pulsations caused by alternate drive action



### 5.7.3 *General Summary*

Wear and damage is a problem due to the amount of contact between the parts and as such can only be used with clean fluids. The working life of the device also depends on the fluid being measured, this relates to solids build-up and temperatures of the fluid.

They are an obstruction to the flow path and consequently cause some pressure loss. Errors can occur due to leakage around the gears or pistons, but are reduced by using fluids that have some resistance to flow. Such viscous fluids have the ability to seal the small clearances. However if the fluid is too viscous then it can coat the inner chambers of the device and reduce the volume passed thus causing further errors.

Liquid positive displacement meters are one of the most common and widely used devices for measuring volumetric flow for custody transfer. They are simple and easy to maintain by regular maintenance personnel.

### 5.7.4 *Application Limitations*

Overspeeding can damage positive displacement meters. When the outlet pressure needs to be maintained due to an unacceptable pressure drop across the meter, it is quite common for the inlet pressure to be increased.

Specifications do vary, but in general they are primarily suited for clean, lubricating and non-abrasive applications.

Filters may be required to filter debris and clean the fluid before the meter. Regular maintenance is an obvious addition in this case. The added pressure drop may also need to be considered, especially if regular maintenance is not carried out.

Limitations on operating temperature can prove to be an inhibiting factor. If leakage does occur and is calibrated for, it can change with temperature as the viscosity varies.

One of the main limitations with this form of flow measurement is that the meter is driven by the flow. Particularly in the case of the oval gear meter, the force required to rotate the gear action is not constant and results in pulsations. These pulsations may make the use of this type of meter impossible, particularly in controlled applications requiring a steady flow.

Positive displacement meters become limited when high volume measurement is required. They are primarily used for low volume applications.

In comparison, they are more expensive than magnetic flowmeters, but do have the added advantage of being able to measure non-conductive fluids.

### 5.7.5 *Advantages*

- Can measure non-conductive fluids.
- Very high accuracy.
- Unaffected by viscosity.
- High Rangeability of up to 10:1.

### 5.7.6 *Disadvantages*

- Clean fluids only, limited life due to wear.
- Some unrecoverable pressure loss.
- Requires viscous fluid, not suitable for gas.
- Limited operating range.
- Mechanical failure likely to cause blockage in pipe.
- Cost.

## 5.8 **Ultrasonic Flow Measurement**

There are two types of ultrasonic flow measurement:

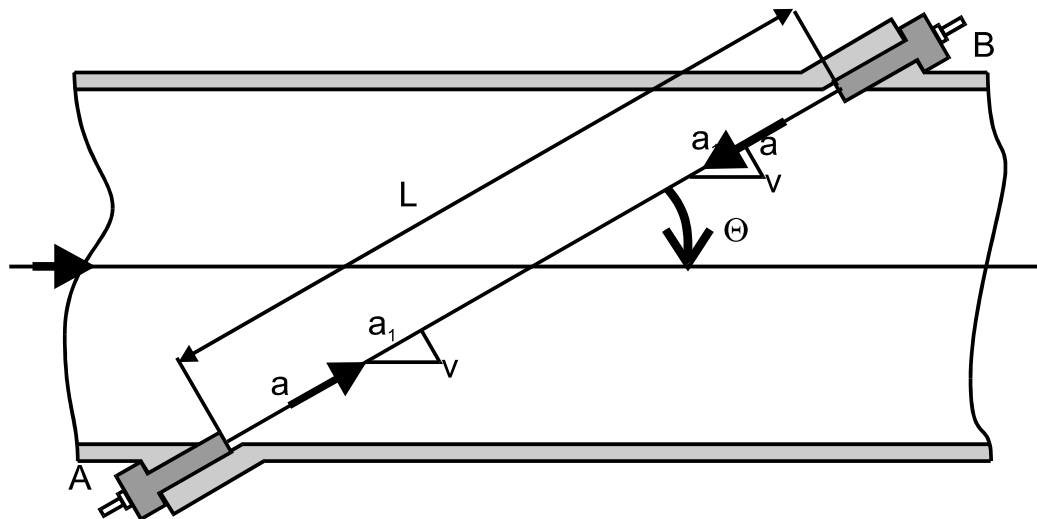
- Transit time measurement
- Doppler effect

The fundamental difference is that the transit-time method should be used for clean fluids, while the Doppler reflection type used for dirty, slurry type flows.

### 5.8.1 *Transit time*

The transit-time flowmeter device sends pulses of ultrasonic energy diagonally across the pipe. The transit-time is measured from when the transmitter sends the pulse to when the receiver detects the pulse.

Each location contains a transmitter and receiver. The pulses are sent alternatively upstream and downstream and the velocity of the flow is calculated from the time difference between the two directions.



**Figure 5.36**  
**Transit time measurement**

### 5.8.2 Installation Techniques

Designs are available that allow installation and removal of the transducers without interrupting the process flow. However there are three main options available:

- Fitted section of pipe
- Clamp on
- Transducers installed in-situ

The first option is where the manufacturer supplies a section of pipe fitted with the transducers factory mounted. These units have the advantage of being calibrated by the manufacturer to meet specifications. Allowances need to be made when fitting this section of pipe - something that can complicate existing installations.

Clamp-on transducers have the added advantage of being easy to install. They are mounted outside of the existing pipe. Since no section of pipe need to be installed then this type of flowmeter is easily retrofitted onto an existing system. They can be installed on metal, plastic and ceramic pipes.

Because they are portable and non-intrusive, clamp-on devices provide a good means of determining flowrates of unknown flows in existing installations.

A cheaper option is to install the transducers into the pipework. This does require tapping into the pipe and care needs to be taken to ensure the correct angles and tolerances are adhered to. This method generally requires calibration by the user once installed.

### 5.8.3 Application Limitations

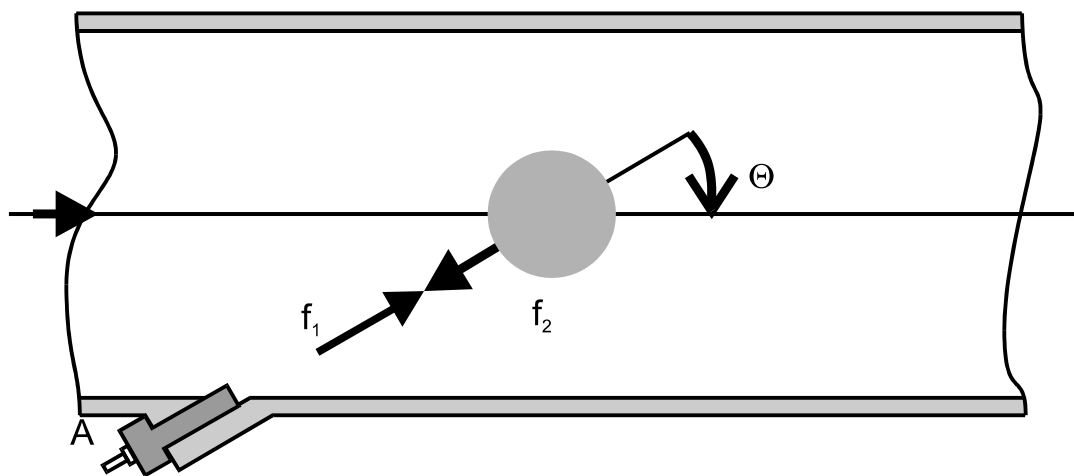
Clamp-on designs are limited because of the differing mediums in which the ultrasonics signals pass through. For optimum results, a sound-conductive path is required between the transducer and the process fluid inside the pipe. Couplings are available for reducing these effects but are quite expensive.

### 5.8.4 Typical Applications

Transit-time ultrasonic flow measurement is suited for clean fluids. Some of the more common process fluids consist of water, liquefied gases and natural gas.

### 5.8.5 Doppler Effect

The Doppler effect device relies on objects with varying density in the flowstream to return the ultrasonic energy. With the Doppler effect meter, a beam of ultrasonic energy is transmitted diagonally through the pipe. Portions of this ultrasonic energy are reflected back from particles in the stream of varying density. Since the objects are moving, the reflected ultrasonic energy has a different frequency. The amount of difference between the original and returned signals is proportional to the flow velocity.



**Figure 5.37**  
**Doppler effect**

It is quite common for only one sensor to be used. This contains both the transmitter and receiver. These can also be mounted outside of the pipe.

### 5.8.6 Application Limitations

As the Doppler flowmeter relies on reflections from the flowstream, it therefore requires sufficiently sized solids or bubbles. It is also required that the flow be fast enough to maintain a suitable quantity of solids and bubbles in suspension.

Higher frequency Doppler flowmeters are available, but are limited to cleaner fluids.

### **5.8.7 Summary - General**

Most ultrasonic flowmeters are mounted on the outside of the pipe and thus operate without coming in contact with the fluid. Apart from not obstructing the flow, they are not affected by corrosion, erosion or viscosity. Most ultrasonic flowmeters are bi-directional, and sense flow in either direction.

### **5.8.8 Advantages**

- Suitable for large diameter pipes.
- No obstructions, no pressure loss.
- No moving parts, long operating life.
- Fast response.
- Installed on existing installations.
- Not affected by fluid properties.

### **5.8.9 Disadvantages**

- Accuracy is dependent on flow profile.
- Fluid must be acoustically transparent.
- Errors cause by build up in pipe.
- Only possible in limited applications.
- Expensive.
- Pipeline must be full.

### **5.8.10 Application Limitations**

Turbulence or even the swirling of the process fluid can affect the ultrasonic signals. In typical applications the flow needs to be stable to achieve good flow measurement, and typically allowing sufficient straight pipe up and downstream of the transducers does this. The straight section of pipe upstream would need to be 10 to 20 pipe diameters with a downstream requirement of 5 pipe diameters.

For the transit time meter, the ultrasonic signal is required to traverse across the flow, therefore the liquid must be relatively free of solids and air bubbles. Anything of a different density (higher or lower) than the process fluid will affect the ultrasonic signal.

### **5.8.11 Summary**

Doppler flowmeters are not high accuracy or high performance devices, but do offer an inexpensive form of flow monitoring. Their intended operation is for dirty fluids, and find applications in sewage, sludge and waste water processes.

Being dependent on sound characteristics, ultrasonic devices are dependent on the flow profile, and are also affected by temperature and density changes.

## 5.9 Mass Flow Meters

Mass flow measurement gives a more accurate account of fluids, and is not affected by density, pressure and temperature (unlike volumetric measurements).

Although most meters can infer mass flow rate from volumetric flow measurements, there are a number of ways to measure mass flow directly:

- The Coriolis meter
- Thermal mass flowmeter
- Radiation density

### 5.9.1 The Coriolis Meter

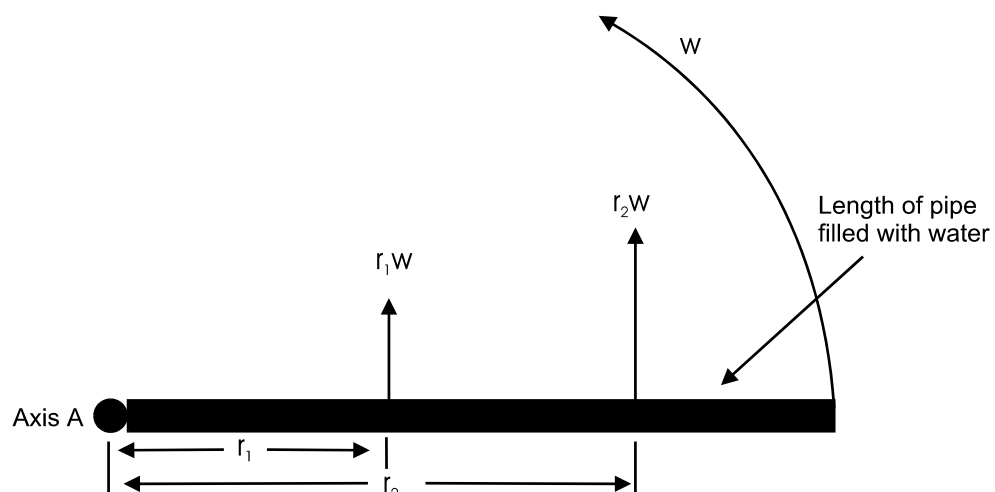
#### The Coriolis Effect

The basis of the Coriolis meter is Newtons' Second Law of Motion, where:

Force = Mass x Acceleration.

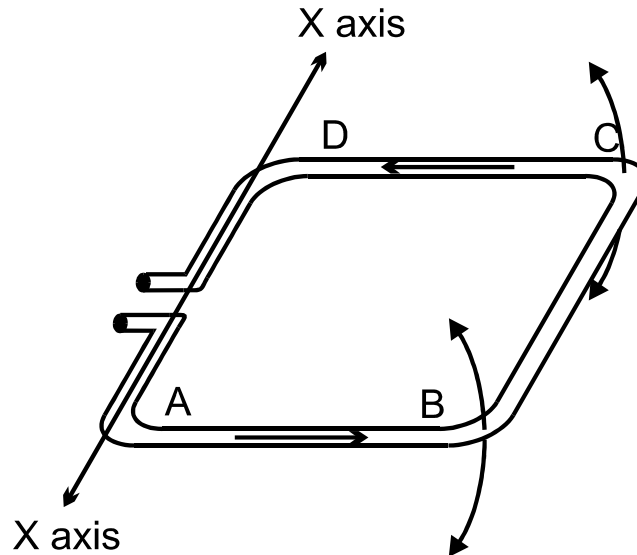
The conventional way to measure the mass of an object is to weigh it. In weighing, the force is measured with a known acceleration ( $9.81\text{m/sec}^2$ ). This type of measuring principle is not easy or possible with fluids in motion, particularly in a pipe.

However, it is possible to manipulate the above formula and apply a known force and measure, instead, the acceleration to determine the mass.



**Figure 5.38**  
**Principle of Coriolis effect**

The Coriolis effect causes a retarding force on a rotating section of pipe when flow is moving outward, conversely producing an advance on the section of pipe for flow moving towards the axis of rotation.



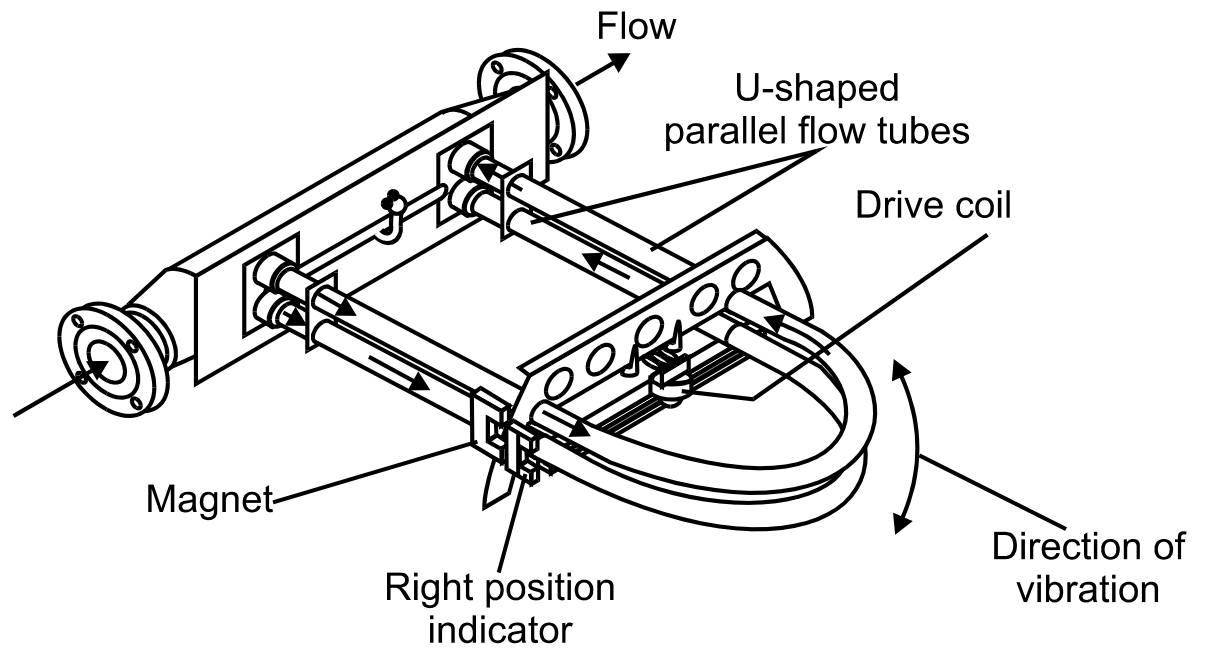
**Figure 5.39**  
*Application of Coriolis force to a meter*

When the full section of pipe is moved about its axis in an oscillatory motion, the outgoing section of pipe is retarded (or decelerated) and the return section is advanced (or accelerated), producing a twist in the pipe.

### **Coriolis Meter**

The force is applied to oscillate the flow pipes and the Coriolis effect is the principle used to determine the acceleration due to the torque (the amount of twisting). Sensors are used to measure the amount of twist in the flowtubes within the meter as a result of the flowtube vibration and deflection due to the mass flow. The amount of twist measured is proportional to the mass flow rate and is measured by magnetic sensors mounted on the tubes.

Developments on the looped pipe Coriolis meter were made to keep to the pipes straight. This is done by making the pipes straight and parallel. The force is applied by oscillating the pipes at the resonant frequency. This has the advantage of reducing pressure loss in the pipeline.



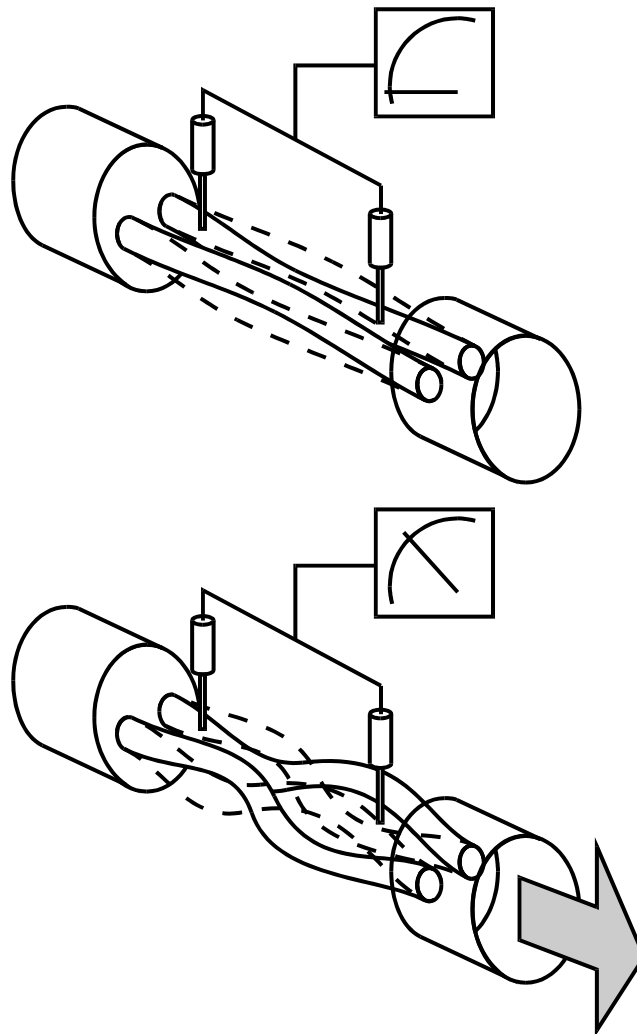
**Figure 5.40**  
**Coriolis meter construction**

### **Straight Through Meter**

A development to the looped typed Coriolis meter is the straight through pipe version, which has the added advantage of lower pressure loss.

The rotational movement in this type of meter is provided by vibrating the pipes and the Coriolis force develops in the pipes. The pipes are vibrated at their resonant frequency and sensors are used to detect the movement of the pipe. For no flow the sensors detect the same movement, however when liquid flows there is a difference between the oscillations of the two pipes. This is caused as the flow is accelerated on the inlet and decelerated on the outlet. As before with twist, this difference in the phase of the oscillations is proportional to mass flow.





**Figure 5.41**  
**Basic principle of 'Straight Through' pipe (a) without fluid, and**  
**(b) with fluid flow**  
*(Courtesy of Endress & Hauser)*

### Advantages

- Direct, in-line mass flow measurement.
- Independent of temperature, pressure, density, conductivity and viscosity.
- Sensor capable of transmitting mass flow, density and temperature information.
- High density capability.
- Conductivity independent.
- Suitable for hydrocarbon measurements.
- Suitable for density measurement.

### **Disadvantages**

- Cost.
- Affected by vibration.
- Installation costs.
- Adjustment of zero point.

### **Application Limitations**

- High temperature.
- Vibration.
- Amount of gas in fluid.
- Restricted to low flow rates.
- Limited to pipe sizes of up to 150mm.

### **Summary**

Coriolis meters provide direct, in-line and accurate mass flow measurements that are independent of temperature, pressure, viscosity and density. Mass flow, density and temperature can be accessed from the one sensor. They can also be used for almost any application when calibrated.

For critical control, mass flow rate is the preferred method of measurement and because of their accuracy Coriolis meters are becoming very common for applications requiring very tight control. Apart from custody transfer applications, they are used for chemical processes and expensive fluid handling.

### **5.9.2 Thermal Mass Flowmeters**

The two main types of thermal mass flow measuring devices are:

- Thermal Anemometer
- Temperature rise flowmeter

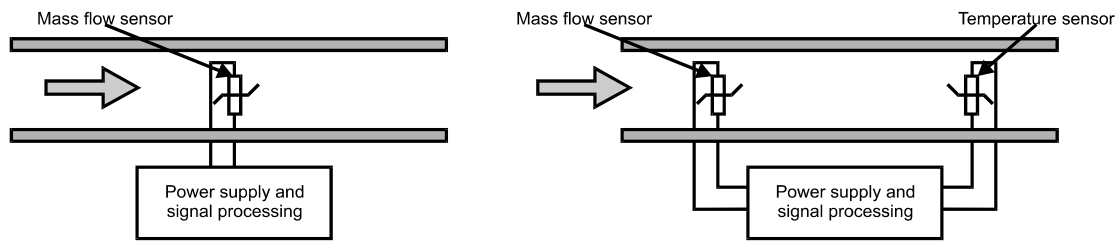
#### *Thermal anemometer*

The thermal anemometer works by measuring the heat dissipation from a probe inserted in the line. The amount of heat taken from the probe is dependent on the fluid velocity and density, but is also a direct measure of the mass flow rate. The temperature is also measured for the calculation. They are also referred to as 'Hot wire probes'.

The probe can either be constant current or constant temperature.

In the constant current type, a fixed current is passed through the probe which causes heating in the probe. As the flow rate varies, so does the amount of heat taken from

the probe and hence the temperature changes. The temperature is measured to derive the flow.



**Figure 5.42**  
**Thermal mass flowmeters**

For the constant temperature type, a feedback loop is required to maintain a constant temperature. As the change of flow affects the temperature, the current needs to be regulated to maintain probe temperature. The flow rate is determined by the power required to heat the probe.

In comparing the constant current and constant temperature types it is shown that constant temperature devices have a faster response to flow changes.

These devices are primarily used for gases and are dependent on flow profile. They are therefore limited if the flow profile changes as they only measure at one point in the flowstream. Their limitations are similar to pitot tubes, which are also an insertion device into a flowstream.

To achieve laminar flow, 10 diameters of straight pipe are required upstream of the sensor. Later developments of these sensors incorporate a conditioning nozzle which concentrates the flow onto the sensor.

The temperature probe must protrude into the flowstream, and therefore may be easily damaged by corrosion and erosion. In addition the robustness of the system is compromised by the protrusions into the fluid stream, increasing the chances of leakage.

### Advantages

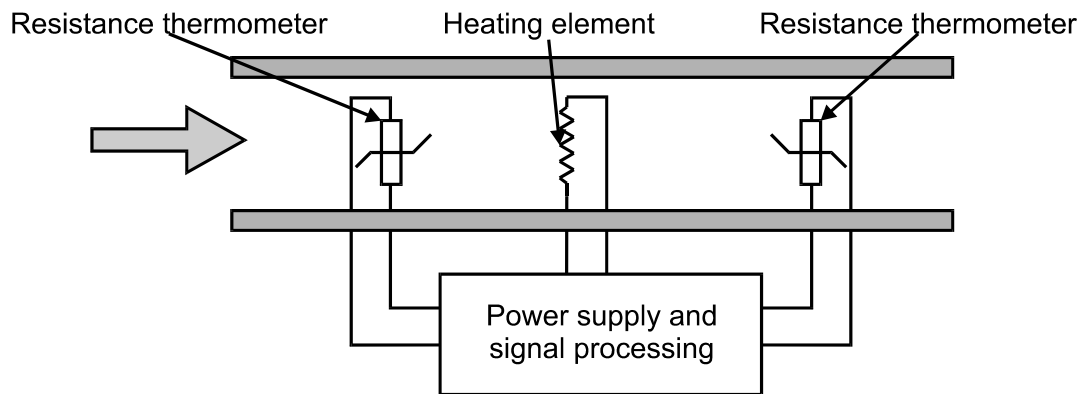
- Fast response times, < 0.5 milliseconds.

### Disadvantages

- Require 10 diameters of straight pipe upstream.
- Have similar limitations to pitot tubes.

### *Temperature rise flowmeter - insertion type*

Temperature rise flowmeters work on the principle of heating the flowstream. By heating the flowstream at one point, the temperature can be measured both upstream and downstream of the heating point. Calculating the difference between the temperatures gives information about the flowrate.



**Figure 5.43**  
**Principle of 'Temperature Rise' method**

This method requires the measurement of actually heating the process fluid. It is therefore limited to gas applications at low flow rates.

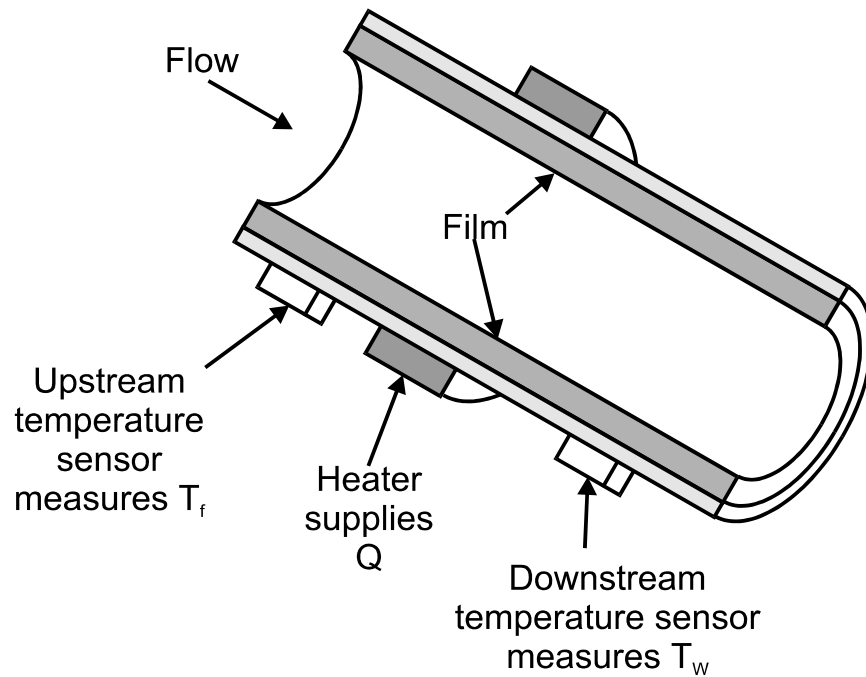
As with the hot wire probe, the temperature sensors and the heater must protrude into the flowstream, and therefore may be easily damaged by corrosion and erosion. Also the robustness of the system is compromised by the protrusions into the fluid stream, increasing the chances of leakage.

### **Disadvantages**

- Suitable for low gas flows only.
- Subject to erosion and corrosion.
- More tapping points, increased chances of leakage.

### *Temperature rise flowmeter - external type*

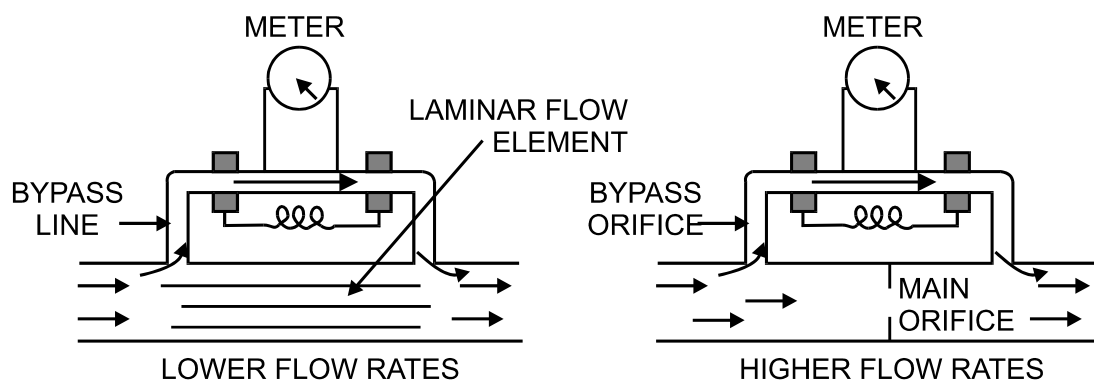
Developments of the insertion type of sensing have moved the heating and sensing elements to outside the pipe to overcome the problems with tapping points. By limiting the tapping points, the chance of leakage (and associated maintenance) is greatly reduced, if not eliminated.



**Figure 5.44**  
**Thermal flowmeter with external elements and heater**

This type of sensing mainly applies to small pipe diameters.

For larger pipe diameters, a sample of the flow can be taken and sensing applied in this way.



**Figure 5.45**  
**Bypass-type thermal mass flowmeter**

### **Advantages**

- Non contact, non intrusive sensing
- No obstruction to flow
- Reduced maintenance

### **Disadvantages**

- Suitable for low gas flows only
- Subject to erosion and corrosion

### **Summary**

Thermal mass flowmeters are mainly used to measure the flow of clean gases with known heat capacities. They are commonly used in the refining and chemical industries.

#### **5.9.3 Radiation Density**

One of the limitations of flow meters is that they measure volumetric flow only. As mentioned previously, if the density is known and is constant, then mass flow rate can be calculated. Problems arise when the density varies.

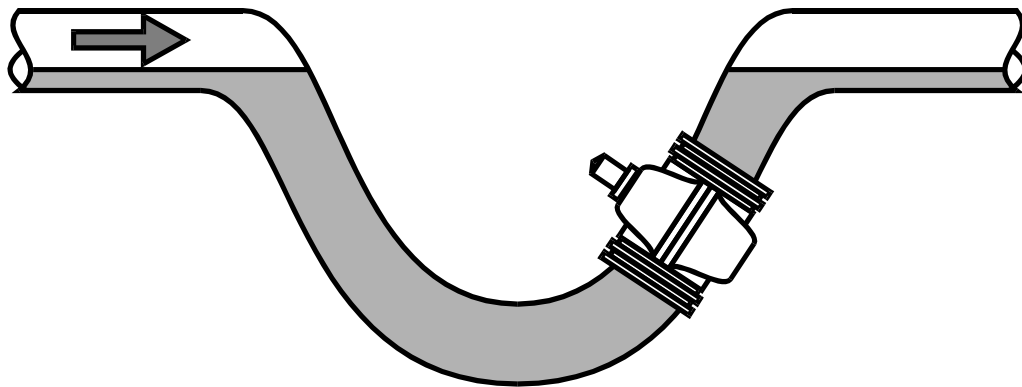
It is however possible and quite acceptable practice to combine volumetric flow equipment with density measuring devices to obtain accurate mass flow measurements. One such combination is the use of a magmeter with a radiation densitometer.

### **5.10 Installation Considerations**

#### **Full Pipe Meters**

It is often a requirement in flow measurement that the level in the pipe be maintained. Options are sometimes available for taking into account the level in the pipe, however this can prove to be an expensive alternative.

It is possible, at the expense of a very small added pressure loss, to lower the section of pipe containing the flowmeter so that the liquid pools in that area.



**Figure 5.46**  
*Flowmeter remains full when installed in (a) an invert, or (b) a V-section*

## 5.11 Impact on the Overall Control Loop

There are two main problems at low flow rates:

- The minimum flow
- The increased error

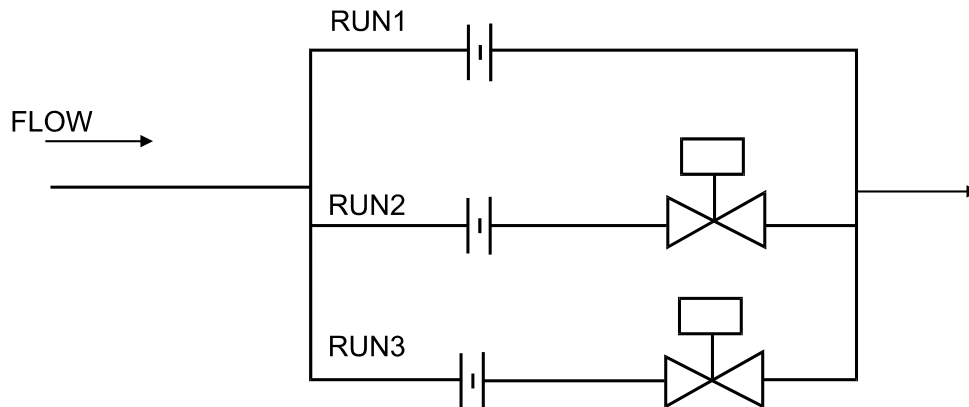
One of the main problems with controlling a system from the flow rate is the range of control. The turndown defines the minimum flow compared with the maximum rated flow. Problems arise when controlling at or near the minimum flow, or if flow is required below the minimum flow rate.

Another problem is the increased error that results from low flow rates, particularly with differential pressure devices, where the flow rate is the square root of pressure.

### 5.11.1 The Minimum Flow

A single flow meter needs to be sized for the maximum flow of the application, however this may not allow suitable control at the lower flow rates. One method to increase the rangeability of the system is to use parallel piping. If the flow decreases then one of the runs can be closed to sustain an increased flow in the operating runs. This reduces the Rangeability required and maintains the highest accuracy of the system.

The accuracy of the measurement is optimised by maintaining the flowrate through the meters. The valves shown are for isolation of the separate runs.



**Figure 5.47**  
**Parallel arrangement**

### The Increased Error

In relation to orifice meters, the orifice plate has an error of about 2% of the true flowrate. Problems arise with the differential pressure measurement as the error is in terms of percent of span.

Flow Rate	Max DP error
10	0.5%
7.5	1.0%
5	2.0%
3	5.0%

**Table 5.9**  
**Maximum differential pressure error**

For higher turndown ratios to be achieved or maintained, the accuracy needs to be kept in check. The components of the accuracy are:

- Reference accuracy
- Ambient temperature effect
- Static pressure effect
- Time drift

The time drift can be reduced by regular calibration and the temperature effect can also be reduced using suitable enclosures or operating environments.



## 5.12 Selection Tables

Flowmeter Technology	Accuracy ( $\pm$ )	Range - ability	Fluids	Pipe sizes (in.)	Max press (PSIG)	Temperature range ( $^{\circ}$ F)	Rel. Press. loss
<i>Inferential Meters</i>							
Orifice & DP xmtr	1-5%F	4:1	L,G,S	$\geq 2$	6000	$\leq 1000$	H
Integral orifice assembly	1-2%F	4:1	L,G,S	0.5-1.5	3000	-40-300	H
Variable area-purge	5-10%F	10:1	L,G	0.125-1.5	200	0-250	M
Variable area-glass tube	1-2%F	10:1	L,G	0.25-2	500	0-250	M
Variable area-metal tube	2-10%F	10:1	L,G	0.5-6	6000	$\leq 1000$	M
<i>Velocity Meters</i>							
Electromagnetic	0.25%-1%R	30:1	L	0.15-60	5000	$\leq 350$	L
Vortex	0.5%-1.25%R	20:1	L,G,S	1-8	1500	-150-800	M
Turbine	0.15-0.5%R	10:1	L	0.5-30	6000	-450-	M
Propeller	2%R	15:1	L	2-12	230	6000	M
Vane	2.5%R	10:1	L	1	5000	0-300 $\leq 180$	M
<i>Mass Meters</i>							
Coriolis	0.15%R	80:1	L,G,S	0.25-3	1450	-400-400	L
	0.2%R	20:1	L,G,S	0.06-6	5700	-400-400	M
	0.2%R	20:1	L,G,S	0.5-1.5	900	32-800	M
	0.2%R	20:1	L,G,S	0.25-2	1500	-400-400	M
	1%F	50:1	G	0.125-8	4500	32-150	L
Thermal	0.5%F	50:1	L	0.06-0.25	4500	40-165	L
<i>Volumetric Meters</i>							
BiRotor PD	0.15-0.5%R	10:1	L	1.5-16	1440	-20-450	M
Oval Gear PD	0.25-0.5%R	10:1	L	0.25-4	300	-40-600	M
Nutating disc	2.0%R	10:1	L	1.25	2000	32-200	H
Oscillating piston	0.5%R	5:1	L	0.5-2	400	$\leq 300$	H

**Table 5.10**  
**Flowmeter Selection Criteria**  
 (Courtesy of Fisher Rosemount)

## 5.13 Future Technologies

The newer technologies in flowmeters such as the Coriolis mass, ultrasonic and vortex are replacing the traditional differential pressure flowmeters and their orifice plates and other restrictive primary elements.

The selection of newer technologies, such as the coriolis mass flowmeter is primarily driven by the need for high accuracy in measurements. Ultrasonic flowmeters are becoming more popular due to their increased accuracy over previous versions. In addition they are non-intrusive and have a wide rangeability. Vortex flowmeters are also commonly used, as they are less expensive and can measure steam, liquid and gas.

### 5.13.1 Limiting Factors

The growth of the new technology is determined by a number of factors, such as:

1. Traditional technologies.

Traditional technologies such as the orifice plate, turbine, and positive displacement meters are widely used in existing applications. Many users prefer to stay with a proven technology.

2. No reason to change

Users generally require a compelling reason to change to a different or newer technology. As a result they usually choose the same type of flowmeter when selecting a replacement meter.

3. Familiarity

It is quite often that the newer technologies are not well understood by the user.

4. Approvals

Traditional technologies have a strong advantage in having approvals granted by industry associations.

### 5.13.2 Multivariable Flowmeters

Technological developments with pressure transmitters have seen the introduction of multivariable flowmeters that provide a measurement of the inferred mass flow. There is also a demand for improving the primary elements used with pressure transmitters.

As previously mentioned, most volumetric flowmeters, such as differential pressure types, sense one process variable. This is used to calculate the volumetric flow or calculate the mass flow.

Multivariable flowmeters measure more than one process variable and can produce more than one output. A multivariable flowmeter may have sensors for differential pressure, static pressure and process temperature, which it uses to calculate mass flow.

Multivariable technology is not limited to differential pressure devices. Magnetic flowmeters can be used with process temperature measurement and a density compensation formula to calculate mass flow.

Devices such as these claim to measure mass flow, but the measurement obtained is a calculated or inferred value rather than a direct measurement, such as that obtained with a coriolis meter. Calculated mass flow is less accurate than a direct measurement because of the inaccuracies in the variables involved.

It is not uncommon for the primary elements to be purchased from one supplier, with the pressure transmitters purchased elsewhere. Manufacturers are recognising these limitations and are developing integral devices. By integrating a sensing element with a transmitter in a single unit, this system resembles most other flowmeters. This combination also simplifies installation and calibration procedures.

This approach sees more pressure sensing devices remaining in operation, with the ability of changing primary elements, or to change to multivariable flowmeters.

The limitation in sensing remains in the primary device. As flowmeters become more accurate, the electronics become quite precise in their interpretation and relaying of the signal, but are subject to the accuracy of the primary element.

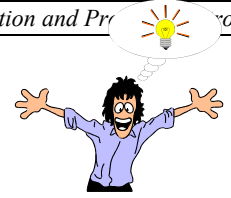
The future of flow measurement is subject to the search and development of improved primary elements, whether they be existing or new technology.

# Tips and Tricks



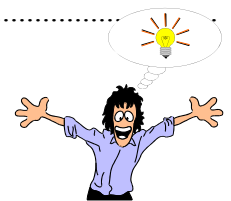
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# Tips and Tricks



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## Tips and Tricks







# **6**

## **Control Values**

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# Chapter 6

## Control Valves

### 6.1 Principles of Control Valves

Control valves are used to provide a number of functions and are typically selected on the following basis:

- Application function
- Operating conditions
- Construction
- Sizing

#### 6.1.1 *Application Function*

This relates to the function which the valve is to perform.

- Isolation, ON-OFF valves

These are typically ball valves and are used for shut off and isolation purposes.

- Flow control

This course is primarily aimed at regulating valves for the purpose of modulation control in continuous systems.

- Directional control

Check valves are typically used for this purpose.

- Protection, overpressure

Pressure relief valves provide suitable overpressure protection.

#### 6.1.2 *Operating Conditions*

As with all process equipment, the conditions of the system and the environment in which it is to perform are of significant importance. Such factors of consideration are:

- Process pressures
- Process temperature
- Ambient conditions
- Process material and nature of fluid

### **6.1.3 Construction**

A large range of valve designs are available and provide differing performance, both with advantages and disadvantages.

- Valve body type
- Plug and stem design
- Stem seals
- Materials of construction

### **6.1.4 Sizing**

The size of a valve is dependent on the flow that is required through the valve. The performance of valves is well defined which simplifies the selection process for a valve without the need to resort to complicated calculations.

## **6.2 Sliding Stem Valves**

Valve trim designs are provided by most manufacturers to give three different flow characteristics:

- Equal percentage
- Linear
- Quick opening

The basic body styles are:

- Globe
- Cage
- Angle body
- Y pattern
- Split body
- Three way
- Single seated
- Double seated

The trim configurations are:

- Unbalanced
- Balanced

The guiding configurations are:

- Cage
- Post
  - Top
  - Top and bottom
- Stem
- Skirt

### 6.2.1 *Globe Valves*

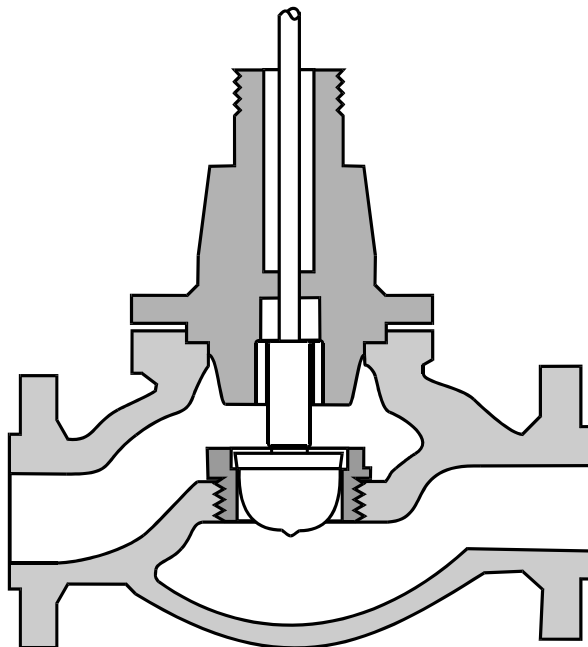
The globe is one of the most common types of body style for sliding-stem valves.

The trim of a valve is essentially the internal parts that are in contact with the flow stream. Because the trim absorbs the pressure of the flow (with a pressure loss across the valve) the trim design is an important consideration in determining the flow characteristics of the valve.

The globe body differs considerably depending on the trim used.

The main components of the valve trim are the plug and stem and the seat ring.

The most widely used valve is the single-stage orifice and plug assembly. Multi-stage orifice elements are usually found in trim designs to reduce noise, erosion and cavitation.



**Figure 6.1**  
***Top-entry, top guided single-seated globe valve.***

### **Advantages**

Minimises disassembly for maintenance.  
Streamlined flow path with a minimum of parts and no irregular cavities.

### **Disadvantages**

Leaking of the central joint due to thermal cycles or piping loads.  
Valves cannot be welded in-line since the valve body is required to be split.

### **Summary**

Fewer of these valves are now used.

## **6.2.2 Cage Valves**

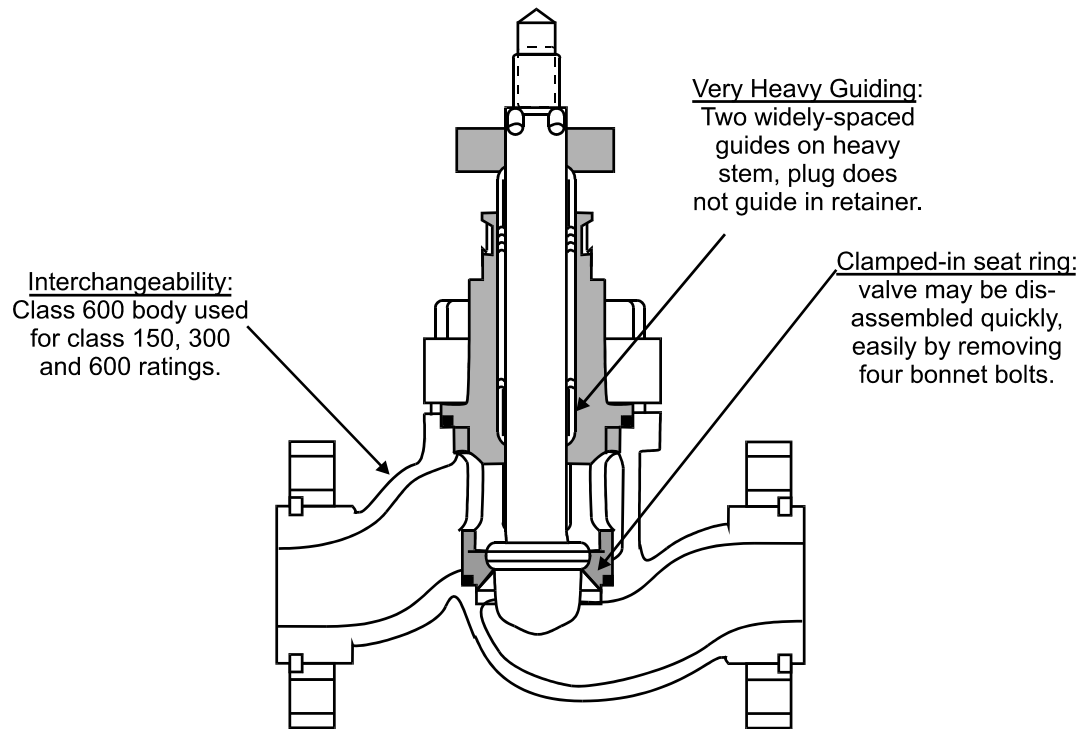
Cage valves use the principle of cage guiding, where the plug rides inside the cage. This is quite common in most valves, because the bearing forces on the plug are near the fluid forces. As the plug is aligned by the cage, the valve effectively self-aligns itself so that during assembly all the pieces fit together. Correct alignment reduces the problems of side loads.

Cage guiding is not recommended when the fluid is highly viscous. Such fluids that are sticky or gummy can also cause problems, as can fluids that contain solids. The problem is the possible build up between the plug and cage which can cause operational problems. This problem of build up is also referred to as fouling. Fouling can cause a restriction of travel in the valve movement, or a delayed response time to a control signal.

Block and bypass valves are used for assisting in the maintenance of valves. The need for block and bypass valves is eliminated since cage valves are very rugged and have a good service life.

Whereas globe valves (also known as post-guided) are characterised by the shape and contours of the valve plug, Cage valves are characterised by the shape of the cage window.

Cage valves are popular due to the variety of trim types available. Trim type may be selected for various performance such as reducing cavitation (anti-cavitation trim), or for reducing noise.



**Figure 6.2**  
**Cage valves with clamped-in seat ring and characterised plug**  
*(courtesy of Valtek, Inc.).*

### Advantages

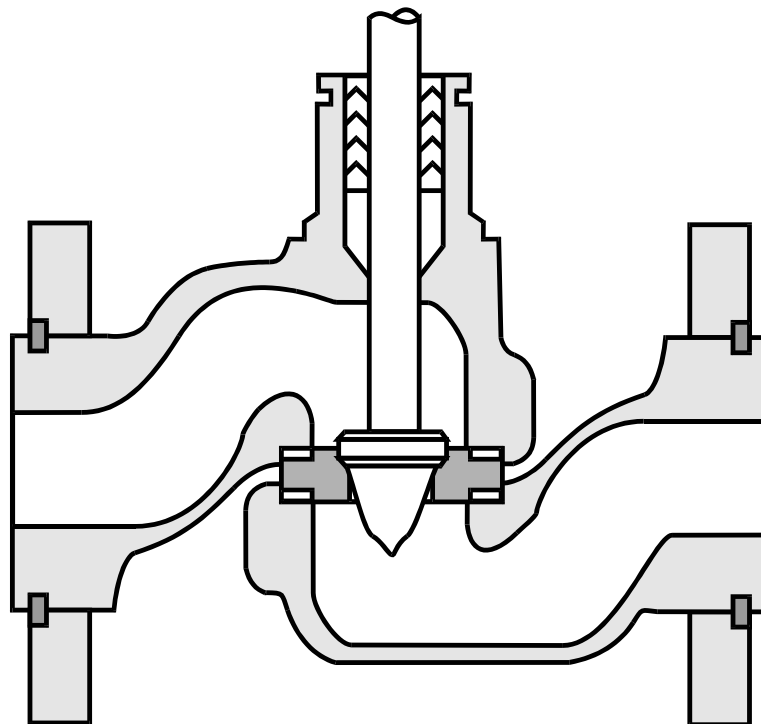
- No threaded joints.
- Suitable for many trim types to be used.
- Easy to maintain.
  - Top entry.
  - No threaded joints to corrode.
- Trouble-free when specified correctly.

### 6.2.3 Split Body Valves

Split body valves provide streamlined flow and reduce the number of bolted joints. These valves use one bolt to secure the valve with the seat ring clamped between the body halves.

Their original design and subsequent operation was for difficult flows with high viscosity. Fouling is minimised due to the valves simple streamlined construction.

Maintenance requires that in order to service the valve, the flange connections must be broken. The advantages from simple valve design are outweighed by the concerns over line flange leakage after maintenance.



**Figure 6.3**  
*Split body valve with removable flanger (courtesy of Masoneilan).*

**Advantages**

- Streamlined flow.
- Minimum number of parts.
- No irregular cavities.

**Disadvantages**

- Leakage problems with central joint.
- Inability to weld.
- Maintenance complications.
- Limitations on trim modifications.

Fewer of these valves are used today.

**6.2.4 Angle Valves**

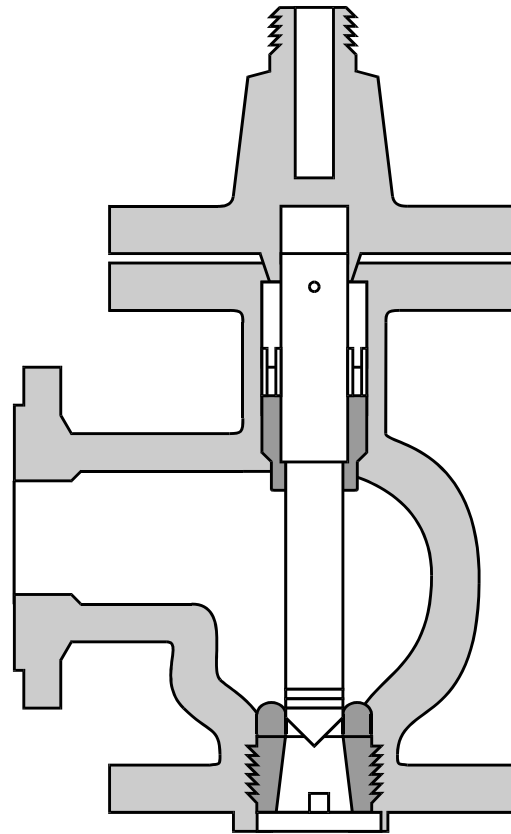
These valves can be likened to mounting a globe valve in an elbow. The exiting flow is 90 degrees to the inlet flow.

The obvious advantage is the elimination of an elbow, should one be required, however the flow does make fewer turns as it passes through the body.

The Angle valve has little restriction on the out flow, so if flashing or cavitation occurs then it tends to do so further downstream from the valve. This saves not only on the maintenance life of the valve, but also minimises any degradation in valve performance.

Angle valves are limited in use and are generally used for erosive applications requiring replaceable inserts on the out-flow piping.





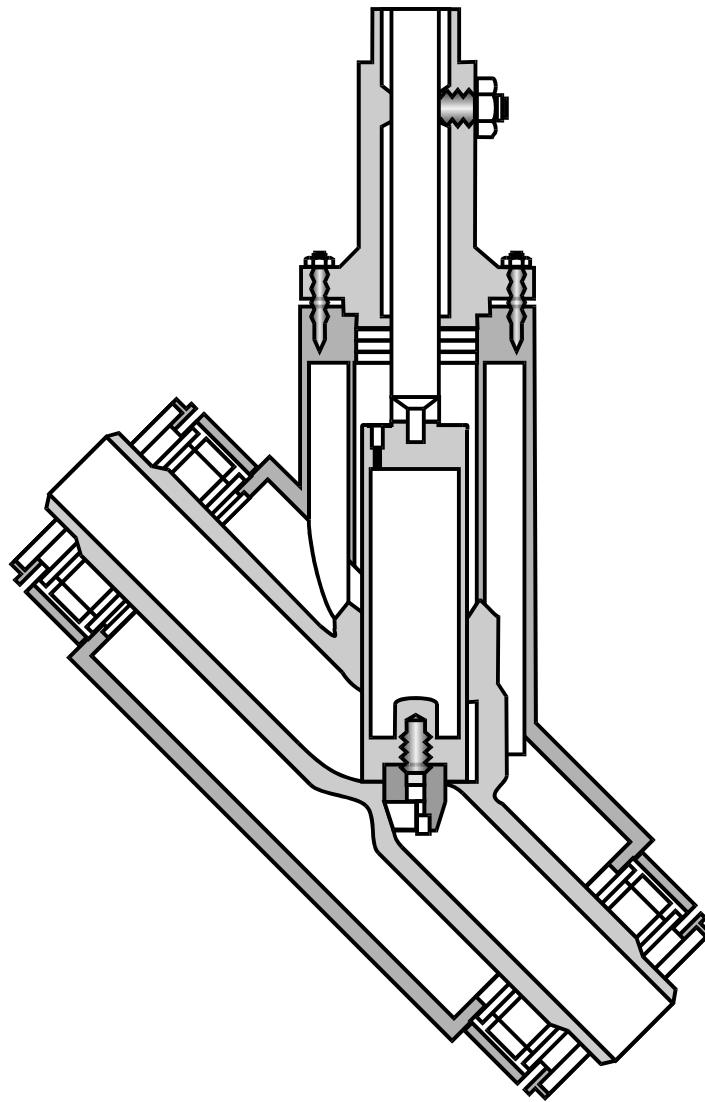
**Figure 6.4**  
*Streamlined angle valve with lined Venturi outlet.*

### 6.2.5 *Y-Style Valves*

This style of valve has the operating components tilted at a 45 degree angle to the flow path. In theory, the flow stream has fewer turns when fully open. In practice they are mainly used for drainage applications, operating at or near the closed position.

When installed in horizontal pipe, maintenance is impaired with the added difficulty of aligning and handling the components. This is true for any extraction angle other than vertical.

Another inhibiting factor is that when installed with the moving parts not vertical, the added side load due to gravity increases wear with the need for more frequent maintenance.



*Figure 6.5  
Y-valve fitted with vacuum jacket.*

### **6.2.6 Three-Way Valves**

Three-way valves are a special type of double ported valve.

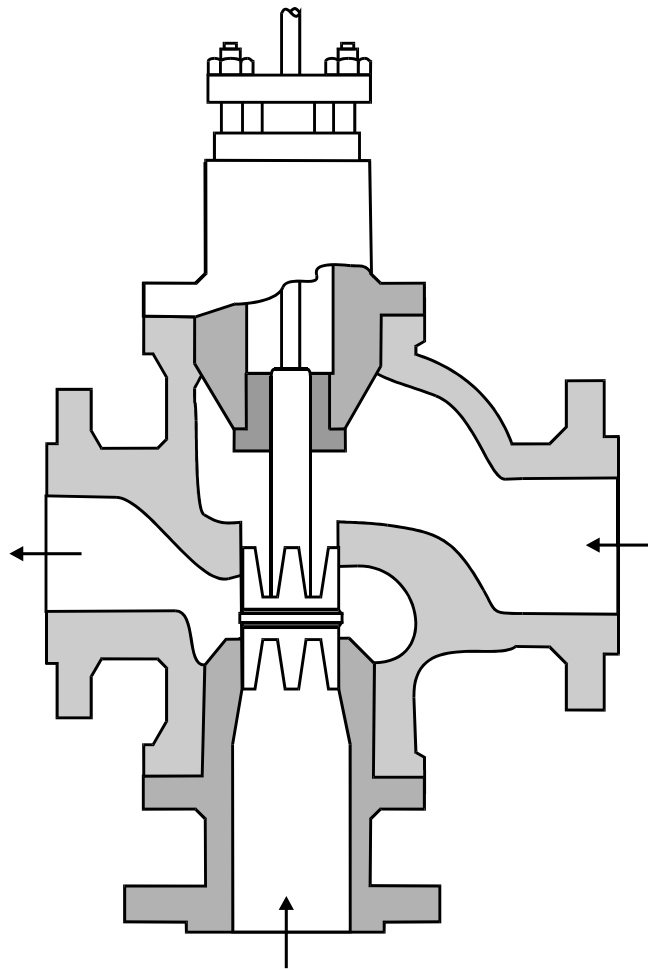
Two types of Three-way valve are available:

- Mixing
- Diverting

#### ***Mixing***

The mixing valve has two inlets and one outlet.

This type of valve would be used for blending of two fluids with the associated ratio control of the mix.

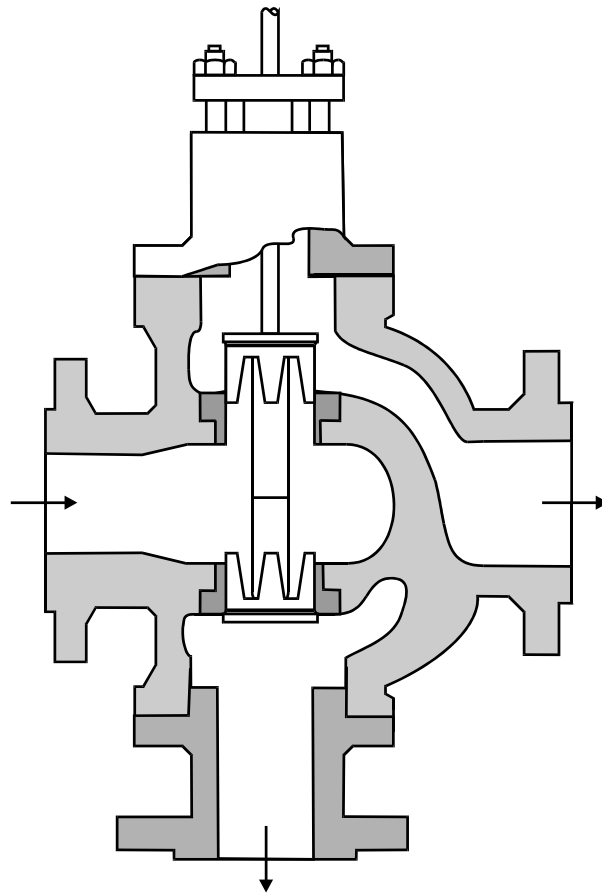


**Figure 6.6**  
**Three-way valve mixing flow.**

### ***Diverting***

The diverting valve has one inlet and two outlets.

Diverting valves can be used for switching or for bypass operations. The relative split provides the required controlled flow with one outlet, while allowing a constant flow through the system with the other outlet. Such valves are used in chilled water systems to prevent freezing in the pipes.



**Figure 6.7**  
**Three-way valve for diverting service.**

### **Operation**

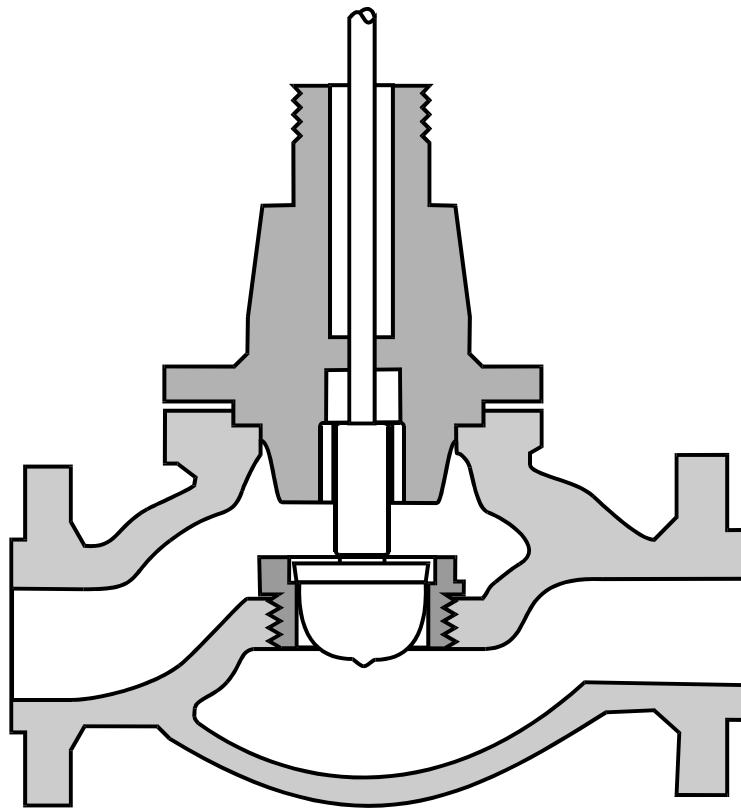
Because of the dual function of the plug, these valves are generally not pressure balanced, however the stem forces required for operation are similar to single port valves.

### 6.2.7 *Single Seated*

Single seated valves are one form of globe valve that are very common and quite simple in design. These valves have few internal parts. They are also smaller than double seated valves and provide good shut off capability.

Maintenance is simplified due to easy access with top entry to the valve components.

Because of their widespread usage, they are available in a variety of trim configurations, and therefore a greater range of flow characteristics are available. They also produce less vibration due to the reduced plug mass.



**Figure 6.8**  
*Top-entry, top guided single-seated globe valve.*

#### **Advantages**

- Simple design.
- Simplified maintenance.
- Smaller and lighter.
- Good shutoff.

### **Disadvantages**

- More complex designs required for balancing.

#### **6.2.8 Double Seated**

Another globe valve body design is double seated. In this approach, there are two plugs and two seats that operate within the valve body.

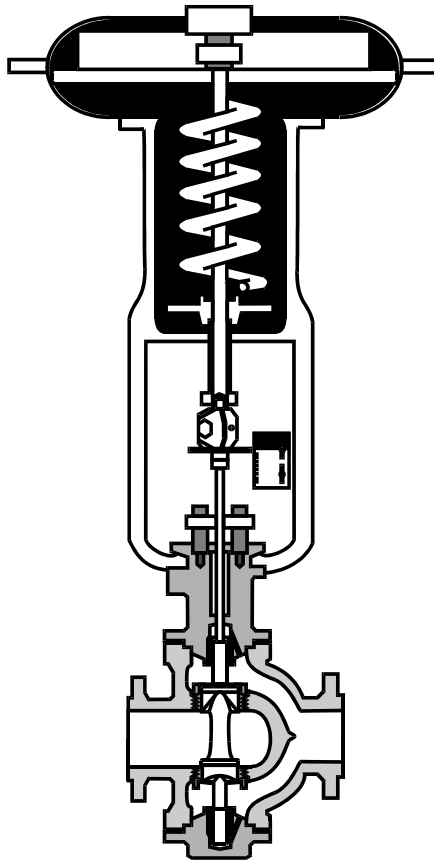
In a single seated valve, the forces of the flow stream can push against the plug, requiring greater actuator force to operate the valve movement. Double seated valves use opposing forces from the two plugs to minimise the actuator force required for control movement. Balancing is the term used when the net force on the stem is minimised in this way.

These valves are not truly balanced. The result of the hydrostatic forces on the plugs may not be zero due to the geometry and dynamics. They are therefore termed semi-balanced. It is important to know the combined loading due to the amount of balancing and dynamic forces when sizing the actuator.

Shutoff is poor with the double seated valve and is one of the downfalls with this type of construction. Even though manufacturing tolerances may be tight, due to different forces on the plugs it is not possible for both plugs to make contact at the same time.

Maintenance is increased with the added internal parts required. Also these valves tend to be quite heavy and large.

These valves are an older design that have fewer advantages compared with the inherent disadvantages. Although they can be found in older systems, they are seldom used in newer applications.



*Figure 6.9*  
*Double ported valve*  
*(courtesy of Fisher Controls International).*

#### **Advantages**

- Reduced actuator force due to balancing.
- Action easily changed (Direct/Reverse).
- High flow capacity.

#### **Disadvantages**

- Poor shutoff.
- Heavy and bulky.
- More parts to service.
- Only semi-balanced.

### **6.2.9 *Balanced Valves***

Balancing is the term used when the resultant force on a plug is neutral. This means that the plug is neither forced up or down by the pressure of the flow stream.

The advantage with balancing is that the actuator force required for controlled movement is greatly reduced. This allows for smaller and cheaper actuators.

Balancing is applied to single-seated and double-seated valves in different ways.

### ***Double-Seated Balancing***

Double-seated valves were originally designed for balancing. These valves use opposing forces from the two plugs to minimise the actuator force required for control movement. That is, the pressure of the flowstream acting on the upper plug is intended to cancel the pressure acting on the lower plug.

The force on the upper plug is in the opposite direction to that on the lower plug and as such the result should be zero. However, because the plug sizes differ, the forces are not equal and the result is an unbalanced force.

Double-seated valves are actually semi-balanced.

### ***Single-Seated Balancing***

In a single seated valve, the forces of the flow stream can push against the plug, requiring greater actuator force to operate the valve movement.

To balance a single-seated valve, balancing holes are added to equalise the pressure on both sides of the plug. This eliminates any unbalanced force on the plug, however further seals are required for the extra leakage path between the plug and the cage.

An unbalanced valve has better shut off capability because there is only the problem of leakage between the seat and the plug.

A balanced valve however, has a total leakage of the sum of the following:

- leakage between the seat and the plug
- leakage between the plug and the cage

The seal for the seat and the plug is a closing seal. This is applicable to both balanced and unbalanced valves. But the seal between the plug and the cage is a dynamic seal and applies to balanced valves only. Being a dynamic seal, maintenance and service life need to be considered, as do the operating conditions on the sealing material.

Maintenance on unbalanced valves can involve the machining of the valve seats to rectify leakage problems.

If leakage occurs with balanced valves, there are two types of seals responsible. It is not uncommon for the seat to be machined to rectify the problem when in fact the cause of the leakage is due to the trim. Although Teflon is limited by temperature



compared to graphite, it does have better sealing properties. Better sealing can be achieved, by not over specifying operating temperature ratings.

### **6.2.10 Guiding**

The control valve guide is used to support and position the valve plug over the full range of travel. Various control valve guiding designs are available and should be considered as they affect the operating life and reliability of a valve.

The guide provides the support for the valve plug. Any forces on the plug are resisted by the guide. If the guide wears or fails then vibration can become a problem.

Under high bearing loads, the surface of the guide can break down causing increased friction and impeding valve performance.

In choosing suitable guides:

- Use bearing materials with different hardness levels
- Avoid nickel and unhardened stainless steel

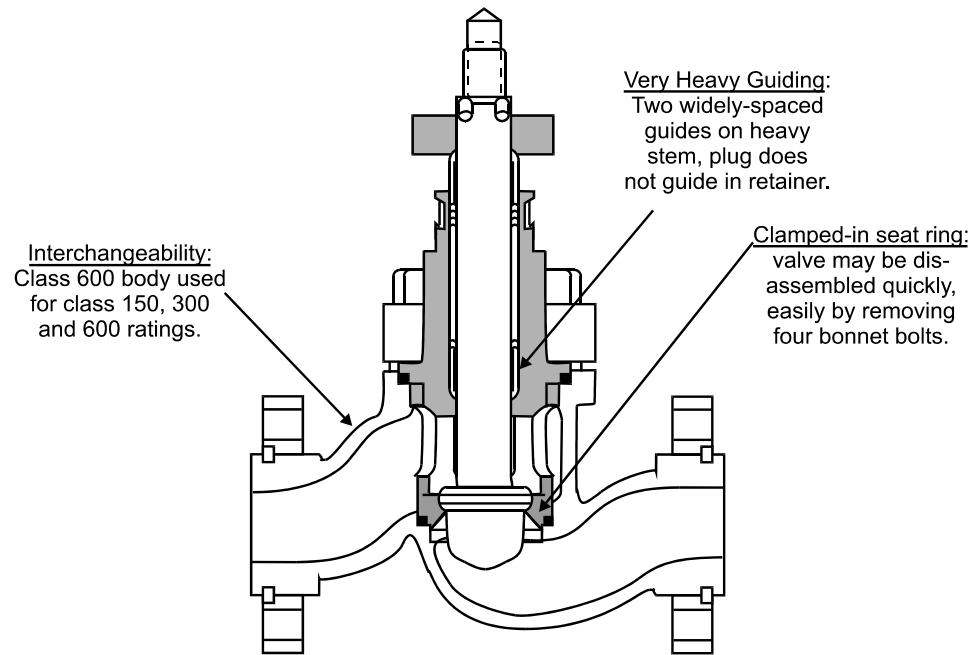
Types of guiding designs:

- Cage
- Stem
- Post
  - Top
  - Top and bottom
- Port

#### **Cage guiding**

The most common type of guiding is Cage guiding. The plug moves within a cage with little tolerance between the two. This design enables the loading on the plug to be supported by the cage with a large bearing area between the two.

Maintenance is reduced as the assembly is simplified with the components self aligning.

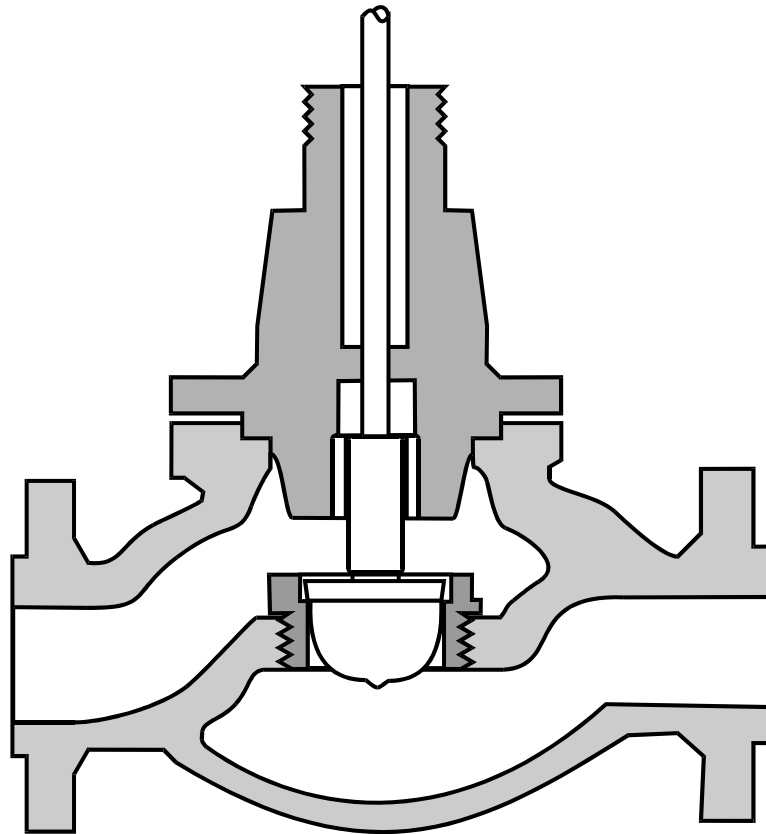


**Figure 6.10**  
**Cage valve with clamped-in seat ring and characterised plug**  
*(courtesy of Valtek, Inc).*

### Stem guiding

Stem guiding is a simple design where the stem itself is responsible for supporting and controlling the plug.

Limitations occur due to the stem's strength as the support of the stem is farther away from the load on the plug. Guiding performance is impaired but this type of valve is cheaper to manufacture and maintain.



**Figure 6.11**  
*Top-entry, top guided single seated globe valve.*

### **Post guiding**

Post guiding is mostly used if there is a risk of fouling. The post is a section of the stem from the plug that extends into the valve body. The post is smaller in diameter than the plug but larger than the stem.

The post supports the plug from bearing loads, with the narrower stem providing positioning control.

This type of guiding also helps keep the bearing surfaces out of the flow stream. This reduces the buildup of fluid.

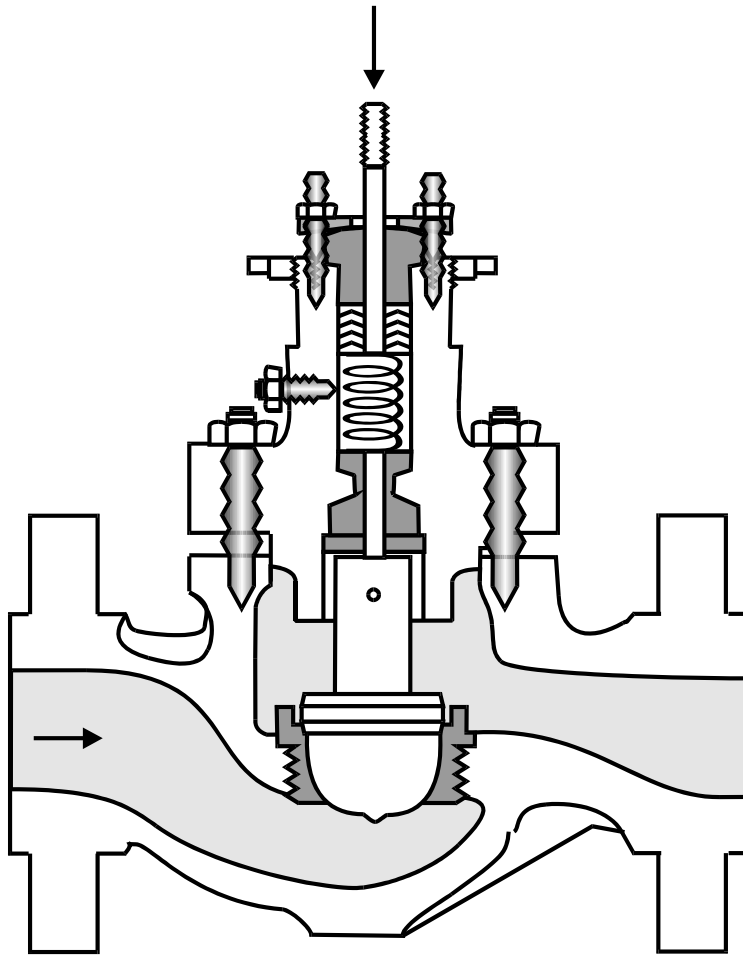
The two types of post guiding are:

- Top guided

When the post is above the plug, the valve is termed 'Top guided'.

- Top and bottom guided

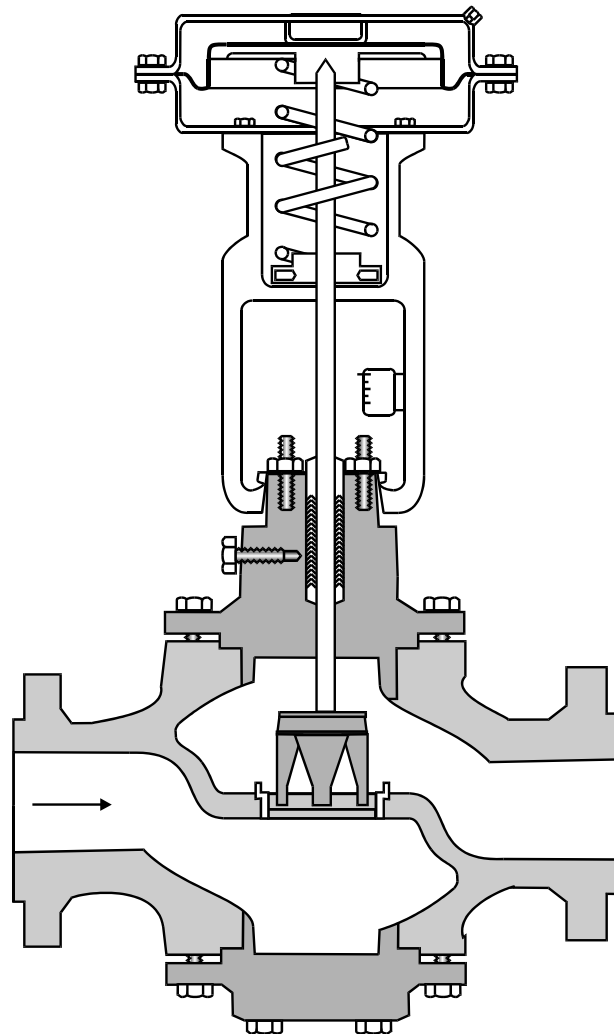
When the plug is supported from above and below, or in the case of some dual port valves, the valve is termed 'Top and bottom guided'.



*Figure 6.12  
Post guiding – top  
(courtesy of Fisher Controls International).*

### **Port guided**

Very seldom used but still in existence is the port guided valve. In this design the port is used to align and guide the plug. The port guided design also has a relatively small bearing surface and has the same problems with fouling as with the cage guided valves.



**Figure 6.13**  
**Port or skirt guiding**  
*(courtesy of Fisher Controls International).*

## 6.3 Rotary Valves

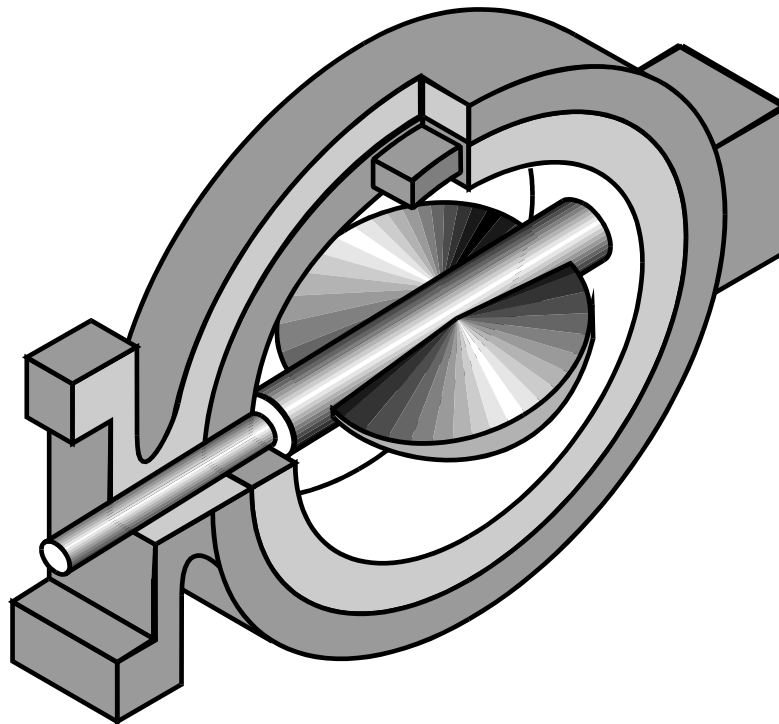
### 6.3.1 Butterfly Valves

Standard butterfly valves are dampers that are shaped from discs which rotate in the flow path to regulate the rate of flow. The disc is quite narrow and occupies little space in the pipeline. The shaft is centred on the axis of the pipeline and is in line with the seal.

The disc pulls away from the seal upon opening. This minimises seal wear and reduces friction. Control of the valve near the closed position can be difficult due to the breakout torque required to pull the valve out of the seat.

The flow characteristics are essentially equal percentage, but the rotation is limited to about 60 degrees as the leading edges are hidden in the shaft area as the disc is

rotated further. The Fishtail is one modification of the disc that permits effective control out to 90 degrees of rotation.



*Figure 6.14  
Fish tail butterfly disc  
(courtesy of Fisher Controls International).*

### ***Seals***

The swivel through design of seal has very poor shutoff. For tight shutoff are the adjustable or inflatable elastomeric seals. These provide bubble tight shutoff.

### ***High Performance Butterfly Valves***

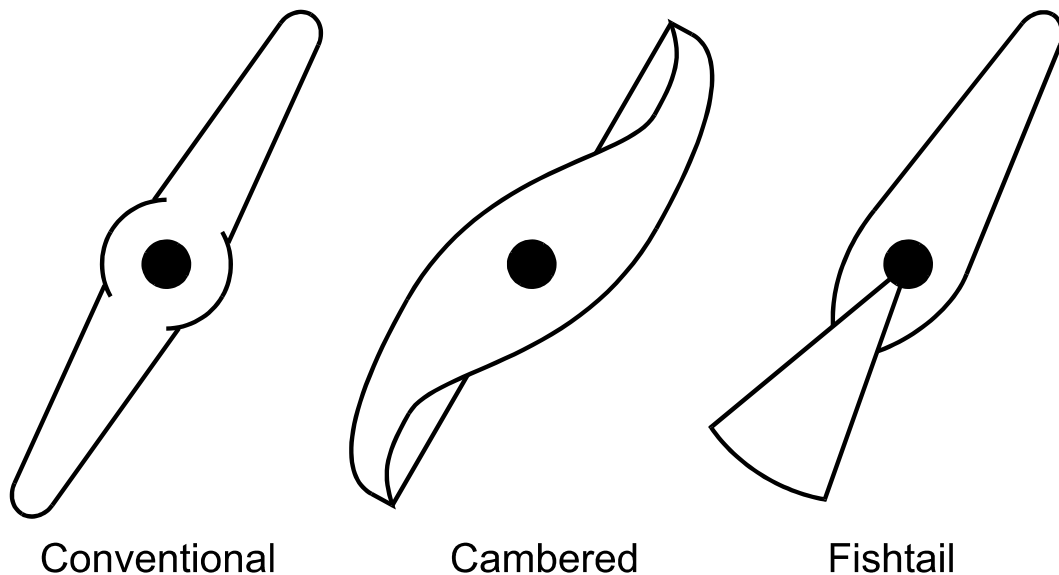
The high performance butterfly valve is a development from the conventional valve where the rotation axis of the disc is offset from both the centreline of flow and the plane of the seal.

This design produces a number of advantages, including better seal performance, lower dynamic torque, and higher allowable pressure drops. The seal performance is improved because the disc cams in and out of the seat, only contacting it at closure and so wear is reduced. As the disc only approaches the seal from one side, the pressure drop across the valve can be used to provide a pressure assisted seal. This further improves performance.

The modified shape and contour of the disc are used to reduce dynamic torque and drag. This also permits higher pressure drops. As the disc is never hidden behind

the shaft, good control through the 90 degrees of operation is possible with a linear characteristic.

The high performance butterfly valve is gaining greater acceptance and use due to its increased capability and the relatively high capacity to cost ratio.



**Figure 6.15**  
**Disc shapes.**

#### **Advantages**

- Low cost and weight.
- High flow capacity.
- Fire safe design.
- Low stem leakage.

#### **Disadvantages**

- Oversizing.

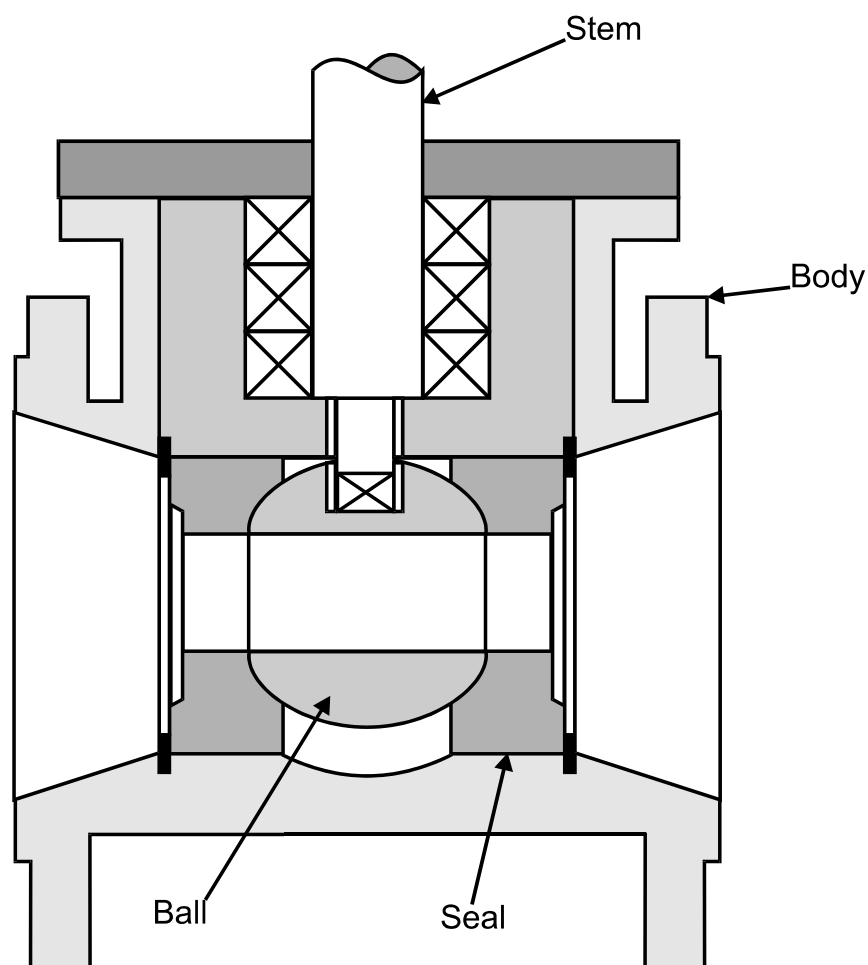
By over designing the capacity of a flow system, the result is either oversized valves, or correctly sized valves in oversized pipes. The valves in either case cause pressure drops in the flow due to the restriction. In the application of ball valves, the recovery of the pressure loss is good, but noise and cavitation then may become a problem.

### **6.3.2 Ball Valves**

The Ball valve is one of the most common types of Rotary valves available. The valve is named from the valve plug segment being a ball or sphere that rotates on an axis perpendicular to the flowstream. Fully open to fully closed is performed by a 90 degree rotation of the plug segment.

### The full-ball valve

The full ball valve is shaped from a spherical segment with a cylindrical hole for the flow of fluid. Among the various configurations, the 'floating' ball has two seals which provide bearing support to the ball segment. This does provide simplicity in the design, however the friction levels are higher than conventional bearing designs which can affect control performance.



*Figure 6.16*  
*Top-entry pierced ball valve.*

### The Characterised ball valve

The Full-ball valve was originally designed for ON-OFF control. Although modulation control is possible, the flow characteristics can be difficult to work with.

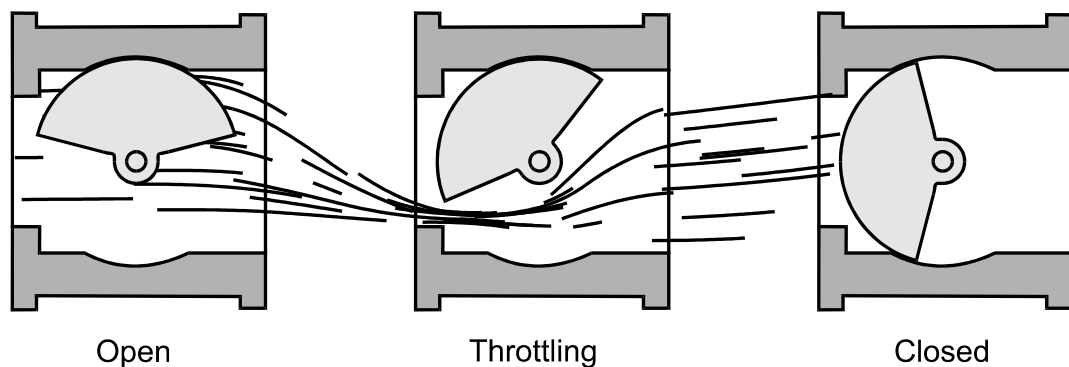


The opening between the ball and the seal can be modified to provide different flow characteristics. The V-notch is one example that produces a more gradual opening to give better Rangeability and throttling capability.

Most characterised ball valves are modified so that only a portion of the ball is used. The edge of the partial ball can be shaped to obtain the desired flow characteristics. Various manufacturers promote their valves on the characteristics achieved by this design.

Apart from the V-notch, other designs can be U-notch or parabolic curve. Although favourable characteristics may be achieved with the characterisation of the ball, problems may occur due to the reduced strength of the partial ball. Bending is one such problem which occurs under operating loads.

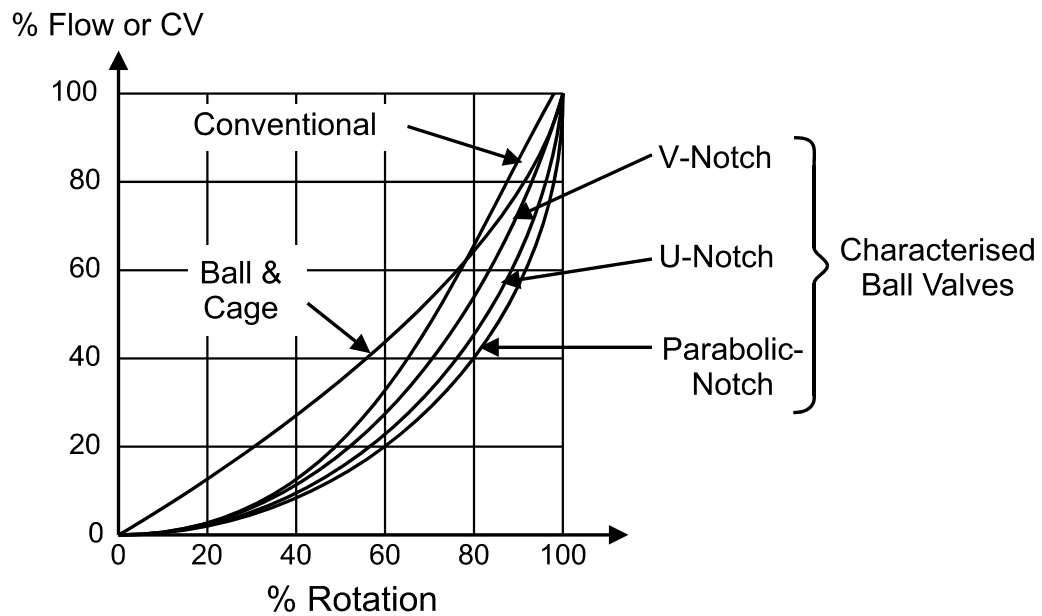
Care also needs to be taken during installation as overtightening of the flange bolts can damage the seals.



**Figure 6.17**  
**Positions of the characterised ball valve.**

Ball valves open at a faster rate than comparative sliding stem valves.  
Use sliding stem for severe service applications

The flow characteristics of a ball valve are similar to those of an equal-percentage plug.



**Figure 6.18**  
*Flow characteristics.*

### Advantages

- Lower cost and weight.
- Higher flow capacity (2-3 times that of the globe valve).
- Tight shutoff.
- Fire safe .
- Low stem leakage.

### Disadvantages

- Oversizing.
- 

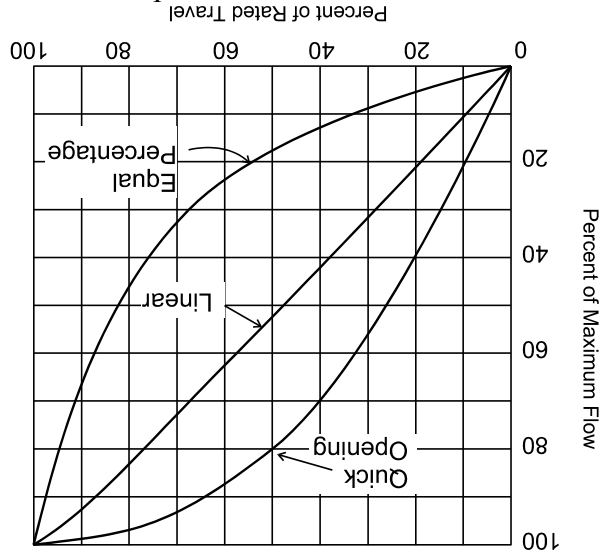
By over designing the capacity of a flow system, the result is either oversized valves, or correctly sized valves in oversized pipes. The valves in either case cause pressure drops in the flow due to the restriction. In the application of ball valves, the recovery of the pressure loss is good, but noise and cavitation then may become a problem.

## 6.4 Control Valve Selection and Sizing

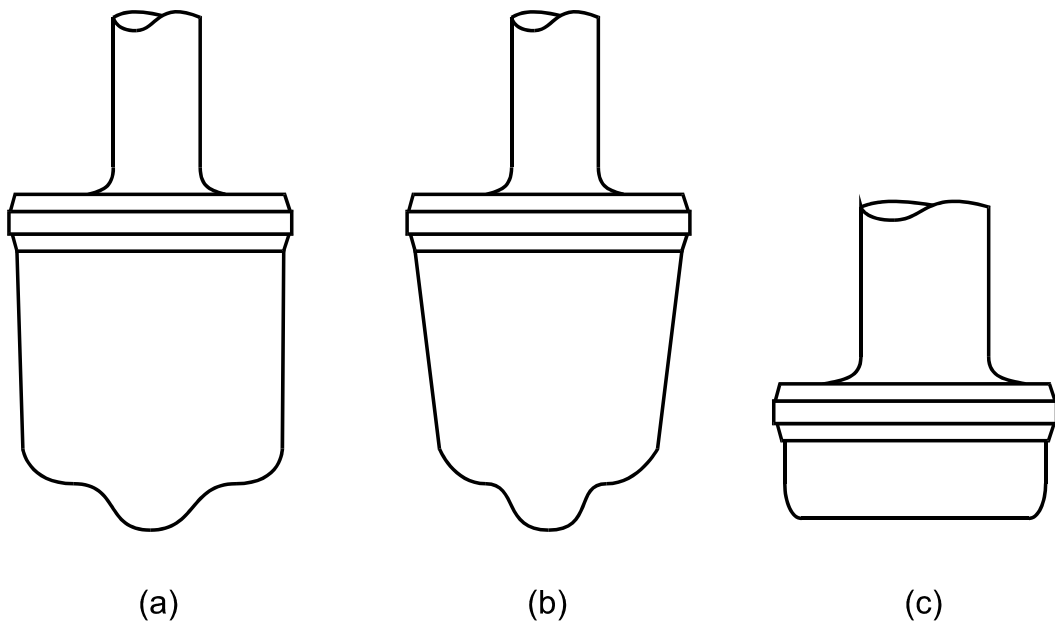
### 6.4.1 Selection

The correct selection of a control valve requires the valve characteristics to be matched to the characteristics of the process. If done correctly, the control valve can assist in the effective control and stability of the system.

Matching of the valve characteristics to a particular system requires an excellent knowledge of the system performance. Where this is not available or justified, an equal percentage characteristic is usually specified if less than half of the system pressure drop is across the valve. If most of the system pressure drop is across the valve, a linear characteristic is preferred.



**Figure 6.19**  
*Equal percentage linear, and quick opening characteristics (courtesy of Fisher Controls International).*



**Figure 6.20**  
*Plug characteristic (a) equal percentage, (b) linear, (c) quick opening.*

### 6.4.2 *Problems with oversized valves*

In practice, many control valves are oversized. This can be due to a number of reasons. Some are:

- Insufficient information about the process.
- Inaccurate input conditions.
- Accumulated safety margins.

Although they do provide the ability for greatly increased capacity (which in practice will never be reached), oversized valves are a problem. An oversized valve results in operations at or near the closed position.

Some of the problems are listed below:

- Poor control results as the gain of the process (control valve) is quite low at the bottom end of its operation. Because the resolution and accuracy are low, control becomes difficult and cycling can occur near the closed position. Also, the combination of the resolution of control and the valve friction may cause the valve plug to repeatedly slam into and bounce out of the valve seat.
- Near the closed position, high velocity flows occur which can cause excessive seat wear between the plug and seat.
- The operating range of an oversized valve is only a fraction of the full range of operation. The flow characteristic of this reduced range of operation is different from the original design intent. It is generally 'flatter' and almost linear for the range of operation for the oversized valve. This change in characteristic requires different controller gains.

### 6.4.3 *Control valve sizing*

To optimise the performance of a valve, it must be correctly sized for the application of intended operation.

The sizing of a control valve is simplified by using the 'valve flow coefficient'. The valve flow coefficient is a measure of the capacity for a control valve in the fully open position.

This empirically determined factor is the flow coefficient and is designated as follows:

- Cv - when expressed in imperial units
- Kv - when in European units
- Av - when in SI metric units

The relationships shown below are only valid if the flowing conditions are both turbulent (non-viscous) and non-cavitating. These conditions are the most common encountered in liquid flow applications.

#### 6.4.4 *Flow Coefficient, Cv*

The valve flow coefficient is defined as the number of US gallons of water per minute (at 60°F) that will flow through a wide-open valve with a pressure drop of 1psi.

The valve sizing formulas (also known as Cv formulas) are based on the basic equation of liquid flow:

$$\text{Liquids: } Q_L = C_v \sqrt{\frac{DP}{G_L}}$$

Where: Q = flow rate in US gallons per minute  
G = specific gravity of liquid (water = 1.0)  
DP = pressure drop across the valve in psi

From this formula the value of the valve coefficient ( $C_v$ ) can be calculated.

#### 6.4.5 *Flow Coefficient, Kv*

The valve flow coefficient, Kv is defined as the number of cubic metres per hour (at 15°C) that will flow through a wide-open valve with a pressure drop of 1bar (100kPa).

The valve sizing formula is based on the basic equation of liquid flow:

$$\text{Liquids: } Q_L = K_v \sqrt{\frac{DP}{G_L}}$$

Where: Q = flow rate in cubic metres per minute  
G = specific gravity of liquid (water = 1.0)  
DP = pressure drop across the valve in bar

From this formula the value of the valve coefficient ( $K_v$ ) can be calculated.

#### 6.4.6 *Flow Coefficient, Av*

The control valve capacity can be evaluated using the flow coefficient Av, and is described in the British standard 4740.

The valve sizing formula is based on liquid flow:

$$\text{Liquids: } Q_L = A_v \sqrt{\frac{DP}{P}}$$

Where:  $Q$  = flow rate in cubic metres per second  
 $G$  = density of liquid in  $\text{kg/m}^3$  (water = 1000)  
 $DP$  = pressure drop across the valve in pascals

From this formula the value of the valve coefficient ( $A_v$ ) can be calculated.

#### 6.4.7 Conversion Factors For Flow Coefficients

$$\begin{aligned} C_v &= 1.7 K_v \\ K_v &= 0.86 C_v \end{aligned}$$

$$\begin{aligned} C_v &= 41660 A_v \\ A_v &= 0.000024 C_v \end{aligned}$$

To simplify the calculations, manufacturers supply graphs from which the value of the flow coefficient can be read off.

Once the value of the flow coefficient is obtained, it is converted to a suitable valve size in accordance with the manufacturers information. An example of such a conversion is shown below. Note that this is only for one particular type of valve. Manufacturers also supply software packages that perform these calculations and conversions.

Valve size (in.)	$C_v$
0.25	0.3
0.5	3
1	14
1.5	35
2	55
3	108
4	174
6	400
8	725
10	1100

**Table 6.1**  
**Valve size and  $C_v$ .**

The specific gravity of the fluid is required as it has a bearing on the requirements for the valve.

<i>Specific Gravity (Sg) of Various Liquids</i>					
<b>Liquid</b>	<b>Sg</b>	<b>Liquid</b>	<b>Sg</b>	<b>Liquid</b>	<b>Sg</b>
Acetaldehyde	0.782	Diethyl ether	0.714	Naphthalene	1.145
Acetic Acid	1.049	Ether	0.736	Nitric acid, 60%	1.370
Acetone	0.790	Ethyl acetate	0.900	Nitrobenzene	1.203
Acid Sulphuric, 87%	1.800	Ethyl bromide	1.450	Nonane-n	0.700
Alcohol butyl	0.810	Formic acid	1.221	Octane-n	0.700
Alcohol ethyl	0.789	Freon	1.490	Oil, vegetable	0.910
Alcohol methyl	0.796	Fuel Oil No. 1	0.850	Oil, mineral	0.880
Alcohol methyl	0.662	Gasoline	0.710	Pentane-n	0.630
Ammonia	1.022	Glycerine	1.260	Quenching oil	0.870
Aniline	0.910	Glycol, ethyl	1.125	Rapeseed oil	0.910
Oil SAE 10-70	1.010	Heptane-n	0.684	Sugar 20%	1.080
Beer	0.879	Hexane-n	0.660	Sugar 40%	1.180
Benzene	2.900	Kerosene	0.800	Turbine oil	0.910
Bromine	0.959	Linseed oil	0.930	Turpentine	0.861
Butyric acid	1.080	Mercury	13.54	Water (fresh)	1.000
Carbolic acid	0.960	Methyl iodide	2.280	Water (sea)	1.030
Castor oil	1.489	Milk	1.030	Xylene-O	0.870
Chloroform					

**Table 6.2**  
*Specific gravity of various liquids.*

#### 6.4.8 Rangeability

Rangeability is defined as the ratio of maximum to minimum controllable flow. The minimum controllable flow can be considered however, to be about twice the clearance flow as the plug lifts off the seat. Valve manufacturers often specify rangeabilities of 30:1 for plug valves with an equal percentage flow characteristic. For a linear flow characteristic, 50:1 may be quoted.

The true installed characteristic can be less than a third of these values. Such figures as 7:1 and 15:1 for equal percentage and linear have been documented.

This may seem like a disadvantage, but is still usually sufficient as many processes do not operate much over a 5:1 turndown ratio.

## 6.5 Control Valve Characteristics/Trim

### 6.5.1 Flow Characteristics

The flow characteristics of a control valve show the rate of flow for the range of valve operation. There are two types of flow characteristics for control valves:

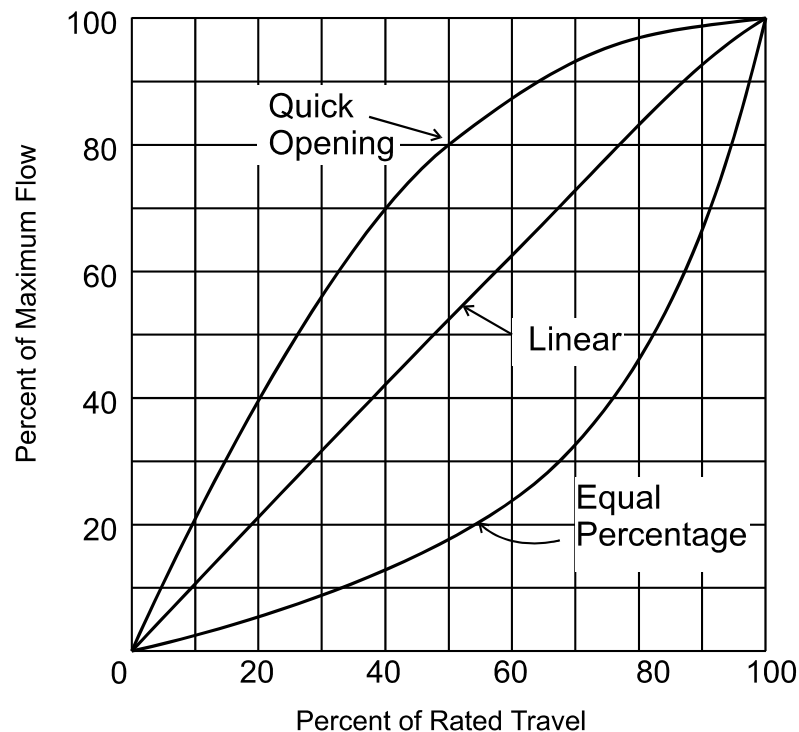
- inherent
- installed

The inherent characteristic is determined by testing the valve flow versus valve lift using a constant differential pressure drop across the valve throughout the test.

It should be noted that the manufacturer's characteristic curves are different from installed flow characteristic. In operation, the differential pressure across the valve varies throughout the valve position due to the system characteristics.

Control valves are generally supplied with three curves which show the expected flow rate (Cv) for valve position. These curves represent three basic characteristics:

- Quick opening
- Linear
- Equal percentage



**Figure 6.21**  
**Equal percentage, linear, and quick opening characteristics**  
**(courtesy of Fisher Controls International).**



These are ideal or theoretical valve characteristics and generally change when the valve is installed. If actual tests are performed on the installed valve, variations of 10% (or more) in valve position versus flow rate can be seen. The actual curve will not only be offset in parts, but may show slope variations and other distortions from the ideal curve.

The differences in the characteristic curves can be due to the reproducibility of the valve. This includes the quality control of manufacturing tolerances.

In operation, these distortions generally have little effect on the actual valve characteristic and system performance. The ideal characteristic (valve position versus flow rate) is used to approximate the valve characteristic behaviour for the actual system. This is used to select the best valve trim for the process to be controlled in order to keep the control loop gain constant.

The inherent characteristic is based on a constant differential pressure drop across the valve throughout the test. The installed characteristic differs in that the pressure drop changes in relation to the valve stroke.

When the valve opens and flow increases, the pressure drop across the valve decreases. Because of this, a valve which has an inherent equal percentage characteristic will produce a more linear flow curve when installed. This occurs as the reduced pressure drop counteracts the increasing flow area when the valve opens.

The installed characteristics are the important concern when considering valve performance. As such, a valve with inherent equal percentage characteristics is often favourable because its installed characteristics are linear.

It follows that a valve with inherent linear characteristics will exhibit a quick opening characteristic when installed. Quick opening characteristics, inherent or installed, are not generally considered for controlled applications.

The installed characteristics of a valve depends on how much of the total system pressure drop is across the valve. If all of the system pressure drop is across the valve, the installed characteristic is the same as the inherent characteristic. As the percentage pressure drop across the valve decreases, the installed characteristic of the linear valve approaches the quick opening response, and the installed characteristic of the equal percentage approaches that of the linear characteristic.

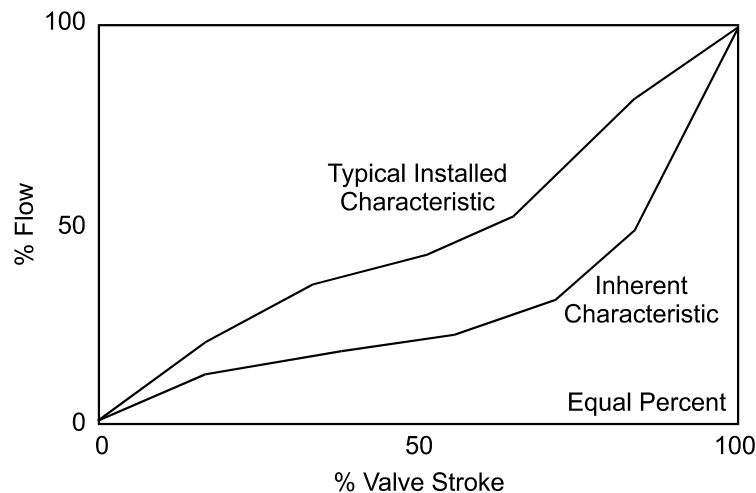
The installed valve characteristic can be modified to approximate the theoretical one using compensators in the control system. Generally, if the control valve pressure drop is relatively constant then use a linear trim. However, if there is significant pressure variation as flow changes, then use equal-percentage trim.

### - Equal Percentage

This is the flow characteristic most commonly selected for control applications. It is also referred to as increasing sensitivity as the flow rate increases at a greater rate for wider valve openings.

This type of response from a valve is good for control because it gives relatively small changes in flow for the first 50% of the stroke, but still has good capacity as the valve opens at a faster rate after that.

This characteristic also provides for high rangeability in a control valve. The advantage of a high rangeability control valve is that it increases the applications for use of the valve. High rangeability is also desirable in applications that require good control for a wide range of operation of the valve stroke.

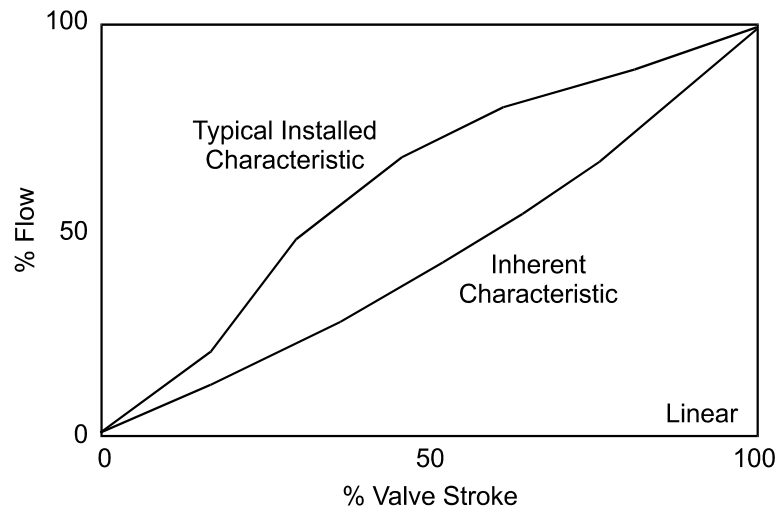


**Figure 6.22**  
*Inherent versus installed characteristics : decreasing AP (a).*

### - Linear

The linear characteristic is simply a proportional relationship between the flow rate and valve travel. Although rangeability is not as good as the equal percentage trim, they still provide high capacity.

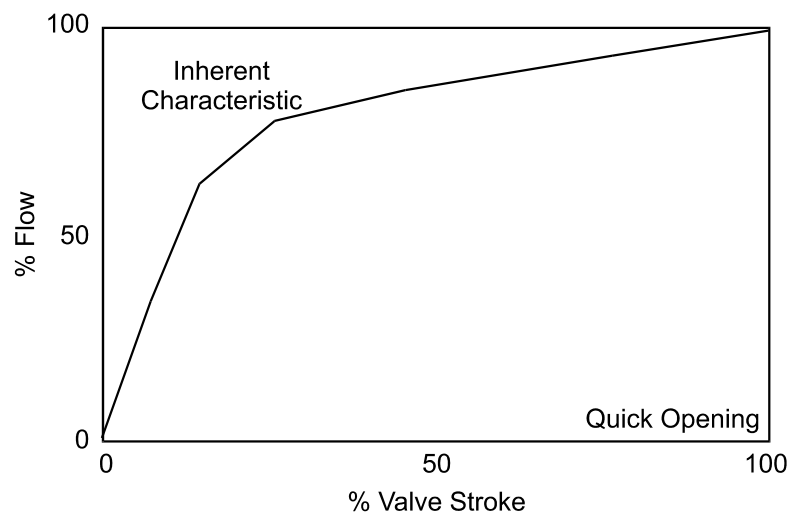
A linear characteristic may be a more suitable choice if the maximum flow capacity is the selecting factor.



**Figure 6.23**  
*Inherent versus installed characteristics : decreasing AP (b).*

- **Quick Opening**

This type of trim provides a majority of the flow as quickly as possible. Valves with this type of trim are normally used for ON-OFF control.



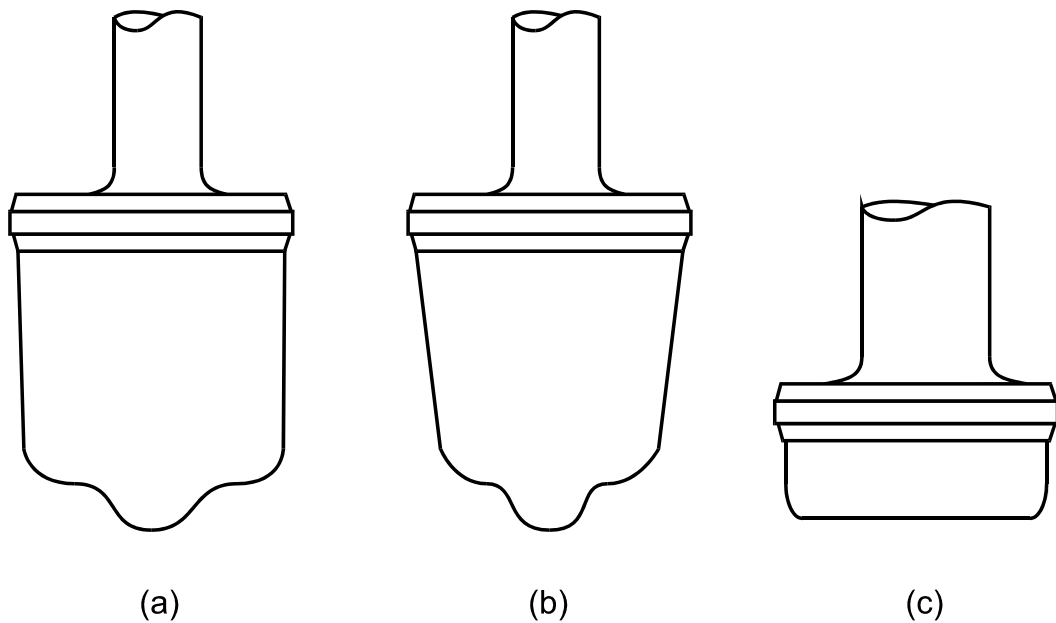
**Figure 6.24**  
*Inherent versus installed characteristics : decreasing AP (c).*

### 6.5.2 Sliding Stem Valves

- **Globe**

Globe valves are characterised by the shape and contours of the valve plug. These valves are generally available in designs that cater for the three basic

flow characteristics. With these types of valves, the flow characteristics can be easily changed by substituting a different plug.

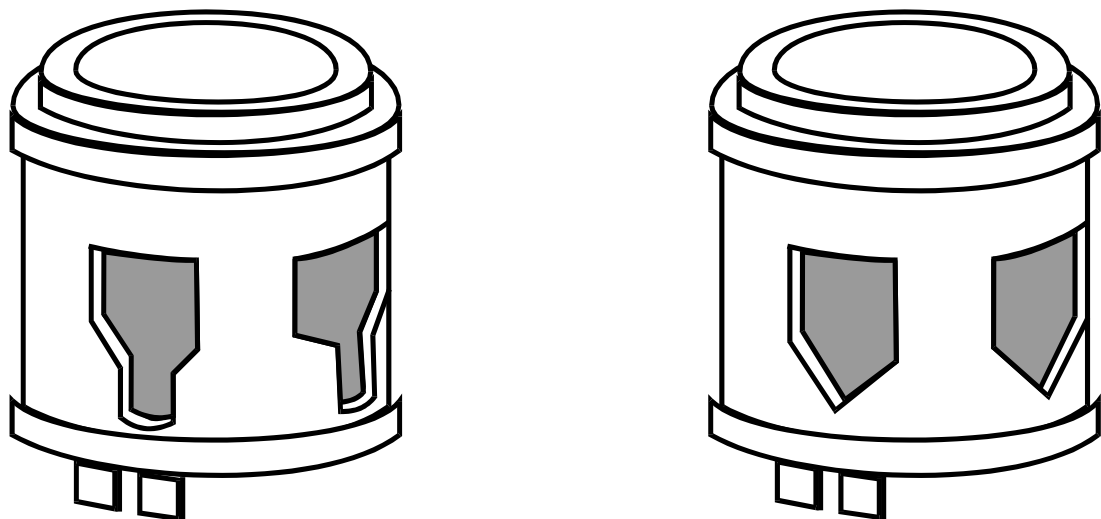


**Figure 6.25**

**Plug characteristics (a) equal percentage; (b) linear; (c) quick opening.**

- **Cage**

Cage valves are characterised by the shape of the cage window. Cage valves have the same range of flow characteristics as globe valves, and are easily changed with different cage designs.



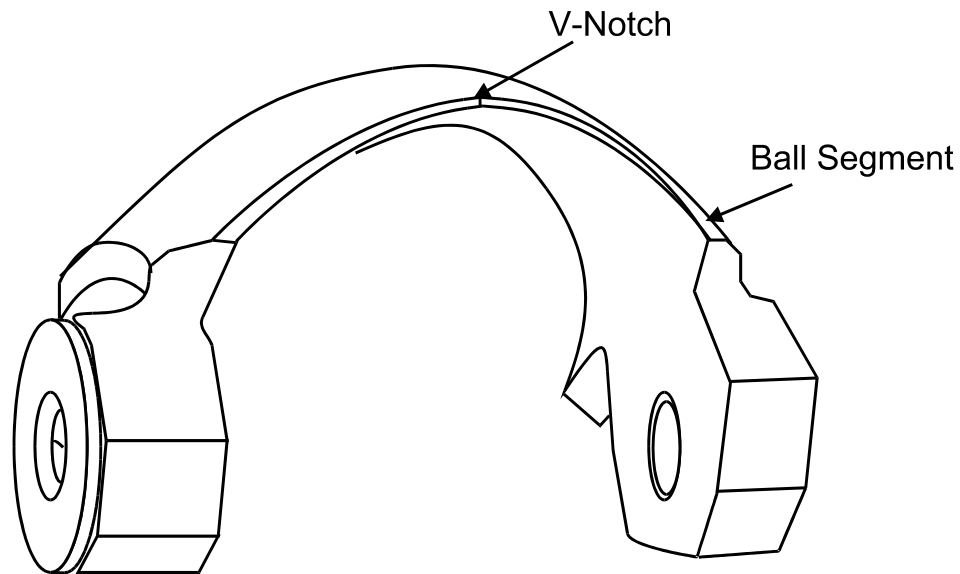
**Figure 6.26**

**Types of valve plug configurations for various valve designs (courtesy of ITT Conoflow).**

### 6.5.3 Rotary Valves

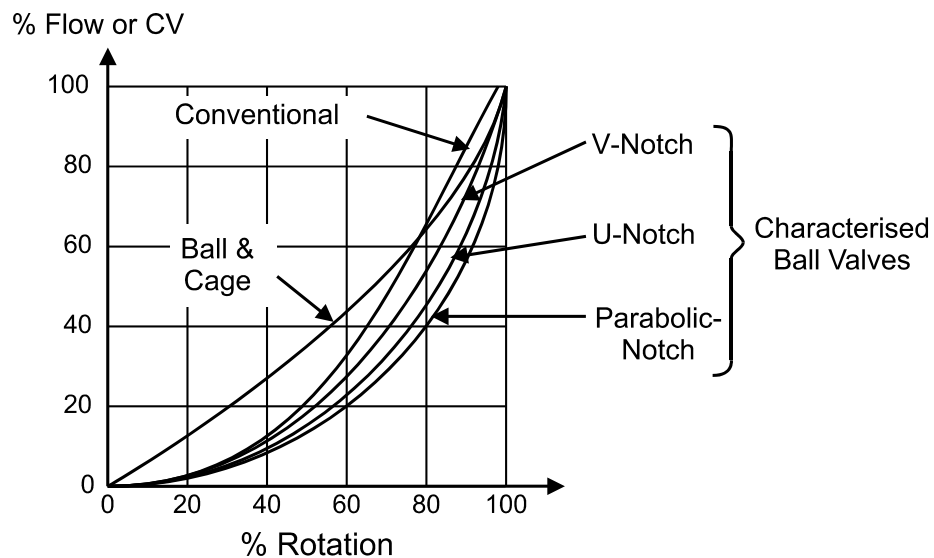
#### - Ball

The flow characteristics of a ball valve are dependent upon the shape of the edge of the partial ball. The characterised ball valve with a parabolic notch provides a flow characteristic that is nearly equal percentage.



**Figure 6.27**

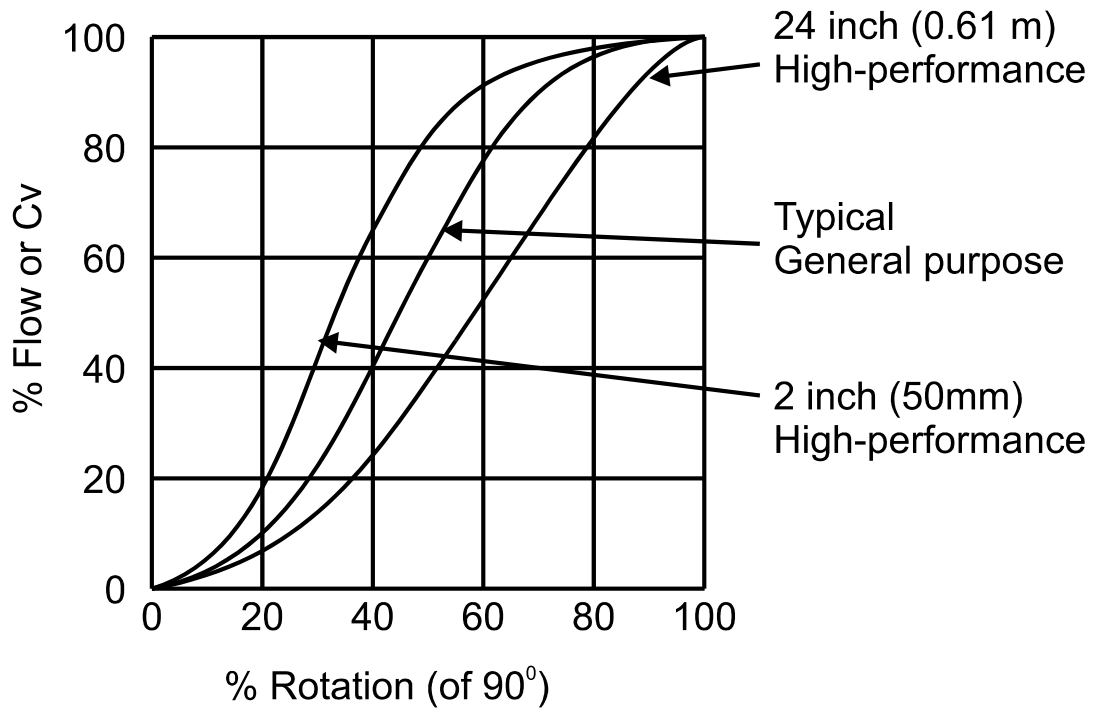
*Because of its shear-on-close action; the V-notch ball valve is well suited for slurry applications and for fluids that include fibrous and stringy material.*



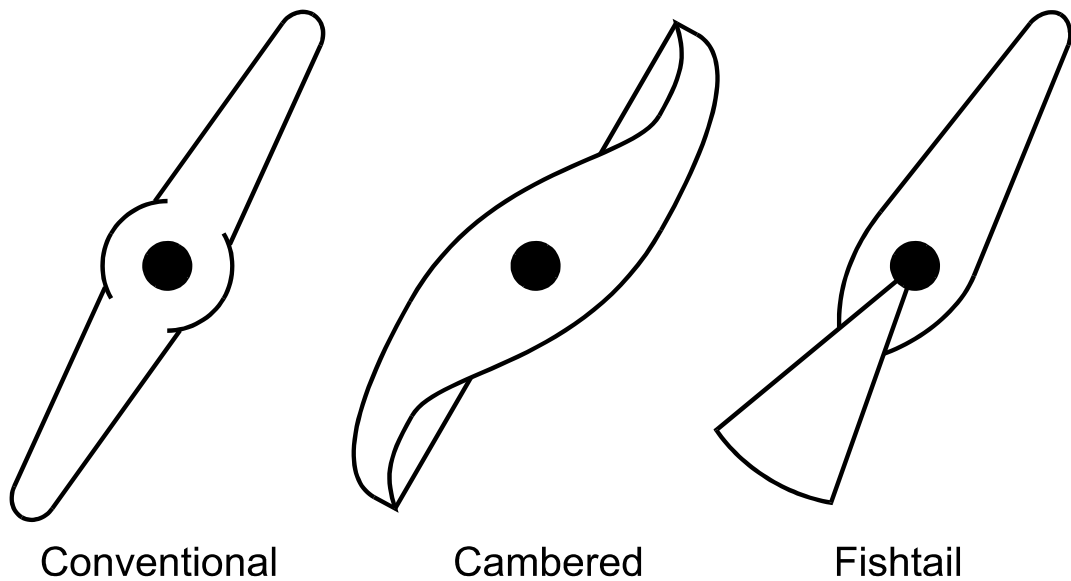
**Figure 6.28**

- **Butterfly**

The flow characteristics of a butterfly valve are dependent on the shaft location and the comparative size of the shaft to the valve. Butterfly valves have a unique flow characteristic unlike those above.



**Figure 6.29**  
*Flow characteristics of the butterfly valve.*



**Figure 6.30**  
*Disc shapes.*

## 6.6 Control Valve Noise and Cavitation

### 6.6.1 Noise

Sound is generated from the movement of fluid through a valve. It is only when the sound is undesirable that it is termed 'noise'. If the noise exceeds certain levels then it can become dangerous to personnel.

Noise is also a good diagnostic tool. As sound or noise is generated by friction, excessive noise indicates the possible damage occurring within a valve. The damage can be caused by the friction itself or vibration.

There are three main sources of noise:

- Mechanical vibration
- Hydrodynamic noise
- Aerodynamic noise

#### ***Mechanical Vibration***

Mechanical vibration is a good indication of the deterioration of valve components. Because the noise generated is usually low in intensity and frequency, it is generally not a safety problem for personnel.

Vibration is more of a problem with stem valves compared with cage valves. Cage valves have a larger supporting area and are therefore less likely to cause vibration problems.

#### ***Hydrodynamic Noise***

Hydrodynamic noise is produced in liquid flows. When the fluid passes through a restriction and a pressure change occurs it is possible that the fluid forms vapour bubbles. This is called flashing. Cavitation is also a problem, where the bubbles form but then collapse.

The noise generated is generally not dangerous to personnel, but is a good indication of potential damage to trim components.

#### ***Aerodynamic Noise***

Aerodynamic noise is generated by the turbulence of gases and is a main source of noise. The noise levels generated can be dangerous to personnel, and are dependent on the amount of flow and the pressure drop.

## 6.6.2 Cavitation and Flashing

### Flashing

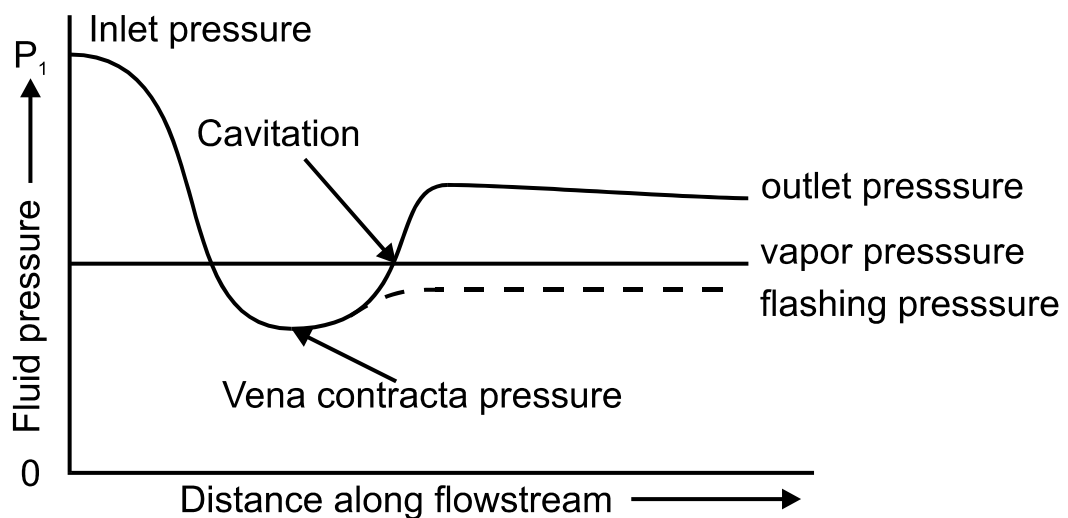
Flashing is the first stage of cavitation. However, it is possible for flashing to occur by itself without cavitation occurring.

Flashing occurs in liquid flows when some of the liquid changes permanently into vapour. This is brought on by a reduction in pressure forcing the liquid to change to the gaseous state.

The reduction in pressure is caused by the restriction in the flowstream generating a higher flow rate through the restriction and therefore a reduction in pressure.

The two main problems caused with flashing are:

- Erosion
- Reduced capacity



**Figure 6.31**  
*Pressure profile in a valve with cavitation*  
*(courtesy of Fisher Controls International).*

### Erosion

When flashing occurs, the flow from the outlet of the valve is composed of liquid and vapour. With increased flashing, the vapour carries the liquid. As the velocity of the flowstream is increased, the liquid acts like solid particles as it strikes the internal parts of the valve.

The velocity of the outlet flow can be reduced by increasing the size of the valve outlet which would reduce the damage. Options of using hardened materials are



another solution. Angle valves are suitable for this application as the flashing occurs further downstream away from the trim and valve assembly.

### Reduced Capacity

When the flowstream partly changes to a vapour, as in the case of flashing, the space that it occupies is increased. Because of the reduced available area, the capacity for the valve to handle larger flows is limited.

Choked flow is the term used when the flow capacity is limited in this way.

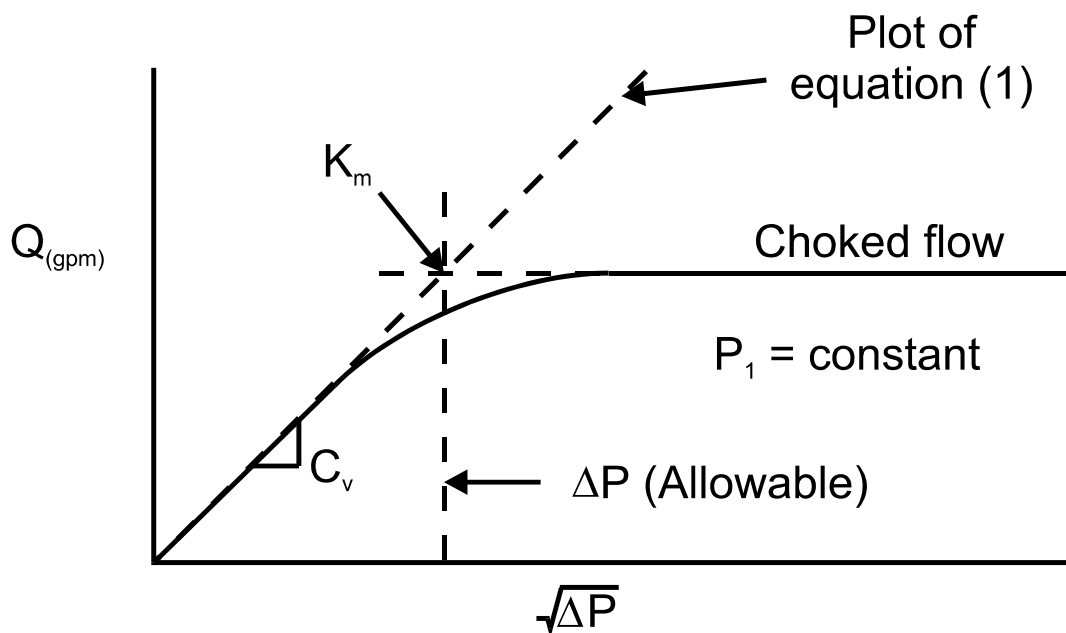


Figure 6.32  
 $K_v$  defined  
 (courtesy of Fisher Controls International).

### Cavitation

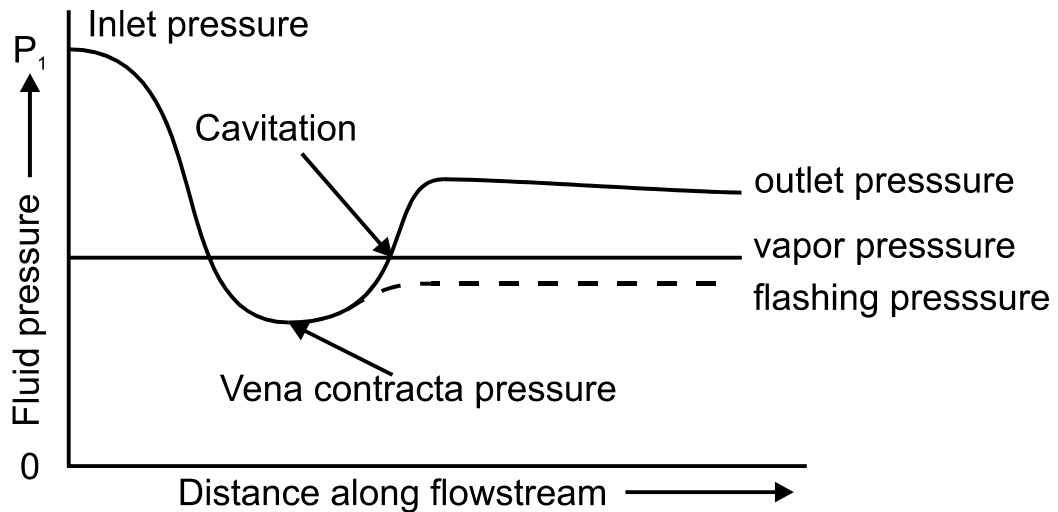
Cavitation is the same as flashing except that the pressure is recovered in the outlet flowstream such that the vapour is returned to a liquid. The critical pressure is the vapour pressure of the fluid.

Flashing occurs just downstream of the valve trim when the pressure drops below the vapour pressure, and then the bubbles collapse when the pressure recovers above the vapour pressure. When the bubbles collapse, they send severe shock waves into the flow stream.

The main concern with cavitation, is the damage to the trim and body of the valve. This is primarily caused by the collapsing of the bubbles.

Depending on the extent of the cavitation developed, its effects can range from a mild hissing sound with little or no equipment damage to a highly noisy installation causing severe physical damage to the valve and downstream piping.

Severe cavitation is noisy and can sound as if gravel were flowing through the valve. The noise produced is not a major concern from a personal safety point of view, as it is usually low in frequency and intensity and as such does not pose a problem to personnel.



**Figure 6.33**  
*Pressure profile in a valve with cavitation*  
(courtesy of Fisher Controls International).

Cavitation occurs under different conditions for various valves. This is attributable to the individual pressure recovery characteristics of the valve.

## 6.7 Actuators and Positioners Operation

### 6.7.1 Actuators

Actuators provide the driving force that controls a valves position. They are also required to reliably perform the following:

- Move the valve ball, plug or stem to the required position.
- Hold the position against the forces of the flowstream.
- Close off the flow by applying sufficient force.
- Provide the required operation for full control, from fully open to fully closed.
- Operate the movement at the required speed.

## **Electromechanical**

Using a motor through a gearbox, this type of actuator provides either reciprocating or rotary action depending on the type of valve being used. A power screw is used to transfer the rotary action to linear or reciprocating action if applicable.

This type of actuator is suitable for applications requiring high torques. However, the movement is slower and may impede system response. These actuators are limited in their control capability so they are seldom used in control applications.

### ***Typical Applications***

Electric actuators are often used where it is not practical to locate and properly maintain the required air supply needed for pneumatic actuators. Because they interface easily with electrical control systems, electric actuators are becoming more popular.

### **Advantages**

- High thrust.
- Easily interfaced to control system.

### **Disadvantages**

- Large.
- More expensive than pneumatic.
- High power electrical source.
- Poor controllability.

### ***Application Limitations***

Electric actuators normally have a duty cycle, which limits their continued use. A duty cycle of 25% means that the device should be at rest for 75% of the time.

Stalling is another limitation with electric actuators. Stalling occurs when the actuator still has power applied to it, but it is at the limit of its operation. Stalling in electric actuators is generally caused by poor sizing for the application, where the actuator is sized below the required torque.

The problem with electric actuators is that they can overheat when stalled. This reduces the life of the device, but more seriously can become a fire hazard.

## ***Hydraulic***

Simple hydraulics are used, where a piston is hydraulically driven and provides the necessary movement to position and control the valve. Although a fast response is

achieved in the stroke action, an external hydraulic supply is however required. As with most hydraulic devices, they are suitable for very high loads.

### **Advantages**

- Fast response to control signals.
- High loads.
- Variable stroking speed and stiffness.

### **Disadvantages**

- Requires external hydraulic supply.
- Not spring loaded, generally not fail-safe.

### ***Pneumatic - Piston***

Piston actuators provide very long travel with a very high thrust. They are more compact than the spring and diaphragm but do have increased stiffness. The increased stiffness is a result of the higher loading pressures due to the air/spring forces.

Springless piston actuators are available, but require a separate pneumatic system to provide a fail safe mode.

### **Advantages**

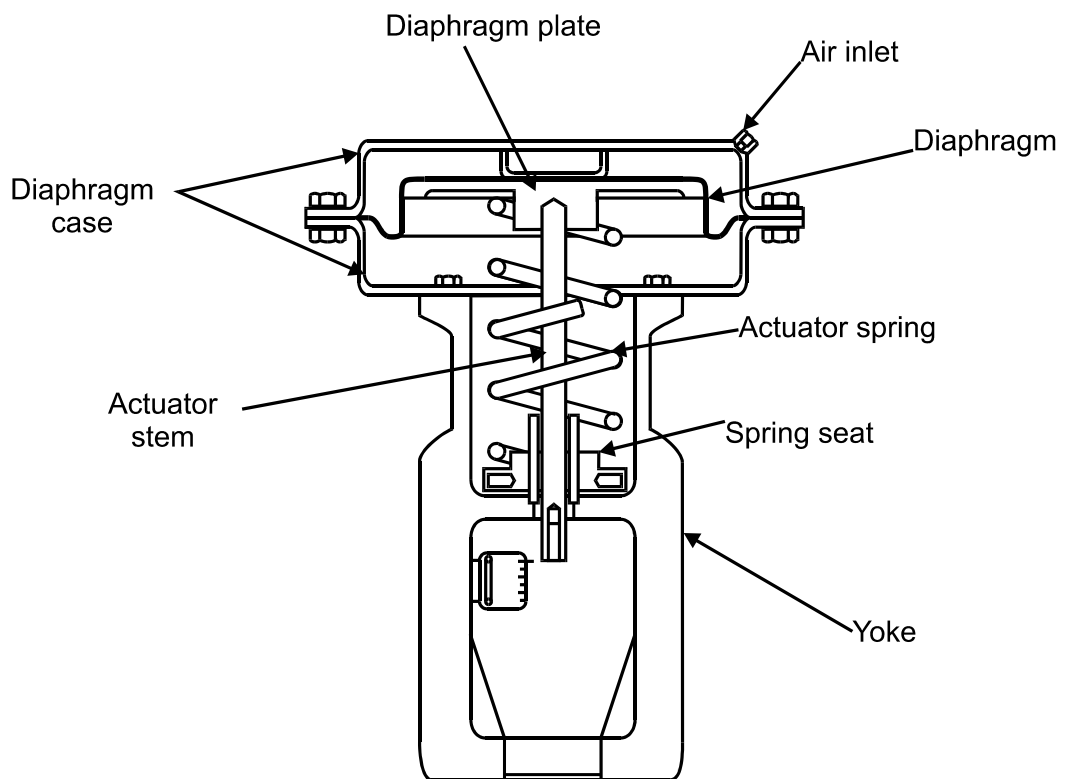
- Very long travel.
- High thrust.
- Compact size.
- Increased stiffness.

### **Disadvantages**

- Fail safe requires trip system.

### ***Pneumatic - Spring and diaphragm***

Spring and diaphragm actuators are very simple and reliable. The major advantage is the spring fail action that provides full shutoff in the event that the pneumatic air supply fails. Depending on the construction, the fail mode can either move the stem up or down. This provides fail-open or fail-closed operation.



**Figure 6.32**  
**Spring and diaphragm actuator – directing acting.**

### **Advantages**

- Fail safe operation.

### **Disadvantages**

- Actuator force must work against spring.

### **Application Limitations**

Pneumatic actuators are susceptible to clogged air lines, particularly in low temperature applications which can cause condensate to freeze.

### **Solenoid**

With the solenoid actuator, an electric current is applied to a solenoid coil which forces a metal plunger. The position of the plunger is determined by the applied voltage.

Solenoid actuators give good control but are limited by thrust capability. They are more expensive than comparative pneumatic actuators, but less expensive than electromechanical actuators.

### **Advantages**

- Electrically controlled, therefore interface directly.
- Less expensive than electromechanical actuators.

### **Disadvantages**

- Limited thrust.
- More expensive than pneumatics.

### ***Summary - Pneumatic And Electric Actuators***

When a high frequency of operations is required, pneumatic actuators are superior to electric actuators. Pneumatic actuators do not have a duty cycle and can operate continuously. Electric actuators usually have a duty cycle rating. An electric actuator with a duty cycle of 25% means that it is required to be at rest for 75% of the time.

Pneumatic actuators are safer than electric actuators because they do not overheat if they stall.

Pneumatic actuators are typically more cost effective than electric actuators and have a more rugged and reliable design. They are also inherently explosion proof as they generate no sparks or heat, and they are not sensitive to wet environments, as are electric actuators.

#### **6.7.2 Positioners**

In applying a force to an actuator, there is no guarantee that the actuator is in the correct position. Positioners are used to feedback position information and ensure that the valve is in the correct position regardless of the opposing forces.

For pneumatic control, the positioner attempts to put the valve into the correct position. The output of the control device is not related to the input signal, but relies on the positioner to achieve the correct valve position.

Positioners can be limited if the correct position is opposed by forces greater than the actuator can provide.

The performance of the positioner is dependent on the accuracy of the position feedback and linkage used. For critical control applications, the linkage needs to be more accurate and robust.

Note that the flow characteristic can be modified by the feedback system. On positioners with cams, the shape of the cam can determine the characteristic. However it is better to characterise a valve with trim configurations.

Control pressures are generally 3 to 15 psi, but positioners can operate up to 100psi which provide a greater force and a stiffer action that is less sensitive to load changes. Although, high supply pressures can affect stroking response time.

### Advantages

- Assist in overcoming friction.
- Greater actuating pressures available.

## 6.8 Valve Benchset and Stroking

**Benchset** are the actual pressure ranges for travel of the actuator with no friction. These are the actual maximum and minimum pressures that move the actuator from end to end of its range of operation. This is typically performed on the actuator before it is mounted onto the valve.

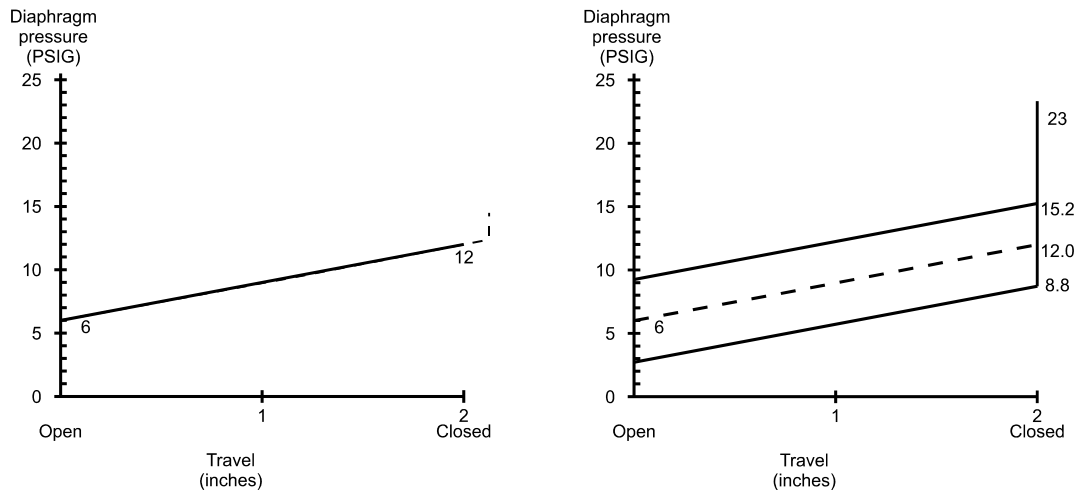
**Stroking** is the pressure range for the operation with friction. Stroking takes into account the added pressure required to overcome friction forces when the actuator is connected to the valve assembly.

When stroking a valve, two sets of pressure ranges are produced. There is one pressure range that actuates the valve from fully open to fully closed. The other range is generated from actuating the valve from fully closed to fully open.

The **operational stroking** range adds pressure and flow effects.

With any type of friction, the problems arise where the pressure to drive the device in one direction will be different to that required to drive it in the other direction. To move the valve in the positive direction, then the force has to exceed the benchset pressure by the amount of the friction. To drive the actuator in the opposite direction, the force has to go below the benchset pressure by the amount of the friction. This is the hysteresis and applies when friction is present.

The amount of friction determines the amount of variation from the benchset pressure range.



**Figure 6.35**  
**(a) – Benchset. (b) - Stroking range.**

## 6.9 Impact on the Overall Control Loop

There are at least two concerns when integrating control valves into a control loop application.

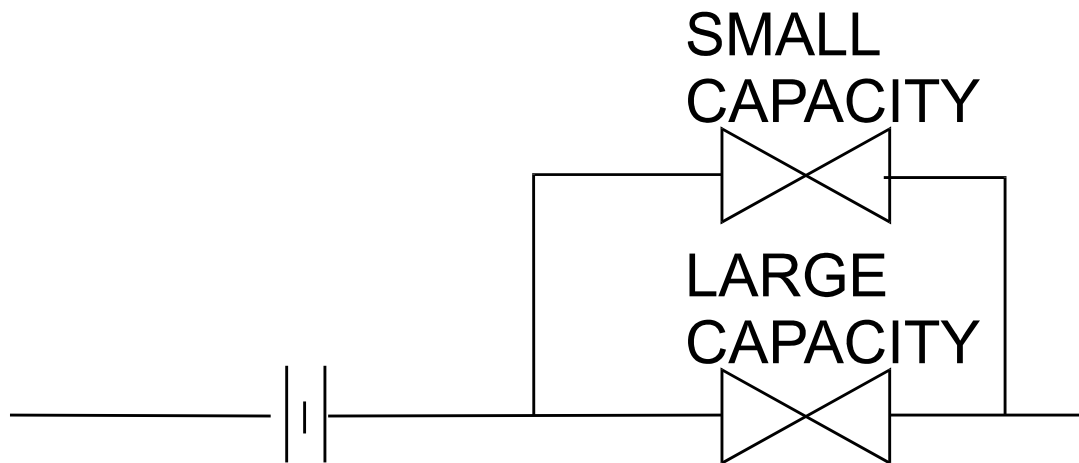
- Response time of the control valve
- Error and control at low flow/shutoff

The response time of the control valve adds to the overall response time of the control loop. If there is too much of a ramp delay on the valve then this can make control of the process quite sluggish.

Depending on the rangeability of the control valve, control can be difficult at low flow rates as the accuracy and resolution of actuation is diminished. The problem arises when the valve is sized for a large flow rate with an associated large pipe diameter. When low flow rates are required the valves do not have the physical capacity to control to the tolerances required.

In critical control applications it is possible to connect a smaller valve in parallel. At low flow rates the accuracy and resolution will be maintained by the control of the smaller valve.





**Figure 6.36**  
**Parallel connection of valves.**

Positioners are essentially a fast responding control loop that accounts and corrects for any difference between where the valve needs to be and where it is currently situated. When used in a control system it becomes a slave to the controller driving it. For it to be effective it must be at least ten times faster than the controller driving it. The main recommendation is not to use positioners if the positioned valve is slower than the process variable to which it is controlling to.

## 6.10 Selection Tables

<i>Valve Selection Orientation Table</i>																
<i>Feature and Applications</i>	Ball: Conventional	Ball: Characterised	Butterfly: Conventional	Butterfly: High Performance	Digital	Globe: Single-ported	Globe: Double-ported	Globe: Angle	Globe: Eccentric disc	Pinch	Plug: Conventional	Plug: Characterised	Saunders	Sliding gate: V-insert	Sliding gate: Positioned disc	Special: Dynamically balanced
<b>Features:</b>																
ANSI class pressure rating (max.)	2500	600	300	600	2500	2500	2500	2500	600	150	2500	300	150	150	2500	1500
Max. capacity (Cd)	45	25	40	25	14	12	15	12	13	60	35	25	20	30	10	30
Characteristics	F	G	P	F,G	E	E	E	E	G	P	P	F,G	P,F	F	F	F,G
Corrosive service	E	E	G	G	F,G	G,E	G,E	G,E	F,G	G	G,E	G	G	F,G	G	G,E
Cost (relative to single port globe)	0.7	0.9	0.6	0.9	3.0	1.0	1.2	1.1	1.0	0.5	0.7	0.9	0.6	1.0	2.0	1.5
Cryogenic service	A	S	A	A	A	A	A	A	A	NA	A	S	NA	A	NA	NA
High pressure drop (over 200 PSI)	A	A	NA	A	E	G	G	E	A	NA	A	A	NA	NA	E	E
High temperature (over 500°F+A6)	Y	S	E	G	Y	Y	Y	Y	Y	NA	S	S	NA	NA	S	NA
Leakage (ANSI class)	V	IV	I	IV	V	IV	II	IV	IV	IV	IV	IV	V	I	IV	II
<b>Liquids:</b>																
Abrasive service	C	C	NA	NA	P	G	G	E	G	G,E	F,G	F,G	F,G	NA	E	G
Cavitation resistance	L	L	L	L	M	H	H	H	M	NA	L	L	NA	L	H	M
Dirty service	G	G	F	G	NA	F,G	F	G	F,G	E	G	G	G,E	G	F	F
Flashing applications	P	P	P	F	F	G	G	E	G	F	P	P	F	P	G	P
Slurry including fibrous service	G	G	F	F	NA	F,G	F,G	G,E	F,G	E	G	G	E	G	P	F
Viscous service	G	G	G	G	F	G	F,G	G,E	F,G	G,E	G	G	G,E	F	F	F
<b>Gas / Vapour</b>																
Abrasive, erosive	C	C	F	F	P	G	G	E	F,G	G,E	F,G	F,G	G	NA	E	E
Dirty	G	G	G	G	NA	G	F,G	G	F,G	G	G	G	G	G	F	G
<b>Abbreviations</b>																
A = Available	E = Excellent	NA = Not available														
C = All ceramic design available	H = High	P = Poor														
F = Fair	L = Low	S = Special designs only														
G = Good	M = Medium	Y = Yes														

**Table 6.3**  
**Selection table for valves.**

## 6.11 Future Technologies

### *Smart Valves*

The microprocessor gives an instrument the 'smarts' to look at other information and calculate an optimum output for the process.

Information that the device may monitor would be:

- Inlet pressure.
- Outlet pressure.
- Inlet temperature.
- Position of stem.
- Top and bottom actuator pressure.
- Positioner signal.

Some of the functions that the smart instrument can perform are:

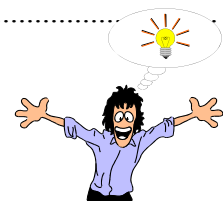
- Instrument signature  
This enables the instrument to be tagged electronically for easy identification with any communicating device.
- Local process control  
It is possible for the device to perform its own control since it has information about the pressure drop, valve position and temperature.
- Valve diagnostics  
It is possible to diagnose the valve with the information obtained. Problems such as sticking in the trim and high packing friction can be detected with the travel and actuator pressures.
- Process diagnostics  
Characteristics about the flow compared to travel can be evaluated over time to give performance details about the process.
- Configurable failure modes  
The device can be configured to execute different tasks depending on loss of power, air supply, process signal or output.

# Tips and Tricks



A series of horizontal dotted lines providing a space for writing tips and tricks.

# Tips and Tricks





# **7**

## **Process Considerations**

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# Chapter 7

## Other Process Considerations

### 7.1 The New Smart Instrument and FieldBus

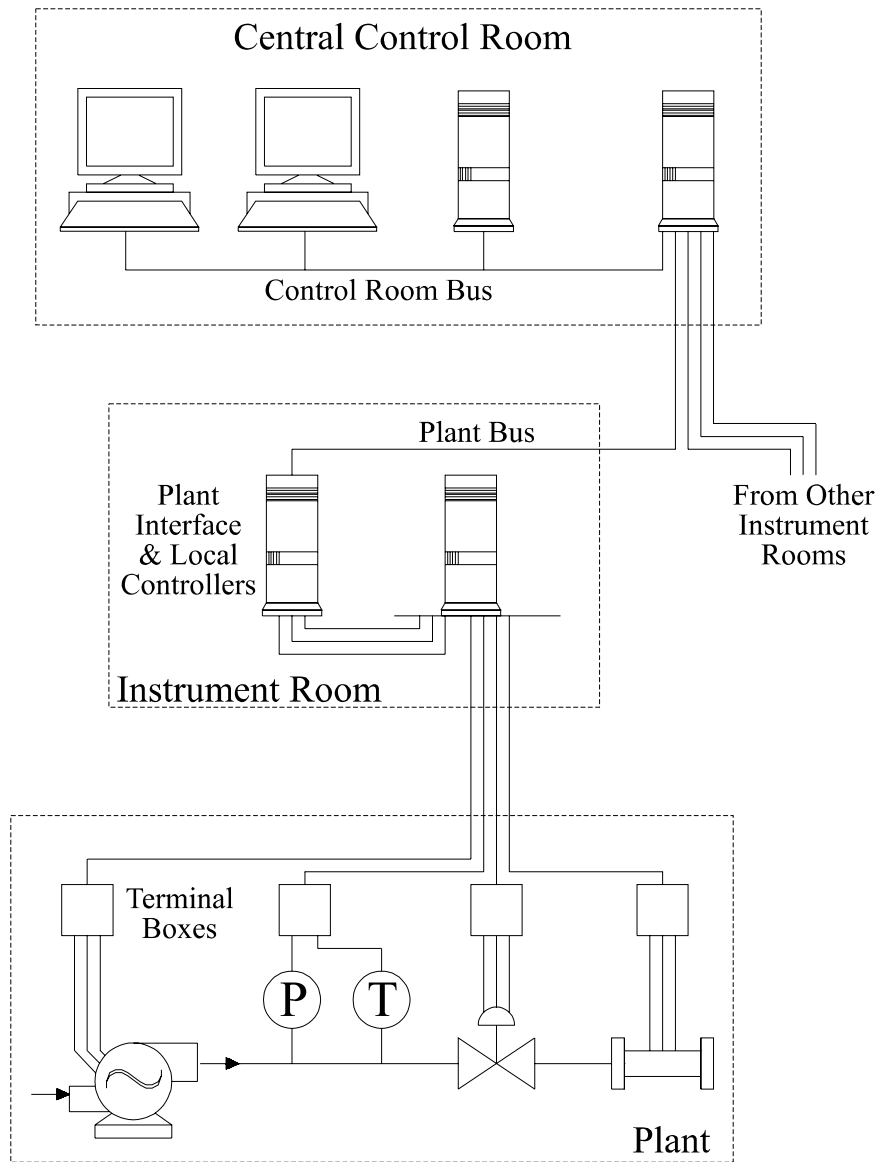
There has been a strong movement over the past five years towards the use of smart instruments. Essentially a smart instrument has the following features:

- Intelligent Digital microprocessor based sensor
- Digital data communications capability

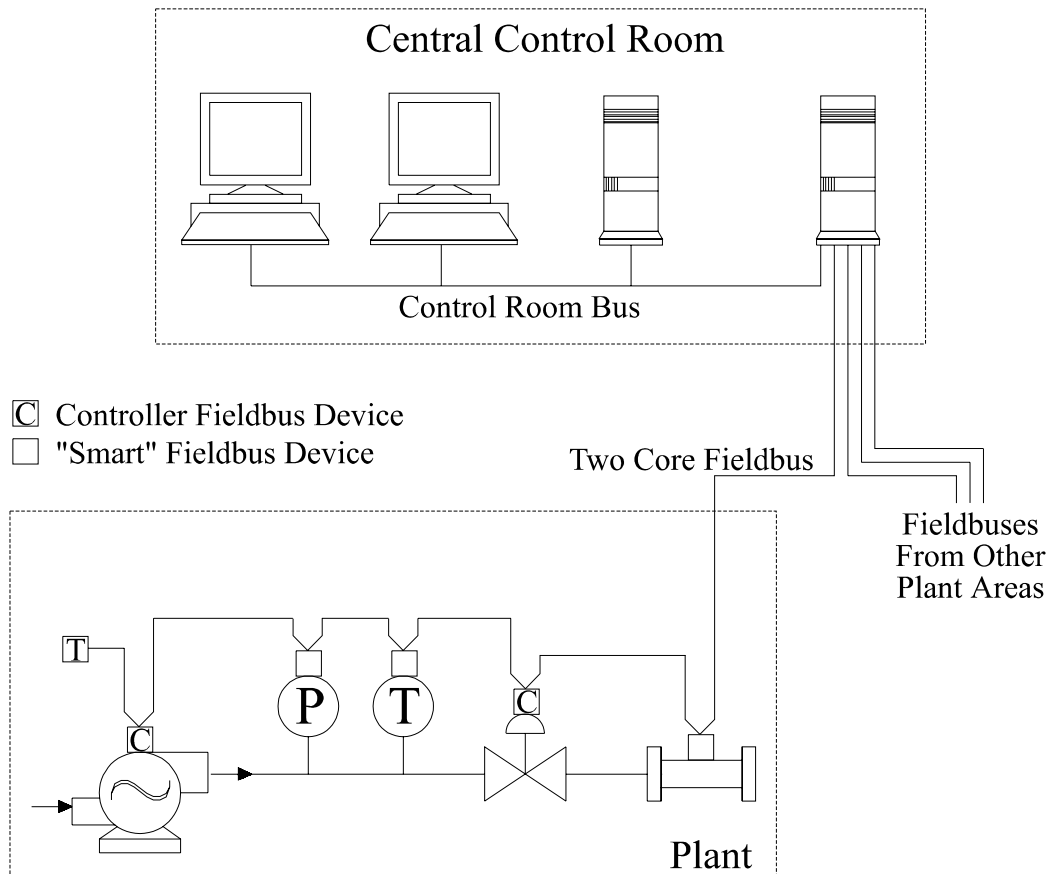
The real benefits to be gained from smart instruments are:

- Greatly reduced wiring costs
- Reduced installation and start-up time
- Improved on-line monitoring and diagnostics
- Easier change-out and expansion of devices
- Improved local intelligence in the devices
- Improved Interoperability between different (competing) manufacturers





**Figure 7.1**  
**Current Approach to Instrumentation Systems**

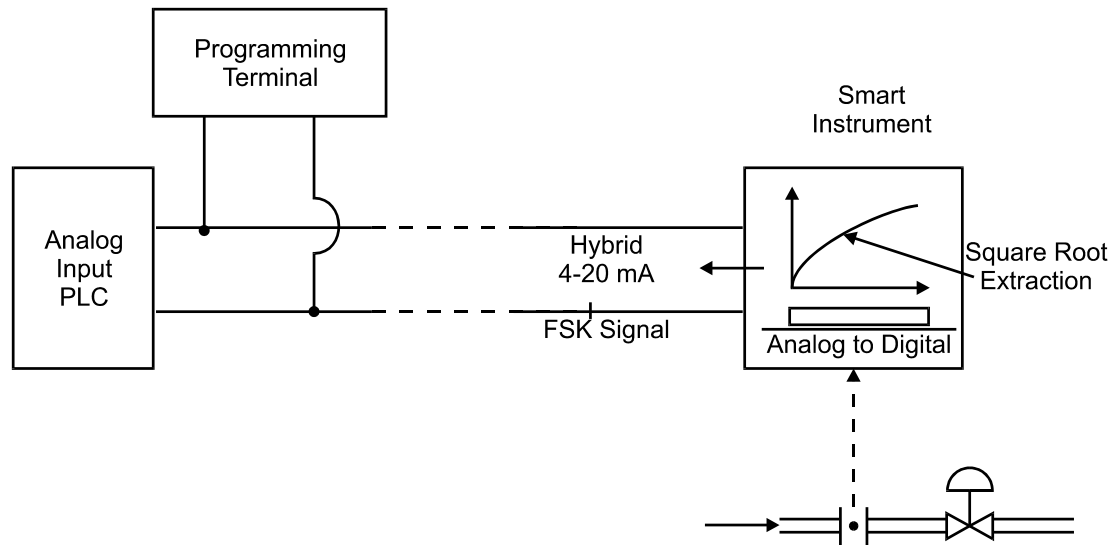


**Figure 7.2**  
***New FieldBus approach to Typical Control System***

There are a number of intelligent digital sensors for most traditional applications. These include sensors for measuring temperature, pressure, level, flow, mass and density. A schematic of a typical smart instrument is given in figure 7.3. You will notice that they are often multidropped to minimise cabling requirements. At a basic level, most smart instruments provide core functions such as:

- Control of range/zero/span of instruments.
- Diagnostics to verify functionality.
- Memory to store configuration and status information (such as Tag Numbers).

Accessing these functions allows major gains in the speed and efficiency of the installation and maintenance process. For example, the time consuming 4-20 mA loop-check phase can be achieved in minutes – a considerable time saving.



**Figure 7.3**  
**Diagram of a typical Smart Instrument**

There are a proliferation of standards on the market at present. Two common ones are HART (Highway Addressable Remote Transducer) and Profibus. HART is a hybrid analogue digital standard whilst Profibus is a pure digital standard.

This section discusses the following two Protocols in more detail:

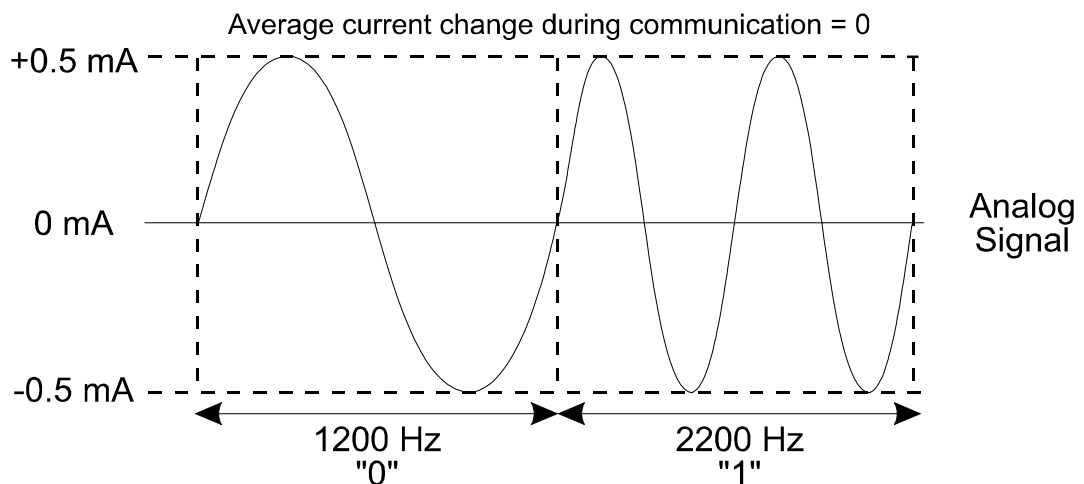
- HART Protocol
- FieldBus

### 7.1.1 Highway Addressable Remote Transducer Protocol

This protocol was developed by Rosemount and is regarded as an open standard. Its main advantage is that it enable the end-user to keep the existing 4-20 mA instrumentation cabling and simultaneously to use the same wires to carry digital information superimposed on the analogue signal.

HART is a hybrid analogue and digital protocol as opposed to FieldBus which is purely digital.

The HART protocol uses the Frequency Shift Keying approach to transfer the digital information. Two individual frequencies of 1200 and 2200 Hz representing digits 1 and 0 respectively are used. The average value of the sine wave (at the 1200 Hz and 2200 Hz frequencies) which is superimposed on the 4 –20 mA signal is zero. Hence the 4-20 mA analogue information is not affected.



**Figure 7.4**  
**Structure of the HART Digital Messages**

The HART Protocol can be used in three ways:

- In conjunction with the 4 – 20 mA current signal in point-to-point mode.
- In conjunction with other field devices in multi drop mode.
- In point-to-point mode with only one field device broadcasting in burst mode.

Traditional point-to-point loops use zero for the smart device polling address. A multi drop loop is created by setting the smart device polling address to a number greater than zero. The smart device then sets its analogue output to a constant 4 mA and communicates only digitally.

The HART protocol has two formats for digital transmission of data:

- Poll /response mode
- Burst or broadcast mode

In the poll/response mode the master polls each of the smart devices on the highway and requests the relevant information. In burst mode the field device continuously transmits process data without the need for the host to send request messages. Although this mode is fairly fast (up to 3.7 times per second) it cannot be used in multidrop networks.

### **Application Layer**

This allows the host device to obtain and interpret field device data. There are three classes of commands:

- Universal commands.
- Common practice commands.
- Device Specific commands.

### **Universal commands**

Read Manufacturer and device type.  
Read PV and units.  
Read current output and percent of range.  
Read up to 4 pre defined dynamic variables.  
Read or write 8-character tag, 16-character descriptor, date.  
Read or write 32 character message.  
Read device range, units and damping time constant.  
Read or write final assembly number.  
Write polling address.

### **Common Practice Commands**

Read selection of up to 4 dynamic variables.  
Write damping time constant.  
Write device range.  
Calibrate (Set zero, set span).  
Set fixed output current.  
Perform self-test.  
Trim PV zero.  
Write PV units.  
Trim DAC zero and gain.  
Write transfer function (square root/linear).  
Write sensor serial number.  
Read or write dynamic variable assignments.

### **Instrument Specific Commands**

Read or write low flow cut-off value.  
Start, stop or clear totaliser.  
Read or write density calibration factor.  
Choose PV (mass flow or density).  
Read or write materials or construction information.  
Trim sensor calibration.

## FieldBus

FieldBus is the general name for a number of competing standards such as Profibus (the German national standard); Interbus-S (originated from Phoenix Contactor), FIP (the French National standard) and Foundation FieldBus (the so-called international standard). It is not possible at this stage to comment on who will “win the race” to be the worldwide standard. However arguably Foundation FieldBus is technically the “best” standard. However, Interbus-S and Profibus are extremely popular standards. Foundation FieldBus is supported by approximately 70% of the world’s instrument manufacturers and it will be briefly discussed here.

The Physical Layer has been approved for (and supports) communications of 31.25kbps, 1.0 Mbps and 2.5 Mbps. The 31.25 Kbps will support from 2 to 32 devices that are not bus powered, two to twelve devices that are bus powered or two to six devices that are bus powered in an intrinsic safe area. This bus is intended to support the existing plant wiring and can operate up to 1200m.

A Link Access Scheduler (or LAS) station controls access to the bus by granting permission to each device according to predefined schedules. There are two types of schedules:

The Cyclic Messages are used for information (such as Process Variables) that require periodic regular updating between the devices on the bus. The technique used for information transfer on the bus is known as the Publisher-Subscriber method. Based on the user predefined schedule the LAS grants permission to each device in turn access to the bus. Once the device receives permission to access the bus it publishes information. All other devices can then listen to the published information and read it into memory if it requires it for its own use.

The second type of message referred to as acyclic messages are used for special cases that may not occur on a regular basis. These may be alarm acknowledgement or special commands such as retrieving diagnostic information from a specific device on the bus. The LAS detects time slots available between acyclic messages and uses these to send the acyclic messages.

Function blocks provide an easy interface by the end-user to access the different parameters.

### 7.1.2 Selection Issues

The end-user may feel confused as to which standard to select but no standard is dominant at this stage. The competing standards have now been fully defined and released onto the market - the next two years will clearly indicate the leading contenders in this field.

## 7.2 Noise and Earthing Considerations

Many instrumentation systems involve the measurement of signals in which noise can be a prominent component. This discussion examines the various sources of noise in instrumentation systems and how to minimise this problem. A brief discussion on earthing practice is also included.

Noise or interference can be defined as undesirable electrical signals that distort or interfere with an original (or desired) signal. Noise can arise from such sources as currents and voltages in power cables adjacent to the signal cables, lightning and other electrical surges or transients, cross-talk from other nearby cables and radio frequency interference. These forms of noise are referred to as external noise. It should be mentioned that there is a second category called internal noise from such items as thermal noise and imperfections in the electrical design. In this section, the emphasis will be on external noise as it is the more common problem for instrumentation systems.

It is commonly accepted that the main techniques to reduce noise are to apply some form of shielding around the signal wires, increase the distance between the noise source and the signal, and twist the signal wires and to ensure proper grounding (or earthing). The next section examines what the precise causes of noise are and what the particular techniques are to minimise this problem.

This section is broken down into:

- Sources of Noise and how to minimise the problem
- Good earthing practice
- Other Sources of Noise

### 7.2.1 Sources of Noise and How to minimise the Problem

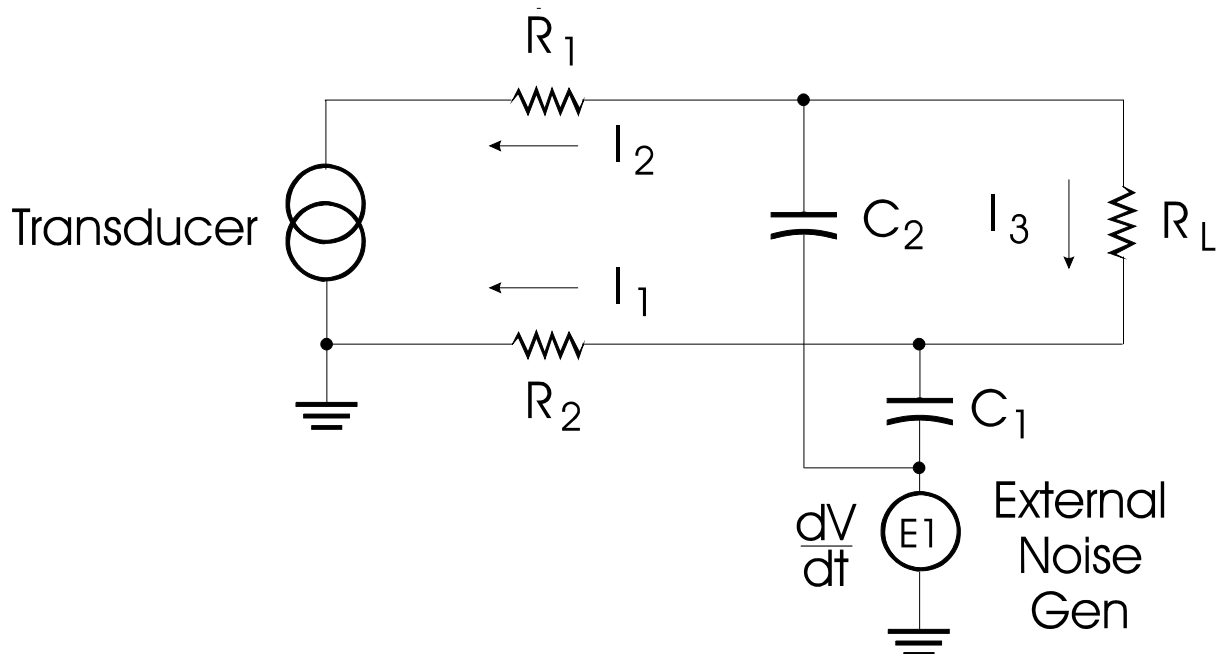
Essentially there are five sources of external noise. These are:

- Capacitive (or electrically coupled ) interference
- Inductive (or magnetically coupled) interference
- Impedance (or Conductance) Coupled noise
- Electromagnetic interference
- Ground Loop (or common mode) interference

#### ***Capacitive Coupling***

This form of noise is proportional to the capacitance between the noise source and the signal wires. Other contributing factors to the noise include the rate of change of the and magnitude of the noise voltage. In the figure 7.5 the noise voltage is coupled into the signal wires through the two capacitors  $C_1$  and  $C_2$ , and a noise voltage is produced across the resistance in the circuit. The size of the noise voltage in the signal wires is proportional to:

- Inverse of the distance of noise voltage from each of the signal wires
- Length (and hence) impedance of the signal wires
- Amplitude of the noise voltage
- Frequency of the noise voltage



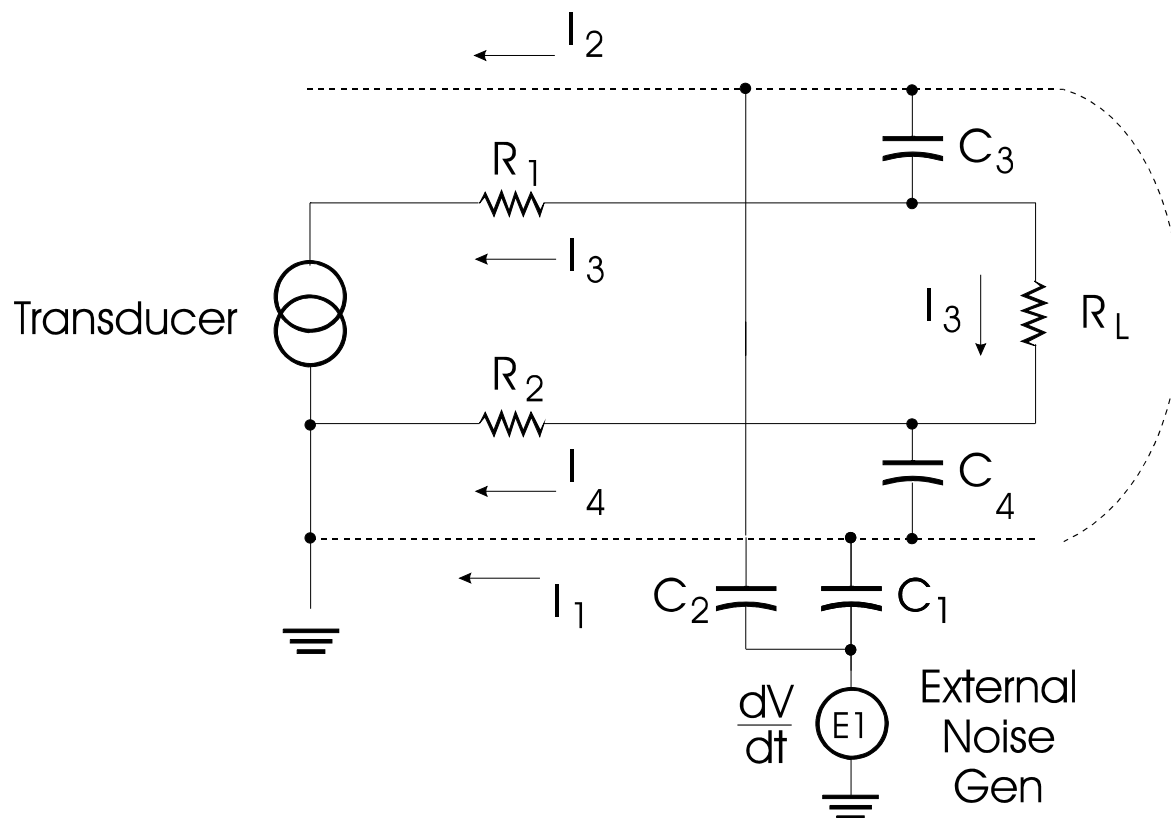
**Figure 7.5**  
**Cause of Electrostatic Coupling**

There are four ways of reducing the noise induced by electrostatic coupling. These are:

- Shielding of the signal wires with low resistance material
- Separating from the source of the noise
- Reducing the amplitude of the noise voltage (and possibly the frequency)
- Twisting of the signal wires

Figure 7.6 indicates the situation when a shield is installed around the signal wires. The noise voltage generated currents prefer to flow down the lower impedance path of the shield rather than the signal wires. If one of the signal wires and the shield are tied to earth at one point, then no signal current flows between the signal wires and the shield.





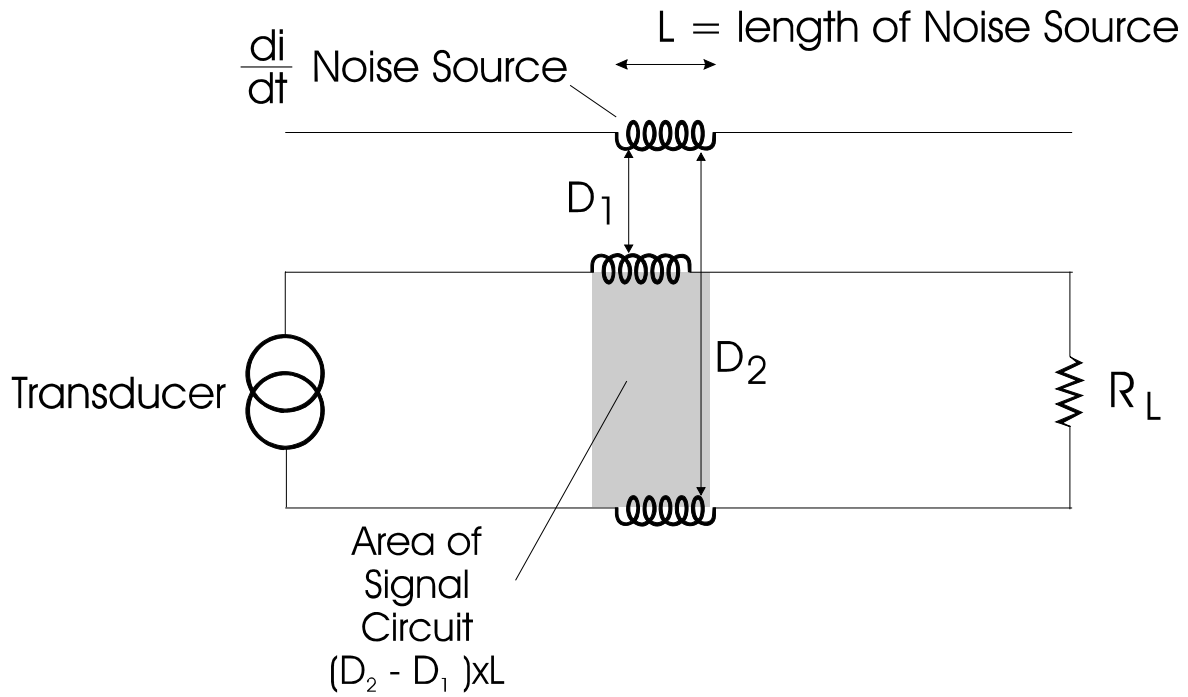
**Figure 7.6**  
**Minimisation of Electrostatic Coupling**

Interestingly enough twisting of the signal wires provides only a small improvement. This occurs because  $C_3$  and  $C_4$  are closer to each other in value; thus ensuring that any noise voltages induced in the signal wires tend to cancel one another out.

### ***Magnetic or Inductive Coupling***

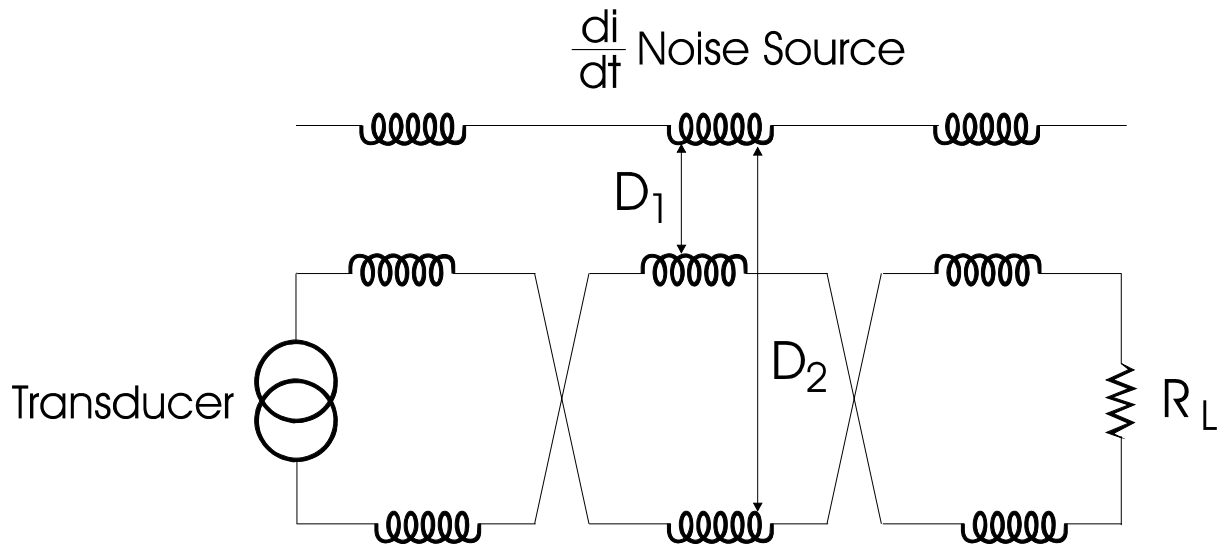
This depends on the rate of change of the noise current and mutual inductance between the noise system and the signal wires. The degree of noise induced will depend on:

- Magnitude of the noise current
- Frequency of the noise current
- Area enclosed by the signal wires
- Inverse of the distance between the noise source and the signal wires



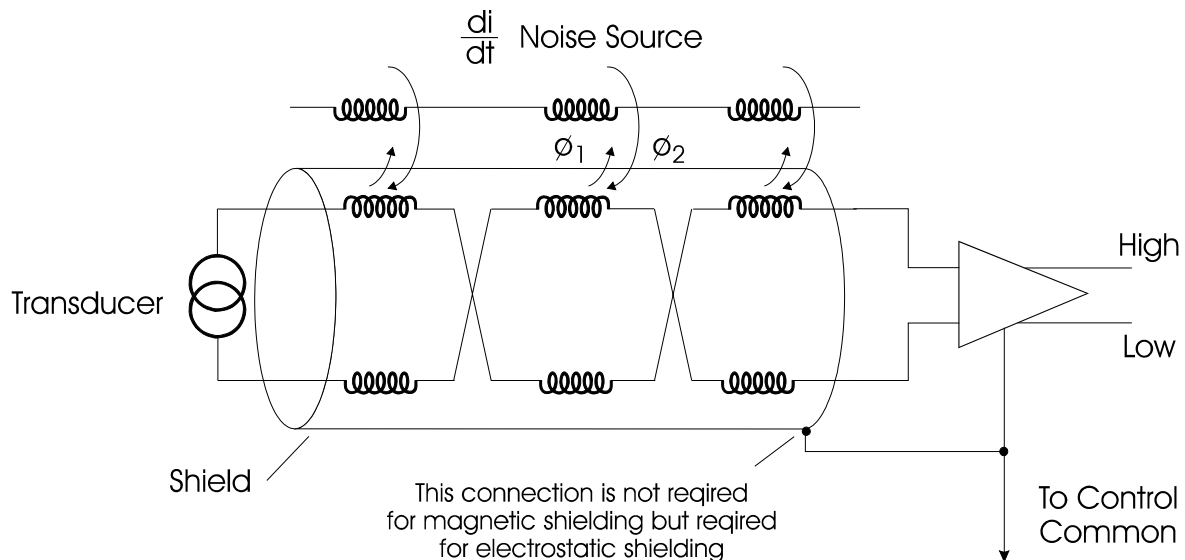
**Figure 7.7**  
**Magnetic or Inductive Coupling Effect.**

The quickest way to reduce the noise voltage is by twisting the signal wires. This reduces the size of each loop that the magnetic flux cuts through and also allows the noise voltage that is induced in each loop to cancel out the voltage in the sequential loop. This is illustrated in figure 7.8.



**Figure 7.8**  
**Twisting of Wires Reduces Magnetic Coupling.**

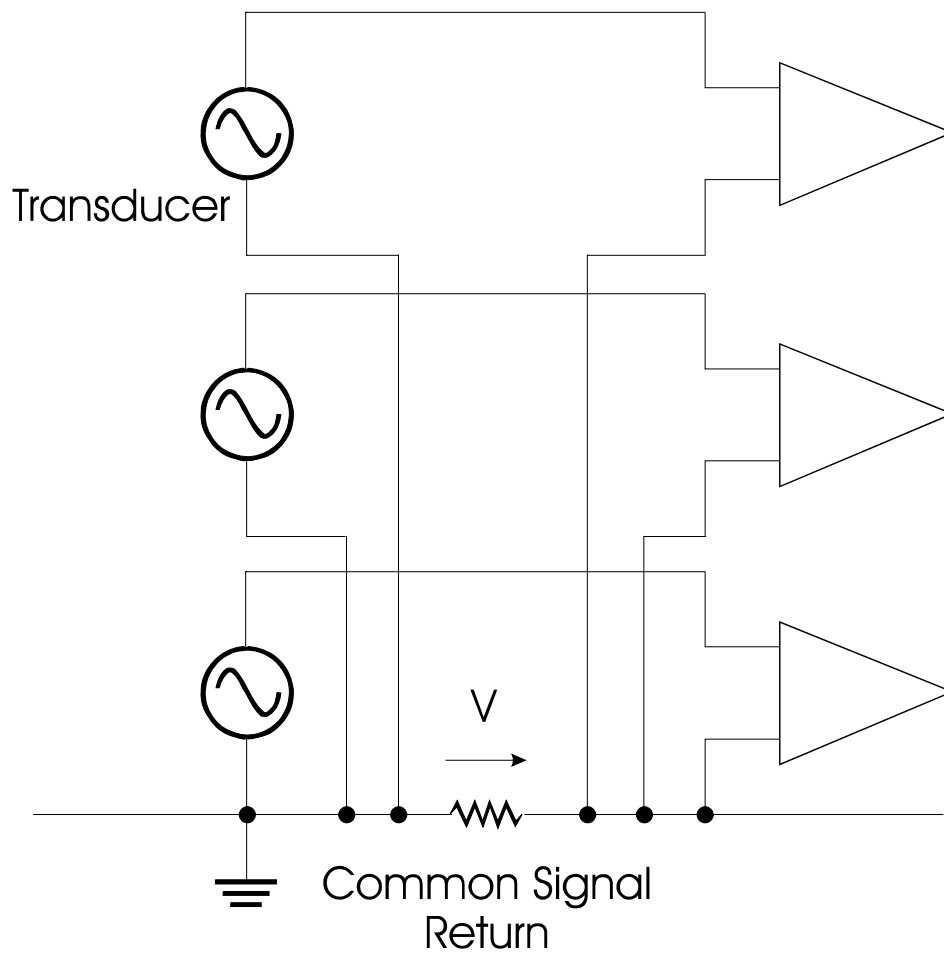
A second albeit more difficult approach is to use a magnetic shield around the signal wires. The magnetic flux generated by the noise currents induces small eddy currents in the magnetic shield. These eddy currents then create an opposing magnetic flux to the original flux. Figure 7.9 indicates this effect. This is not really a very practical solution as most shielding is low resistance (designed for capacitive coupling) as opposed to magnetic. Magnetic tape can be obtained and wound around the sensitive areas or the signal wires can be placed in steel conduit (which has magnetic properties).



**Figure 7.9**  
**Use of Magnetic Shield to reduce Magnetic Coupling**

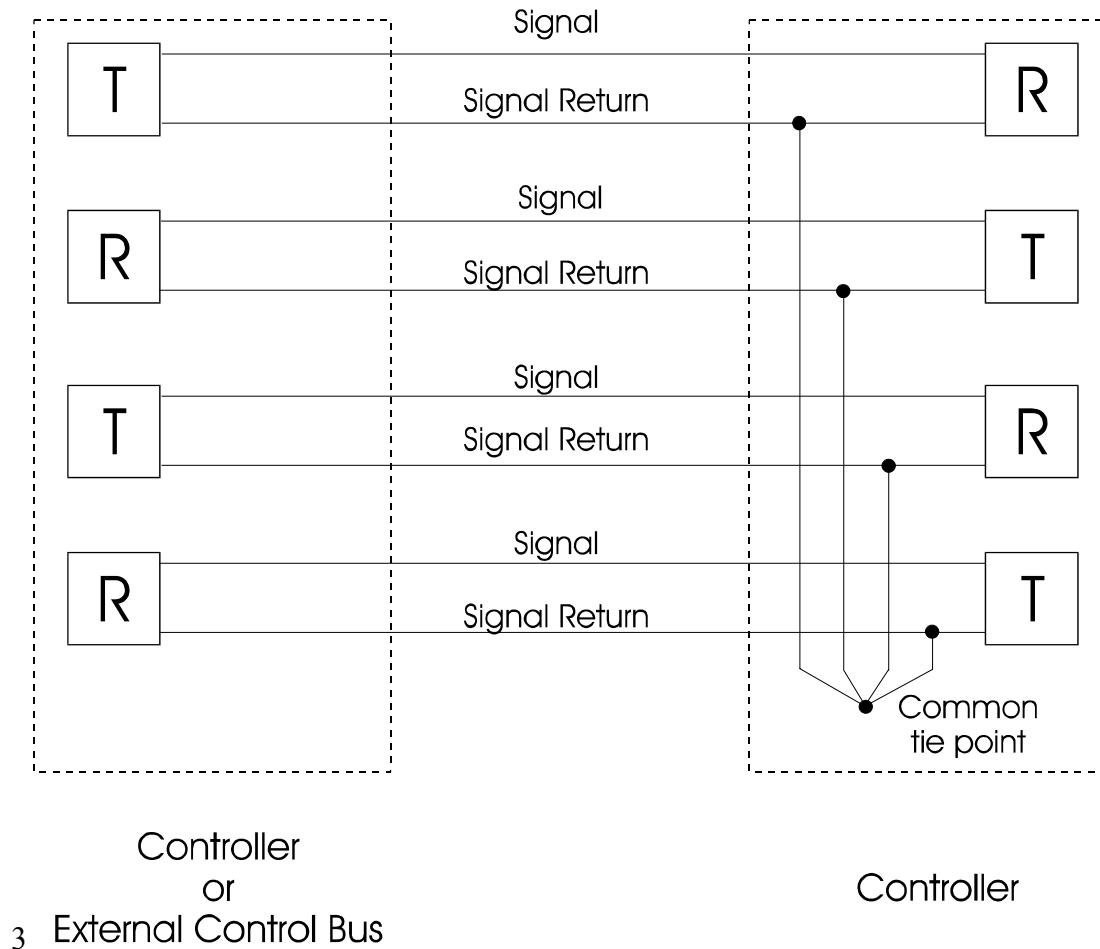
### **Impedance Coupling (or Conductance Coupling)**

For situations where two or more electrical circuits share common conductors, there can be some coupling between the different circuits when the signal current from the one circuit proceeds back along the common conductor resulting in an error voltage along the return bus which affects the other signals. The error voltage is due to the impedance in the return wire.



**Figure 7.10**  
**Impedance Coupling**

One way to reduce the effects of impedance coupling is to minimise the impedance of the return wire. The second solution is to avoid any contact between the circuits and to use separate returns for each individual circuit as indicated in figure 7.11.



**Figure 7.11**  
**Impedance Coupling reduced with Balanced Circuits.**

### ***Electromagnetic interference***

The noise voltages discussed earlier under Electrostatic and Inductive Coupling are examples of the Near Field effect which can be considered to be electromagnetic radiation close to the source of the noise. Electromagnetic Interference discussed here is an example of the Far Field effect. The effects of electromagnetic radiation can be neglected unless the field strength exceeds 1 Volt/metre, calculated with the following formula:

$$\text{Field Strength} = 0.173 \sqrt{\text{Power}} / \text{Distance}$$

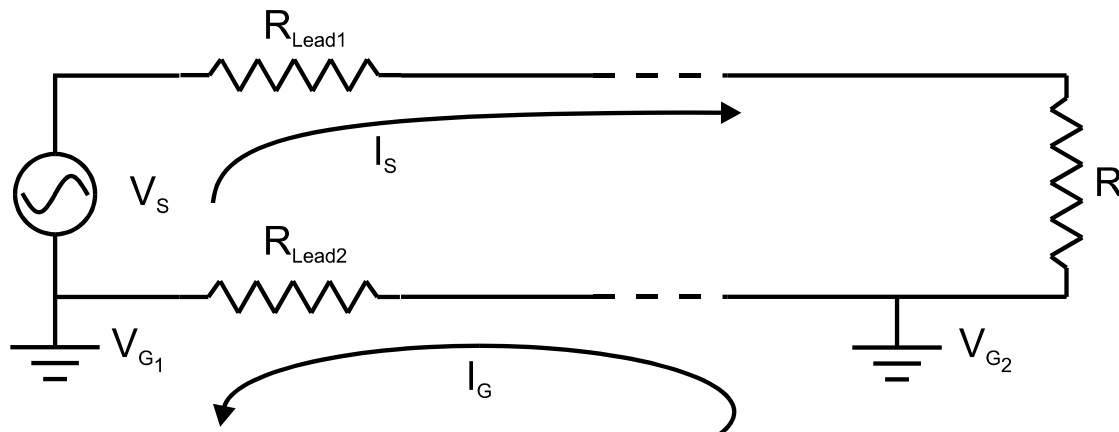
Where  
Field Strength is in volt/metre  
Power is in kilowatts  
Distance is in kms

It is possible to shield against electromagnetic radiation using the principle that electromagnetic radiation must contain both electric and magnetic fields in order to

propagate. Hence if we eliminate either of these fields, the other component will also be removed. Hence an enclosure consisting of a good electric conductor connected to the ground through a low impedance path will provide excellent shielding against electromagnetic radiation. When constructing such enclosures, emphasis should be placed on keeping any holes (in the enclosure) to less than the wavelength of the offending wave.

### 7.2.2 Ground Loop (or Common Mode) Interference

Ground loops occur whenever the ground conductor of an electrical system are connected to the ground plane at multiple points. An example of a ground loop is indicated below.



**Figure 7.12**  
**Example of Ground Loop**

The three main causes of ground loops can be summarised as:

- Differences in potential between the points of the ground plane to which the ground terminals have been connected.
- Inductive coupling
- Capacitive coupling

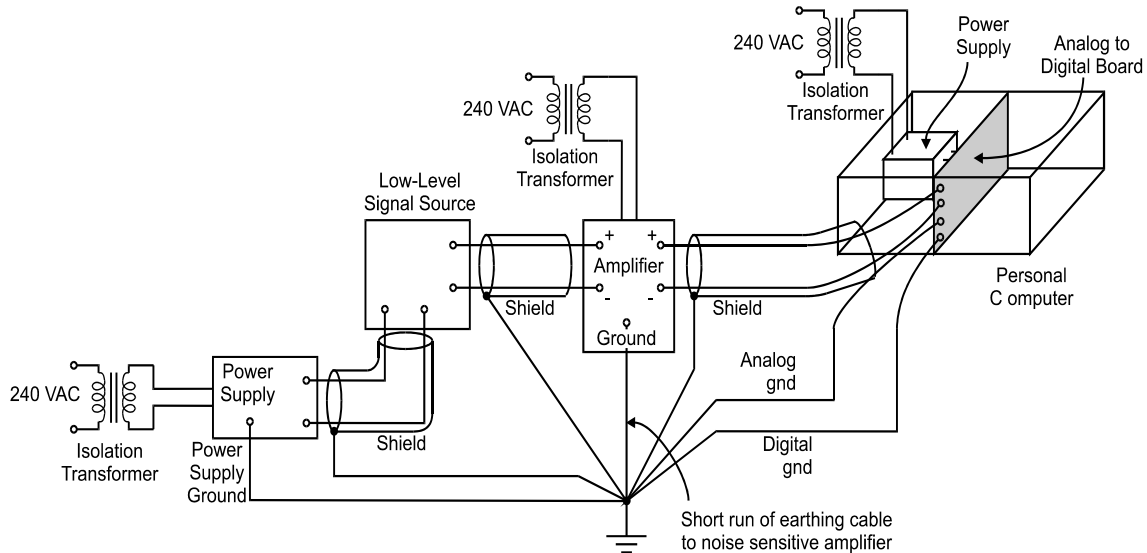
The three methods of correcting for the problems are:

- Single Point grounding
- Use of Differential Inputs
- Use of input guarding
- Use of battery powered instruments

Note that as it is unlikely that input guarding can be easily applied to instrumentation systems discussed in this manual, this will not be considered further.

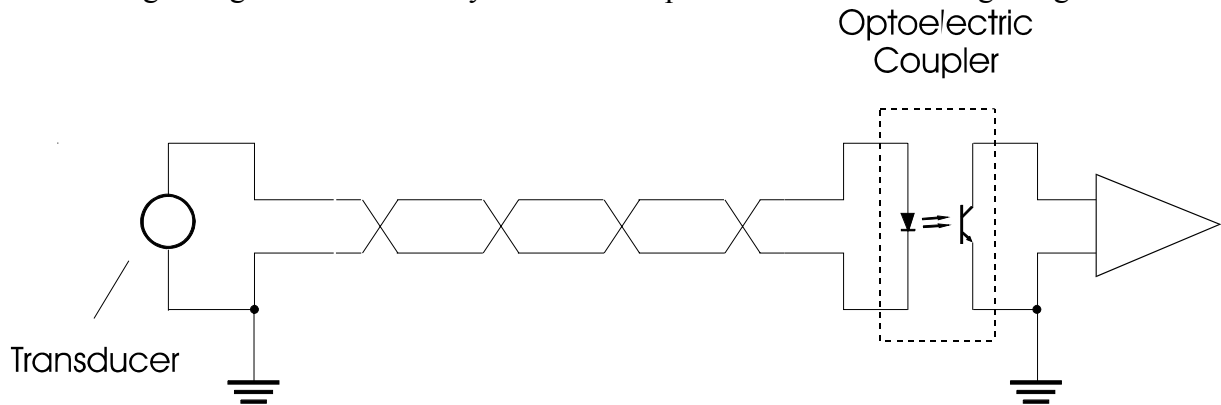
### 7.2.3 Single Point Grounding

A diagram below gives an outline on how single point grounding can be applied.



**Figure 7.13**  
**Single Point Grounding**

If it is difficult to ensure single point grounding, some form of optical isolation should be employed. While this effectively isolates one circuit from the other and eliminates a ground loop, it does not necessarily prevent noise or interference being transmitted from one circuit to the other. Note although the diagram is intended for a digital signal it can be easily extended to optical isolation for analogue signals.

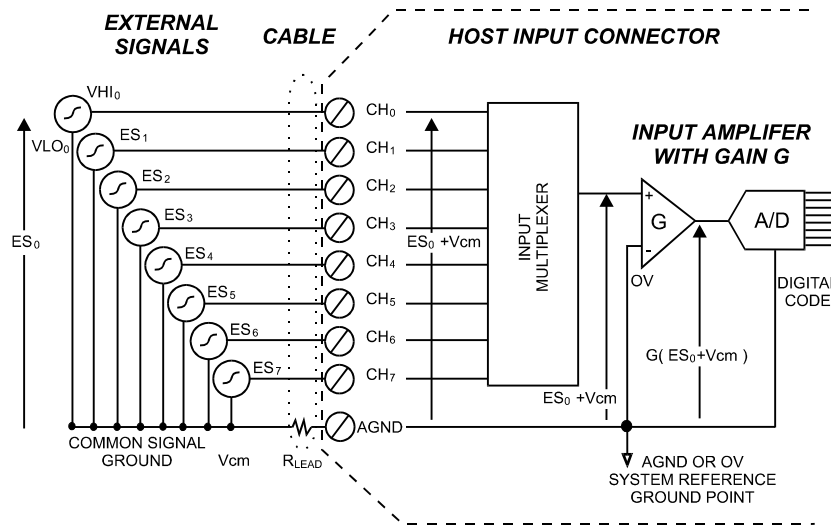


**Figure 7.14**  
**Simple Example of Opto-Isolation of Two circuits.**

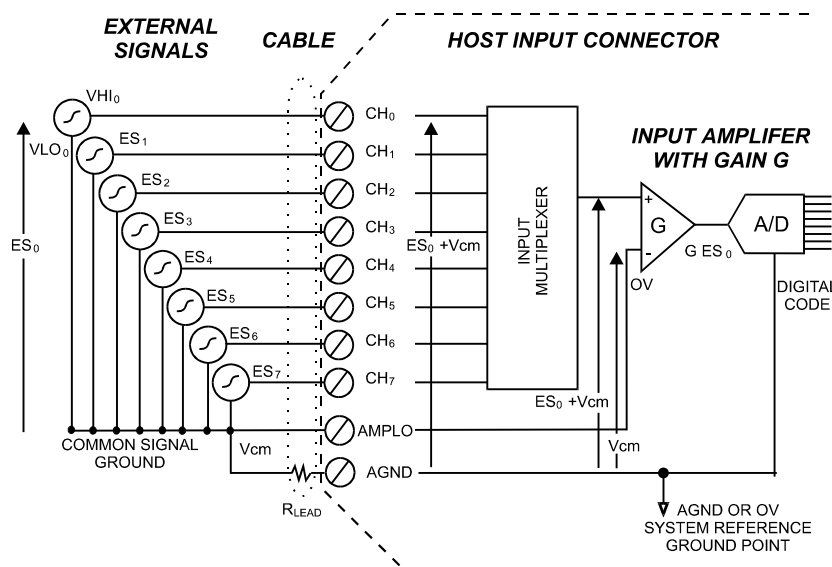
### Use of Differential Inputs versus Single Ended Inputs

The diagrams below summarise the differences between the two approaches. With the single ended approach, the total voltage input to the amplifier consists of the Signal Voltage plus the common mode voltage. The differential approach has the

common mode voltage applied to both inputs. These are cancelled out (because of the differential nature of the inputs); hence only the signal voltage is “seen”.



**Figure 7.15**  
**Single Ended Voltage Input**



**Figure 7.16**  
**Differential Input Voltage Input**

**Battery Powered Instruments**

This is not always convenient due to battery life time; but it can provide excellent isolation.



### 7.2.4 Suppression Techniques

Areas to keep your eye out for as far as limiting the noise at the source are two simple examples:

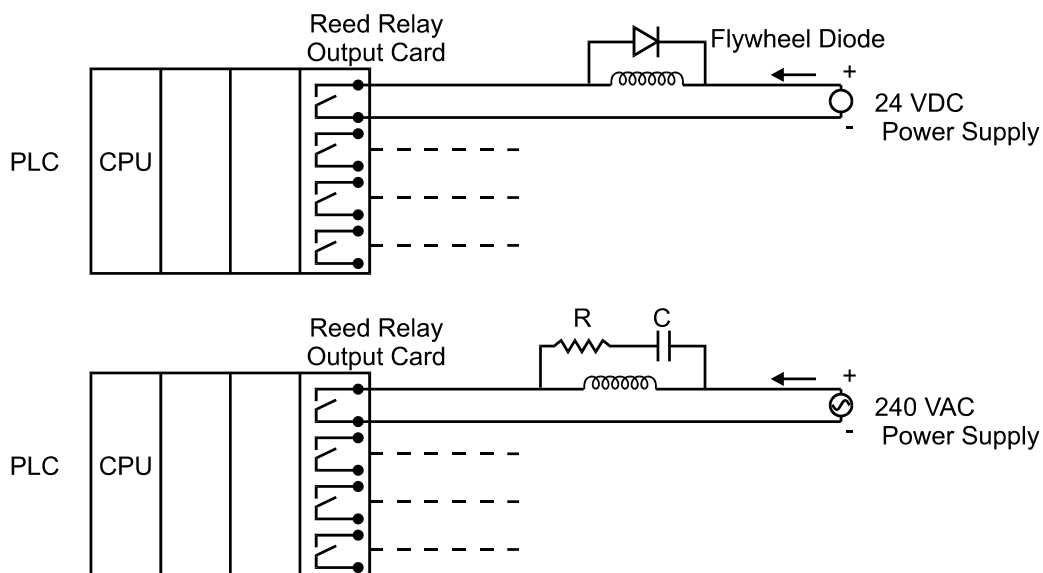
#### Switching Direct Current (dc)

When switching a coil, there is often a back emf generated across the coil when the contact is opened. This can damage the contacts and also put nasty transients into the system and cause a spike on some of the instrumentation signals.

Putting a flywheel diode across the coil can easily reduce this, allowing an easy path for the back emf energy to dissipate.

#### Switching Alternating Current (ac)

There is a similar situation when switching a coil but using ac. In this case a suppression RC network with 0.1 microfarads and 100 ohm resistor may remedy the problem.



**Figure 7.17**  
*Suppression of Transients (for ac circuits)*

## 7.3 Materials of Construction

Often when selecting measurement or control equipment, options are available for the various materials of construction. The primary concern is that the process material will not cause deterioration or damage to the device. Fluid compatibility tables are readily available from suppliers and one such chart is listed in the appendix.

Below is a brief list of other qualities or characteristics that assist in the selection of the material of construction.

316SS

Hastelloy C-276

Monel

Carbon steel

Beryllium copper

- good elastic qualities

Ni-Span C

- very low temperature coefficient of elasticity

Inconel

- extreme operating temperatures and corrosive process

Stainless Steel

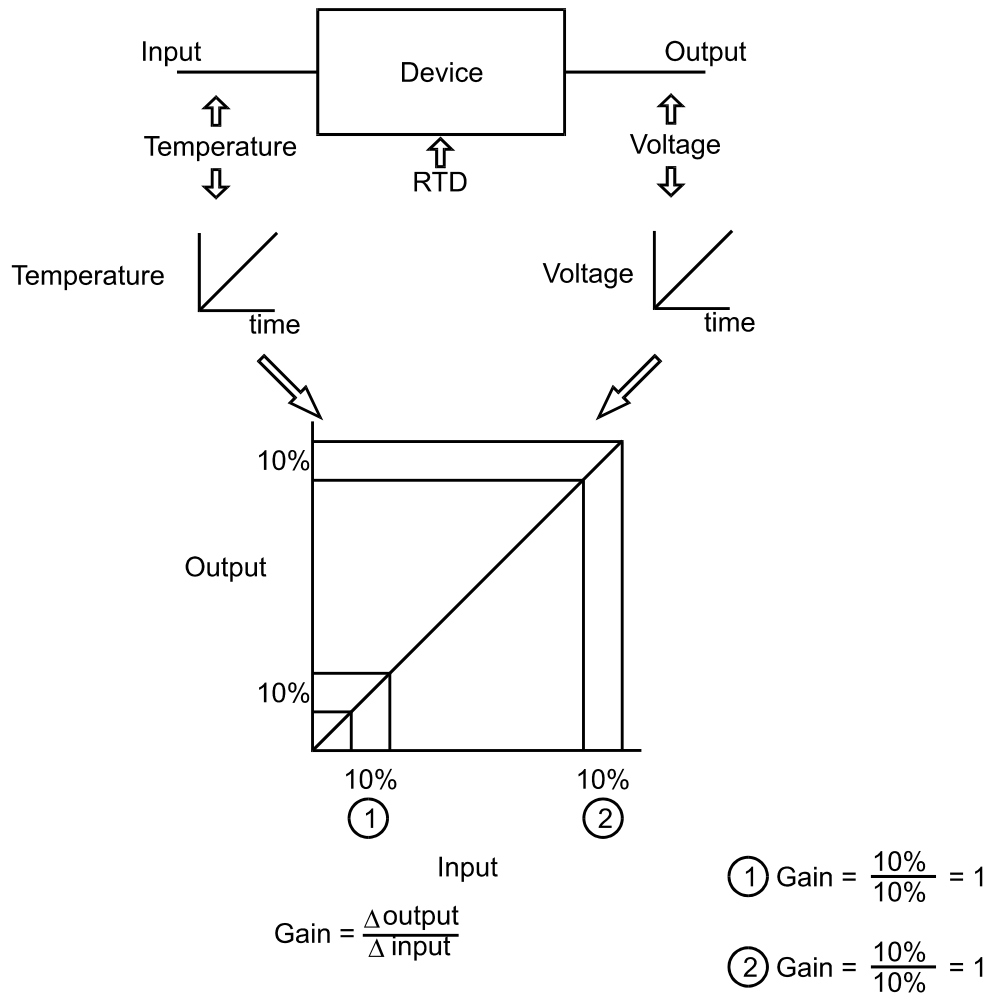
- extreme operating temperatures and corrosive process

Quartz

- Minimum hysteresis and drift

## **7.4 Linearisation**

When the output of a device responds at a proportional rate to changes in the input, then the device is linear.



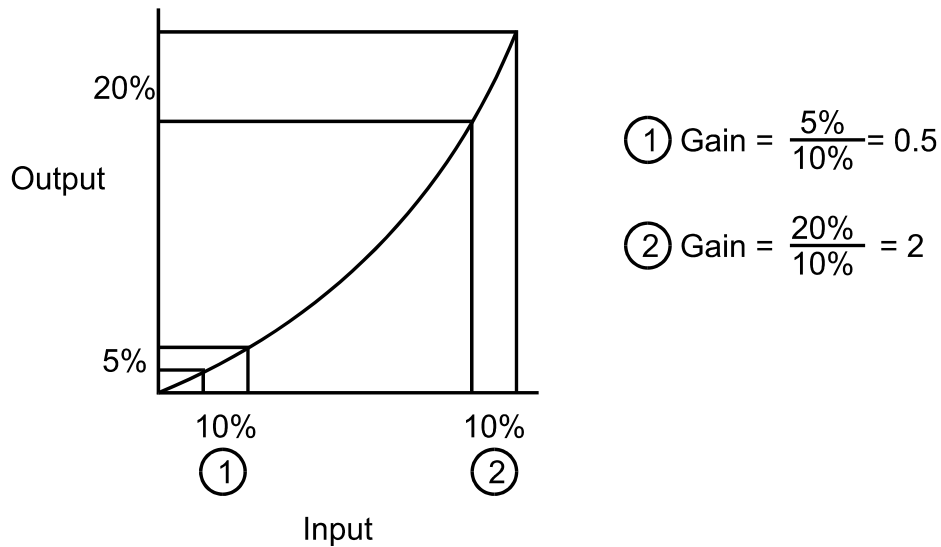
**Figure 7.18**  
**A linear device**

When the device is linear then there is a constant gain (output/input) over the full range of operation and the resolution remains constant.

There are two main problems, when the device is not linear:

- The gain changes
- The resolution and accuracy change

The affect of this mainly occurs in continuous control applications where the control loop dynamics are affected. Data acquisition and alarming are generally unaffected by linearisation problems as they detect and measure point information only. Control systems monitor and provide control based on how the measurement changes over time.



**Figure 7.19**  
**A non-linear device**

If the response or reaction of some device in a system is not linear then it may need to be made linear.

In a control system there are three ways to account for non-linear equipment:

- Base application on the highest gain
- Measure the gain at a number of points
- Modify the gain as a function of the process variable

The simpler way to overcome non-linearity is to linearise the signal before the control system calculations.

Thermocouples are inherently non-linear. In a typical control system (ie. a PLC system) they can be connected by two ways:

- Analogue card
- Thermocouple card

An analogue card would measure the voltage and convert this into a digital number. The problem would arise in that the number is not easily scaled into engineering units (ie. °C).

When the thermocouple is wired into a thermocouple card, the signal is not only converted into engineering units such as °C, but it is therefore also linearised. The thermocouple card has the functions for the various thermocouple types, and the processing power to perform the conversion.

# Tips and Tricks



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# Tips and Tricks







# 8

## Integration of the System

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# Chapter 8

## Integration of the System

### 8.1 Calculation of Individual Instruments and Total Error for the System

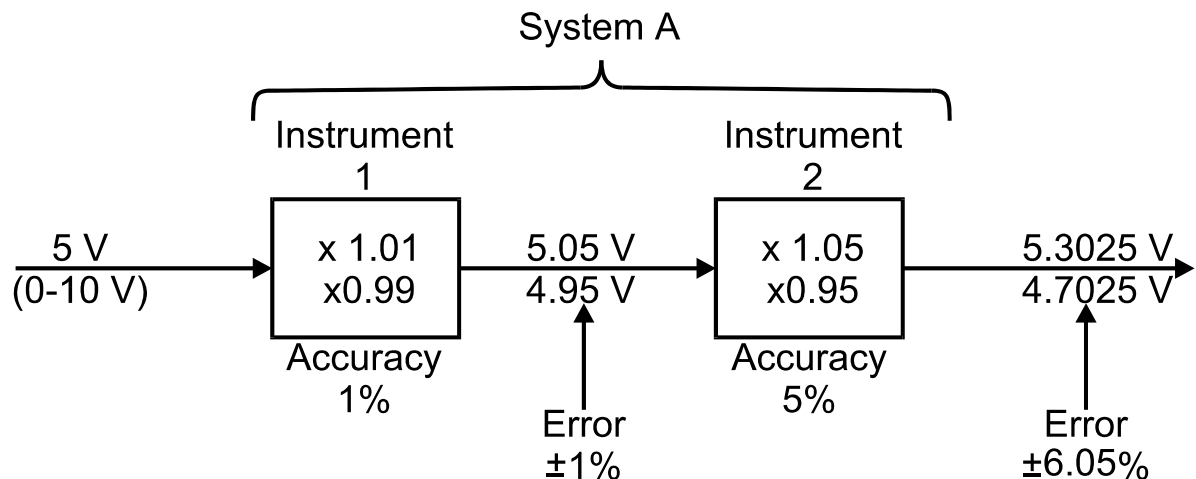
The accuracy specified for an instrument (eg. 1%) is the error or inaccuracy of any measurement performed with that device. This is assuming that the device is operating within its specifications.

Error calculations become more complex when looking at multiple instruments, or systems with more than one component, or even devices that perform calculations on process measurements.

Throughout this section we will use a signal of 0 - 10V to represent 0 - 100%, this will simplify calculations.

#### 8.1.1 Linear Devices in Series

When combining devices in series, the errors are multiplied. In multiplying any inaccuracy, it is a common mistake to simply multiply out the inaccuracies. The total error takes into account the total measurement with the variation.



**Figure 8.1**  
*Multiple Instruments connected in Series.*

If Instrument 1 (as shown) has an incoming signal of 5V, with an accuracy of 1%, then the error in the output will give a signal from 4.95V to 5.05V.

Note that:  $5V \times 1.01 = 5.05V$  maximum measurement due to error  
 $5V \times 0.99 = 4.95V$  minimum measurement due to error

When Instrument 2 receives 5.05V, with its accuracy of 5%, then the error in the output will give an upper value of  $5.05V \times 1.05 = 5.3025V$ . The minimum measurement due to error will be  $4.95V \times 0.95 = 4.7025V$ .

Note that:  $5.05V \times 1.05 = 5.3025V$  maximum measurement due to error  
 $4.95V \times 0.95 = 4.7025V$  minimum measurement due to error

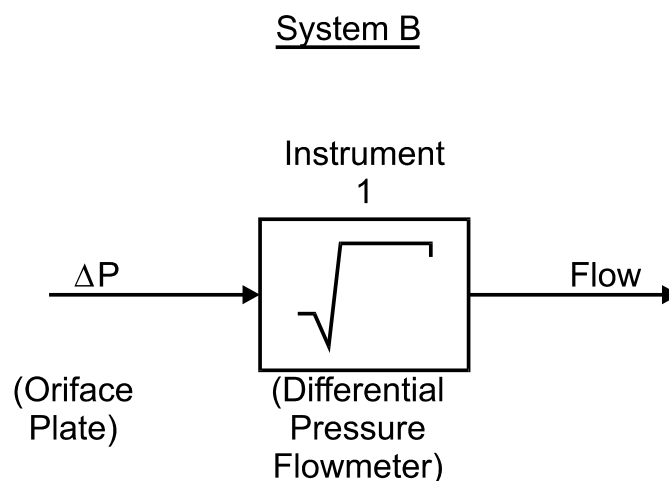
So the maximum output value due to the errors is:

$$\begin{aligned} &5V \times (\text{Instrument 1 error}) \times (\text{Instrument 2 error}) \\ &= 5V \times 1.01 \times 1.05 \\ &= 5V \times 1.0605 \\ &= 5.3025V \end{aligned}$$

The error in this system, System A, is **6.05%**.

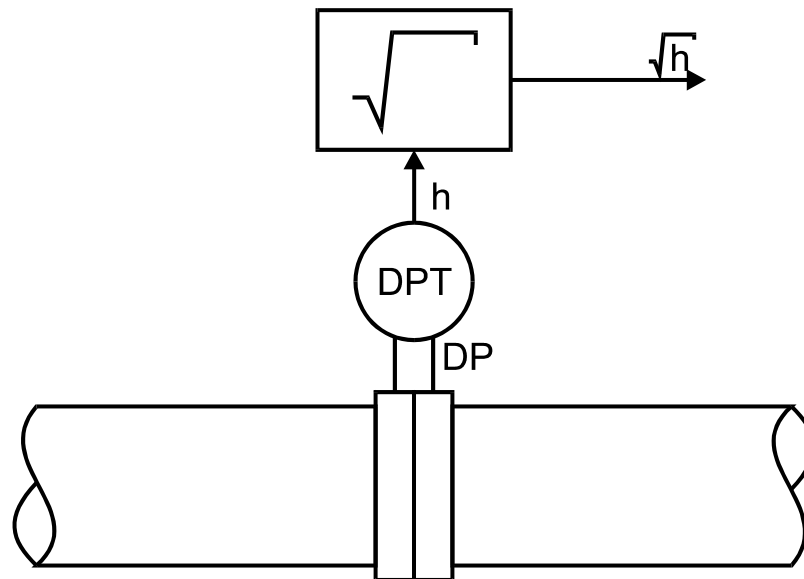
### 8.1.2 Non Linear Devices

One of the most common non linear devices used for process measurement is the flowmeter with differential producers. The flow in these devices is calculated from the square root of the measured pressure in the primary element. Any errors in the differential pressure measurement affects the calculated flow.



**Figure 8.2**  
**Differential Flow Meter.**

As the flow is deduced from the square root calculation, the magnitude of the errors are also affected by such a calculation.



**Figure 8.3**  
**Calculation of Total Error.**

Actual flow, f (%)	Actual flow, df (0-1.0)	Change in DP, dDP	Change in transmitted signal, dh	Change in calculated flow, dSQRT(h)	Error in calculated flow
100	1.00	2.00	2.02	1.01	1%
80	0.80	1.28	1.30	0.82	2%
60	0.60	0.72	0.76	0.64	4%
40	0.40	0.32	0.41	0.51	11%
20	0.20	0.08	0.26	0.66	46%
10	0.10	0.02	0.25	1.25	115%
5	0.05	0.005	0.26	2.50	245%

**Table 8.1**  
**Calculation of error in non-linear device**

**Column 1: Actual flow, f(%)**

This is the actual volumetric flow through the system.

**Column 2: Actual flow, df (0-1.0)**

This is the normalised flow, simply converted from percent for calculations.

**Column 3: Change in DP, dDP**

This is the change in DP detected for the specified flow rates.

This is calculated from the flow as follows:

$$DP = f^2$$

therefore, the change in DP is represented as,

$$dDP = 2f \cdot df$$

#### **Column 4: Change in transmitted signal, dh**

The transmitted signal is the pressure measurement with the combined transmitter error. For this example an error of 0.25% is used.

$$dh = dDP$$

However, the error needs to be added in. This is done by root mean square as follows,

$$dh = \text{SQRT}(dDP^2 + e^2)$$

#### **Column 5: Change in calculated flow, dSQRT(h)**

$$d\text{SQRT}(h) = dh / 2f$$

#### **Column 6: Error in calculated flow**

Without an error in the transmitter ( $e = 0$ ), then column 2 (Actual flow,  $df$ ) should be equal to column 5 (Change in calculated flow). The differences are due to the error,  $e=0.25\%$  in the transmitter and can be seen to be quite large at lower flowrates.

### **8.1.3 Other Non Linear Devices**

Other such instruments with non linear calculations are:

- Flumes and rectangular weirs with flows calculated as follows,

$$f = h^{3/2}$$

- V-notch weirs use a separate formula,

$$f = h^{5/2}$$

## 8.2 Selection Considerations

A comprehensive list for selecting instruments would take into account the following:

- Accuracy
- Reliability
- Purchase price
- Installed cost
- Cost of ownership
- Ease of use
- Process medium, liquid/ steam/ gas
- Degree of smartness
- Repeatability
- Intrusiveness
- Sizes available
- Maintenance
- Sensitivity to vibration

Particular requirements for flow would include:

- Capability of measuring liquid, steam and gas
- Rangeability
- Turndown
- Pressure drop
- Reynolds number
- Upstream and downstream piping requirements

A more systematic approach to selection process measurement equipment would cover the following steps:

### ***Step 1      Application***

This is the requirement and purpose of the measurement.

- Monitor
- Control
- Indicate
- Point or continuous
- Alarm

### ***Step 2      Process Material Properties***

Many process measuring devices are limited by the process material that they can measure.

- Solids, liquids, gas or steam

- Conductivity
- Multiphase, liquid/gas ratio
- Viscosity
- Pressure
- Temperature

### ***Step 3 Performance***

This relates to the performance required in the application.

- Range of operation
- Accuracy
- Linearity (Accuracy may include linearity effects)
- Repeatability (Accuracy may include repeatability effects)
- Response time

### ***Step 4 Installation***

Mounting is one of the main concerns, but the installation does involve the access and other environmental concerns.

- Mounting
- Line size
- Vibration
- Access
- Submergence

### ***Step 5 Economics***

The associated costs determine whether the device is within the budget for the application.

- Purchase cost
- Installation cost
- Maintenance cost
- Reliability/ replacement cost

### ***Step 6 Environmental And Safety***

This relates to the performance of the equipment to maintain the operational specifications, and also failure and redundancy should be considered.

- Process emissions
- Hazardous waste disposal
- Leak potential
- Trigger system shutdown

### ***Step 7 Measuring Device/Technology***

At this stage the selection criteria is established and weighed up with readily available equipment. A typical example for flow is shown:

- |                         |                 |
|-------------------------|-----------------|
| - DP                    | - Orifice plate |
|                         | - Variable area |
| - Velocity              | - Magmeter      |
|                         | - Vortex        |
|                         | - Turbine       |
|                         | - Propeller     |
| - Positive displacement | - Oval gear     |
|                         | - Rotary        |
| - Mass flow             | - Coriolis      |
|                         | - Thermal       |

### ***Step 8 Supply By Vendors***

Limitations may be imposed, particularly with larger companies that have preferred suppliers, in which case the selections may be limited, or the procedure for purchasing new equipment may not warrant the time and effort for the application.

### ***Summary***

With any type of measurement (temperature, pressure, level, flow etc.) there is always the possibility of more than one available device being able to satisfy the selection criteria. Conversely there is also the chance that there is no equipment that will perform the task to the required specifications. The order of priority of the selection criteria is very much dependent on the application.

## **8.3 Testing and Commissioning of the Subsystems**

Test procedures vary from one operation to the next, and are generally dependent on how critical the equipment going into service is. In a non-critical application, where the instrument operation will not affect production, the preliminary checks can be performed on the device with it tested insitu.

More critical applications may involve the instrument to be tested on the bench before being placed in operation. Even after installation any outputs should be disabled until the correct operation of the device is proven.

Correct operation requires more than checking that the instrument works. To ensure that it is configured correctly, both for the process measurement and any alarming, trip or indication points should be tested. The interface to the Operator Interface Terminal (OIT) should also be checked.



Below are steps for a testing procedure for the worst case (most critical) application, with steps easily omitted for less critical cases as required.

- Check correct installation of the instrument  
This also includes grounding and isolation as required. Termination of the wire shields should be at one end only, unless used for an instrument ground path. Verify wire numbering and device tag number.
- Check power supply.  
The reliability of the instrument is also dependent on the supply. Obviously if the main supply fails then that part of the process will not be able to proceed. However, from the instrument point of view, checks should be performed to verify the voltage rating and the proper allocation of breakers or fuses. This will also include the power supplied to I/O cards on such systems.
- Before applying power  
The field wiring should be isolated as well as possible from the digital system until loop commissioning or checkout is complete. This mainly applies to any output devices and can be done by removing fuses, unplugging terminal blocks or lifting isolation links.
- Apply power  
Initial checks should be performed on the system sensibility.  
Check:
  - Indicating lights on system modules
  - Any alarms for validity
  - Temperature inputs for ambient readings
  - Pressure, level and flow for minimum readings
  - System communications
  - Smart instrument communications
- Check loop voltages  
Loop voltages should be checked under load and monitored.
- Check proper calibration of the instrument.  
The vendor usually does this to meet equipment specifications. If required this can be performed remotely with appropriated test equipment before installation into service.
- Loop checkout  
Each loop should be checked for proper operation from the instrument to the digital system. It often depends on the test equipment available and the process as to how much simulation is performed.
- Simulations  
A number of parts of the system can be simulated. This is not always a necessity, but by checking parts of the system faulty components can be eliminated. Such simulations are:
  - The transducer signal, or the input to the instrument

- The instrument signal, or the input to the controller
- The signal to the control device

Simulations can be performed at a number of values, but the more common being:

- The minimum or lower range value, 0%
  - The maximum or upper range value, 100%
  - The mid range value, 50%
  - Alarming points
  - Control points
- 
- Check trips, interlocks and shutdown procedure.  
This is vital before the system is placed into any form of automatic control operation. This is often performed by manually actuating switches and checking that interlocks function as required.
  - Automatic Control  
PID controllers should be started in manual mode. Progression to automatic mode should be done under stable conditions and with one loop at a time. The actual procedure for achieving full automatic control of a plant is quite specific to the application. However, by activating automatic control with one loop at a time, it will be much easier to troubleshoot, test and tune the individual loops.

### **8.3.1 *Prior considerations and budgeting requirements***

This test procedure assumes that all associated personnel are familiar with instrumentation and digital systems. Allowances may be required should suitable experience not be available. This may require additional supervision or even the assistance of consulting support.

Loop checkout can be tedious and may require a substantial amount of organisation for large installations. Usually several stages of loop checkout occur before the final check. Sometimes, the application may require a more extensive test, such as running nitrogen, water, or a similar safe process medium through the facility and checking the control operation. The suitability of the medium used for testing must be checked, as it may not respond as the correct sensing material would, or may not work with the instruments engineered for the actual process.

The project budget and schedule will dictate the extent to which the system can be tested, but thorough testing increases familiarity of personnel involved and the chances for a smooth and safe start-up.

It is also good practice to involve the facility operators and maintenance personnel in the later stages of the installation and start-up of the process, this includes loop commissioning. This eases the handover to the facility personnel who will be using the system and are ultimately responsible for production.

# Tips and Tricks



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