INTRODUCTION: THEORY OF MEASUREMENT

Introduction to measurements Theory:

1.1 Purpose and performance of measurement systems

We begin by defining a **process** as a system which generates **information**. Examples are a chemical reactor, a jet fighter, a gas platform, a submarine, a car, a human heart, and a weather system.

Table 1.1 lists **information variables** which are commonly generated by processes:

Thus a car generates displacement, velocity and acceleration variables, and a chemical reactor generates temperature, pressure and composition variables.

Table 1.1 Common information/measured variables.

Acceleration	Density
Velocity	Viscosity
Displacement	Composition
Force–Weight	pH
Pressure	Humidity
Torque	Temperature
Volume	Heat/Light flux
Mass	Current
Flow rate	Voltage
Level	Power

We then define the **observer** as a person who needs this information from the process. This could be the car driver, the plant operator or the nurse. The purpose of the **measurement system** is to link the observer to the process, as shown in Figure 1.1. Here the observer is presented with a number which is the current value of the information variable. We can now refer to the information variable as a **measured variable**. The input to the measurement system is the **true value** of the variable; the system output is the **measured value** of the variable.

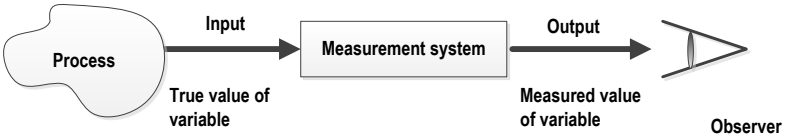


Figure 1.1 Purpose of measurement system

In an ideal measurement system, the measured value would be equal to the true value. The **accuracy** of the system can be defined as the closeness of the measured value to the true value. A perfectly accurate system is a theoretical ideal and the accuracy of a real system is quantified using **measurement system error** *E*, where

E = measured value − true value

E = system output − system input

Thus if the measured value of the flow rate of gas in a pipe is 11.0 m3/h and the true value is 11.2 m3/h, then the error *E* = −0.2 m3/h. If the measured value of the rotational speed of an engine is 3140 rpm and the true value is 3133 rpm, then *E* = +7 rpm. Error is the main performance indicator for a measurement system.

1.2 Structure of measurement systems

The measurement system consists of several elements or blocks. It is possible to identify four types of element, although in a given system one type of element may be missing or may occur more than once. The four types are shown in Figure 1.2 and can be defined as follows.

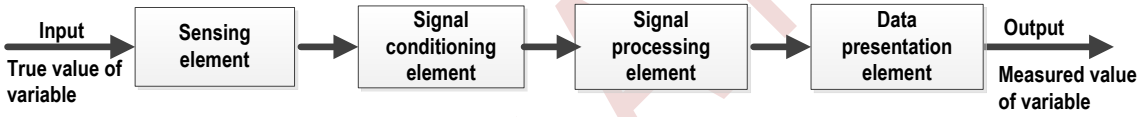


Figure 1.2 General structure of measurement system.

Sensing element

This is in contact with the process and gives an output which depends in some way on the variable to be measured. Examples are:

- Thermocouple where millivolt E.M.F. depends on temperature
- Strain gauge where resistance depends on mechanical strain
- Orifice plate where pressure drop depends on flow rate.

If there is more than one sensing element in a system, the element in contact with the process is termed the primary sensing element, the others secondary sensing elements.

Signal conditioning element

This takes the output of the sensing element and converts it into a form more suitable for further processing, usually a D.C. voltage, D.C. current or frequency signal. Examples are:

- Deflection bridge which converts an impedance change into a voltage change
- Amplifier which amplifies millivolts to volts
- Oscillator which converts an impedance change into a variable frequency voltage.

Signal processing element

This takes the output of the conditioning element and converts it into a form more suitable for presentation.

Examples are:

- Analogue-to-digital converter (ADC) which converts a voltage into a digital form for input to a computer
- Computer which calculates the measured value of the variable from the incoming digital data.

Typical calculations are:

- Computation of total mass of product gas from flow rate and density data
- Integration of chromatograph peaks to give the composition of a gas stream
- Correction for sensing element non-linearity.

Data presentation element

This presents the measured value in a form which can be easily recognized by the observer. Examples are:

- Simple pointer–scale indicator
- Chart recorder
- Alphanumeric display
- Visual display unit (VDU).

1.3 Examples of measurement systems

Figure 1.3 shows some typical examples of measurement systems. Figure 1.3(a) shows a temperature system with a thermocouple sensing element; this gives a millivolt output. Signal conditioning consists of a circuit to compensate for changes in reference junction temperature, and an amplifier. The voltage signal is converted into digital form using an analogue-to-digital converter, the computer corrects for sensor non-linearity, and the measured value is displayed on a VDU.

In Figure 1.3(b) the speed of rotation of an engine is sensed by an electromagnetic tachogenerator which gives an a.c. output signal with frequency proportional to speed. The Schmitt trigger converts the sine wave into sharp-edged pulses which are then counted over a fixed time interval. The digital count is transferred to a computer which calculates frequency and speed, and the speed is presented on a digital display.

The flow system of Figure 1.3(c) has an orifice plate sensing element; this gives a differential pressure output. The differential pressure transmitter converts this into a current signal and therefore combines both sensing and signal conditioning stages. The ADC converts the current into digital form and the computer calculates the flow rate, which is obtained as a permanent record on a chart recorder. The weight system of Figure 1.3(d) has two sensing elements: the primary element is a cantilever which converts weight into strain; the strain gauge converts this into a change in electrical resistance and acts as a secondary sensor. There are two

signal conditioning elements: the deflection bridge converts the resistance change into millivolts and the amplifier converts millivolts into volts. The computer corrects for non-linearity in the cantilever and the weight is presented on a digital display.

The word '**transducer**' is commonly used in connection with measurement and instrumentation. This is a manufactured package which gives an output voltage (usually) corresponding to an input variable such as pressure or acceleration. We see therefore that such a transducer may incorporate both sensing and signal conditioning elements; for example a weight transducer would incorporate the first four elements shown in Figure 1.3(d).

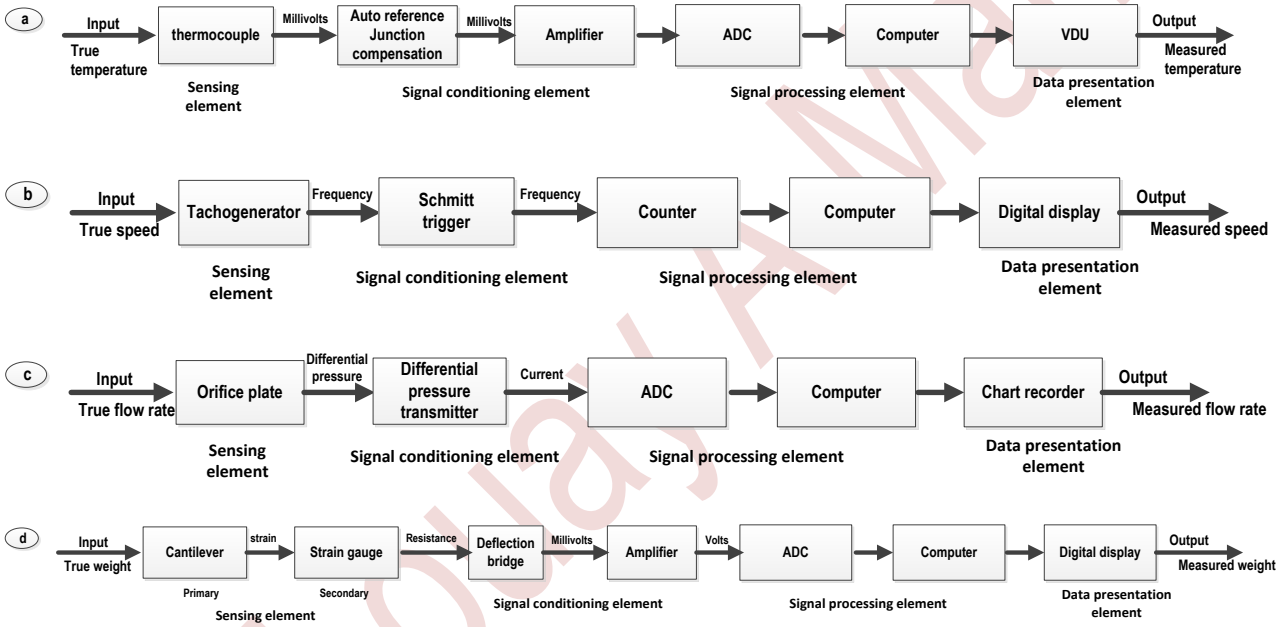


Figure 1.3 Examples of measurement systems.

Calibration:

Principles of Calibration

Calibration: consists of comparing the output of the instrument or sensor under test against the output of an instrument of known accuracy when the same input (the measured quantity) is applied to both instruments. This procedure is carried out for a range of inputs covering the whole measurement range of the instrument or sensor. Calibration ensures that the measuring accuracy of all instruments and sensors used in a measurement system is known over the whole measurement range, provided that the calibrated instruments and sensors are used in environmental conditions that are the same as those under which they were calibrated. For use of instruments and sensors under different environmental conditions, appropriate correction has to be made for the ensuing modifying inputs. Whether applied to instruments or sensors, calibration procedures are identical, and hence only the term instrument will be with the understanding that whatever is said for instruments applies equally well to single measurement sensors.

Instrument calibration has to be repeated at prescribed intervals because the characteristics of any instrument change over a period. Changes in instrument characteristics are brought about by such factors as:

Mechanical wear

The effects of dirt

Dust

Fumes

Chemicals

Temperature change in the operating environment.

Control of Calibration Environment

Any instrument used as a standard in calibration procedures must be kept solely for calibration duties and must never be used for other purposes. Most particularly, it must not be regarded as a spare instrument that can be used for process measurements if the instrument normally used for that purpose breaks down. Proper provision for process instrument failures must be made by keeping a spare set of process instruments. Standard calibration instruments must be totally separate.

To ensure that these conditions are met, the calibration function must be managed and executed in a professional manner. This will normally mean setting aside a particular place within the instrumentation department of a company where all calibration operations take place and where all instruments used for calibration are kept. As far as possible this should take the form of a separate room rather than a sectioned-off area in a room used for other purposes as well. This will enable better environmental control to be applied in the calibration area and will also offer better protection against unauthorized handling or use of calibration instruments. The level of environmental control required during calibration should be considered carefully with

due regard to what level of accuracy is required in the calibration procedure, but should not be over specified, as this will lead to unnecessary expense. Full air conditioning is not normally required for calibration at this level, as it is very expensive, but sensible precautions should be taken to guard the area from extremes of heat or cold; also, good standards of cleanliness should be maintained.

While it is desirable that all calibration functions are performed in this carefully controlled environment, it is not always practical to achieve this. Sometimes, it is not convenient or possible to remove instruments from a process plant, and in these cases, it is standard practice to calibrate them in situ. In these circumstances, appropriate corrections must be made for the deviation in the calibration environmental conditions away from those specified. This practice does not obviate the need to protect calibration instruments and maintain them in constant conditions in a calibration laboratory at all times other than when they are involved in such calibration duties on plant.

As far as management of calibration procedures is concerned, it is important that the performance of all calibration operations is assigned as the clear responsibility of just one person. That person should have total control over the calibration function and be able to limit access to the calibration laboratory to designated, approved personnel only. Only by giving this appointed person total control over the calibration function can the function be expected to operate efficiently and effectively. Lack of such definite management can only lead to unintentional neglect of the calibration system, resulting in the use of equipment in an out-of-date state of calibration and subsequent loss of traceability to reference standards.

Professional management is essential so that the customer can be assured that an efficient calibration system is in operation and that the accuracy of measurements is guaranteed.

Calibration procedures that relate in any way to measurements used for quality control functions are controlled by the international standard ISO 9000 (this subsumes the old British quality standard BS 5750). One of the clauses in ISO 9000 requires that all persons using calibration equipment be adequately trained. The manager in charge of the calibration function is clearly responsible for ensuring that this condition is met. Training must be adequate and targeted at the particular needs of the calibration systems involved. People must understand what they need to know and especially why they must have this information. Successful completion of training courses should be marked by the award of qualification certificates. These attest to the proficiency of personnel involved in calibration duties and are a convenient way of demonstrating that the ISO 9000 training requirement has been satisfied.

Calibration Chain and Traceability

The calibration facilities provided within the instrumentation department of a company provide the first link in the calibration chain. Instruments used for calibration at this level are known as ***working standards***. As such, working standard instruments are kept by the instrumentation department of a company solely for calibration duties, and for no other purpose, and then it can be assumed that they will maintain their accuracy over a

reasonable period of time because use-related deterioration in accuracy is largely eliminated. However, over the longer term, the characteristics of even such standard instruments will drift, mainly due to aging effects in components within them. Therefore, over this longer term, a program must be instituted for calibrating working standard instruments at appropriate intervals of time against instruments of yet higher accuracy. The instrument used for calibrating working standard instruments is known as a ***secondary reference standard***. This must obviously be a very well-engineered instrument that gives high accuracy and is stabilized against drift in its performance with time. This implies that it will be an expensive instrument to buy. It also requires that the environmental conditions in which it is used be controlled carefully in respect of ambient temperature, humidity, and so on.

When the working standard instrument has been calibrated by an **authorized standards laboratory**, a calibration certificate will be issued. This will contain at least the following information:

- identification of the equipment calibrated
- calibration results obtained
- measurement uncertainty
- any use limitations on the equipment calibrated
- date of calibration
- authority under which the certificate is issued

The establishment of a company standards laboratory to provide a calibration facility of the required quality is economically viable only in the case of very large companies where large numbers of instruments need to be calibrated across several factories. In the case of small to medium size companies, the cost of buying and maintaining such equipment is not justified.

Instead, they would normally use the calibration service provided by various companies that specialize in offering a standards laboratory. What these specialist calibration companies do effectively is to share out the high cost of providing this highly accurate but infrequently used calibration service over a large number of companies. Such standards laboratories are closely monitored by national standards organizations.

National standards organizations usually monitor both instrument calibration and mechanical testing laboratories. The national standards organizations lay down strict conditions that a standards laboratory has to meet before it is approved. These conditions control laboratory management, environment, equipment, and documentation. The person appointed as head of the laboratory must be suitably qualified, and independence of operation of the laboratory must be guaranteed. The management structure must be such that any pressure to rush or skip calibration procedures for production reasons can be resisted. As far as the laboratory environment is concerned, proper temperature and humidity control must be provided, and high standards of cleanliness and housekeeping must be maintained. All equipment used for calibration purposes must be maintained to reference standards and supported by calibration certificates that establish this traceability.

Finally, full documentation must be maintained. This should describe all calibration procedures, maintain an index system for recalibration of equipment, and include a full inventory of apparatus and traceability schedules. Having met these conditions, a standards laboratory becomes an accredited laboratory for providing calibration services and issuing calibration certificates. This accreditation is reviewed at approximately 12 monthly intervals to ensure that the laboratory is continuing to satisfy the conditions for approval laid down.

Primary reference standards, describe the highest level of accuracy achievable in the measurement of any particular physical quantity. All items of equipment used in standards laboratories as secondary reference standards have to be calibrated themselves against primary reference standards at appropriate intervals of time. This procedure is acknowledged by the issue of a calibration certificate in the standard way.

National standards organizations maintain suitable facilities for this calibration. In the United States, this is the National Bureau of Standards, and in the United Kingdom it is the National Physical Laboratory. Similar national standards organizations exist in many other countries. In certain cases, such primary reference standards can be located outside national standards organizations. For instance, the primary reference standard for dimension measurement is defined by the wavelength of the orange-red line of krypton light, and it can therefore be realized in any laboratory equipped with an interferometer. In certain cases (e.g., the measurement of viscosity), such primary reference standards are not available and reference standards for calibration are achieved by collaboration between several national standards organizations who perform measurements on identical samples under controlled conditions [ISO 5725 (1994) and ISO 5725-2/Cor1 (2002)].

Example of micrometers typical calibration chain:

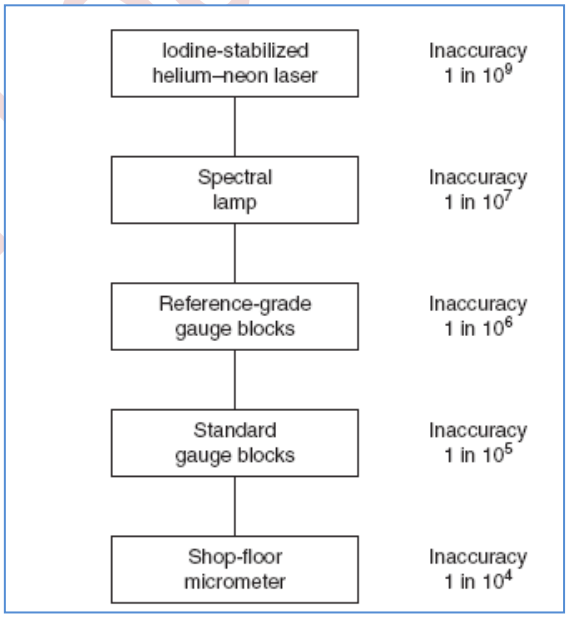


Figure 1.4 Typical calibration chain for micrometers.

To illustrate a typical calibration chain, consider the calibration of micrometers (Figure 1.4). A typical shop floor micrometer has an uncertainty (inaccuracy) of less than 1 in 10^4. These would normally be calibrated in the instrumentation department or standards laboratory of a company against laboratory standard gauge blocks with a typical uncertainty of less than 1 in 10^5. A specialist calibration service company would provide facilities for calibrating these laboratory standard gauge blocks against reference-grade gauge blocks with a typical uncertainty of less than 1 in 10^6. More accurate calibration equipment still is provided by national standards organizations. The National Bureau of Standards and National Physical Laboratory maintain two sets of standards for this type of calibration, a working standard and a primary standard. Spectral lamps are used to provide a working reference standard with an uncertainty of less than 1 in 10^7. The primary standard is provided by an iodine-stabilized helium–neon laser that has a specified uncertainty of less than 1 in 10^9. All of the links in this calibration chain must be shown in any documentation that describes the use of micrometers in making quality-related measurements.

Calibration Records

An essential element in the maintenance of measurement systems and the operation of calibration procedures is the provision of full documentation. This must give a full description of the measurement requirements throughout the workplace, instruments used, and calibration system and procedures operated. Individual calibration records for each instrument must be included within this.

This documentation is a necessary part of the quality manual, although it may exist physically as a separate volume if this is more convenient. An overriding constraint on the style in which the documentation is presented is that it should be simple and easy to read. This is often facilitated greatly by a copious use of appendices.

The starting point in the documentation must be a statement of what measurement limits have been defined for each measurement system documented. Such limits are established by balancing the costs of improved accuracy against customer requirements, and also with regard to what overall quality level has been specified in the quality manual. The technical procedures required for this, which involve assessing the type and magnitude of relevant measurement errors.

Instruments specified for each measurement situation must be listed next. This list must be accompanied by full instructions about the proper use of the instruments concerned. These instructions will include details about any environmental control or other special precautions that must be taken to ensure that the instruments provide measurements of sufficient accuracy to meet the measurement limits defined. The proper training courses appropriate to plant personnel who will use the instruments must be specified.

Having disposed of the question about what instruments are used, documentation must go on to cover the subject of calibration. Full calibration is not applied to every measuring instrument used in a workplace because ISO 9000 acknowledges that formal calibration procedures are not necessary for some equipment

where it is uneconomic or technically unnecessary because the accuracy of the measurement involved has an insignificant effect on the overall quality target for a product. However, any equipment excluded from calibration procedures in this manner must be specified as such in the documentation. Identification of equipment that is in this category is a matter of informed judgment.

For instruments that are the subject of formal calibration, documentation must specify what standard instruments are to be used for the purpose and define a formal procedure of calibration. This procedure must include instructions for the storage and handling of standard calibration instruments and specify the required environmental conditions under which calibration is to be performed. Where a calibration procedure for a particular instrument uses published standard practices, it is sufficient to include reference to that standard procedure in the documentation rather than to reproduce the whole procedure. Whatever calibration system is established, a formal review procedure must be defined in the documentation that ensures its continued effectiveness at regular intervals. The results of each review must also be documented in a formal way.

A standard format for the recording of calibration results should be defined in the documentation. A separate record must be kept for every instrument present in the workplace, irrespective of whether the instrument is normally in use or is just kept as a spare. A form similar to that shown in Figure 4.3 should be used that includes details of the instrument's description, required calibration frequency, date of each calibration, and calibration results on each occasion. Where appropriate, documentation must also define the manner in which calibration results are to be recorded on the instruments themselves.

Documentation must specify procedures that are to be followed if an instrument is found to be outside the calibration limits. This may involve adjustment, redrawing its scale, or withdrawing an instrument, depending on the nature of the discrepancy and the type of instrument involved. Instruments withdrawn will either be repaired or be scrapped. In the case of withdrawn instruments, a formal procedure for marking them as such must be defined to prevent them being put back into use accidentally.

Two other items must also be covered by the calibration document.

A) The traceability of the calibration system back to national reference standards must be defined and supported by calibration certificates (figure 1.6).

B)Training procedures must also be documented, specifying the particular training courses to be attended by various personnel and what, if any, refresher courses are required.

Kestrel® Pocket Weather® Meters
Certificate of Calibration – Air Speed

Figure 1.6 Example of temperature calibration simple.

Definitions and classification of variables:

Measurement Units

The first measurement units were those used in barter trade to quantify the amounts being exchanged and to establish clear rules about the relative values of different commodities. Such early systems of measurement were based on whatever was available as a measuring unit. For purposes of measuring length, the human torso was a convenient tool and gave us units of the hand, the foot, and the cubit. Although generally adequate for barter trade systems, such measurement units are, of course, imprecise, varying as they do from one person to the next. Therefore, there has been a progressive movement toward measurement units that are defined much more accurately.

The early establishment of standards for the measurement of physical quantities proceeded in several countries at broadly parallel times; in consequence, several sets of units emerged for measuring the same physical variable. For instance, length can be measured in yards, meters, or several other units. Apart from the major units of length, subdivisions of standard units exist such as feet, inches, centimeters, and millimeters, with a fixed relationship between each fundamental unit and its subdivisions. Yards, feet, and inches belong to the **Imperial system** of units, which is characterized by having varying and cumbersome multiplication factors relating fundamental units to subdivisions such as 1760 (miles to yards), 3 (yards to feet), and 12 (feet to inches). The **metric system** is an alternative set of units, which includes, for instance, the unit of the meter and its centimeter and millimeter subdivisions for measuring length.

Table 1.1 Definitions of Standard Units

(a) Fundamental Units		
Physical Quantity	**Standard**	**Definition**
Length	Meter/ symbol	Length of path traveled by light in an interval of 1/299,792,458 seconds
Mass	Kilogram kg	Mass of a platinum–iridium cylinder kept in the International Bureau of Weights and Measures, Sevres, Paris
Time	Second s	9.192631770 x10^9 cycles of radiation from vaporized cesium 133 (an accuracy of 1 in 10^{12} or one second in 36,000 years)
Temperature	Degrees K	Temperature difference between absolute zero Kelvin and the triple point of water is defined as 273.16 K
Current	Amphere A	One ampere is the current flowing through two infinitely long parallel conductors of negligible cross section placed 1 meter apart in vacuum and producing a force of 2 x 10 $^{-7}$ newtons per meter length of conductor
Luminous intensity	Candela cd	source emitting monochromatic radiation at a frequency of 540 terahertz (Hz x 10^{12}) and with a radiant density in that direction of 1.4641 mW/steradian (1 steradian is the solid angle, which, having its vertex at the center of a sphere, cuts off an area of the sphere surface equal to that of a square with sides of length equal to the sphere radius)
Matter	Mole mol	Number of atoms in a 0.012-kg mass of carbon 12
(b) Supplementary Fundamental Units		
Plane angle	Radian rad	
Solid angle	Steradian sr	

As a result of this, an internationally agreed set of standard units (SI units or Syste`mes internationales d'unite´s) has been defined, and strong efforts are being made to encourage the adoption of this system throughout the world. In support of this effort, the SI system of units is used exclusively in this book. However, it should be noted that the Imperial system is still widely used in the engineering industry, particularly in the United States. The full range of fundamental SI measuring units and the further set of units derived from them are given in Tables 1.1 and 1.2.

Table 1.2 Derived SI Units

Quantity	**Standard Unit**	**Symbol**	**Derivation Formula**
Area	Square meter	m^2	
Volume	cubic meter	m^3	
Velocity	meter per second	m/s	
Acceleration	metre per second squared	m/s^2	
Angular velocity	radian per second	rad/s	
Angular acceleration	radian per second squared	rad/s^2	
Density	kilogram per cubic meter	kg/m^3	
Specific volume	cubic meter per kilogram	m^3/kg	
Mass flow	rate kilogram per second	kg/s	
Volume flow rate	cubic meter per second	m^3/s	
Force	newton	N	$kg\text{-}m/s^2$
Pressure	pascal	Pa	N/m^2

Torque	newton meter	N-m	
Momentum	kilogram meter per second	kg-m/s	
Moment of inertia	kilogram meter squared	kg-m^2	
Kinematic viscosity	square meter per second	m^2/s	
Dynamic viscosity	newton second per square meter	N-s/m^2	
Work, energy, heat	joule	J	N-m
Specific energy	joule per cubic meter	J/m^3	
Power	watt	W	J/s
Thermal conductivity	watt per meter Kelvin	W/m-K	
Electric charge	coulomb	C	A-s
Voltage, e.m.f., pot diff	volt	V	W/A
Electric field strength	volt per meter	V/m	
Electric resistance	ohm	Ω	V/A
Electric capacitance	farad	F	A-s/V
Electric inductance	henry	H	V-s/A
Electric conductance	siemen	S	A/V
Resistivity	Ohm-meter	Ω-m	
Permittivity	farad per meter	F/m	
Permeability	henry per meter	H/m	
Current density	ampere per square meter	A/m^2	
Magnetic flux	weber	Wb	V-s
Magnetic flux	density tesla	T	Wb/m^2
Magnetic field strength	ampere per meter	A/m	
Frequency	hertz	Hz	s^{-1}
Luminous flux	lumen	lm	cd-sr
Luminance	candela per square meter	cd/m^2	
Illumination	lux	lx	lm/m^2
Molar volume	cubic meter per mole	m^3/mol	
Molarity	mole per kilogram	mol/kg	
Molar energy	joule per mole	J/mol	

TYPES OF INSTRUMENTS

2. Introduction

Two of the important aspects of measurement covered in the opening chapter concerned how to choose appropriate instruments for a particular application and a review of the main applications of measurement. Both of these activities require knowledge of the characteristics of different classes of instruments and, in particular, how these different classes of instrument perform in different applications and operating environments.

2.1 Instrument Types:

Instruments can be subdivided into separate classes according to several criteria. These sub classifications are useful in broadly establishing several attributes of particular instruments such as accuracy, cost, and general applicability to different applications.

2.1.1 Active and Passive Instruments

Instruments are divided into active or passive ones according to whether instrument output is produced entirely by the quantity being measured or whether the quantity being measured simply modulates the magnitude of some external power source. This is illustrated by examples:

An example of a *passive instrument* is the pressure-measuring device shown in Figure 2.1. The pressure of the fluid is translated into movement of a pointer against a scale. The energy expended in moving the pointer is derived entirely from the change in pressure measured: there are no other energy inputs to the system.

An example of an *active instrument* is a float-type petrol tank level indicator as sketched in Figure 2.2. Here, the change in petrol level moves a potentiometer arm, and the output signal consists of a proportion of the external voltage source applied across the two ends of the potentiometer. The energy in the output signal comes from the external power source: the primary transducer float system is merely modulating the value of the voltage from this external power source.

In *active instruments*, the external power source is usually in electrical form, but in some cases, it can be other forms of energy, such as a pneumatic or hydraulic one. One very important difference between active and passive instruments is the level of measurement resolution that can be obtained. With the simple pressure gauge shown, the amount of movement made by the pointer for a particular pressure change is closely defined by the nature of the instrument. While it is possible to increase measurement resolution by making the pointer longer, such that the pointer tip moves through a longer arc, the scope for such improvement is clearly restricted by the practical limit of how long the pointer can conveniently be. In an *active instrument*, however, adjustment of the magnitude of the

external energy input allows much greater control over measurement resolution. While the scope for improving measurement resolution is much greater incidentally, it is not infinite because of limitations placed on the magnitude of the external energy input, in consideration of heating effects and for safety reasons.

In terms of cost, passive instruments are normally of a more simple construction than active ones and are therefore less expensive to manufacture. Therefore, a choice between active and passive instruments for a particular application involves carefully balancing the measurement resolution requirements against cost.

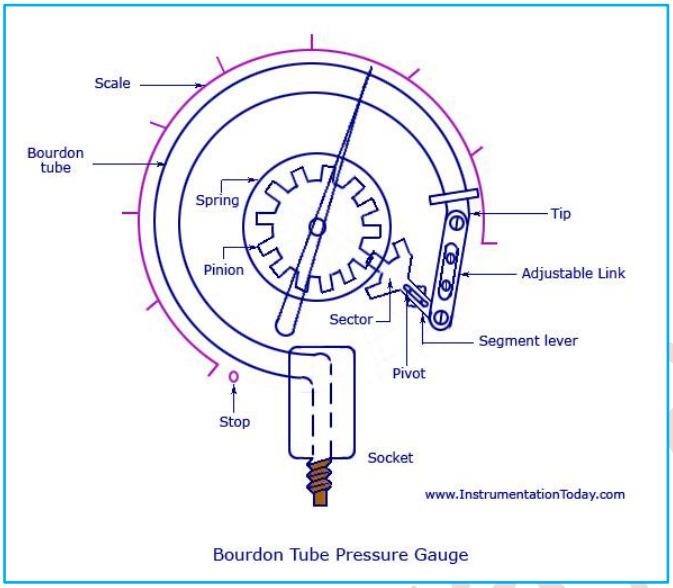


Figure 2.1 passive pressure gauge.

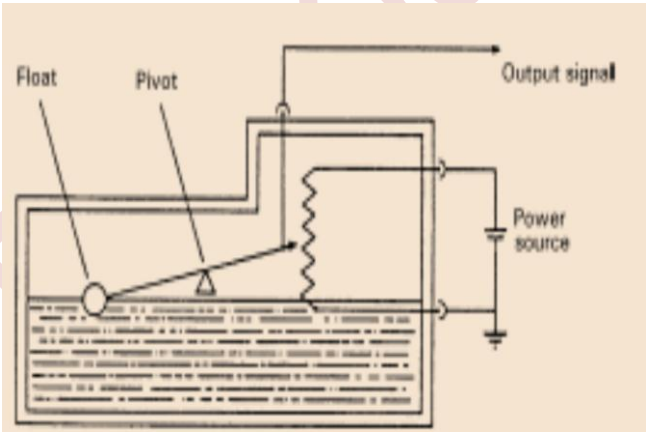


Figure 2.2 petrol –tank level indicator

2.1.2 Null-Type and Deflection-Type Instruments

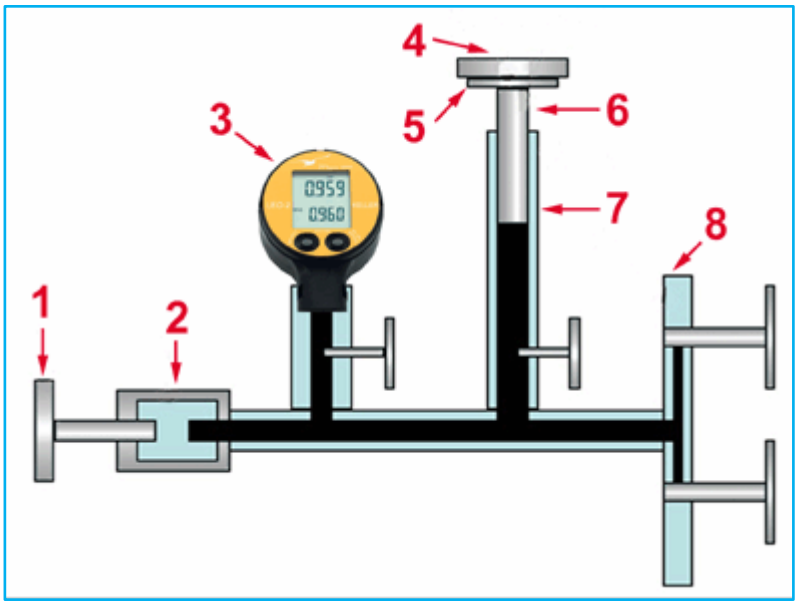
The *pressure gauge* just mentioned is a good example of a *deflection type* of instrument, where the value of the quantity being measured is displayed in terms of the amount of movement of a pointer. An alternative type of pressure gauge is the dead-weight gauge shown in Figure 2.3, which is a null-type instrument. Here, weights are put on top of the piston until the downward force balances the fluid pressure. Weights are added until the piston reaches a datum level, known as the null point. Pressure measurement is made in terms of the value of the weights needed to reach this null position.

The accuracy of these two instruments depends on different things. For the *first* one it depends on the linearity and calibration of the spring, whereas for the *second* it relies on calibration of the weights. As calibration of weights is much easier than careful choice and calibration of a linear-characteristic spring, this means that the second type of instrument will normally be the more accurate. This is in accordance with the general rule that null-type instruments are more accurate than deflection types.

In terms of usage, a deflection-type instrument is clearly more convenient. It is far simpler to read the position of a pointer against a scale than to add and subtract weights until a null point is reached. A deflection-type instrument is therefore the one that would normally be used in the workplace. However, for calibration duties, a null-type instrument is preferable because of its superior accuracy. The extra effort required to use such an instrument is perfectly acceptable in this case because of the infrequent nature of calibration operations.

Figure 2.3 Dead-weight pressure gauge.

1 - Hand pump
2 - Testing Pump
3 - Pressure Gauge to be calibrated
4 - Calibration Weight
5 - Weight Support
6 - Piston
7 - Cylinder
8 - Filling Connection



2.1.3 Analogue and Digital Instruments

An *analogue instrument* gives an output that varies continuously as the quantity being measured changes. The output can have an infinite number of values within the range that the instrument is designed to measure. The deflection-type of pressure gauge described is a good example of an analogue instrument. As the input value changes, the pointer moves with a smooth continuous motion. While the pointer can therefore be in an infinite number of positions within its range of movement, the number of different positions that the eye can discriminate between is strictly limited; this discrimination is dependent on how large the scale is and how finely it is divided.

A *digital instrument* has an output that varies in discrete steps and so can only have a finite number of values. The rev counter sketched in Figure 2.4 is an example of a digital instrument. A cam is attached to the revolving body whose motion is being measured, and on each revolution the cam opens and closes a switch. The switching operations are counted by an electronic counter. This system can only count whole revolutions and cannot discriminate any motion that is less than a full revolution.

The distinction between *analogue* and *digital* instruments has become particularly important with rapid growth *in the application of microcomputers to automatic control systems*. Any digital computer system, of which the microcomputer is but one example, performs its computations in digital form. An instrument whose output is in digital form is therefore particularly advantageous in such applications, as it can be interfaced directly to the control computer. *Analogue instruments* must be interfaced to the microcomputer by an analogue to- digital (A/D) converter, which converts the analogue output signal from the instrument into an equivalent digital quantity that can be read into the computer. This conversion has *several disadvantages*. *First*, the A/D converter adds a significant cost to the system. *Second*, a finite time is involved in the process of converting an analogue signal to a digital quantity, and this time can be critical in the control of fast processes where the accuracy of control depends on the speed of the controlling computer. Degrading the speed of operation of the control computer by imposing a requirement for A/D conversion thus impairs the accuracy by which the process is controlled.

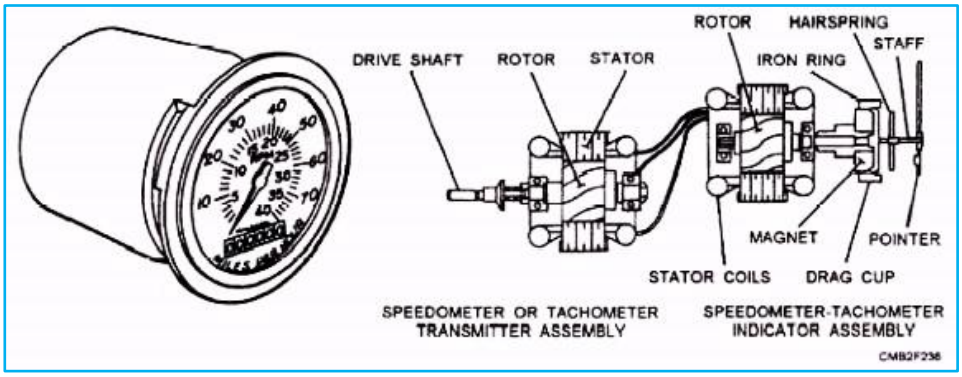


Figure2.4 revaluation counter

2.1.4 Indicating Instruments and Instruments with a Signal Output

The final way in which instruments can be divided is between those that merely give an audio or visual indication of the magnitude of the physical quantity measured and those that give an output in the form of a measurement signal whose magnitude is proportional to the measured quantity.

The class of indicating instruments normally includes all null-type instruments and most passive ones. Indicators can also be further divided into those that have an analogue output and those that have a digital display. A common *analogue indicator* is the liquid-in-glass thermometer. Electronic forms of bathroom scales have a digital output consisting of numbers presented on *an electronic* display. One major drawback with indicating devices is that human intervention is required to read and record a measurement. This process is particularly prone to error in the case of analogue output displays, although digital displays are not very *prone to error unless the human reader is careless.*

Instruments that have a signal-type output are used commonly as part of automatic control systems. In other circumstances, they can also be found in measurement systems where the output measurement signal is recorded in some way for later use. Usually, the measurement signal involved is an electrical voltage, but it can take other forms in some systems, such as an electrical current, an optical signal, or a pneumatic signal.

PERFORMANCE CHARACTERISTICS

3.0 Static Characteristics of Instruments:

If we have a thermometer in a room and its reading shows a temperature of 20°C, then it does not really matter whether the true temperature of the room is 19.5 or 20.5°C. Such small variations around 20°C are too small to affect whether we feel warm enough or not. Our bodies cannot discriminate between such close levels of temperature and therefore a thermometer with an inaccuracy of ±0.5°C is perfectly adequate.

If we had to measure the temperature of certain chemical processes, however, a variation of 0.5°C might have a significant effect on the rate of reaction or even the products of a process. A measurement inaccuracy much less than ±0.5°C is therefore clearly required.

Accuracy of measurement is thus one consideration in the choice of instrument for a particular application. Other parameters, such as sensitivity, linearity, and the reaction to ambient temperature changes, are further considerations. These attributes are collectively known as the static characteristics of instruments and are given in the data sheet for a particular instrument. It is important to note that values quoted for instrument characteristics in such a data sheet only apply when the instrument is used under specified standard calibration conditions. Due allowance must be made for variations in the characteristics when the instrument is used in other conditions.

The static characteristics are:

3.1.1 Accuracy and Inaccuracy (Measurement Uncertainty):

The ***accuracy*** of an instrument is a measure of how close the output reading of the instrument is to the correct value. In practice, it is more usual to quote the inaccuracy or measurement uncertainty value rather than the accuracy value for an instrument.

Inaccuracy or measurement uncertainty is the extent to which a reading might be wrong and is often quoted as a percentage of the full-scale (f.s.) reading of an instrument.

The aforementioned example carries a very important message. Because the maximum measurement error in an instrument is usually related to the full-scale reading of the instrument, *measuring quantities that are substantially less than the full-scale reading means that the possible measurement error is amplified*. For this reason, it is an important system design rule that instruments are chosen such that their range is appropriate to the spread of values being measured in order that the best possible accuracy is maintained in instrument readings. Clearly, if we are measuring pressures with expected values between 0 and 1 bar, we would not use an instrument with a measurement range of 0–10 bar.

Example 3.1

A pressure gauge with a measurement range of 0–10 bar has a quoted inaccuracy of ±1.0% f.s. (±1% of full-scale reading).

(a) What is the maximum measurement error expected for this instrument?

(b) What is the likely measurement error expressed as a percentage of the output reading if this pressure gauge is measuring a pressure of 1 bar?

Solution

(a) The maximum error expected in any measurement reading is 1.0% of the full-scale reading, which are 10 bars for this particular instrument. Hence, the maximum likely error is 1.0% x10 bar = **0.1 bar**.

(b) The maximum measurement error is a constant value related to the full-scale reading of the instrument, irrespective of the magnitude of the quantity that the instrument is actually measuring. In this case, as worked out earlier, the magnitude of the error is 0.1 bar. Thus, when measuring a pressure of 1 bar, the maximum possible error of 0.1 bar is **10%** of the measurement value.

3.1.2 Precision/Repeatability/Reproducibility:

Precision is a term that describes an instrument's degree of freedom from random errors. If a large number of readings are taken of the same quantity by a high-precision instrument, then the spread of readings will be very small. Precision is often, although incorrectly, confused with accuracy. High precision does not imply anything about measurement accuracy. A high-precision instrument may have a low accuracy. *Low accuracy measurements from a high-precision instrument are normally caused by a bias in the measurements, which is removable by recalibration.*

The terms ***repeatability*** and reproducibility mean approximately the same but are applied in different contexts. ***Repeatability*** describes the closeness of output readings when the same input is applied repetitively over a short period of time, with the same measurement conditions, same instrument and observer, same location, and same conditions of use maintained throughout.

Reproducibility describes the closeness of output readings for the same input when there are changes in the method of measurement, observer, measuring instrument, location, conditions of use, and time of measurement. Both terms thus describe the spread of output readings for the same input. This spread is referred to as repeatability if the measurement conditions are constant and as reproducibility if the measurement conditions vary.

3.1.3 Tolerance:

Tolerance is a term that is closely related to accuracy and defines the maximum error that is to be expected in some value. While it is not a static characteristic of measuring instruments, it is mentioned here because the accuracy of some instruments is sometimes quoted as a tolerance value. When used correctly, tolerance describes the maximum deviation of a manufactured component from some specified value. For instance, crankshafts are machined with a diameter tolerance quoted as so many micrometers (10^{-6} m), and electric circuit components such as resistors have tolerances of perhaps 5%.

Example 3.2

A packet of resistors bought in an electronics component shop gives the nominal resistance value as 1000 Ω and the manufacturing tolerance as ±5%. If one resistor is chosen at random from the packet, what is the minimum and maximum resistance value that this particular resistor is likely to have?

Solution

The minimum likely value is 1000 Ω – 5% = 950 Ω.

The maximum likely value is 1000 Ω + 5% = 1050 Ω.

3.1.4 Range or Span:

The range or span of an instrument defines the minimum and maximum values of a quantity that the instrument is designed to measure.

3.1.5 Linearity:

It is normally desirable that the output reading of an instrument is linearly proportional to the quantity being measured. The Xs marked on Figure 3.1 show a plot of typical output readings of an instrument when a sequence of input quantities is applied to it. Normal procedure is to draw a good fit straight line through the Xs, as shown in Figure 3.1. (While this can often be done with reasonable accuracy by eye, it is always preferable to apply a mathematical least-squares line-fitting technique).

Nonlinearity is then defined as the maximum deviation of any of the output readings marked X from this straight line. Nonlinearity is usually expressed as a percentage of full-scale reading.

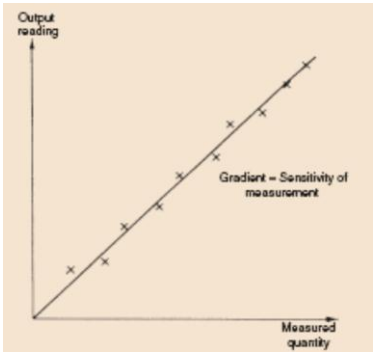


Figure 3.1 Instrument output characteristic.

3.1.6 Sensitivity of Measurement:

The sensitivity of measurement is a measure of the change in instrument output that occurs when the quantity being measured changes by a given amount. Thus, sensitivity is the ratio:

$$= \frac{scale\ of\ deflection}{value\ of\ measurand\ producing\ deflection}$$

The sensitivity of measurement is therefore the slope of the straight line drawn on Figure 3.1. If, for example, a pressure of 2 bar produces a deflection of 10 degrees in a pressure transducer, the sensitivity of the instrument is 5 degrees/bar (assuming that the deflection is zero with zero pressure applied).

Example 3.3

The following resistance values of a platinum resistance thermometer were measured at a range of temperatures. Determine the measurement sensitivity of the instrument in ohms/°C.

Resistance (Ω)	Temperature (°C)
307	200
314	230
321	260
328	290

Solution

If these values are plotted on a graph, the straight-line relationship between resistance change and temperature change is obvious.

For a change in temperature of 30°C, the change in resistance is 7Ω. Hence the measurement sensitivity = 7/30 = 0.233 Ω/°C.

3.1.7 Threshold:

If the input to an instrument is increased gradually from zero, the input will have to reach a certain minimum level before the change in the instrument output reading is of a large enough magnitude to be detectable. This minimum level of input is known as the threshold of the instrument. Manufacturers vary in the way that they specify threshold for instruments. Some quote *absolute values*, whereas others quote threshold as a *percentage of full-scale readings*. As an illustration, a car speedometer typically has a threshold of about 15 km/h. This means that, if the vehicle starts from rest and accelerates, no output reading is observed on the speedometer until the speed reaches 15 km/h.

3.1.8 Resolution:

When an instrument is showing a particular output reading, there is a lower limit on the magnitude of the change in the input measured quantity that produces an observable change in the instrument output. Like threshold, resolution is sometimes specified as an absolute value and sometimes as a percentage of f.s. deflection. One of the major factors influencing the resolution of an instrument is how finely its output scale is divided into subdivisions. Using a car speedometer as an example again, this has subdivisions of typically 20 km/h. This means that when the needle is between the scale markings, we cannot estimate speed more accurately than to the nearest 5 km/h. This value of 5 km/h thus represents the resolution of the instrument.

3.1.9 Sensitivity to Disturbance:

All calibrations and specifications of an instrument are only valid under controlled conditions of temperature, pressure, and so on. These standard ambient conditions are usually defined in the instrument specification. As variations occur in the ambient temperature, certain static instrument characteristics change, and the sensitivity to disturbance is a measure of the magnitude of this change. Such environmental changes affect instruments in two main ways, known as zero drift and sensitivity drift. **Zero drift** is sometimes known by the alternative term, bias. Zero drift or bias describes the effect where the zero reading of an instrument is modified by a change in ambient conditions. This causes a constant error that exists over the full range of measurement of the instrument. The mechanical form of a bathroom scale is a common example of an instrument prone to zero drift. It is quite usual to find that there is a reading of perhaps 1 kg with no one on the scale. If someone of known weight 70 kg were to get on the scale, the reading would be 71 kg, and if someone of known weight 100 kg were to get on the scale, the reading would be 101 kg. *Zero drift is normally removable by calibration.* In the case of the bath room scale just described, a thumbwheel is usually provided that can be turned until the reading is zero with the scales unloaded, thus removing zero drift.

The typical unit by which such zero drift is measured is volts/°C. This is often called the zero drift coefficient related to temperature changes. If the characteristic of an instrument is sensitive to several environmental parameters, then it will have several zero drift coefficients, one for each environmental parameter. A typical change in the output characteristic of a pressure gauge subject to zero drift is shown in Figure 3.2a.

Sensitivity drift (also known as scale factor drift) defines the amount by which an instrument's sensitivity of measurement varies as ambient conditions change. It is quantified by sensitivity drift

coefficients that define how much drift there is for a unit change in each environmental parameter that the instrument characteristics are sensitive to. Many components within an instrument are affected by environmental fluctuations, such as temperature changes: for instance, the modulus of elasticity of a spring is temperature dependent. Figure 3.2b shows what effect sensitivity drift can have on the output characteristic of an instrument. Sensitivity drift is measured in units of the form (angular degree/bar)/°C. If an instrument suffers both zero drift and sensitivity drift at the same time, then the typical modification of the output characteristic is shown in Figure 3.2c.

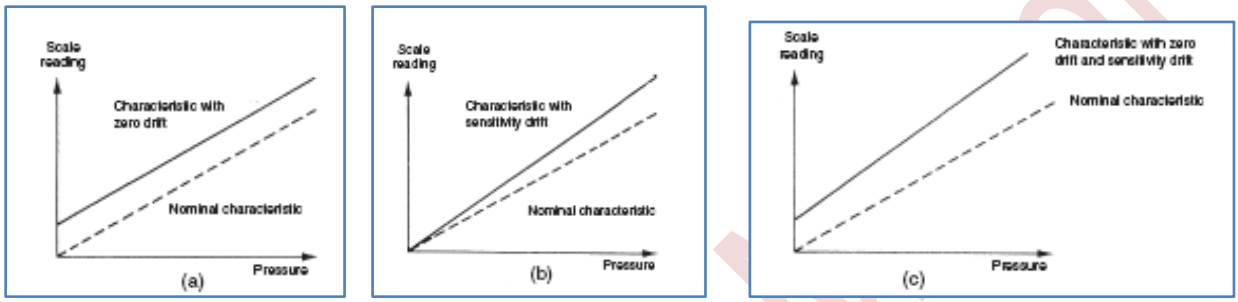


Figure 3.2 Effects of disturbance: (a) zero drift, (b) sensitivity drift, and (c) zero drift plus sensitivity drift.

Example 3.4
The following table shows output measurements of a voltmeter under two sets of conditions:

(a) Use in an environment kept at 20°C which is the temperature that it was calibrated at.

(b) Use in an environment at a temperature of 50°C.

Voltage readings at calibration temperature of 20°C(assumed correct)	Voltage readings at temperature of 50°C
10.2	10.5
20.3	20.6
30.7	40.0
40.8	50.1

Determine the zero drift when it is used in the 50°C environment, assuming that the measurement values when it was used in the 20°C environment are correct. Also calculate the zero drift coefficients.

Solution
Zero drift at the temperature of 50°C is the constant difference between the pairs of output readings, that is, 0.3 volts.
The zero drift coefficients are the magnitude of drift (0.3 volts) divided by the magnitude of the temperature change causing the drift (30°C). Thus the zero drift coefficients is 0.3/30= 0.01 volts/°C.

Example 3.5

A spring balance is calibrated in an environment at a temperature of 20°C and has the following deflection/load characteristic:

Load (kg)	0	1	2	3
Deflection (mm)	0	20	40	60

It is then used in an environment at a temperature of 30°C, and the following deflection/load characteristic is measured:

Load (kg)	0	1	2	3
Deflection (mm)	5	27	49	71

Determine the zero drift and sensitivity drift per °C change in ambient temperature.

Solution

At 20°C, deflection/load characteristic is a straight line. Sensitivity = 20 mm/kg.

At 30°C, deflection/load characteristic is still a straight line. Sensitivity = 22 mm/kg.

Zero drift (bias)= 5 mm (the no-load deflection)

Sensitivity drift = 2 mm/kg

Zero drift/°C= 5/10 = 0.5 mm/°C

Sensitivity drift/°C= 2/10 = 0.2 (mm/kg)/°C

3.1.10 Hysteresis Effects

Figure 3.3 illustrates the output characteristic of an instrument that exhibits hysteresis. If the input measured quantity to the instrument is increased steadily from a negative value, the output reading varies in the manner shown in curve A. If the input variable is then decreased steadily, the output varies in the manner shown in curve B. The non-coincidence between these loading and unloading curves is known as hysteresis. Two quantities are defined, maximum input hysteresis and maximum output hysteresis, as shown in Figure 3.3. These are normally expressed as a percentage of the full-scale input or output reading, respectively.

Hysteresis is found most commonly in instruments that contain springs, such as a passive pressure gauge. It is also evident when friction forces in a system have different magnitudes depending on the direction of movement, such as in the pendulum-scale mass-measuring device. Devices such as the mechanical fly ball (a device for measuring rotational velocity) suffer hysteresis from both of the aforementioned sources because they have friction in moving parts and also contain a spring. Hysteresis can also occur in instruments that contain electrical windings formed round an iron core, due to magnetic hysteresis in the iron. This occurs in devices such as the variable inductance

displacement transducer, the linear variable differential transformer, and the rotary differential transformer.

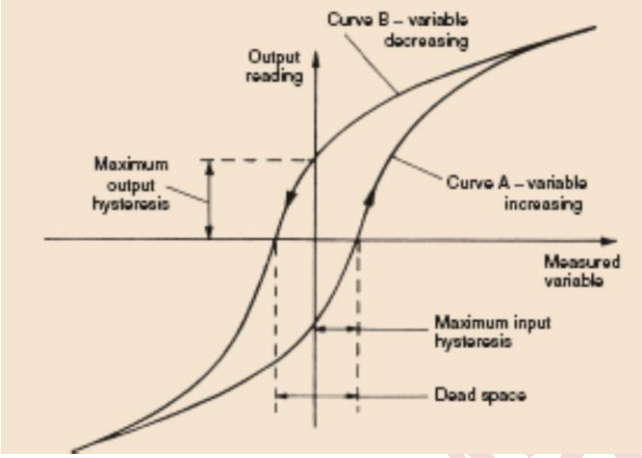


Figure3.3 Instrument characteristic with hysteresis.

3.1.10.1 Dead Space:

Dead space is defined as the range of different input values over which there is no change in output value. Any instrument that exhibits hysteresis also displays dead space, as marked on Figure 3.3. Some instruments that do not suffer from any significant hysteresis can still exhibit a dead space in their output characteristics, however. Backlash in gears is a typical cause of dead space and results in the sort of instrument output characteristic shown in Figure 3.3.

3.2 Dynamic Characteristics of Instruments:

The static characteristics of measuring instruments are concerned only with the steady-state reading that the instrument settles down to, such as accuracy of the reading.

The dynamic characteristics of a measuring instrument describe its behavior between the time a measured quantity changes value and the time when the instrument output attains a steady value in response. As with static characteristics, any values for dynamic characteristics quoted in instrument data sheets only apply when the instrument is used under specified environmental conditions. Outside these calibration conditions, some variation in the dynamic parameters can be expected.

$$a_n * \frac{d^n q_o}{dt^n} + a_{n-1} * \frac{d^{n-1} q_o}{dt^{n-1}} + \cdots + a_1 * \frac{dq_o}{dt} + a_o q_o = b_o q_i \qquad 3.1$$

Further simplification can be made by taking certain special cases of Equation (2.1), which collectively apply to nearly all measurement systems.

3.2.1. Zero-Order Instrument

If all the coefficients $a_1 \ldots a_n$ other than a_0 in Equation (3.1) are assumed zero, then:

$$a_o q_o = b_o q_i \ or \ q_o = b_o q_i / a_o = k q_i \qquad 3.2$$

Where *k* is a constant known as the instrument sensitivity as defined earlier.

Any instrument that behaves according to Equation (2.1) is said to be of a zero-order type. Following a step change in the measured quantity at time t, the instrument output moves immediately to a new value at the same time instant t, as shown in Figure 3.4. A potentiometer, which measures motion is a good example of such an instrument, where the output voltage changes instantaneously as the slider is displaced along the potentiometer track.

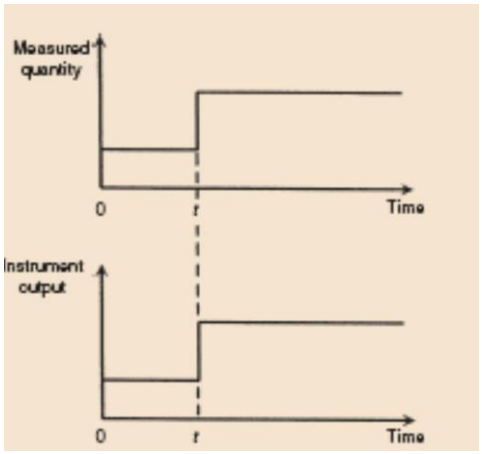


Figure 3.4 Zero-order instrument characteristic

3.2.2 First-Order Instrument:

If all the coefficients $a_2 \ldots a_n$ except for a_o and a_1 are assumed zero in Equation (3.1) then

$$a_1 * \frac{dq_o}{dt} + a_o q_o = b_o q_i \qquad 3.3$$

Any instrument that behaves according to Equation (3.3) is known as a first-order instrument.

If Equation (3.3) is solved analytically, the output quantity q_0 in response to a step change in qi at time t varies with time in the manner shown in Figure 3.5. The time constant t of the step response is time taken for the output quantity q0 to reach 63% of its final value.

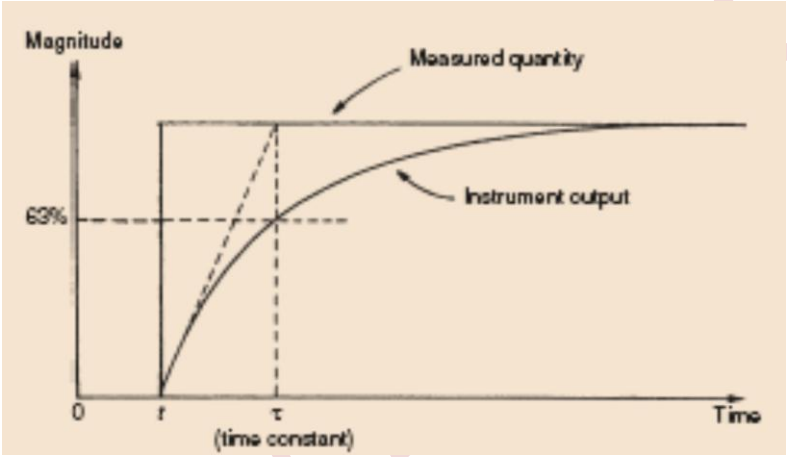


Figure 3.5 First order instrument characteristic

The thermocouple is a good example of a first-order instrument. It is well known that if a thermocouple at room temperature is plunged into boiling water, the output e.m.f. does not rise instantaneously to a level indicating 100°C, but instead approaches a reading indicating 100°C in a manner similar to that shown in Figure 2.9.

3.2.3 Second-Order Instrument:

If all coefficients a3 . . . an other than a_0, a_1, and a_2 in Equation (3.1) are assumed zero, then we get

$$a_2 * \frac{d^2 q_o}{dt^2} + a_1 * \frac{dq_o}{dt} + a_o q_o = b_o q_i \qquad 3.4$$

The output responses of a second-order instrument for various values of x following a step change in the value of the measured quantity at time t are shown in Figure 3.6.

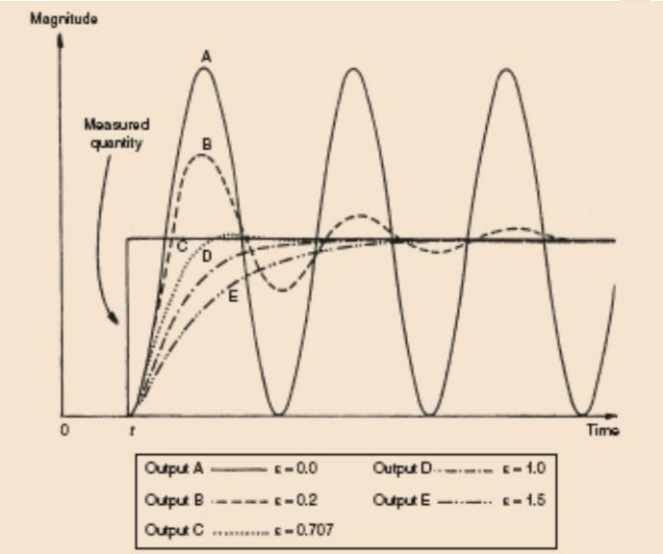


Figure 3.6 Second order response characteristics

SENSORS AND TRANSDUCERS

4.0 Basic definitions:

The sensing element is the first element in the measurement system; it is in contact with, and draws energy from, the process or system being measured. American National Standards Institute (ANSI) definition is A device which provides a usable output in response to a specified measurement. The input to this element is the true value of the measured variable; the output of the element depends on this value. The elements are classified according to whether the output signal is:

- Electromagnetic: - photo sensors
  - Current, voltage,
- Mechanical: - physical like pressure, force,
  - accelerometer
  - sound
  - Heat.
- chemical: - smell
  -taste
  -pH
- Biological: DNA, T cell count.
- Nuclear

Elements with an electrical output are further divided into passive and active. Passive devices such as resistive, capacitive and inductive elements require an external power supply in order to give a voltage or current output signal; active devices, e.g. electromagnetic and thermoelectric elements, need no external power supply. In this part the main physical principles used in measurement sensors, and then it goes on to discuss the range of sensors and instruments that are available for measuring various physical quantities.

4.1 Specifications of Sensor:

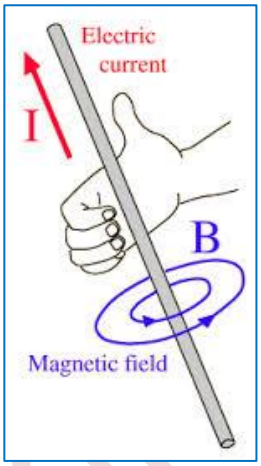
The specifications are clarified in lecture. 3

4.2 Attributes of Sensors:

- **Operating Principle**: Embedded technologies that make sensors function, such as electro-optics, electromagnetic, piezoelectricity, active and passive ultraviolet.
- **Dimension of Variables**: The number of dimensions of physical variables.
- **Size**: The physical volume of sensors.
- **Data Format**: The measuring feature of data in time; continuous or discrete/analog or digital.
- **Intelligence**: Capabilities of on-board data processing and decision-making.
- **Active versus Passive Sensors**: Capability of generating vs. just receiving signals.
- **Physical Contact**: The way sensors observe the disturbance in environment.
- **Environmental durability**: will the sensor robust enough for its operation conditions.

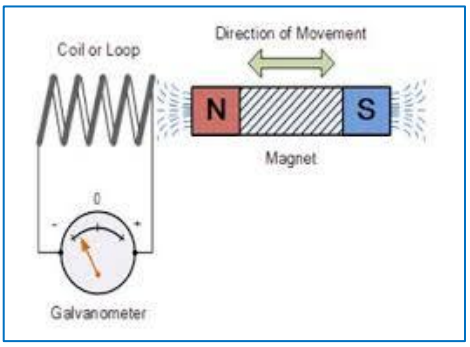
4.3 Physical Principles:

- **Ampere's Law**: A current carrying conductor in a magnetic field experiences a force (e.g. galvanometer)

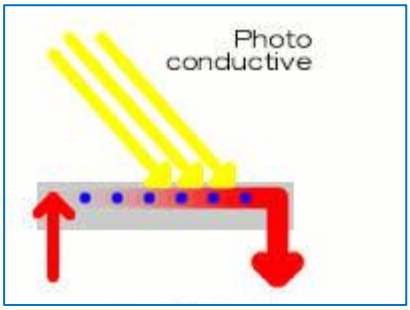


- **Curie-Weiss Law**: There is a transition temperature at which ferromagnetic materials exhibit paramagnetic behavior.

- **Faraday's Law of Induction** :A coil resist a change in magnetic field by generating an opposing voltage/current (e.g. transformer)



- **Photoconductive Effect**: When light strikes certain semiconductor materials, the resistance of the material decreases. Photoelectric cell can detect light or convert it into electricity.



4.4Types:

4.4.1 Resistive sensing elements:

Resistive sensors rely on the variation of the resistance of a material when the measured variable is applied to it. This principle is most commonly applied in temperature measurement, and in displacement measurement. In addition, some moisture meters work on the resistance-variation principle. The types are:

i. Potentiometers for linear and angular displacement measurement.

Figure 4.1 shows potentiometers for the measurement of (a) linear (rectilinear) and (b) angular (rotary) displacement. They consist of a former with a cylindrical cross-section which is either a straight cylinder or an arc of a circle. Resistive material is then placed on the former so that the resistance per unit length is constant (the usual case). This means that resistance is proportional to the distance *d* travelled by the wiper between A and B.

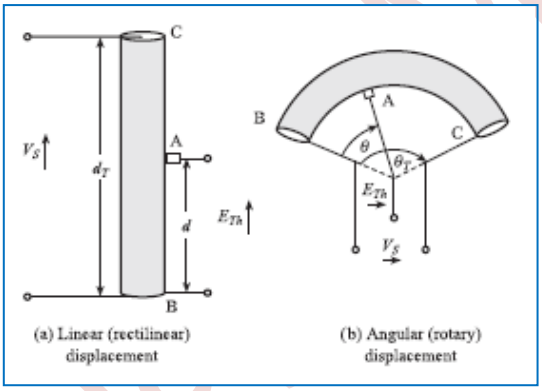


Figure 4.1 linear and angular displacements.

ii. Resistive metal and semiconductor sensors for temperature measurement.

This principle is most commonly applied in temperature measurement using resistance thermometers or thermistors.

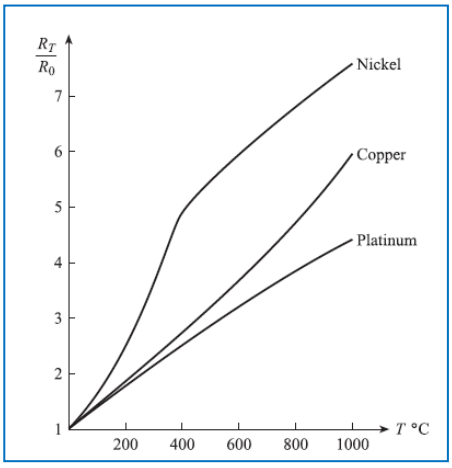


Figure 4.2 Metal resistive temperature sensors, Resistance/ temperature characteristics of commonly used metals.

iii. Metal and semiconductor resistive strain gauges.

Before discussing strain gauges we must first briefly explain the concepts of stress, strain, elastic modulus and Poisson's ratio.

Stress is defined by force/area, so that in Figure 4.3(a) the stress experienced by the body is $+F/A$, the positive sign indicating a tensile stress which tends to increase the length of the body. In Figure 4.3(b) the stress is $-F/A$, the negative sign indicating a compressive stress which tends to reduce the length of the body. The effect of the applied stress is to produce a strain in the body which is defined by (change in length)/(original unstressed length). Thus in Figure 2.3(a) the strain is $e = +\Delta l / l$ (tensile), and in 2.3(b) the strain is $e = -\Delta l / l$ (compressive); in both cases the strain is longitudinal, i.e. along the direction of the applied stress. The relationship between strain and stress is linear for a given body over a certain range of values; the slope of the straight line is termed the elastic modulus of the body:

$$Elastic\ modulus = \frac{stress}{strain}$$

For linear tensile or compressive stress the elastic modulus is called **Young's modulus** E; for shear stress the relevant elastic modulus is **shear modulus** S. Returning to Figure 3.3(a) we note that the increase in length of the body is accompanied by a decrease in cross-sectional area, i.e. a reduction in width and thickness. Thus in Figure 3.3(a) the longitudinal tensile strain is accompanied by a transverse compressive strain, and in Figure 3.3(b) the longitudinal compressive strain is accompanied by a transverse tensile strain. The relation between longitudinal strain e_L and accompanying transverse strain e_T is:

$$e_T = -\nu e_L$$

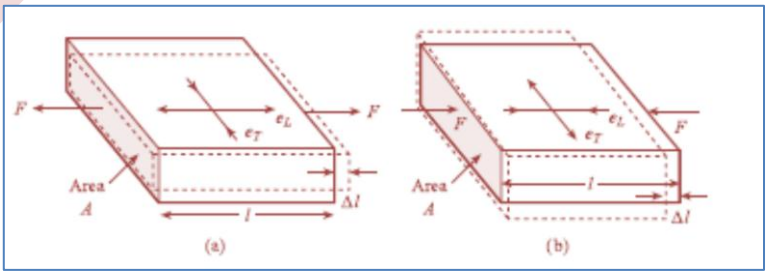


Figure 4.3 Stress and strain**: (a)** Effect of tensile stress **(b)** Effect of compressive stress**.**

Strain gauges are devices that experience a change in resistance when they are stretched or strained. They are able to detect very small displacements, usually in the range 0–50 μm, and are typically used as part of other transducers, for example diaphragm pressure sensors that convert

pressure changes into small displacements of the diaphragm. Measurement inaccuracies as low as 0.15% of full-scale reading is achievable and the quoted life expectancy is usually three million reversals. Strain gauges are manufactured to various nominal values of resistance, of which 120Ω, 350Ω and 1000Ω are very common. The typical maximum change of resistance in a 120Ω device would be 5Ω at maximum deflection. The traditional type of strain gauge consists of a length of metal resistance wire formed into a zigzag pattern and mounted onto a flexible backing sheet, as shown in Figure 4.4(a). The wire is nominally of circular cross-section. As strain is applied to the gauge, the shape of the cross-section of the resistance wire distorts, changing the cross- sectional area. As the resistance of the wire per unit length is inversely proportional to the cross-sectional area, there is a consequential change in resistance. The input–output relationship of a strain gauge is expressed by the *gauge factor*, which is defined as the change in resistance (R) for a given value of strain (S), i.e.

In use, strain gauges are bonded to the object whose displacement is to be measured. The process of bonding presents a certain amount of difficulty, particularly for semiconductor types. The resistance of the gauge is usually measured by a d.c. bridge circuit and the displacement is inferred from the bridge output measured. The maximum current that can be allowed to flow in a strain gauge is in the region of 5 to 50 mA depending on the type. Thus, the maximum voltage that can be applied is limited and consequently, as the resistance change in a strain gauge is typically small, the bridge output voltage is also small and amplification has to be carried out. This adds to the cost of using strain gauges.

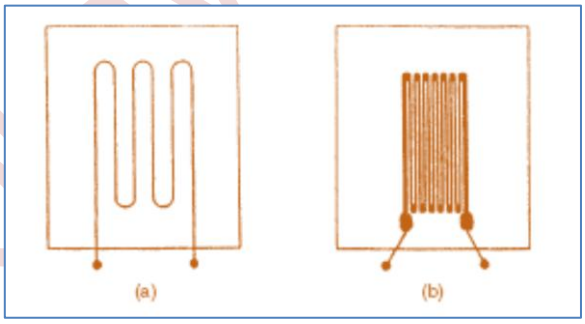


Figure 4.4 Strain gauges**: (a)** wire type**; (b)** foil type**.**

iv. Semiconductor resistive gas sensors.

Metal oxide sensors have semiconducting properties which are affected by the presence of gases. The resistance of chromium titanium oxide is affected by reducing gases such as carbon monoxide (CO) and hydrocarbons. Here oxygen atoms near the surface react with reducing gas molecules; this reaction takes up conduction electrons so that fewer are available for conduction. This causes a decrease in electrical conductivity and a

corresponding increase in resistance. The resistance of tungsten oxide is affected by oxidizing gases such as oxides of nitrogen (NO_x) and ozone.

Figure 4.5 shows a typical construction of a metal oxide sensor using thick film technology. This consists of an alumina substrate with a film of oxide printed on one side and a platinum heater grid on the other. A typical NO_X sensor has an ambient temperature range of −20 °C to +60 °C and operating power of 650 mW. The resistance is typically 6 kΩ in air, 39 kΩ in 1.5 ppm NO2 and 68 kΩ in 5.0 ppm NO_2.

A typical CO sensor has an ambient temperature range of −20 °C to +60 °C and an operating power of 650 mW. The resistance is typically 53 kΩ in air, 85 kΩ in 100 ppm CO and 120 kΩ in 400 ppm CO.

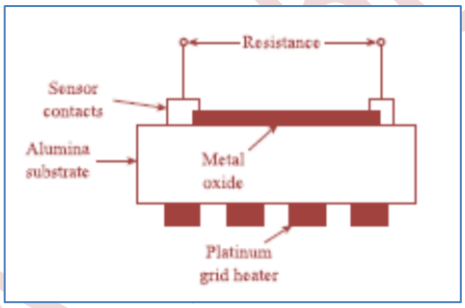


Figure 4.5 Typical construction of metal oxide gas sensor.

4.4.2 Capacitive sensing elements:

Capacitive devices are often used as displacement sensors, in which motion of a moveable capacitive plate relative to a fixed one changes the capacitance. Often, the measured displacement is part of instruments measuring pressure, sound or acceleration. Alternatively, fixed plate capacitors can also be used as sensors, in which the capacitance value is changed by causing the measured variable to change the dielectric constant of the material between the plates in some way. This principle is used in devices to measure moisture content, humidity values and liquid level.

The simplest capacitor consists of two parallel metal plates separated by a dielectric or insulating material (Figure 4.6).

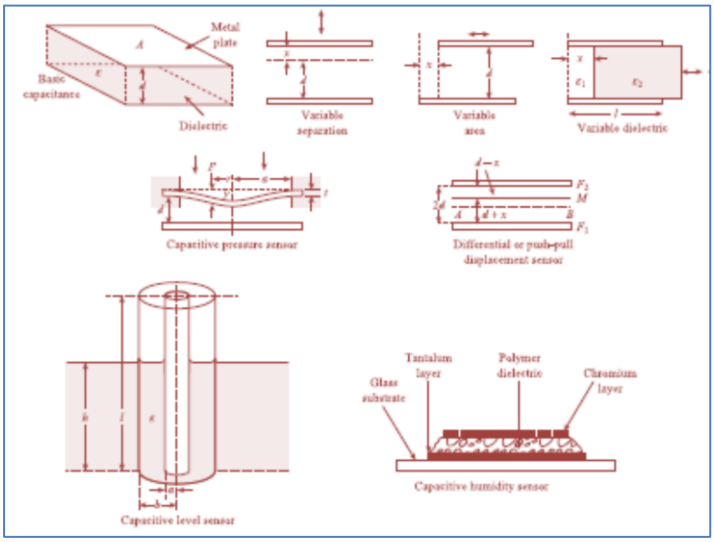


Figure 4.6 Capacitive sensing elements.

4.4.3 Inductive sensing elements:

i. Variable inductance (variable reluctance) displacement sensors.

In order to discuss the principles of these elements we must first introduce the concept of a magnetic circuit. In an electrical circuit an electromotive force (e.m.f.) drives a current through an electrical resistance and the magnitude of the current is given by

e.m.f. = current × resistance

A simple magnetic circuit is shown in Figure 4.7(a): it consists of a loop or core of ferromagnetic material on which is wound a coil of *n* turns carrying a current *i*. By analogy we can regard the coil as a source of magneto motive force (m.m.f.) which drives a flux through the magnetic circuit.

Figure 4.7(b) shows the core separated into two parts by an air gap of variable width. The total reluctance of the circuit is now the reluctance of both parts of the core together with the reluctance of the air gap. Since the relative permeability of air is close to unity and that of the core material many thousands, the presence of the air gap causes a large increase in circuit reluctance and a corresponding decrease in flux and inductance. Thus a small variation in air gap causes a measurable change in inductance so that we have the basis of an **inductive displacement sensor**.

Figure 4.7(c) shows a typical variable reluctance displacement sensor, consisting of three elements: a ferromagnetic core in the shape of a semi toroid (semicircular ring), a variable air gap and a ferromagnetic plate or armature.

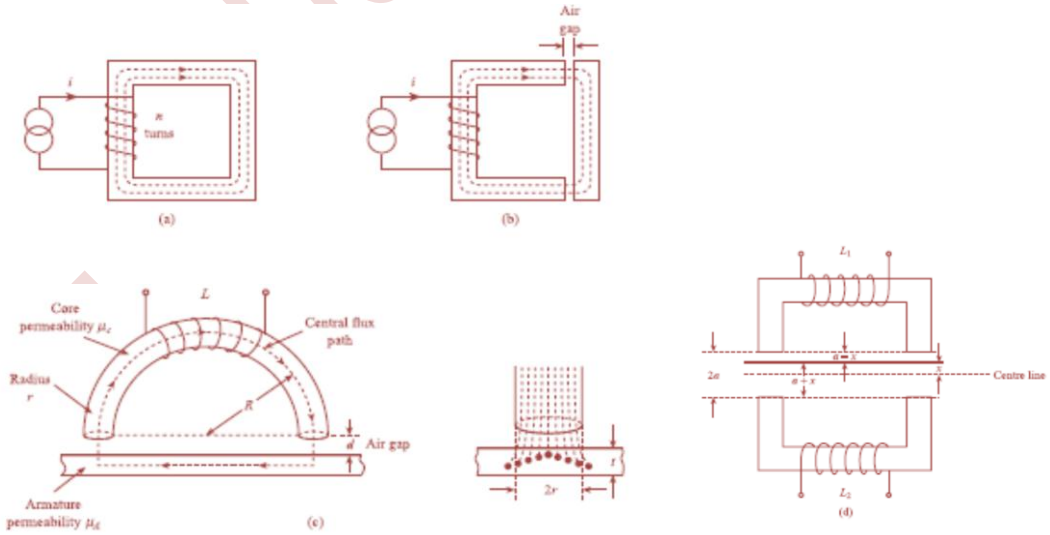


Figure 4.7 Variable reluctance elements: (a)&(b) Basic principle of reluctance sensing elements (c) Reluctance calculation for typical element (d) Differential or push/pull reluctance displacement sensor.

ii. Linear Variable Differential Transformer (LVDT) displacement sensor.

This sensor is a transformer with a single primary winding and two identical secondary windings wound on a tubular ferromagnetic former (Figure 4.8). The primary winding is energized by an a.c. voltage of amplitude V_P and frequency f Hz; the two second Aries are connected in series opposition so that the output voltage V_{OUT} $\sin(2\pi f t + \varphi)$ is the difference $(V_1 - V_2)$ of the voltages induced in the second Aries. A ferromagnetic core or plunger moves inside the former; this alters the mutual inductance between the primary and second Aries. With the core removed the secondary voltages are ideally equal so that $V_{OUT} = 0$. With the core in the former, V_1 and V_2 change with core position x, causing amplitude V_{OUT} and phase φ to change.

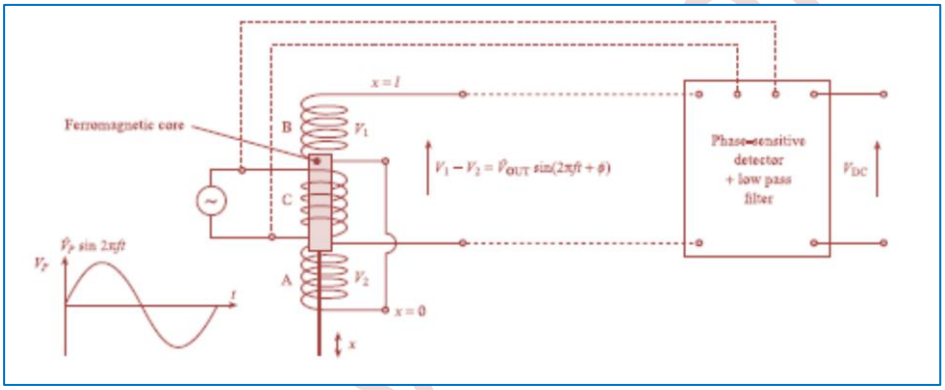


Figure 4.8 LVDT and connections to phase-sensitive detector.

4.4.4 Electromagnetic sensing elements.

These elements are used for the measurement of linear and angular velocity an based on Faraday's law of electromagnetic induction. This states that if the flux linked by a conductor is changing with time, then a back e.m.f. is induced in the conductor with magnitude equal to the rate of change of flux.

In an electromagnetic element the change in flux is produced by the motion being investigated; this means that the induced e.m.f. depends on the linear or angular velocity of the motion. A common example of an electromagnetic sensor is the variable reluctance tacho generator for measuring angular velocity (Figure 4.9).

It consists of a toothed wheel of ferromagnetic material (attached to the rotating shaft) and a coil wound onto a permanent magnet, extended by a soft iron pole piece. The wheel moves in close proximity to the pole piece, causing the flux linked by the coil to change with time, thereby inducing an e.m.f. in the coil.

The magnitude of the e.m.f. can be calculated by considering the magnetic circuit formed by the permanent magnet, air gap and wheel. The e.m.f. is constant with time and depends on the field strength of the permanent magnet. The reluctance of the circuit will depend on the width of the air gap between the wheel and pole piece. When a tooth is close to the pole piece the reluctance is minimum but will increase as the tooth moves away. The reluctance is maximum when a 'gap' is adjacent to the pole piece but falls again as the next tooth approaches the pole piece.

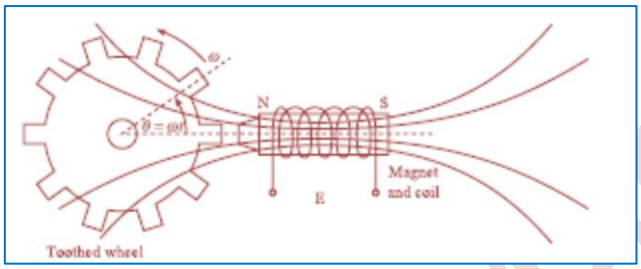


Figure 4.9 Variable reluctance tacho generator, angular variations in reluctance and flux.

4.4.5 Thermoelectric sensing elements.

Thermoelectric or thermocouple sensing elements are commonly used for measuring temperature. If two different metals *A* and *B* are joined together, there is a difference in electrical potential across the junction called the junction potential. This junction potential depends on the metals *A* and *B* and the temperature *T* °C of the junction.

A thermocouple is a closed circuit consisting of two junctions (Figure 4.10), at different temperatures T_1 and T_2 °C. If a high-impedance voltmeter is introduced into the circuit, so that current flow is negligible, then the measured e.m.f. is, to a close approximation, the difference of the junction potentials, i.e.

Thus the measured e.m.f. depends on the temperatures T_1, T_2 of both junctions. In the following discussion T_1 will be the temperature to be measured, i.e. the temperature of the measurement junction, and T_2 will be the temperature of the reference junction. In order to accurately infer T_1 from the measured e.m.f., the reference junction temperature T_2 must be known.

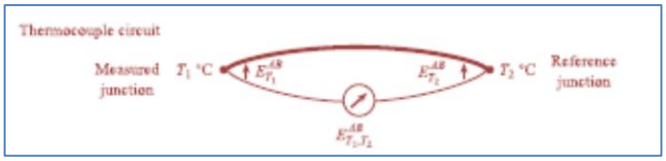


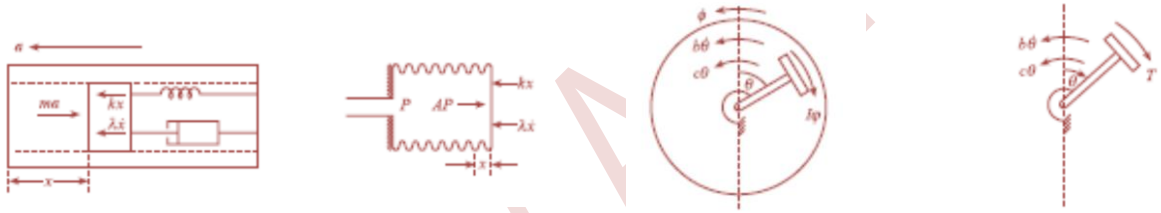
Figure 4.10 thermocouple principles.

4.4.6 Elastic sensing elements.

If a force is applied to a spring, then the amount of extension or compression of the spring is approximately proportional to the applied force. This is the principle of elastic sensing elements which convert an input force into an output displacement. Elastic elements are also commonly used for measuring torque, pressure and acceleration.

In a measurement system an elastic element will be followed by a suitable secondary displacement sensor, e.g. potentiometer, strain gauge or LVDT, which converts displacement into an electrical signal. The displacement may be translational or rotational.

Elastic sensing elements have associated mass (interance) and damping (resistance) as well as spring characteristics. Figure 4.11 shows dynamic models of elastic elements for measuring linear acceleration, torque, pressure and angular acceleration.



a b c d

Figure 4.11 Dynamic models of elastic elements:

(a) Linear accelerometer (b) Pressure sensor (c) Angular accelerometer (d) Torque sensor.

4.4.7 Piezoelectric sensing elements.

If a force is applied to any crystal, then the crystal atoms are displaced slightly from their normal positions in the lattice. This displacement is proportional to the applied force: i.e., in the steady state, the dynamic relation between *and can* be represented by the second-order transfer function.

Piezoelectric elements are commonly used for the measurement of acceleration and vibration. The following are same types of the piezoelectric sensing materials.

Figure 4.12 Single crystals (Quarts) Polycrystalline ceramics (PTZ) Polymer (PVDF)

4.4.8 Piezo resistive sensing elements.

The Piezo resistive effect was defined as the change in resistivity of a material with applied mechanical strain; silicon doped with small amounts of *n*- or *p*-type material exhibits a large Piezo resistive effect and is used to manufacture strain gauges with high gauge factors as shown in figure 4.13.

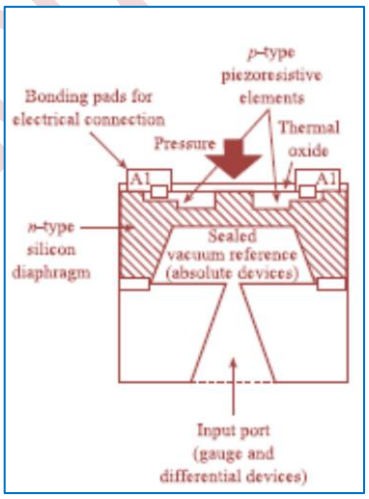


Figure 4.13 Piezo resistive sensors

4.4.9 Electrochemical sensing elements:

i. Ion selective electrodes.

Ion selective electrodes (ISEs) are sensors which directly measure the activity or concentration of ions in solution. They could, for example, be used to measure the concentration of lead, sodium or nitrate ions in drinking water. When an ISE is immersed in a solution, a reaction takes place between the charged species in the solution and those on the sensor surface. Equilibrium is then established between these species: there is a corresponding equilibrium potential difference between the sensor and solution, which depends mainly, but not entirely, on the activity of a single ion. This output signal depends also, to some extent, on the activity of other ions present in the solution; the electrodes are therefore *selective* rather than *specific*. Figure 4.14 show the basic system for ion concentration.

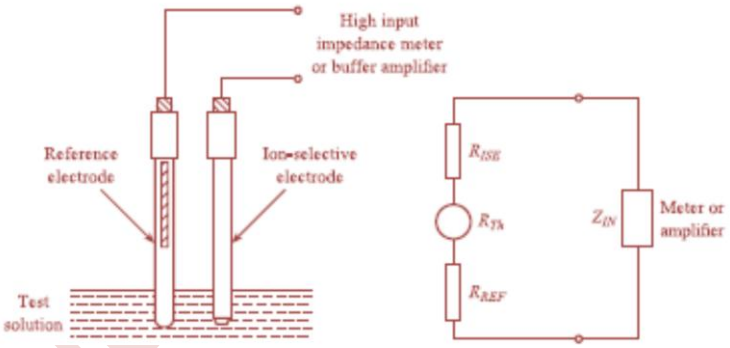


Figure 4.14 Basic system for ion concentration measure and equivalent circuit

ii. Electrochemical gas sensors.

Some solid-state materials give an electrochemical response to certain gases. An example is zirconia, which is sensitive to oxygen. Zirconia is based on zirconium oxide (ZrO2) with small amounts of other metal oxides present. These atoms replace Zr atoms at lattice sites and enable the material to conduct both electrons and oxygen O2− ions. Opposite surfaces of a slab of zirconia are coated with a thin layer of platinum, which is porous to oxygen molecules, to give two electrodes. If a surface is exposed to a gas containing oxygen, then oxygen molecules diffuse into the zirconia.

A practical sensor consists of a small hollow cone of zirconia, coated on both the inside and outside with a layer of porous platinum and held at a constant temperature of 640 °C.

iii. Chemically sensitive field effect transistors (CHEMFET).

It is a chip of silicon crystal with impurities added to create areas of *n*-type and *p*-type material. The device has four terminals. The source S and drain D are regions of enriched *n*-type material, the body or substrate (B) is *p*-type material and the gate G is metal or polysilicon material. The body is often connected to the source to give a three-terminal device. The gate is insulated from the substrate by a thin layer of silicon dioxide so that negligible current is drawn through the gate terminal. Figure 4.15 shows the construction of chemically sensitive field effect transistors. This type is used to analyze the liquids and the gases.

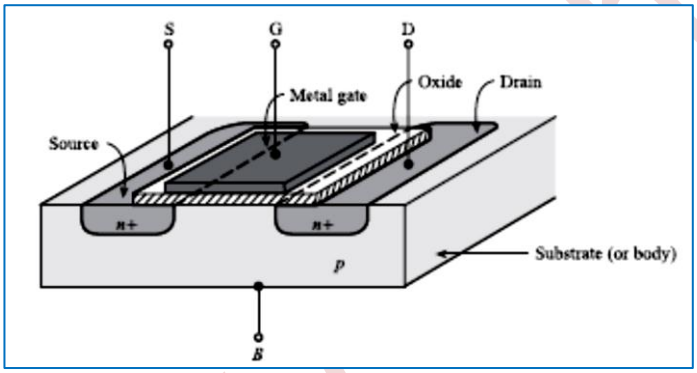


Figure 4.15 The construction of chemically sensitive field effect transistors.

4.4.10 Hall Effect sensors.

An important application of Hall devices is to measure magnetic field. It consists of a conductor carrying a current that is aligned orthogonally with the magnetic field, as shown in Figure 4.16. This produces a transverse voltage difference across the device that is directly proportional to the magnetic field strength. For an excitation current I and magnetic field strength B, the output voltage is given by V = KIB, where K is known as the Hall constant.

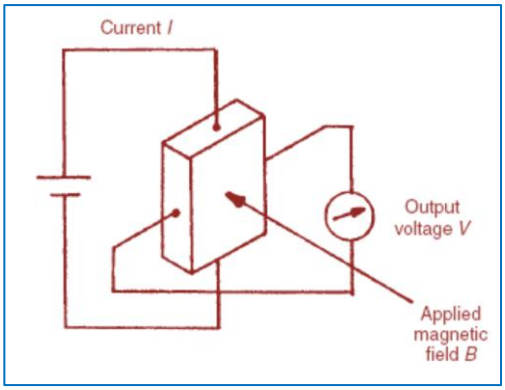


Figure 4.16 principles of Hall-effect sensor.

The conductor in Hall-effect sensors is usually made from a semiconductor material as opposed to a metal, because a larger voltage output is produced for a magnetic field of a given size. In one

common use of the device as a proximity sensor, the magnetic field is provided by a permanent magnet that is built into the device. The magnitude of this field changes when the device becomes close to any ferrous metal object or boundary. The Hall-effect is also commonly used in keyboard pushbuttons, in which a magnet is attached underneath the button. When the button is depressed, the magnet moves past a Hall-effect sensor. The induced voltage is then converted by a trigger circuit into a digital output. Such pushbutton switches can operate at high frequencies without contact bounce.

4.4.11 Optical sensors

Optical sensors are based on the modulation of light travelling between a light source and a light detector, as shown in Figure 4.17. The transmitted light can travel along either an air path or a fibre-optic cable. Either form of transmission gives immunity to electromagnetically induced noise, and also provides greater safety than electrical sensors when used in hazardous environments. Light sources suitable for transmission across an air path include tungsten-filament lamps, laser diodes and light-emitting diodes (LEDs). However, as the light from Tungsten lamps is usually in the visible part of the light frequency spectrum, it is prone to interference from the sun and other sources. Hence, infrared LEDs or infrared laser diodes are usually preferred. These emit light in a narrow frequency band in the infrared region and are not affected by sunlight.

The main forms of light detector used with optical systems are photocells (cadmium sulphide or cadmium selenide being the most common type of photocell), phototransistors and photodiodes. These are all photoconductive devices, whose resistance is reduced according to the intensity of light to which they are exposed. Photocells and phototransistors are particularly sensitive in the infrared region, and so are ideal partners for infrared LED and laser diode sources.

Air-path optical sensors are commonly used to measure proximity, translational motion, rotational motion and gas concentration.

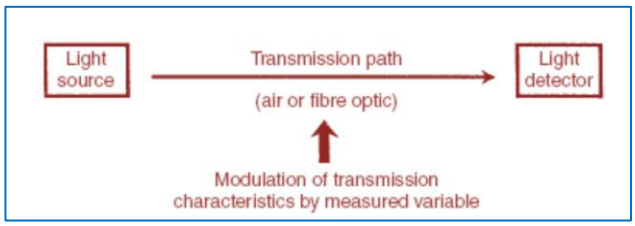


Figure 4.17 principles of optical sensors.

Optical sensors can use fibreoptic cable instead to transmit light between a source and a detector. In such sensors, the variable being measured causes some measurable change in the characteristics of the light transmitted by the cable.

4.4.12 Nuclear sensors.

Nuclear sensors are uncommon measurement devices, partly because of the strict safety regulations that govern their use, and partly because they are usually expensive. Some very low-level radiation sources are now available that largely overcome the safety problems, but measurements are then prone to contamination by background radiation.

The principle of operation of nuclear sensors is very similar to optical sensors in that radiation is transmitted between a source and a detector through some medium in which the magnitude of transmission is attenuated according to the value of the measured variable. Caesium-137 is commonly used as a gamma-ray source and a sodium iodide device is commonly used as a gamma-ray detector. One current use of nuclear sensors is in a non-invasive technique for measuring the level of liquid in storage tanks, They are also used in mass flow rate measurement and in medical scanning applications.

4.4.13 Micro sensors.

Micro sensors are millimeter-sized two- and three-dimensional micro machined structures that have smaller size, improved performance, better reliability and lower production costs than many alternative forms of sensor. Currently, devices to measure temperature, pressure, force, acceleration, humidity, magnetic fields, radiation and chemical parameters are either in production or at advanced stages of research.

Micro sensors are usually constructed from a silicon semiconductor material, but are sometimes fabricated from other materials such as metals, plastics, polymers, glasses and ceramics that are deposited on a silicon base. Silicon is an ideal material for sensor construction because of its excellent mechanical properties. Its tensile strength and Young's modulus is comparable to that of steel, whilst its density is less than that of aluminum. Sensors made from a single crystal of silicon remain elastic almost to the breaking point, and mechanical hysteresis is very small. In addition, silicon has a very low coefficient of thermal expansion and can be exposed to extremes of temperature and most gases, solvents and acids without deterioration.

4.5 Transducers:

A transducer is defined as a device that receives energy from one system and transmits it to another, often in a different form (electrical, mechanical or acoustical).

4.6 Specification of transducers: Same for sensors**.**

4.7 Classification of transducers:

1. Based on principle of transduction
2. Active & passive
3. Analog & digital
4. Inverse transducer

There are mainly **two types** of transducers:

1) Electrical

2) Mechanical

The electrical output of a transducer depends on the basic principle involved in the design.

The output may be analog, digital, or frequency modulated.

4.7.1 Electrical Transducer

Electrical transducers can be classified into two major categories:

Active transducers: Generates an electrical signal directly in response to the physical parameter (does not require external power to operate). Example: piezo-electric sensor and photo cells.

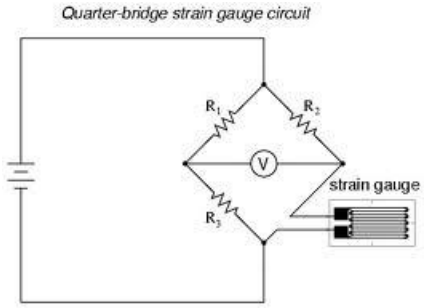
Passive transducers: Requires external power to operate. Example: Strain gauges and thermistors.

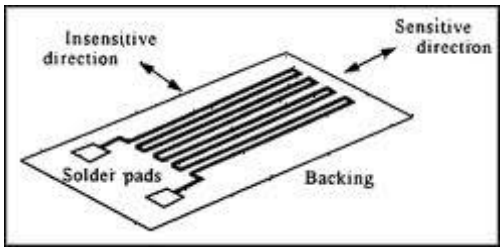
4.7.2 Resistive Position Transducer:

Operates under a principle of **resistance change** by the physical movement under measurement.

, The shaft and wiper can be moved to the left or right causes a change in the circuit resistance.

The **strain gauge** is an example of a passive transducer that senses the strain produced by a force on the wires. When a gauge is subjected to a **positive stress**, its length increases while its area of cross-section decreases thus **increases** its resistance. The main strain gauge is wire strain gauges, A fine wire element is cemented to a thin sheet of paper, Bakelite or Teflon. The measurement of the sensitivity of a material to strain is called the gauge factor.

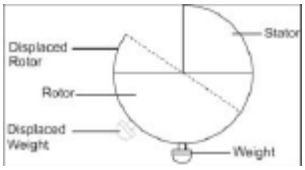




4.7.3 Capacitive Transducer

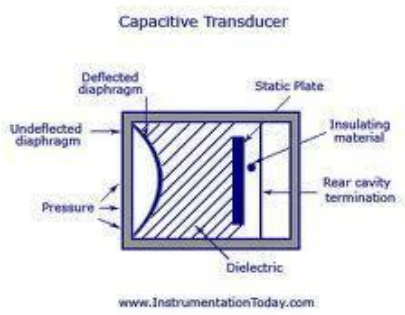
Capacitive transducer operates by a **linear change** in capacitance.

A variable plate area transducer is shown in the figure below.



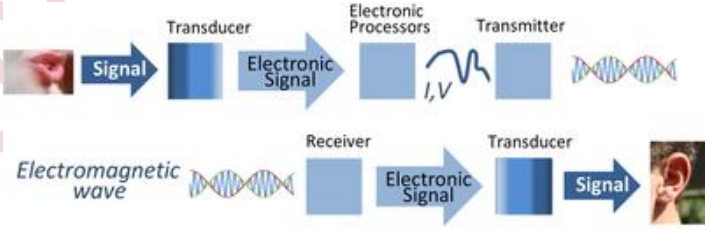
It is made of a fixed plate called **Stator** and a movable plate called the **Rotor**. The capacitance of the transducer is changing as the rotor changes its position relative to the stator. This transducer can be used to detect the amount of roll in an aircraft.

Another example of capacitive transducer is the capacitive pressure transducer as shown in the figure. This sensor is designed to measure pressure (in vacuum). A metallic diaphragm will move to the right when pressure is applied to the chamber and to the left when vacuum is applied. This diaphragm is used as one plate of a variable capacitor. The capacitive transducer is simple to construct, inexpensive, and effective for HF variations.



4.7.4 Inductive Transducer

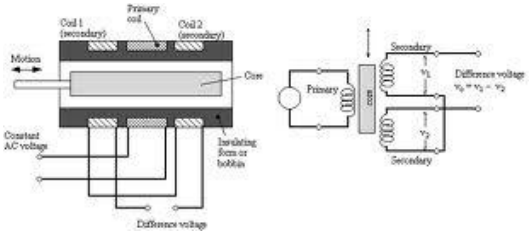
Inductive transducers may be either of the self-generating or the passive type. The **self-generating type** utilizes the basic electrical generator principle. a motion between a conductor and magnetic field induces a voltage in the conductor. A **tachometer** is an example of the self-generating transducer which directly converts speed or velocity into an electrical signal. An inductive **electromechanical transducer** converts physical motion into a change in inductance.



For the measurement of displacement of linear and angular movement respectively. Works on the principle of the variation of **permeability** causing a change in self-inductance. the variable reluctance transducer.

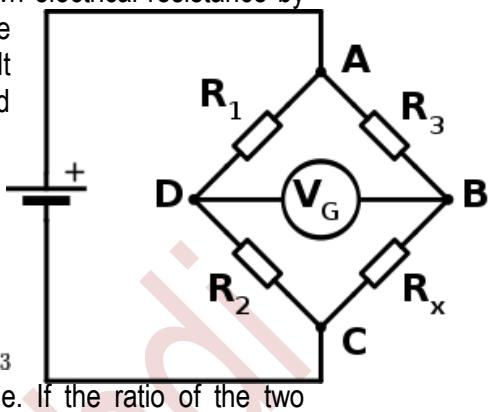
4.7.5 LVDT is Linear Variable Differential Transformer.

An movable soft iron slides within the hollow part of the transformer thus affects the magnetic coupling between the primary and the secondary windings. The frequency of the ac voltage applied to the primary winding ranges from 50 Hz to 20 kHz.



4.8 Wheatstone bridge

A **Wheatstone bridge** is an electrical circuit used to measure an unknown electrical resistance by balancing two legs of a bridge circuit, one leg of which includes the unknown component. Its operation is similar to the original potentiometer. It was invented by Samuel Hunter Christie in 1833 and improved and popularized by Sir Charles Wheatstone in 1843. One of the Wheatstone bridge's initial uses was for the purpose of soils analysis and comparison.



4.8.1 Operation

In the figure, $R_x$is the unknown resistance to be measured; R_1, $R_2$and R_3 are resistors of known resistance and the resistance of $R_2$is adjustable. If the ratio of the two resistances in the known leg $(R_2/R_1)$is equal to the ratio of the two in the unknown leg (R_x/R_3), then the voltage between the two midpoints (**B** and **D**) will be zero and no current will flow through the galvanometer V_g. If the bridge is unbalanced, the direction of the current indicates whether $R_2$is too high or too low. $R_2$is varied until there is no current through the galvanometer, which then reads zero.

Detecting zero current with a galvanometer can be done to extremely high accuracy. Therefore, if R_1 , $R_2$and $R_3$are known to high precision, then $R_x$can be measured to high precision. Very small changes in $R_x$disrupt the balance and are readily detected.

At the point of balance, the ratio of

$$\frac{R_2}{R_1} = \frac{R_x}{R_3}$$
$$\Rightarrow R_x = \frac{R_2}{R_1} \cdot R_3$$

Alternatively, if R_1, R_2, and $R_3$are known, but $R_2$is not adjustable, the voltage difference across or current flow through the meter can be used to calculate the value of R_x, using Kirchhoff's circuit laws (also known as Kirchhoff's rules). This setup is frequently used in strain gauge and resistance thermometer measurements, as it is usually faster to read a voltage level off a meter than to adjust a resistance to zero the voltage.

4.8.2 Derivation

First, Kirchhoff's first rule is used to find the currents in junctions **B** and **D**:

$$I_3 - I_x + I_G = 0$$
$$I_1 - I_2 - I_G = 0$$

Then, Kirchhoff's second rule is used for finding the voltage in the loops **ABD** and **BCD**:

$$(I_3 \cdot R_3) - (I_G \cdot R_G) - (I_1 \cdot R_1) = 0$$
$$(I_x \cdot R_x) - (I_2 \cdot R_2) + (I_G \cdot R_G) = 0$$

The bridge is balanced and $I_G = 0$, so the second set of equations can be rewritten as:

$$I_3 \cdot R_3 = I_1 \cdot R_1$$
$$I_x \cdot R_x = I_2 \cdot R_2$$

Then, the equations are divided and rearranged, giving:

$$R_x = \frac{R_2 \cdot I_2 \cdot I_3 \cdot R_3}{R_1 \cdot I_1 \cdot I_x}$$

From the first rule, $I_3 = I_x$ and $I_1 = I_2$. The desired value of R_x is now known to be given as:

$$R_x = \frac{R_3 \cdot R_2}{R_1}$$

If all four resistor values and the supply voltage (V_S) are known, and the resistance of the galvanometer is high enough that I_G is negligible, the voltage across the bridge (V_G) can be found by working out the voltage from each potential divider and subtracting one from the other. The equation for this is:

$$V_G = \left(\frac{R_x}{R_3 + R_x} - \frac{R_2}{R_1 + R_2} \right) V_s$$

Where V_G is the voltage of node B relative to node D.

4.8.3 Modifications of the fundamental bridge

The Wheatstone bridge is the fundamental bridge, but there are other modifications that can be made to measure various kinds of resistances when the fundamental Wheatstone bridge is not suitable. Some of the modifications are:

1-D.C. bridge measurements

The simplest form of a D.C. four-arm resistance bridge is the Wheatstone bridge. This is suitable for the measurement of resistance typically in the range from 1 Ω to 10 Ω and is shown in Figure above. The detector which may be either a galvanometer or an electronic detector is used to detect a null potential between the points D and B of the bridge, or Strain gauges and platinum resistance thermometers may be situated at a considerable distance from the bridge and the long leads connecting the active element to the bridge will have a resistance which will vary with temperature.

2-A.C. bridge measurements:

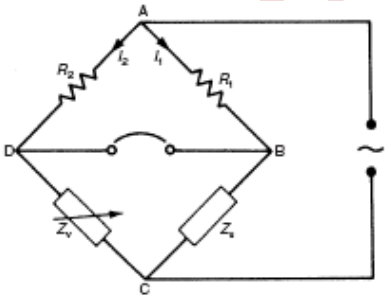
i. Null-type impedance bridge

A typical null-type impedance bridge is shown in Figure below. The null point can be conveniently detected by monitoring the output with a pair of headphones connected via an operational amplifier across the points BD. This is a much cheaper method of null detection than the application of an expensive galvanometer that is required for a D.C. Wheatstone bridge.

$I_1R_1 = I_2R_2$ $I_1Z_u = I_2Z_v$

Thus:

$Z_u = Z_vR_1/R_2$



Z_u is capacitive,

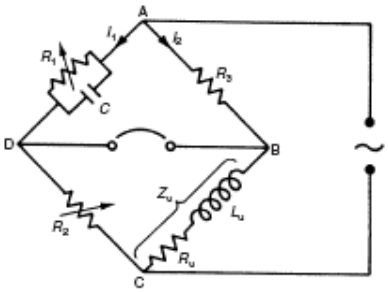
Notice that the expression for Z_u as an inductive impedance has a resistive term in it because it is impossible to realize a pure inductor.

ii. *Maxwell bridge*

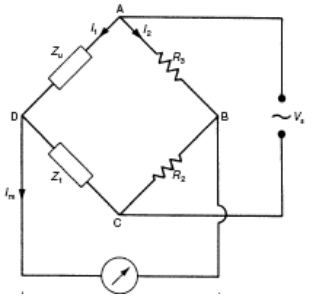
The requirement for a variable inductance box is avoided by introducing instead a second variable resistance. The circuit requires one standard fixed-value capacitor, two variable-resistance boxes and one standard fixed-value resistor, all of which are components that are readily available and inexpensive.

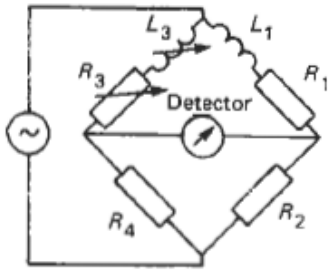
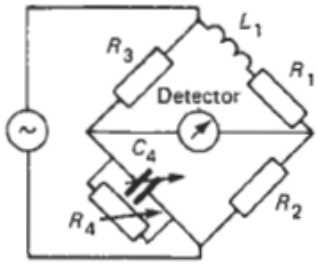
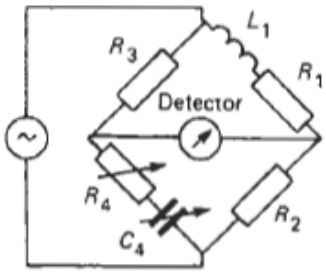
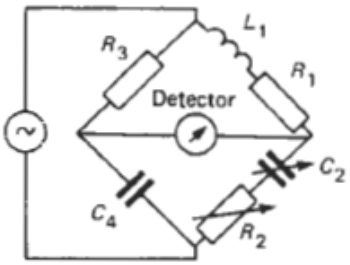
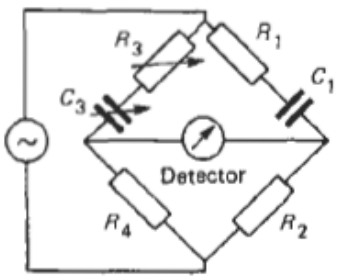
$I_1Z_{AD} = I_2Z_{AB}$ $I_1Z_{DC} = I_2Z_{BC}$

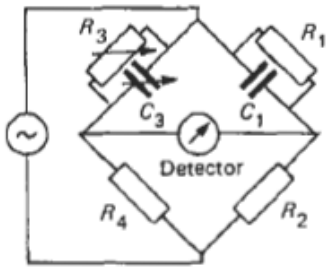
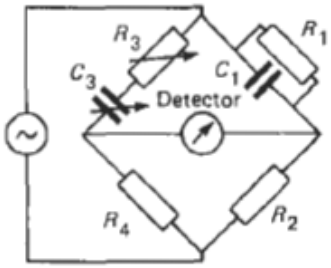
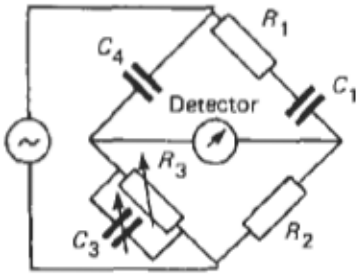
thus: $Z_{BC}/Z_{AB} = Z_{DC}/Z_{AD}$ or $Z_{BC} = (Z_{DC} * Z_{AB})/Z_{AD}$



iii. *Deflection-type A.C. bridge*



A.C. bridges for the measurement of ***capacitance*** and ***inductance***			
Bridge	***Circuit***	***Balance conditions***	***Notes***
Maxwell		$L_1=(R_2/R_4)L_3$	used to measure the parallel components **of** an unknown inductance
Maxwell-Wien1		$L_1=R_2 R_3C_4$ $R_1=R_2R_3/R_4$ $Q_1=\omega C_4R_4$	used for the measurement of inductance; if ***C4*** and ***R4*** are variable bridge measures ***L1*** and ***R1;*** if ***R4*** and ***R2*** or ***R3*** are variable bridge measures ***L1*** and **Q1**
Hay		$L_1=\frac{R_2R_3C_4}{1+\omega^2C_4^2R_4^2}$ $R_1=\frac{R_2R_3\omega^2C_4^2R_4^2}{(1+\omega^2C_4^2R_4^2)}$ $Q_1=\frac{1}{\omega C_4R_4}$	measurement of A.C inductance in the presence of D.C. bias current; used for the measurement *of* inductances with high ***L*** and ***Q***
Owen		***$L_1= C_4R_3. R_2$*** $G_1=1/R_1=(1/C_4R_3)C_2$	measurement of the series inductance and conductance of an unknown inductor; used as a high-precision bridge
Series capacitance Component bridge		$C_1=\frac{R_4}{R_2}.C_3$ $R_1=\frac{R_2}{R_4}.R_3$ $D_1=\omega C_3R_3$	used for the measurement of capacitance; if ***C3*** and ***R3*** are variable bridge measures C1 and ***R1;*** if ***R3*** and ***R4*** are variable bridge measures **C1** and ***D1***

Bridge	Circuit	Balance conditions	Notes
Parallel capacitance component bridge		$C_1 = \frac{R_4}{R_2} \cdot C_3$ $R_1 = \frac{R_4}{R_2} \cdot R_3$ $D_1 = \frac{1}{\omega C_3 R_3}$	measurement of the parallel capacitance and resistance of an unknown capacitor; used particularly for high *D* capacitor measurement
Maxwell-Wien2		$C_1 = \frac{R_4}{R_2} \cdot \frac{C_3}{1+\omega^2 C_3^2 R_3^2}$ $R_1 = \frac{R_2}{R_4} \cdot \frac{1+\omega^2 C_3^2 R_3^2}{\omega^2 C_3^2 R_3}$ $D_1 = \omega C_3 R_3$	measurement of the parallel capacitance and resistance of an unknown capacitor; used as a frequency-dependent circuit in oscillators
Schering		$C_1 = \frac{C_4}{R_2} \cdot R_3$ $R_1 = \frac{R_2}{C_4} \cdot C_3$ $D_1 = \omega C_3 R_3$	measurement of the parallel capacitance and resistance of an unknown capacitor: used for measuring dielectric losses at high voltage and r.f. measurements

MEASUREMENT OF LENGTH,MASS,TIME,LIGHT

Measurement of length:

Introduction

Length is probably the most measured physical parameter. This parameter is known under many alternative names - displacement, movement, motion.

Length is often the intermediate stage of systems used to measure other parameters. For example, a common method of measuring fluid pressure is to use the force of the pressure to elongate a metal element, a length sensor then being used to give an electrical output related to pressure.

Length can now be measured through over thirty decadic orders. Figure 4.1 is a chart of some common methods and their ranges of use. In most cases only two to three decades can be covered with a specific geometrical scaling of a sensor's configuration.

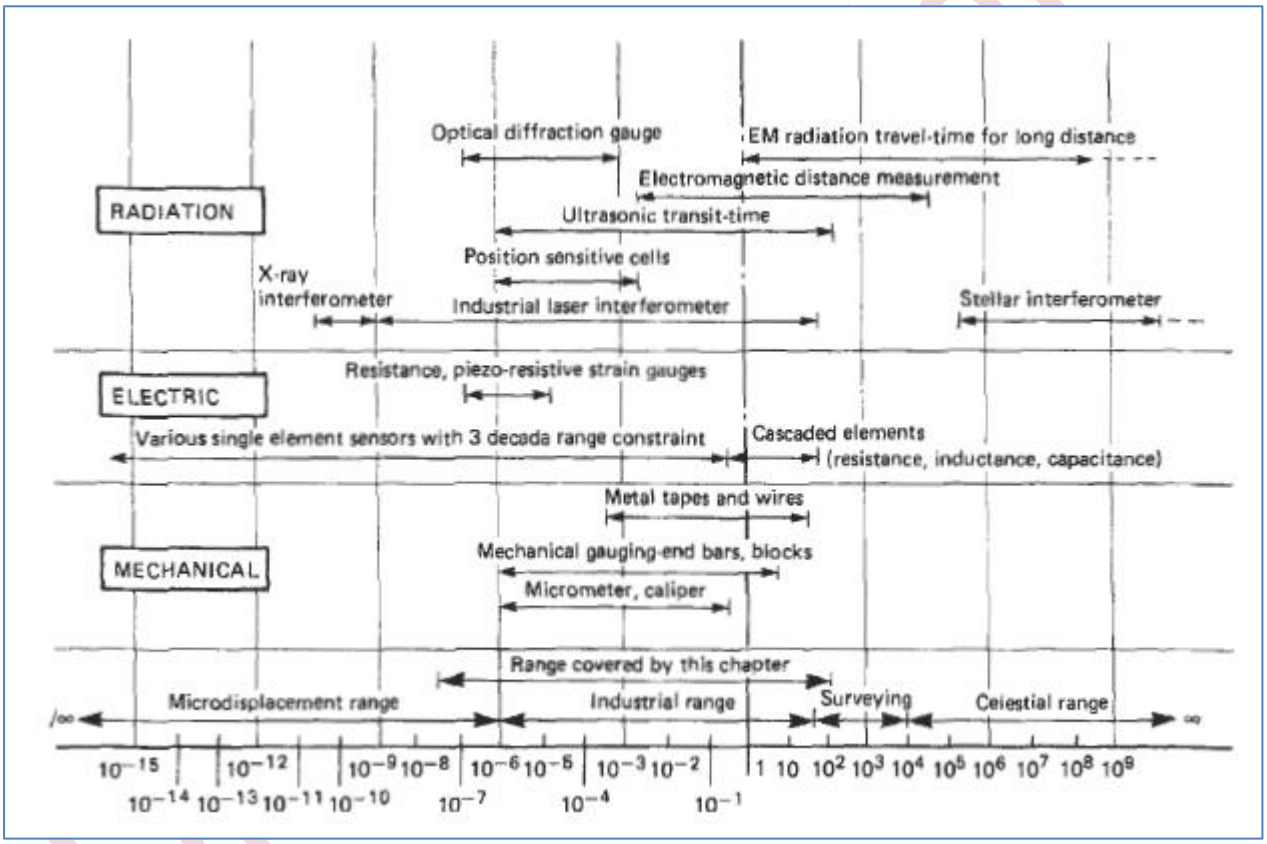


Figure 4.1 Ranges and methods of length measurement.

Definition:

The meter is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.

Derived from length measurement alone:

Length (m) comes into other measurement parameters, including relative length change (m/m), area (m^2) volume (m^3), velocity (m^{-1}), and acceleration (m^{-2}).

To **measure position**, several coordinate systems can be adopted.

Figure 4.2 shows those commonly used. In each instance the general position of a point P will need three measurement numbers, each being measured by separate sensing channels.

The Cartesian (or rectangular) system shown in Figure 4.2(a) is that most adopted for ranges less than a few tens of meters. Beyond that absolute size it becomes very difficult to establish an adequately stable and calibratable framework. Errors can arise from lack of right angles between axes, from errors of length sensing along an axis, and from the imperfection of projection out from an axis to the point.

The polar system of Figure 4.2(b) avoids the need for an all-encompassing framework, replacing that problem with the practical need for a reference base from which two angles and a length are determined. Errors arise here in definition of the two angles and in the length measurement which, now, is not restricted to a slide-way. Practical angle measurement reaches practical and cost barriers at around one arc-second of discrimination. This method is well suited to such applications as radar tracking of aircraft or plotting of location under the sea.

The above two systems of coordinate framework are those mostly adopted. **A** third alternative which is less used, has, in principle, the least error sources. This is the triangular system shown as Figure 4.3(c). In this method three lengths are measured from a triangle formed of three fixed lengths. Errors arise only in the three length measurements with respect to the base triangle and in their definition in space. Where two or more points in space are to be monitored, then their relative position can be obtained accurately even if the base triangle moves in space. The major practical problem in adopting this method is that the three length measurements each require tracking arrangements to keep them following the point. The accuracy of pointing, however, is only subject to easily tolerated cosine forms of error which allow relatively poor following ability to give quite reasonable values. The three alternatives can also be combined to provide other arrangements but in each case there will always be the need to measure three variables (as combinations of at least one length with length and or angle) to define point position in a general manner.

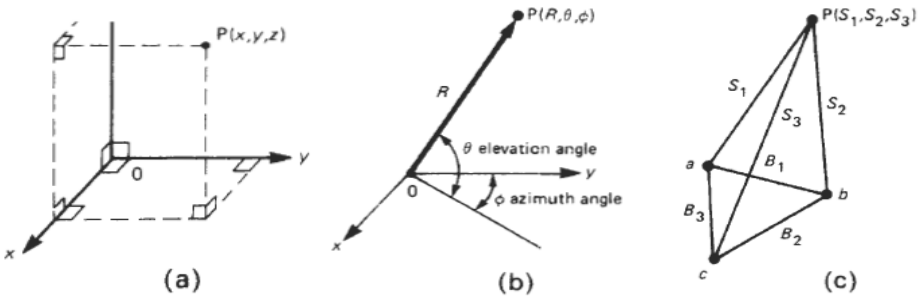


Figure 4.2 Coordinate systems

Space can be described in terms of three length parameters. Three coordinate numbers describe the position of a point in space regardless of the kind of coordinate framework used to define that point's coordinates. The number of coordinates can be reduced if the measurement required is in two dimensions. Measuring position along a defined straight line only requires one length-sensing system channel; to plot position in a defined plane requires two sensors.

Length measurements fall into two kinds. those requiring determination of the absolute value in terms of the defined international standard and those that determine a change in length of a gauge length interval (relative length). For relative length there is no need to determine the gauge interval length to high accuracy. Measuring the length of a structure in absolute terms is a different kind of problem from measuring strains induced in the structure.

Descriptive terminology is needed to simplify general description of the measuring range of a length sensor. Classification into micro displacement, industrial, surveying, navigation, and celestial is included in Figure 3. I.

The actual range of a length sensor is not necessarily that of the size of the task. For example, to measure strain over a long test interval may make use of a long-range, fixed-length, standard structure which is compared with the object of interest using a short-range sensor to detect the small differences that occur. Absolute whole length measurement requires a sensor of longer range. It is often possible to measure a large length by adding together successive intervals, for example by using a single ruler to span a length greater than itself.

Standards and calibration of length:

With very little exception length measurements are now standardized according to SI measurement unit definitions, length being one of the seven base units. It is defined in terms of the unit called the meter.

Until early 1982 the meter was defined in terms of a given number of wavelengths of krypton-86 radiation.

Over the 1970 decade, however, it was becoming clear that there were improved methods available that would enable definition with reduced uncertainty.

Suitable equipment and experimental procedures have now been proven as workable. By choosing a convenient value for c that suited measurement needs (that given above) it was, in 1982, agreed by the signatories of the committee responsible for standardization of the meter that the new definition should be, "The meter is the length of the path travelled by light in vacuum during the fraction (11299, 792,458) of a second."

For lengths over a few meters, solid mechanical bars are less suitable as standard lengths due to handling reasons. Flexible tapes are used which are calibrated against the laser interferometer in standards facilities. Tapes are relatively cheap and easy to use in the field compared with the laser interferometer. They can be calibrated to the order of a part in 10^6.

For industrial use little difficulty will be experienced in obtaining calibration of a length-measuring device. Probably the most serious problem to be faced is that good calibration requires considerable time: the standard under calibration must be observed for a time in order to ensure that it does have the long-term stability needed to hold the calibration.

Practice of length measurement for industrial use

General remarks

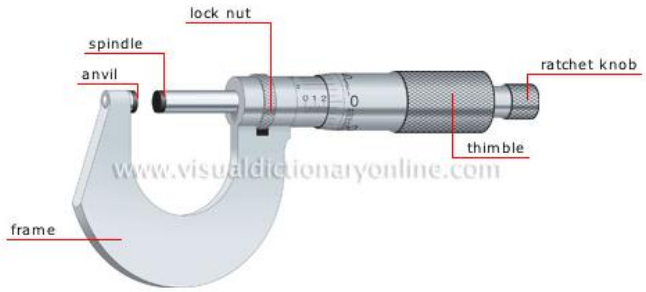
A large proportion of industrial range measurements can be performed quite adequately using simple mechanical gauging and measuring instruments. If, however, the requirement is for automatic measurement such as is needed in automatic inspection or in closed-loop control, then the manual methods must be replaced by transducer forms of length sensor.

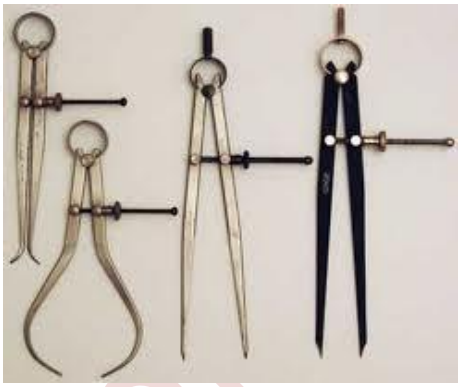
In many applications the speed of response needed is far greater than the traditional mechanical methods can yield. Numerically controlled mills, for instance, could not function without the use of electronic sensors that transduce the various axial dimensions into control signals.

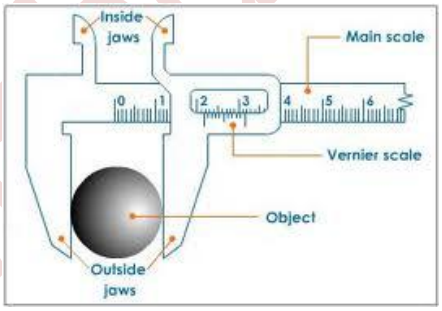
Initially, that is, in the 1950s, the cost of electronic sensors greatly exceeded that of the traditional mechanical measuring tools and their servicing required a new breed of technician. Most of these earlier shortcomings are now removed and today the use of electronic sensing can be more productive than the use of manually read micrometers and scales because of the reduced cost of the electronic part of the sensing system and the need for more automatic data processing. There can be little doubt that solely mechanical instruments will gradually become less attractive in many uses.

Length measurement:

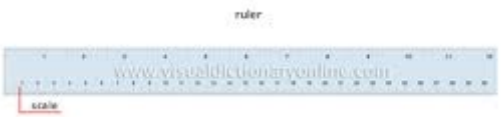
1. **thickness**





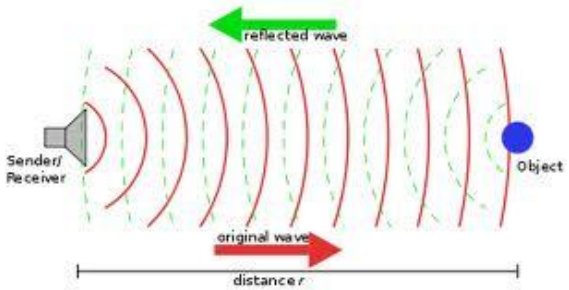


2. **length**



3. **distance**

4. **Measurement of distance at sea**:



ANGULAR MEASURING DEVICES:

INTRODUCTION

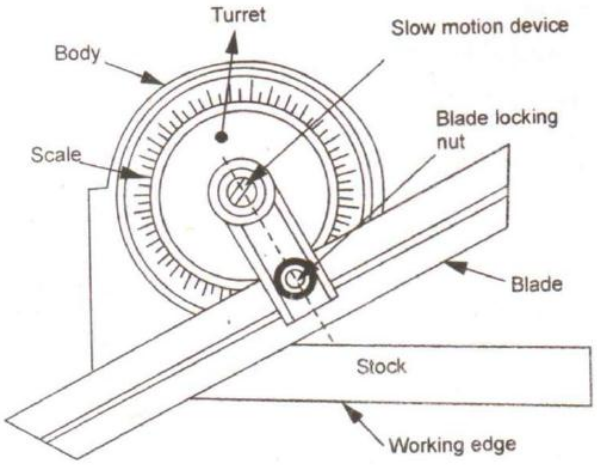
There are a wide variety of geometric features that are measured in angular units. These varieties include angular separation of bounding planes, angular spacing conditions related to circle, digression from a basic direction etc. Because of these diverse geometrical forms, different types of methods and equipment are available to measure angles in common angular units of degree, minute and second. Several factors come into picture in selection of suitable angular measuring instruments. These factors may be the size and general shape of the part, the location and angular accessibilities of the feature to be measured, expected range of angle variations, the required sensitivity and accuracy of measurement etc. Because of the different systems and techniques in angular measuring instruments, it is difficult to categorize them completely. As in linear measurement, they can be categorized in two groups. The first one is line standard instrument. It includes divided scales like protractors, bevel gauges. The second category of angular measuring instruments is called face standard instruments. Sine bars and angle gauges falls in this category. In this unit, we will discuss both types of angular measuring devices and the techniques used in determining the angle. In addition to that, we will have an overview of angle comparators (autocollimators).

LINE STANDARD ANGULAR MEASURING DEVICES

Line standard gives direct angular measurement from the engraved scales in the instruments. They are not very precise. Hence they are not used when high precision is required. However, they can be used in initial estimation of the angles in measurement. We will discuss some of the line standard angular measuring devices in the following sub-sections.

1- Protractor

It is the simplest instrument for measuring angles between two faces. It consists of two arms and an engraved circular scale. The two arms can be set along the faces between which the angle is to be measured. The body of the instrument is extended to form one of the arms, and this is known as the *stock*. It is the fixed part of the protractor and should be perfectly straight. The other arm is in the form of a *blade* that rotates in a *turret* mounted on the body. One of the bodies of the turret carries the divided scale and the other member carries a vernier or index. The ordinary protractor measures angles only in degrees and used for non-precision works. By using angular vernier scale along with it, precision up to 5° can be achieved. Figure shows the diagram of a protractor.



2- Universal Bevel Protractors

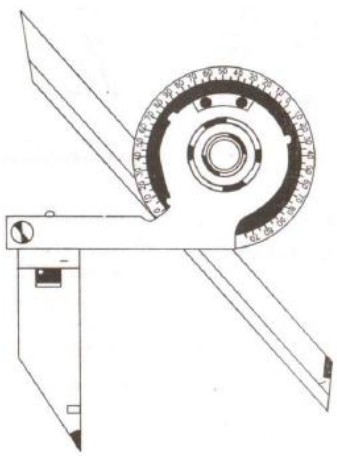
It is an angular measuring instrument capable of measuring angles to within 5 min. The name universal refers to the capacity of the instrument to be adaptable to a great variety of work configurations and angular interrelations. It consists of a *base* to which a vernier scale is attached. A *protractor dial* is mounted on the circular section of the base. The protractor *dial* is graduated in degrees with every tenth degree numbered. The *sliding blade* is fitted into this dial; it may be extended to either direction and set at any angle to the base. The blade and the dial are rotated as a unit. Fine adjustment are obtained with a small knurled headed pinion that, when turned, engages with a gear attached to the blade mount. The protractor dial may be locked in any position by means of the dial clamp nut.

Measurement in a universal bevel protractor is made either by embracing the two bounding elements of the angle or by extraneous referencing, for example, the part and the instrument resting on a surface plate.

The vernier protractor is used to measure an obtuse angle, or an angle greater than 90° but less than 180°. An *acute angle attachment* is fastened to the vernier protractor to measure angles of less than 90. The main scale is divided into two arcs of 180°. Each arc is divided into two quadrants of 90° and has graduation from 0°to 90° to the left and right of the zero line, with every tenth degree numbered.

The vernier scale is divided into 12 spaces on each side of its zero (total 24). The spacing in the vernier scale is made in such a way that least count of it corresponds to $1/12^{th}$ of a degree, which is equal to 5'.

If the zero on the vernier scale coincides with a line on the main scale, the number of vernier graduations beyond the zero should be multiplied by 5 and added to the number of full degrees indicated on the protractor dial. Figure shows a diagram of a bevel protractor.



MEASUREMENT OF INCLINES

Inclination of a surface generally represents its deviation from the horizontal or vertical planes. Gravitational principle can be used in construction of measurements of such inclinations. Spirit levels and clinometer are the instruments of this category. We will discuss these instruments in brief in the following sub-sections.

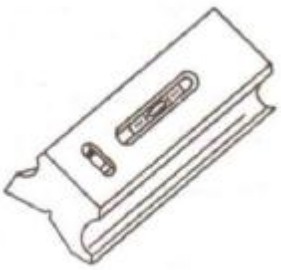
1- Spirit Level

Spirit level is one of the most commonly used instruments for inspecting the horizontal position of surfaces and for evaluating the direction and magnitude of minor deviation from that nominal condition. It essentially consists of a close glass tube of accurate form. It is called as the vial. It is filled almost entirely with a liquid, leaving a small space for the formation of an air or gas bubble. Generally, low viscosity fluids, such as ether, alcohol or benzol, are preferred for filling the vial. The liquid due to its greater specific weight tends to fill the lower portion of the closed space. Upper side of the vial is graduated in linear units. Inclination of a surface can be known from the deviation of the bubble from its position when the spirit level is kept in a horizontal plane. Temperature variations in the ambient condition cause both liquid and vial to expand or contract. Therefore, selection of proper liquid and material for the spirit level is very important for accurate result. To reduce the effect of heat transfer in handling spirit levels are made of a relatively stable casting and are equipped with thermally insulated handles. Figure 6.5 shows a schematic diagram of a spirit level.

Sensitivity of the vial used in spirit level is commonly expressed in the following two ways.

Each graduation line representing a specific slope is defined by a tangent relationship, e.g. 0.01 cm per meter.

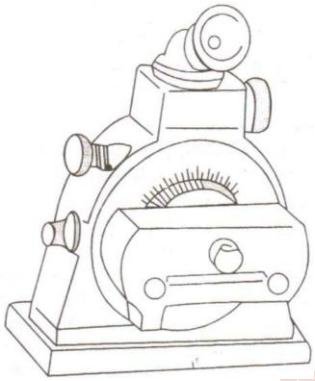
An angular value is assigned to the vial length covered by the distance of two adjacent graduation lines, i.e. the distance moved by the bubble from the zero will correspond the angle directly.



2- Clinometer

A clinometer is a special case of application of spirit level for measuring, in the vertical plane, the incline of a surface in relation to the basic horizontal plane, over an extended range. The main functional element of a clinometer is the sensitive vial mounted on a rotatable disc, which carries a graduated ring with its horizontal axis supported in the housing of the instrument. The bubble of the vial is in its center position, when the clinometer is placed on a horizontal surface and the scale of the rotatable disc is at zero position. If the clinometer is placed on an incline surface, the bubble deviates from the center. It can be brought to the center by rotating the disc. The rotation of the disc can be read on the scale. It represents the deviation of the surface over which the clinometer is placed from the horizontal plane. Figure 6.6 shows a diagram of a clinometer.

A number of commercially available clinometers with various designs are available. They differ in their sensitivity and measuring accuracy. Sensitivity and measuring accuracy of modern clinometers can be compared with any other high precision measuring instruments. For shop uses, clinometers with 10' graduations are available.



Applications

Two categories of measurement are possible with clinometer. Care must be taken to keep the axis of the rotatable disc parallel to the hinge line of the incline. The two categories of measurement are :

(i) Measurement of an incline place with respect to a horizontal plane. This is done by placing the instrument on the surface to be measured and rotating graduated disc to produce zero inclination on the bubble. The scale value of the disc position will be equal to the angle of incline.

(ii) Measurement of the relative position of two mutually inclined surfaces. This is done by placing the clinometer on each of the surface in turn, and taking the readings with respect to the horizontal. The difference of both the readings will indicate the angular value of the relative incline.

Mass and Mass Standards:

Definition of Mass

The following quotation of Condon and Odishaw1 is presented here as a succinct definition of mass:

"The property of a body by which it requires force to change its state of motion is called inertia, and *mass* is the numerical measure of this property."

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

The Mass Unit

According to Maxwell,2 "every physical quantity [mass in the present case] can be expressed as the product of a pure number and a unit, where the unit is a selected reference quantity in terms of which all quantities of the same kind can be expressed." The fundamental unit of mass is the international *kilogram*. At present the kilogram is realized as an artifact, i.e., an object. Originally, the artifact was designed to have ***the mass of 1 cubic decimeter of pure water at the temperature of maximum density of water, 4°C***. Subsequent determination of the density of pure water with the air removed at 4°C under standard atmospheric pressure (101,325 Pa) yielded the present value of 1.000028 cubic decimeters for the volume of 1 kilogram of water.

Mass Artifacts, Mass Standards

The present embodiment of the kilogram is based on the French platinum kilogram of the Archives constructed in 1792. Several platinum-iridium (Pt-Ir) cylinders of height equal to diameter and nominal mass of 1 kg were manufactured in England. These cylinders were polished and adjusted and compared with the kilogram of the Archives. The cylinder with mass closest to that of the kilogram of the Archives was sent to the International Bureau of Weights and Measures (Bureau International des Poids et Mesures, BIPM) in Paris and chosen as the International Prototype Kilogram (IPK) in 1883. It was ratified as the IPK by the first General Conference of Weights and Measures (CPGM) in 1899. Other prototype kilograms were constructed and distributed as national prototypes. The United States received prototypes Nos. 4 and 20. All other mass standards in the United States are referred to these. As a matter of practice, the unit of mass as maintained by the developed nations is interchangeable among them.

FIGURE U.S. kilogram No. 20.

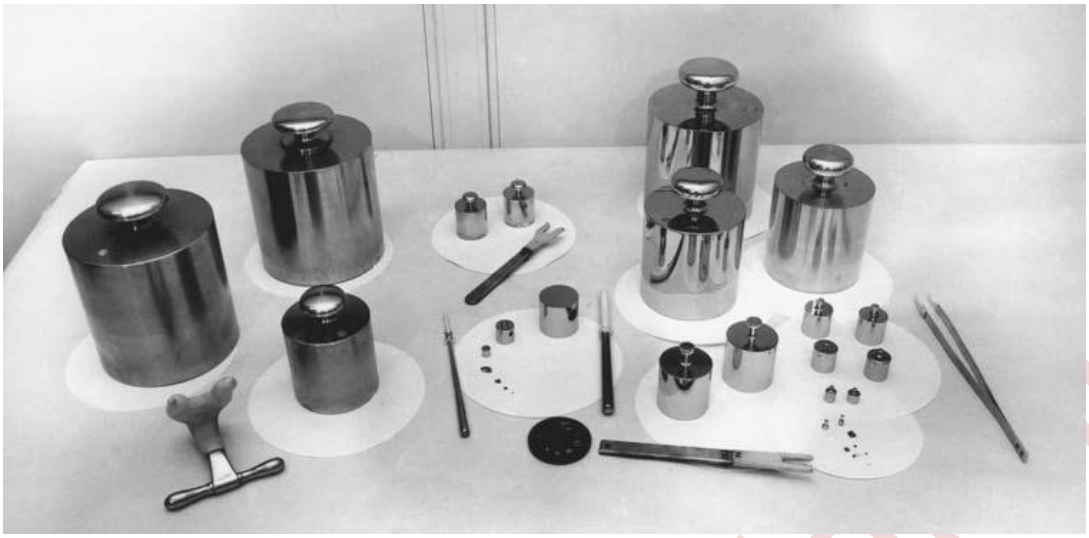


FIGURE Brass weight set.

FIGURE Stainless steel weight set.

Recalibration of the Kilogram

Introduction

In 1984, the U.S. National Prototype Kilogram, K20, and its check standard, K4, were recalibrated at the Bureau International des Poids et Mesures (BIPM). Two additional kilograms, designated CH-1 and D2, made of different alloys of stainless steel, were also included in the calibrations.

The mass of K20 was stated to be 1 kg – 0.039 mg in an 1889 BIPM certification; the mass of K4 was stated to be 1 kg – 0.075 mg in an 1889 BIPM certification. K20 was recalibrated at BIPM in 1948 and certified to have a mass of 1 kg – 0.019 mg. K4 had never before been recalibrated.

The nominal masses of the stainless steel kilograms were 1 kg + 13.49 mg for D2 and 1 kg – 0.36 mg for CH-1. The four 1-kg artifacts were hand-carried from the National Bureau of Standards, NBS (now National Institute of Standards and Technology, NIST), Gaithersburg, MD to BIPM on commercial airlines. The carrying case for K20 was an enclosure in which the kilogram was held firmly on the top and bottom and clamped gently at three places along the side. Clamped areas, conforming to the contour of the adjacent kilogram surfaces, were protected by low-abrasive tissue paper backed by chamois skin, which had previously been degreased through successive soakings in benzene and ethanol. The outer case of the container was metal, the seal of which was not airtight.

In the carrying case for K4, of simpler design, the artifact was wrapped in tissue, then wrapped in chamois skin, and finally placed in a snug-fitting brass container. The container seal was not airtight.

The stainless steel kilograms were wrapped in tissue paper and were then padded with successive layers of cotton batting and soft polyethylene foam. The outer container was a stiff cardboard tube. The kilogram was held fast within the tube by the padding.

1984 BIPM Measurements

The four NBS standards were compared to two platinum-iridium standards of BIPM, first in the state in which they arrived at BIPM. Then they were compared after cleaning with benzene. Platinum-iridium prototypes K4 and K20 were, in addition, washed under a steam jet of doubly distilled water.

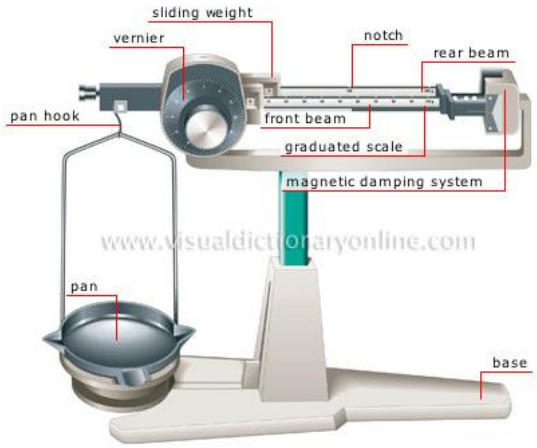
In the course of each weighing, the density of moist air was calculated using the “formula for the determination of the density of moist air (1981).”4 The parameters in the formula, temperature, pressure, relative humidity, and carbon dioxide concentration in the balance chamber were measured using a platinum resistance thermometer, an electro manometer, a hygrometer transducer, and an infrared absorption analyzer, respectively.

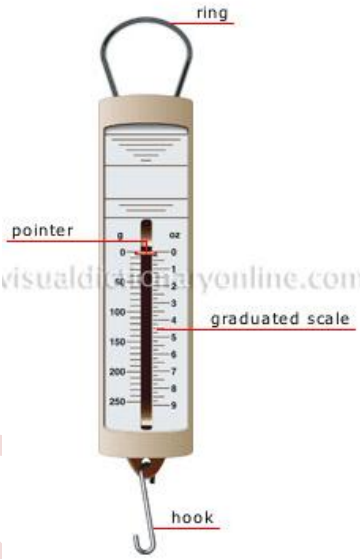
The mass values found at BIPM for the four artifacts are as follows:

	Before Cleaning	After Cleaning
K20	1 kg – 0.001	1 kg – 0.022 mg
K4	1 kg – 0.075 mg	1 kg – 0.106 mg
CH-1	1 kg – 0.377 mg	1 kg – 0.384 mg
D2	1 kg + 13.453 mg	1 kg + 13.447 mg

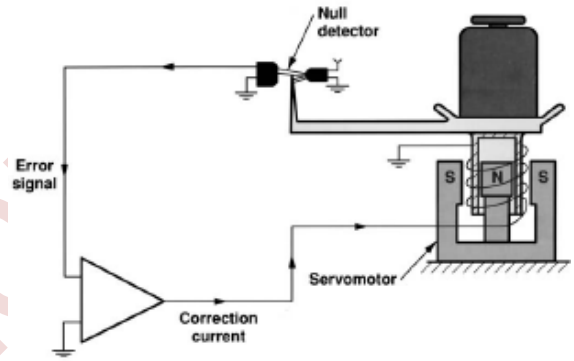
The estimate of the standard deviation of each of the before cleaning results was 1.2 µg. The estimate of the standard deviation of each of the after cleaning results was 1.3 µg.

Mechanical Balancing:

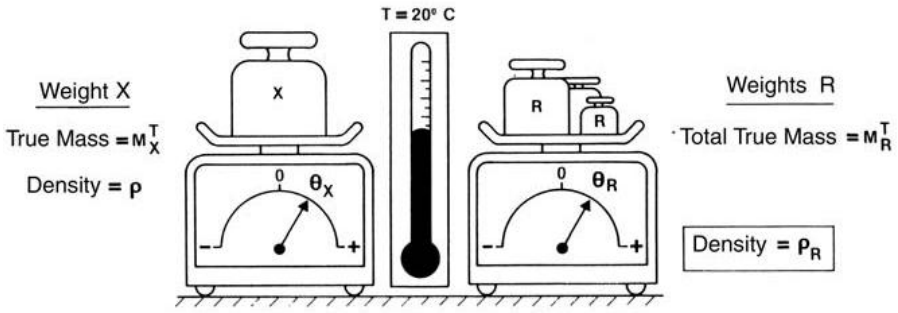




Electronic balancing:



Simplified electromagnetic balancing system.



Time:

the unit of time is indispensable for science and technology,(1967/68) definition of the second by the following:

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.

It follows that the hyperfine splitting in the ground state of the caesium 133 atom is exactly 9 192 631 770 hertz, (hfs Cs) = 9 192 631 770 Hz.

At its 1997 meeting the CIPM affirmed that:

This definition refers to a caesium atom at rest at a temperature of 0 K. This note was intended to make it clear that the definition of the SI second is based on a caesium atom unperturbed by black body radiation, that is, in an environment whose thermodynamic temperature is 0 K. The frequencies of all primary frequency standards should therefore be corrected for the shift due to ambient radiation, as stated at the meeting of the Consultative Committee for Time and Frequency in 1999.

The unit of time, the second, was defined originally as the fraction 1/86 400 of the mean solar day. The exact definition of "mean solar day" was left to astronomical theories. However, measurement showed that irregularities in the rotation of the Earth could not be taken into account by the theory and have the effect that this definition does not allow the required accuracy to be achieved. In order to define the unit of time more precisely, the 11th CGPM (1960) adopted a definition given by the International Astronomical Union which was based on the tropical year. Experimental work had, however, already shown that an atomic standard of time-interval, based on a transition between two energy levels of an atom or a molecule, could be realized and reproduced much more precisely.

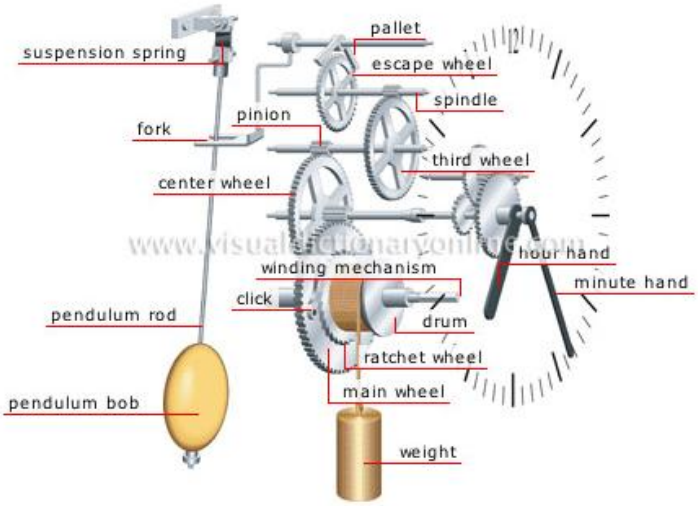
Considering that a very precise definition of the unit of time is indispensable for the International System, the 13th CGPM (**Credential for Green Property Management**) (1967) decided to replace the definition of the second by the following (affirmed by the CIPM (**Certificate in Investment Performance Measurement**) in 1997 that this definition refers to a cesium atom in its ground state at a temperature of 0 K):

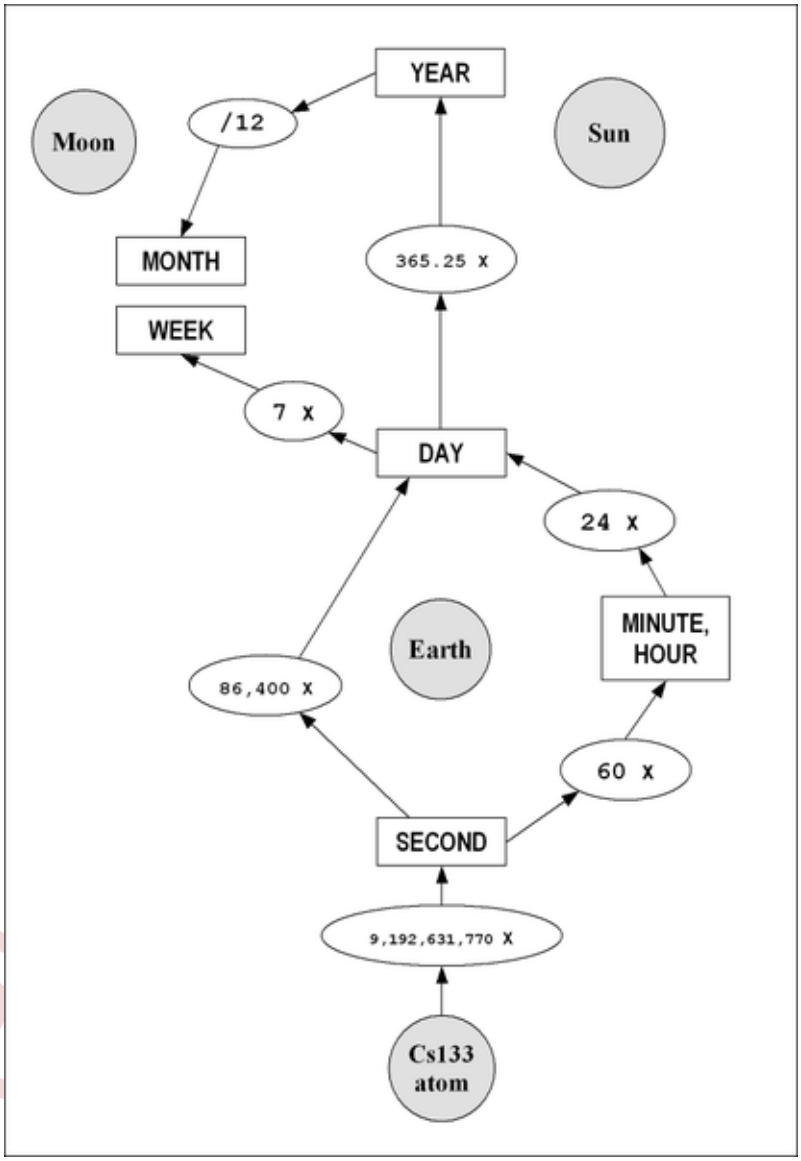
The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.

stop watch

sundialwatch

Mechanical watch:





Tree time

Unit of luminous intensity (candela)

Originally, each country had its own, and rather poorly reproducible, unit of luminous intensity; it was necessary to wait until 1909 to see a beginning of unification on the international level, when the national laboratories of the United States of America, France, and Great Britain decided to adopt the *international candle* represented by carbon filament lamps. Germany, at the same time, stayed with the *Hefner candle*, defined by a flame standard, and equal to about nine-tenths of an international candle. But a standard based on incandescent lamps, and consequently dependent upon their stability, would never have been fully satisfactory and could therefore be only provisional; on the other hand, the properties of a blackbody provided a theoretically perfect solution and, as early as 1933, the principle was adopted that new photometric units would be based on the luminous emission of a blackbody at the freezing temperature of platinum (2045 K).

The units of luminous intensity based on flame or incandescent filament standards in use in various countries before 1948 were replaced initially by the "new candle" based on the luminance of a Planckian radiator (a blackbody) at the temperature of freezing platinum. This modification had been prepared by the International Commission on Illumination (CIE) and by the CIPM before 1937, and was promulgated by the CIPM in 1946. It was then ratified in 1948 by the 9th CGPM which adopted a new international name for this unit, the *candela* (symbol cd); in 1967 the 13th CGPM gave an amended version of the 1946 definition.

In 1979, because of the experimental difficulties in realizing a Planck radiator at high temperatures and the new possibilities offered by radiometry, i.e., the measurement of optical radiation power, the 16th CGPM (1979) adopted a new definition of the candela:

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

MEASUREMENT OF TEMPERATURE

Introduction:

The first recorded temperature measurement was carried out by Galileo at the end of the sixteenth century. His thermometer depended on the expansion of air. Some form of scale was attached to his apparatus, for he mentions "degrees of heat" in his records.

As with any other measurement, it is necessary to have agreed and standardized units of measurement. In the case of temperature the internationally recognized units are the Kelvin and the degree Celsius.

WHAT IS TEMPERATURE concept?

Temperature is the measure of the average kinetic energy in a substance. Kinetic energy makes molecules move: the molecules of solids vibrate in place; the molecules of liquids and gases move about. All the molecules are not moving at exactly the same speed, this is why temperature is defined as a measure of the average kinetic energy of a substance. The higher the temperature, the faster the molecules move.

Temperature is a measure of stored or potential energy in a mass of matter.

Temperature is the potential to cause heat to move from a point of higher temperature to one of lower temperature.

Temperature does not measure the amount of heat in a substance because molecules have both potential and kinetic energy. Temperature can only measure kinetic energy; it cannot measure potential energy.

The rate of heat transfer is a function of that temperature difference.

Temperature scales

To measure and compare temperatures it is necessary to have agreed scales of temperature. These temperature scales are defined in terms of physical phenomena which occur at constant temperatures. The temperatures of these phenomena are known as “fixed points.”

A) Celsius temperature scale

The Celsius temperature scale is defined by international agreement in terms of two fixed points, the ice point and the steam point. The temperature of the ice point is defined as zero degrees Celsius and the steam point as one hundred degrees Celsius. The ice point is the temperature at which ice and water exist together at a pressure of 1.0132×10^5 N.m^{-2} (originally one standard atmosphere = 760mm of mercury). The ice should be prepared from distilled water in the form of fine shavings and mixed with ice-cold distilled water.

The steam point is the temperature of distilled water boiling at a pressure of 1.0132×10^5 N.m^{-2}. The temperature at which water boils is very dependent on pressure. The temperature interval of 100 °C between the ice point and the steam point is called the fundamental interval.

Kelvin, absolute or thermodynamic temperature scale

Lord Kelvin defined a scale based on thermodynamic principles which does not depend on the properties of any particular substance. Kelvin divided the interval between the ice and steam points into 100 divisions so that one Kelvin represents the same temperature interval as one Celsius degree. The unit of the Kelvin or thermodynamic temperature scale is the "Kelvin." The definition of the Kelvin is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. This definition was adopted by the thirteenth meeting of the General Conference for Weights and Measures in 1967 (13th CGPM, 1967).

B) Fahrenheit and Rankine scales

These two temperature scales are now obsolete in Britain and the United States. but as a great deal of engineering data, steam tables, etc., have been published using the Fahrenheit and Rankine temperature a short note for reference purposes is relevant. *Fahrenheit* This scale was proposed in 1714. Its original fixed points were the lowest temperature obtainable using ice and water with added salts (ammonium chloride) which was taken as zero. On this scale the ice point is at 32°F and the steam point at 212°F. There does not appear to be any formal definition of the scale.

Rankine the Rankine scale is the thermodynamic temperature corresponding to Fahrenheit. Zero in Rankine is of course, the same as zero Kelvin. On the Rankine scale the ice point is at 491.67°R. Zero Fahrenheit is 459.67°R.

MEASUREMENT TECHNIQUES:

A) Direct effects:

Scientists have been devising methods of measuring temperature for nearly 2,000 years. In the first century, Hero of Alexandra published his studies on pneumatics in which he described a tube with the top closed and the bottom open. The bottom is submerged in a container of water and the tube is filled with air at the top and water at the bottom. When the air that is trapped in the top of the tube was heated, the expended air would push the water down the tube. When the air cooled, the air would contract and water would rise in the tube. This made a sort of backwards thermometer, Figure 6.1.

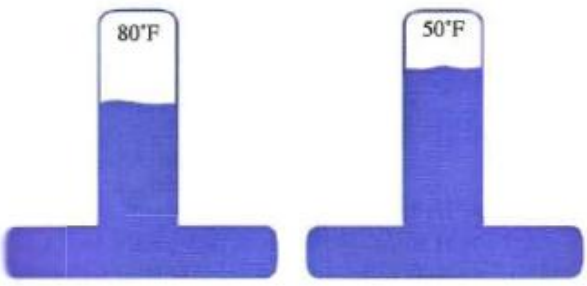


Figure 6.1

Later, in the eleventh century, Abu Ali ibn Sina _ ped air thermometers based on this same principle. In the early seventeenth century Galileo experimented with a device called a thermo scope, Figure 6.2. It consisted of a column of liquid with several glass balls partially filled with varies to give them different densities. The density of the fluid they were immersed in changed with temperature, causing them to rise or fall. The position of the glass balls indicated the relative temperature.

Figure 6.2

All of these early instruments were affected by atmospheric pressure changes as well as temperature changes. In 1654 Ferdinando II de Medici made the first modern-style thermometer that was not affected by changes in atmospheric pressure. His thermometer used sealed tubes that were partially filled with alcohol. Many scientists experimented with different styles of thermometers using different liquids. Unfortunately, each thermometer and scale was unique and no accepted standard existed. In 1724, Daniel Fahrenheit began producing thermometers that used mercury. Mercury's large coefficient of expansion allowed a scale with a wider range and greater precision than previous thermometers. The superiority of Fahrenheit's thermometer led to its wide adoption resulting in the Fahrenheit temperature scale becoming the first widely used temperature scale.

In this section are classified according to the nature of the change in the measurement probe produced by the change of temperature. They have been divided into four classes: **liquid expansion, gas expansion, change of state, and solid expansion.**

A) Direct effect

Liquid-in-glass thermometers

The glass thermometer must be the most familiar of all thermometers. Apart from its industrial and laboratory use it finds application in both domestic and medical fields.

***Mercury-filled glass thermometer**:*

The **principle of the mercury in- glass thermometer:**

The coefficient of cubical expansion of mercury is about eight times greater than that of glass. If, therefore, a glass container holding mercury is heated, the mercury will expand more than the container. At a high temperature, the mercury will occupy a greater fraction of the volume of the container than at a low temperature. If, then, the container is made in the form of a bulb with a capillary tube attached, it can be so arranged that the surface of the mercury is in the capillary tube, its position along the tube will change with temperature and the assembly used to indicate temperature.

Built of thermometer:

The thermometer therefore consists simply of a **stem** of suitable glass tubing having a very small; but **uniform, bore**. At the bottom of this stem there is a **thin-walled glass bulb**. The bulb may be cylindrical or spherical in shape and has a capacity larger than that of the bore of the stem. The bulb and bore are completely filled with mercury, and the open end of the bore sealed off either at a high temperature, or under vacuum, so that no air is included in the system. The thermometer is then calibrated by comparing it with a standard thermometer in a bath of liquid whose temperature is carefully controlled.

Thermometer calibration:

When the thermometer to be calibrated has reached equilibrium with the bath at a definite temperature, the point on the glass of the thermometer opposite the top of the mercury meniscus is marked. The process is repeated for several temperatures. The intervals between these marks are then divided off by a dividing machine. In the case of industrial thermometers, the points obtained by calibration are transferred to a metal or plastic plate, which is then fixed with the tube into a suitable protecting case to complete the instrument.

The stem of the thermometer is usually shaped in such a way that it acts as a lens, magnifying the width of the mercury column. The mercury is usually viewed against a background of glass which has been enameled white. Figure 5.3 shows the typical arrangement for a liquid in-glass thermometer.

Mercury-in-glass thermometers are available in three grades: **A** and B are specified in BS 1041: Part 2.1: 1958; grade C is a commercial grade of thermometer and no limits of accuracy are specified.

Types of errors:

- **Error due to using**:

Whenever possible, thermometers should be calibrated, standardized and used immersed up to the reading, *totally immersed*, to avoid errors due to the emergent column of mercury and the glass stem being at a different temperature than the bulb.

Errors introduced this way should be allowed for if accurate readings are required. Some thermometers, however, are calibrated for *partial immersion* and should be used immersed to the specified depth.

- **Error due to observer position:**

When reading a thermometer an observer should keep his eye on the same level as the top of the mercury column. In this way errors due to parallax will be avoided. Figure 5.4 shows the effect of observing the thermometer reading from the wrong position.

A mercury-in-glass thermometer has a fairly large thermal capacity (i.e., it requires quite an appreciable amount of heat to change its temperature by one degree), and glass is not a very good conductor of heat. This type of thermometer will, therefore, have a definite thermal lag. In other words, it will require a definite time to reach the temperature of its surroundings. This time should be allowed for before any reading is taken. If there is any doubt as to whether the thermometer has reached equilibrium with a bath of liquid having a constant temperature, then readings should be taken at short intervals of time. When the reading remains constant the thermometer must be in equilibrium with the bath. If the temperature is varying rapidly the thermometer may never indicate the temperature accurately, particularly if the tested medium is a gas.

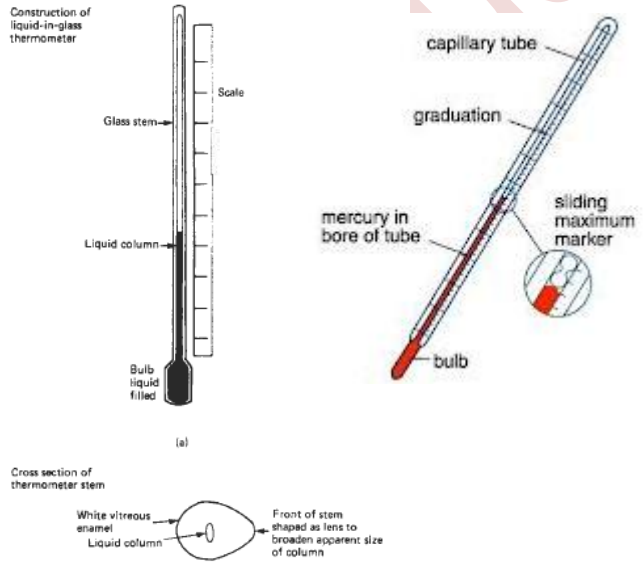


Figure 6.3 Mercury-in-glass thermometer. (a) thermometer and scale, (b) cross-section of thermometer stem.

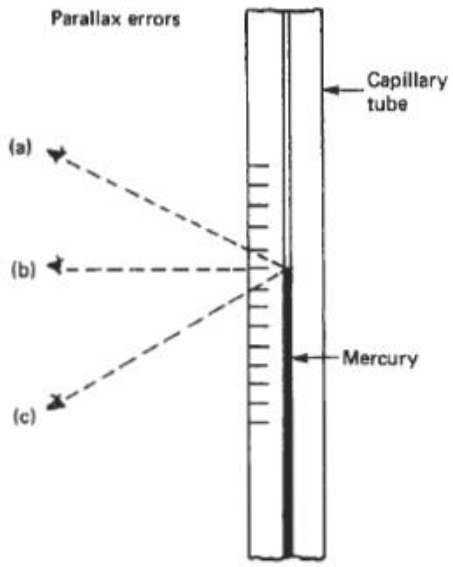


Figure 6.4 Parallax errors when reading glass thermometer.

- **Error due to metal protector:**

Glass thermometers used in industry are usually protected by metal sheaths. These sheaths may conduct heat to or from the neighborhood of the thermometer bulb and cause the thermometer to read either high or low according to the actual conditions prevailing. A thermometer should, therefore, be calibrated, whenever possible, under the conditions in which it will be used, if accurate temperature readings are required. If, however, the main requirement is that the temperature indication be consistent for the same plant temperature, then an error introduced is not so important, so long as the conditions remain the same, and the error is constant.

- **Errors due to aging**:

It is often assumed that provided a mercury-in-glass thermometer is in good condition it will always give an accurate reading. This is not always so, particularly with cheap thermometers. **A** large error may be introduced by changes in the size of the bulb due to aging. When glass is heated to a high temperature, as it is when a thermometer is made, it does not, on cooling, contract to its original volume immediately. Thus, for a long time after it has been made the bulb continues to contract very slowly so that the original zero marks is too low on the stem, and the thermometer reads high. This error continues to increase over a long period, and depends upon the type of glass used in the manufacture of the thermometer. In order to reduce to a minimum the error due to this cause, during manufacture thermometers are annealed by baking for several days at a temperature above that which they will be required to measure, and then cooled slowly over a period of several days. Another error due to the same cause is the depression of the zero when a thermometer is cooled rapidly from a high temperature. When cooled, the glass of the thermometer bulb does not contract immediately to its original size so that the reading on the thermometer at low temperature is too low, but returns to normal after a period of time. This period depends upon the nature of the glass from which the bulb is made.

High temperature thermometers Mercury normally boils at 357 $^{\circ}C$ at atmospheric pressure. In order to extend the range of a mercury-in-glass thermometer beyond this temperature, the top end of the thermometer bore is enlarged into a bulb having a capacity of about 20 times that of the bore of the stem. This bulb, together with the bore above the mercury, is then filled with nitrogen or carbon dioxide at a sufficiently high pressure to prevent the mercury boiling at the highest temperature at which the thermometer will be used.

Use of liquids other than mercury

In certain industrial uses, particularly in industries where the escape of mercury from a broken bulb might cause considerable damage to the products, other liquids are used to fill the thermometer. These liquids are also used where the temperature range of the mercury-in-glass thermometer is not suitable. Table 6.1 lists some liquids together with their range of usefulness.

Table 6.1 Liquids used in glass thermometers

Liquid	*Temperature range ("C)*
Mercury	-35 to +510
Alcohol	-80 to +70
Toluene	-80 to +100
Pentane	-200 to +30
Creosote	-5 to +200

- ***Mercury-in-glass electric contact thermometer***

A mercury-in-glass thermometer can form the basis of a simple on/off temperature controller which will control the temperature of an enclosure at any value between 40 °Cand 350 °C. Mercury is a good electrical conductor. By introducing into the bore of a thermometer two platinum contact wires, one fixed at the lower end of the scale and the other either fixed or adjustable from the top of the stem, it is possible to arrange for an electrical circuit to be completed when a predetermined temperature is reached. The current through the circuit is limited to about 25 mA. This current is used to operate an electronic control circuit. Contact thermometers find applications in laboratories for the temperature control of water baths, fluidized beds and incubators.

Liquid-filled dial thermometers

- ***Mercury-in-steel thermometer***

Two distinct disadvantages restrict the usefulness of liquid-in-glass thermometers in industry: **glass is very fragile**, and **the position of the thermometer** for accurate temperature measurement is not always the best position for reading the scale of the thermometer. These difficulties are overcome in the mercury in-steel thermometer shown in Figure 6.5. This type of thermometer works on exactly the same principle as the liquid-in-glass thermometer. The glass bulb is, however, replaced by a steel bulb and the glass capillary tube by one of stainless steel. As the liquid in the system is now no longer visible, a Bourdon tube is used to measure the and the capillary tube are completely filled with mercury, usually at a high pressure. When suitably designed,

the capillary tube may be of considerable length so that the indicator operated by the Bourdon tube may be some distance away from the bulb.

When the temperature rises, the mercury in the bulb expands more than the bulb so that some mercury is driven through the capillary tube into the Bourdon tube. As the temperature continues to rise, increasing amounts of mercury will be driven into the Bourdon tube, causing it to uncurl. One end of the Bourdon tube is fixed, while the motion of the other end is communicated to the pointer or pen arm. As there is a large force available the Bourdon tube may be made robust and will give good pointer control and reliable readings.

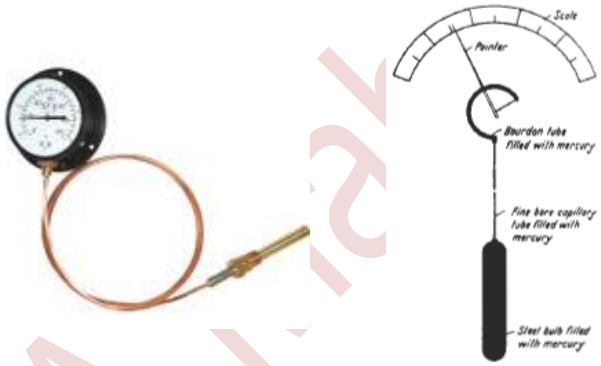


Figure 6.5 Mercury in steel thermometer.

- **Vapor pressure thermometers**

If a thermometer system similar to that described for gas expansion thermometers is arranged so that the system contains both liquid and vapor and the interface between liquid and vapor is in the bulb, that is, at the temperature whose value is required, then the vapor pressure as measured by the Bourdon tube will give an indication of the temperature. This indication will be completely independent of the volume of the bulb, the capillary, and the Bourdon tube and therefore independent of expansion due to ambient temperature changes.

The saturated vapor pressure of a liquid is not linear with temperature. Figure 6.6 shows the temperature-vapor pressure relationship for a typical liquid. The form of the vapor pressure graphs for other volatile liquids **is** of a similar form. It will be seen that pressure versus temperature is non-linear. A thermometer based on vapor pressure will have a scale on which the size of the divisions increases with increasing temperature.

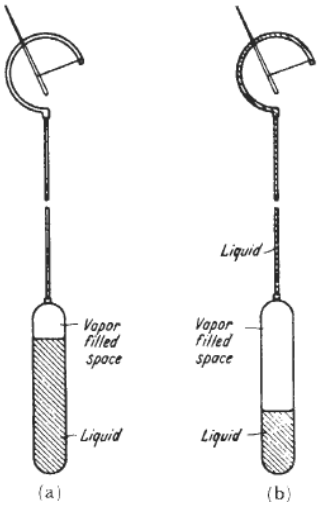


Figure 6.6 saturated vapor pressure thermometer.

Table 6.2 Comparison of three types of dial thermometers

	Liquid-in-metal	Gas expansion (cons tan t volume)	Vapor **pressure**
Scale	Evenly divided	Evenly divided.	Not evenly divided. Divisions increase in size as the temperature increases. Filling liquid chosen to given reasonably uniform scale in the neighborhood of the operating temperatures.
Range	Wide range is possible with a single filling liquid, particularly with mercury. By choice of suitable filling liquid. temperatures may be measured between -200 "C and 570 "C; but not with a single instrument.	Usually has a range of at least 50°C between -130°C and 540°C. Can be used for a lower temperature than mercury in steel.	Limited for a particular filling liquid, but with the choice of a suitable liquid almost any temperature between -50 "C and 320 "C may be measured. Instrument is not usually suitable for measuring temperatures near ambient temperatures owing to the lag introduced when bulb temperature crosses ambient temperature.
Power available to operate the indicator	Ample power is available so that the Bourdon tube may be made robust and arranged to give good pointer control.	Power available is very much less than that from liquid expansion.	Power available is very much less than that from liquid expansion.
Effect of deference **in level** of bulb and Bourdon tube	When the system is filled with a liquid at high pressure, errors due to difference of level between bulb and indicator will be small. If the difference in level is very large a correction may be made.	No head error, as the pressure due to difference in level is negligible in comparison with the total pressure in the system.	Head error is not negligible. as the pressure in the system is not large. Error may be corrected over a limited range of temperature if the ratio pressure to deflection of the pointer can be considered constant over that range. In this case the error is corrected by resetting the pointer.
Effect of changes **in** barometric pressure	Negligible.	May produce a large error. Error due to using the instrument at a different altitude from that at which it was calibrated may be corrected by adjusting the zero. Day-to-day variations in barometric pressure may be corrected for in the same way.	Error may be large, but may be corrected by resetting the pointer as for head error. Dayto-day errors due to variation in barometric pressure may be corrected by zero adjustment.
Capillary error	Compensation for change in ambient temperature	Difficult to eliminate.	No capillary error.
Changes in temperature at the indicator	Compensation obtained by means of a bimetallic strip.	Compensation obtained by means of bimetallic strip.	Errors due to changes in the elasticity of the Bourdon tube are compensated for by means of a bimetallic strip.
Accuracy	±½ % of range to 320 "C ±% of range above 320°C.	±1 % of differential rage of the instrument if the temperature of the capillary and Bourdon tube does not vary too much.	±1 % of differential range even with wide temperature variation of the capillary and Bourdon tube.

Solid expansion

Thermal expansion of solids, usually metals, forms the basis of a wide range of inexpensive indicating and control devices. These devices are not particularly accurate: typically errors may be expected, but due to their low cost they find wide application, especially in consumer equipment. This technique is also used to provide temperature compensation in many instruments. The temperature-sensitive elements using solid expansion fall into two groups: rod sensing probes and bimetal strips. There are so many applications that only one or two examples will be given to illustrate the techniques.

- ***Rod sensing probes***

The widest application of this technique is for immersion thermostats for use in hot water temperature control. Figure 6.7 shows diagrammatically the operation of an immersion thermostat. The micro switch is operated by the thermal expansion of the brass tube. The reference length is provided by a rod of low thermal expansion such as Invar. These thermostats, though not particularly accurate and having a switching differential of several degrees Celsius, provide a very rugged and reliable control system for a non-critical application such as domestic hot water control. Figure 6.8 shows another rod application. In this case to achieve greater sensitivity the expanding component is coiled.

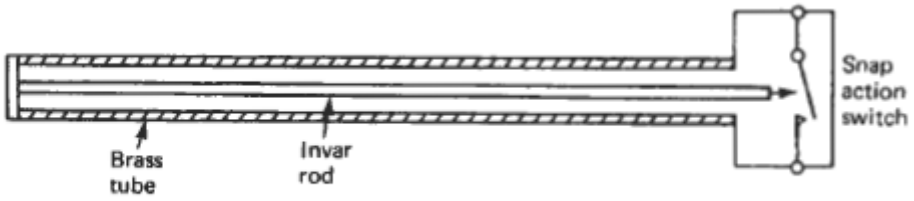


Figure 6.7 Rod thermostat.

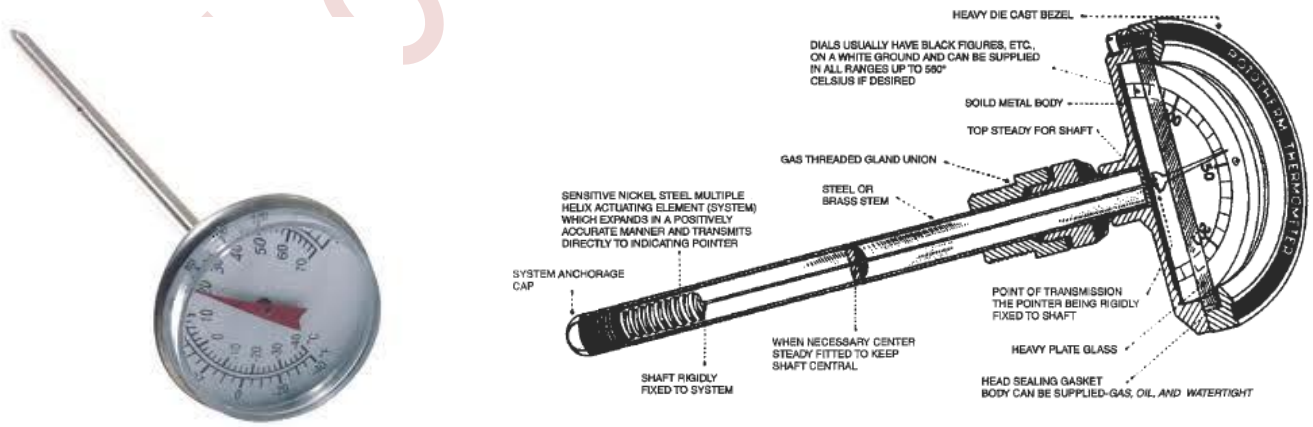


Figure 6.8 Dial thermometer.

- ***Bimetal strip thermometer***

Bimetal strips are fabricated from two strips of different metals with different coefficients of thermal expansion bonded together to form, in the simplest case, a cantilever. Typical metals are brass and Invar. Figure 6.9 illustrates this principle. As The temperature rises the brass side of the strip expands more than the Invar side, resulting in the strip curling, in this case upwards. In this "straight" form a bimetal strip ***can*** form part of a micro-switch mechanism thus forming a temperature-sensitive switch or thermostat. To construct a thermometer the bimetal element is coiled into spiral or helix.

Figure 6.10 shows a typical coiled thermometer element. A long bimetal strip, consisting of an Invar strip welded to a higher expansion nickel-molybdenum alloy wound around without a break into several compensated helices, arranged coaxially one within the other, and forms the temperature-sensitive element of an instrument which may be designed to measure temperature. This method of winding the strip enables a length, sufficient to produce an appreciable movement of the free end, to be concentrated within a small space. It also makes it possible to keep the thermal capacity of the element and its stem at a low value, so the instrument will respond rapidly to small temperature changes.

The helices in the winding are ***so*** compensated that any tendency towards lateral displacement of the spindle in one helix is counteracted by an opposite tendency on the path of one or more of the other helices. Thus, the spindle of the instrument is fully floating, retaining its position at the center of the scale without the help of bearings. The instrument is, therefore, not injured by mechanical shocks which would damage jeweled bearings. This particular design also results in the angular rotation of the spindle being proportional to the change in temperature for a considerable temperature range. The instrument has a linear temperature scale, and can be made to register temperatures up to 300°C to within $\pm 1\%$ percent of the scale range.

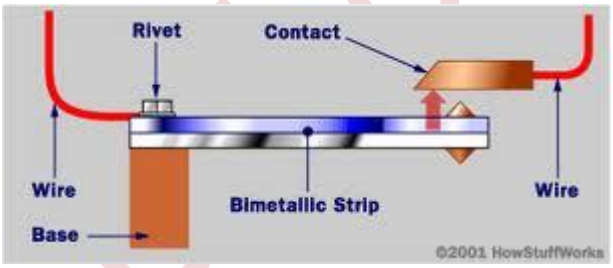


Figure 6.9 Action of bimetal strip

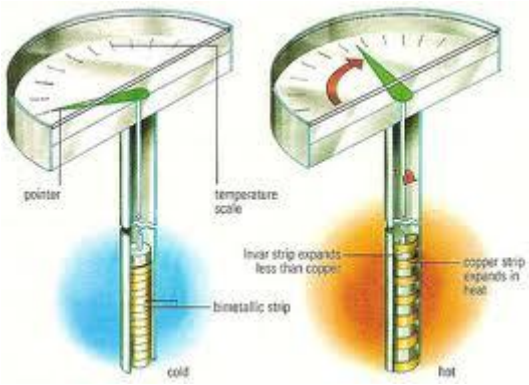


figure 6.10 helical bimetal strip.

B) Electrical

- **Resistance thermometers**

All metals are electrical conductors which at very low temperatures offer resistance to the passage of electric current. The electrical resistance exhibited by a conductor is measured in ohms. The proportional relationship of electrical current and potential difference is given by Ohm's law. Different metals show widely different resistivity, the resistance of a conductor is proportional to its length and inversely proportional to its cross-sectional area. The resistivity of a conductor is temperature dependent. The temperature coefficient of resistivity is positive for metals, that is, the resistance increases with temperature, and for semiconductors

The metals most used for resistance measurement are **platinum, nickel, and copper**. These metals have the advantage that they can be manufactured to a high degree of purity and consequently they can be made with very high reproducibility of resistance characteristics. *Copper* has the disadvantage of a low resistivity resulting in inconveniently large sensing elements and has the further disadvantage of poor resistance to corrosion resulting in instability of electrical characteristics. The main area of application of copper for resistance thermometers is in electronic instrumentation where it is in a controlled environment and where an essentially linear temperature characteristic is required.

Platinum resistance thermometers

Platinum is the standard material used in the resistance thermometer which defines the International Practical Temperature Scale, not because it has a particularly high coefficient of resistivity, but because of its stability in use. In fact, a high coefficient is not, in general, necessary for a resistance thermometer material as resistance values can be determined with a high degree of accuracy using suitable equipment and taking adequate precautions. Platinum, having the highest possible coefficient of resistivity, is considered the best material for the construction of thermometers. A high value of this coefficient is an indication that the platinum is of high purity. The presence of impurities in resistance thermometer material is undesirable, as diffusion, segregation, and evaporation may occur in service, resulting in a lack of stability of the thermometer.

It is essential that the platinum element is mounted in such a way that it is not subject to stress in service.

Platinum is used for resistance thermometry in industry fix temperatures up to 800 °C. It does not oxidize, but must be protected from contamination. Platinum resistance thermometers may be used for temperatures down to about 20 K.

Nickel resistance thermometers

The usable range is restricted to -200°C to +350°C. But the temperature coefficient of resistivity of nickel is 50 percent higher than that of platinum which is an advantage in some instruments. Nickel resistance thermometers find wide use in water-heating and air-conditioning systems.

- **Thermistors**

Negative temperature coefficient thermometers:

An alternative to platinum or nickel for resistance thermometer sensing elements is a semiconductor composed of mixed metal oxides. The composition of these materials depends on the particular properties required. Combinations of two or more of the following oxides are used: **cobalt, copper, iron, magnesium, manganese, nickel, tin, titanium, vanadium, and zinc**. Devices made of these materials are called thermistors. They consist of a piece of the semiconductor to which two connecting wires are attached at opposite sides or ends. Thermistors have a negative temperature coefficient; that is, as the temperature rises the electrical resistance of the device falls.

This variation of resistance with temperature is much higher than in the case of metals. This very high sensitivity allows measurement or control to a very high resolution of temperature differences. The accuracy is not as good as for a metallic resistance thermometer owing to the difficulty in controlling the composition of the thermistor material during manufacture. The total range that can be measured with thermistors is from -100°C to *+300°C*. Thermistors are also available in metal encapsulations like those used for platinum resistance thermometers. The big disadvantage of thermistors is that their characteristics are non-linear.

Figure 6.11 Connections for compensation of resistance thermometer leads.

These devices are manufactured to fine tolerances and are interchangeable with an error of less than $\pm$0.2 percent.

Positive temperature coefficient thermistors

Positive temperature coefficient (PTC) thermistors are manufactured from compounds of **barium, lead, and strontium titanates.** PTC thermistors are primarily designed for the protection of wound equipment such as transformers and motors.

The resistance of PTC thermistors is low and relatively constant with temperature at low temperature.

In use, PTC thermistors are embedded in the windings of the equipment to be protected. They are connected in series with the coil of the equipment contractor or protection relay. If the temperature of the windings exceeds temperature t_R the current becomes so small that power is disconnected from the equipment.

- THERMOCOUPLES:

Thermoelectric effects

If an electrical circuit consists of entirely metallic conductors and all parts of the circuit are at the same temperature, there will be no electromotive force in the circuit and therefore no current flows. However, if the circuit consists of more than one metal and if junctions between two metals are at different temperatures, then there will be an e.m.f. in the circuit and a current will flow. Figure 6.12 illustrates this effect. The e.m.f. generated is called a thermoelectric e.m.f. and the heated junction is a thermocouple.

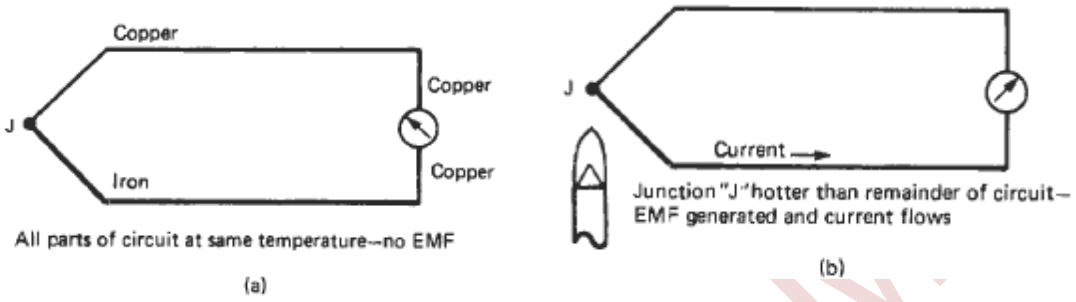


Figure 6.12 Basic thermocouple circuit.

Seebeck effect

In 1821 Seebeck discovered that if a closed circuit is formed of two metals, and the two junctions of the metals are at different temperatures, an electric current will flow round the circuit. Suppose a circuit is formed by twisting or soldering together at their ends, as shown in Figure 6.13, wires of two different metals such as iron and copper. If one junction remains at room temperature, while the other is heated to a higher temperature, a current is produced, which flows from copper to iron at the hot junction, and from iron to copper at the cold one. Seebeck arranged a series of 35 metals in order of their thermoelectric properties. In a circuit made up of any two of the metals, the current flows across the hot junction from the earlier to the later metal of the series. A portion of his list is as follows: **Bi-Ni-Co-Pd-Pt-U-Cu-Mn-Ti-Hg-Pb-Sn-Cr-Mo-Te-Rh-Ir-Au-Zn-W-Cd-Fe-As-Sb-Te**.

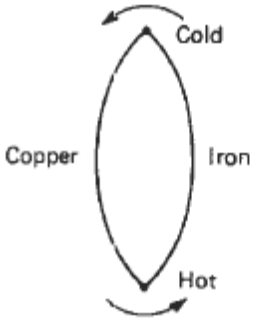


Figure 6.13 simple thermocouple.

Peltier effect

In 1834 Peltier discovered that when a current flow across the junction of two metals heat is absorbed at the junction when the current flows in one direction and liberated if the current is reversed. Heat is absorbed when a current flows across an iron-copper junction from copper to iron.

The size of the e.m.f. depends not only on the materials making up the junction but also upon the temperature of the junction. When both junctions are at the same temperature, the e.m.f at one junction is equal and opposite to that at the second junction: so that the resultant e.m.f. in the circuit is zero, If, however one junction is heated, the e.m.f. across the hot junction is greater than that across the cold junction, and there will be a resultant e.m.f. in the circuit which is responsible for the current. Peltier cooling is used in instrumentation where a small component is required to be cooled under precise control. Figure 6.14 shows diagrammatically the construction of such cross-section to minimize IR heating. The warmer face is clamped to a suitable heat sink while the cold face has the component to be cooled mounted in contact with it. Typical size for such a unit is of the order of 5-25 mm. The conductors in Peltier coolers may be either metals or semiconductors; in the latter case they are called Frigistors.

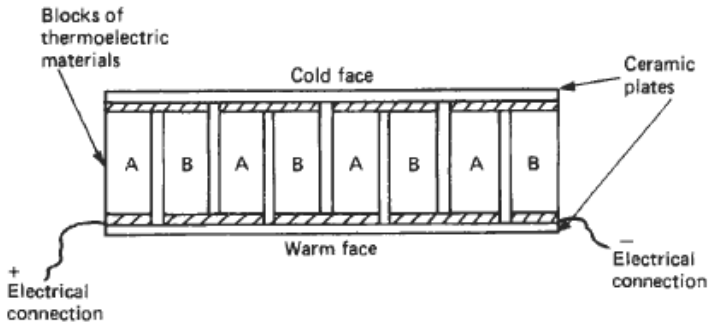
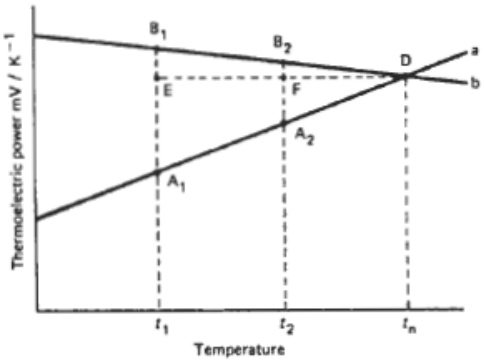


Figure 6.14 Peltier effect.

Thermoelectric diagram

Thermoelectric diagram suggested by Professor Tait in 1871. On this diagram the thermoelectric line for any metal is a line such that the ordinate represents the thermoelectric power of that metal with a standard metal at a temperature the standard metal. The ordinate is taken as positive when, for a small difference of temperature, the current flows from lead to the metal at the hot junction. lines a and b (Figure 6.15) represent the thermoelectric lines for two metals A and B then the e.m.f. round the circuit formed by the two metals. The e.m.f. is zero either if the two junctions are at the same temperature or if the average of the temperature of the two junctions is equal to the neutral temperature.



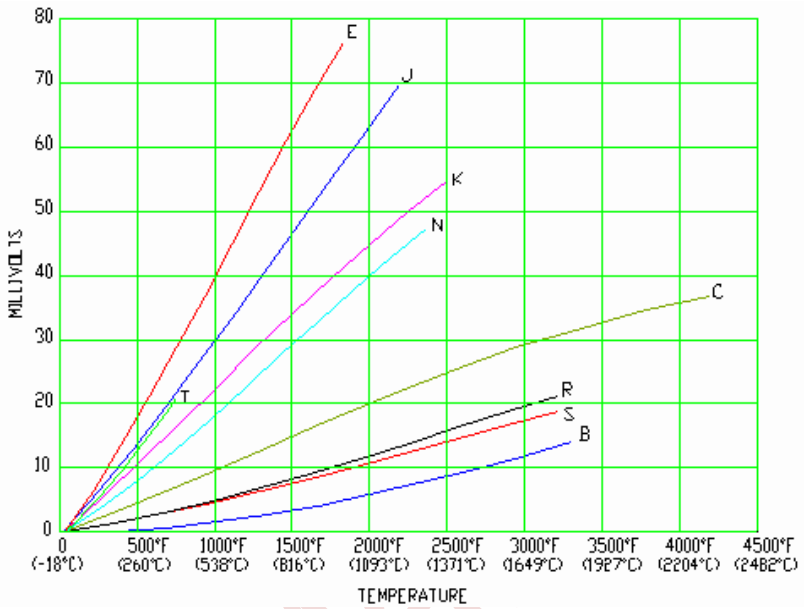


Figure 6.15 behaviour of the pair metal of thermocouple Figure 5.16 behaviour of the pair metal of thermocouples

Thermocouple connecting diagram:

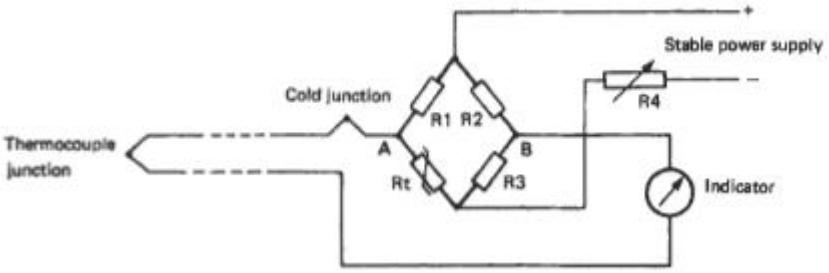


Figure 6.17 show the electric connection diagram for the thermocouples.

Thermocouples material:

Broadly, thermocouple materials divide into two arbitrary groups based upon cost of the materials, namely, base metal thermocouples and precious metal thermocouples.

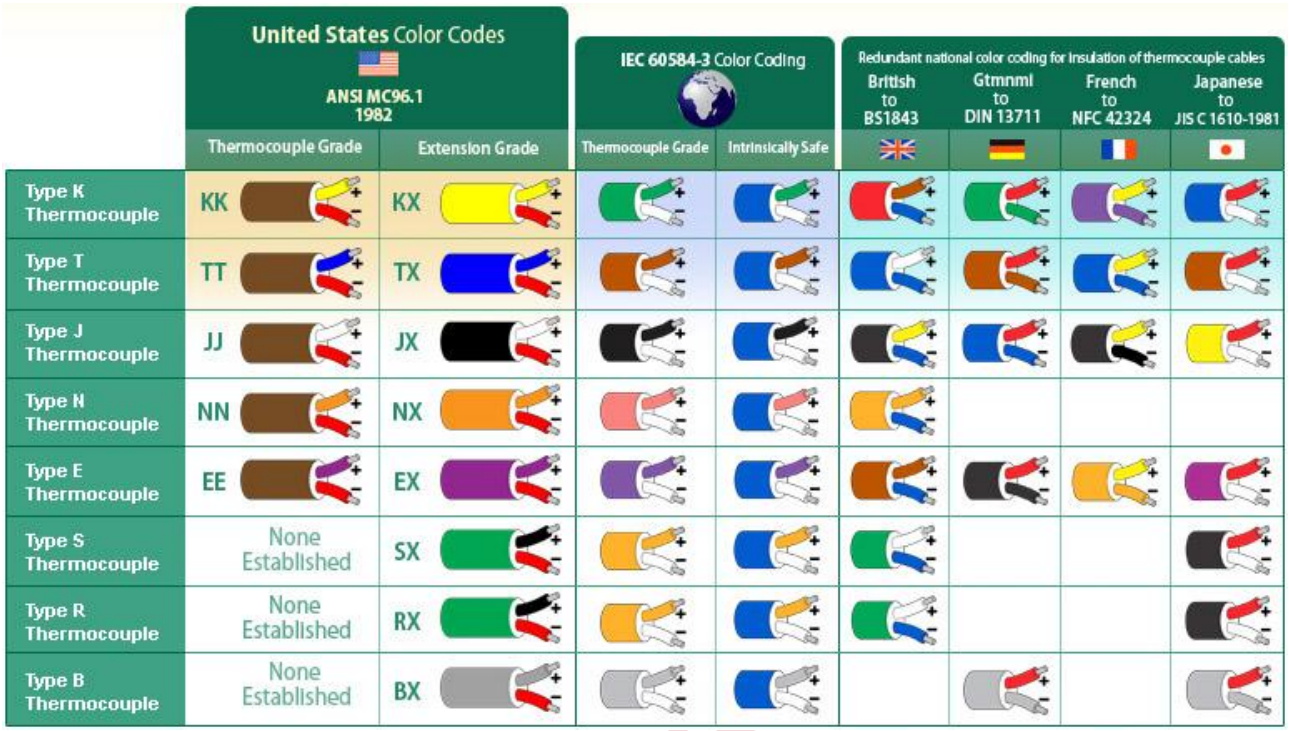
Base metal thermocouples*:*

The most commonly used industrial thermocouples are identified for convenience by type letters. The main types, together with the relevant British Standard specification and permitted tolerance on accuracy, are shown in Table 6.3. Also shown are their output e.m.f.s with the cold junction at 0 °C. These figures are given to indicate the relative sensitivities of the various couples. Full tables of voltages against hot junction temperatures are published in BS 4937. The standard characteristic is very nearly linear. The commonly used base metal thermocouples are types T, J. K, and

Table 6.3 Thermocouples to British Standards

types	Conductors (positive conductor first)	Manufactured to BS 4937 Part No.	Temperature tolerance class 2 thermocouple BS 4537:	Output for indicated temperature (cold junction at 0 "C)	Service temperature (mar intermittent servicer)
B	Platinum: 30% Rhodium/platinum: 6% Rhodium)	Part 7: 1974 (1981)	600 to 1700 °C ±3°C	1.241 mV at 500°C	0-1500 "C (1700 °C). Better life expectancy at high temperature than types R & S.
E	Nickel: chromium / constantan (chromel constantan) (chromel advance)	Part 6: 1974 (1981)	-40 to +333°C ± 3°C 333 to 900°C ± 0.75%	6.317mV at 100°C	-200 to +850°C (1100°C). Resistant to oxidizing atmospheres.
J	Iron/constantan	Part 3: 1973 (1981)	-40 to +333°C ± 2.5°C 300 to 750°C±0.75%	5.268 mV at 100 °C	-280 to +850°C (1100°C). Low cost suitable for general use.
K	Nickel: chromium / nickel: aluminum (chrome/alumel) (C/A) (T1/T2)	Part 4: 1973 (1981)	-40 to +333°C±2.5°C 333 to1200°C± 0.75%	4.095mV at 100°C	-200 to +1100"C (1300°C). Good general purpose. Best in oxidizing atmosphere.
N	Nickel: chromium: Silicon/nickel: silicon: magnesium	Part 8: 1986	-40 to +333°C±2.5°C 333 to1200°C± 0.75%	2.774mV at 100°C	0-1100°C (-270°C to+1300"C°C). Alternative to type K.
R	Platinum: 13% Rhodium/platinum	Part 2: 1973 (1981)	0 to600°C ±1.5°C 600 to1600°C± 0.25%	4.471 mV at 500°C	0-1500°C (1650°C). High temperature. Corrosion resistant.
S	Platinum: 10% rhodium/platinum	Part 1: 1973 (1981)	0 to600°C ±1.5°C 600 to1600°C± 0.25%	4.234mV at 500°C	Type R is more stable than type **S.**
T	Copper/constantan (copper/advance) (Cu/Con)	Part 5: 1974 (1981)	-40 to +375 °C ± 1 °C	4.277mV at 100°C	-250 to 400°C (500°C). High resistance to corrosion by water.

Recommended colors of thermocouples wire:



Calibration:

The very extensive use of thermocouples stems from their great versatility combined with their low cost. However, as seen in Table 5.3, thermocouples have a fairly wide permitted tolerance. This is due to the fact that most metals used for thermocouples are alloys and it is not possible to manufacture alloys to the same reproducibility as pure metals, It must be said that, in general, manufacturers do manufacture their thermocouples to better tolerance than BS 4937 demands. But, where the highest accuracy is required, it is essential to calibrate thermocouples on installation and to recalibrate them at regular intervals to monitor any deterioration due to corrosion or diffusion of foreign elements into the hot junction. Where high accuracy is required it is necessary to calibrate first the thermocouple readout instrument and then the thermocouple itself in conjunction with the instrument.

The calibration of instruments can be done with a precision millivolt source which injects a signal equivalent to the temperature difference between the ambient or cold junction temperature and a temperature in the region in which the thermocouple is to be used. There is two ways to done the calibration according to the temperature limit:

i. **Water path calibration instrumentation**
ii. **Sand path calibration instrumentation**

Radiation thermometers

Introduction

Thermal energy may be transferred from one body to another by radiation as well as by conduction. The amount of thermal energy or heat leaving a body by radiation and the wavelength of that radiation are functions of the temperature of the body. This dependence on temperature of the characteristics of radiation is used as the basis of temperature measurement by radiation thermometers. Radiation thermometers are also known as "**radiation pyrometers**."

Since the energy radiated by an object is a function of its absolute temperature this is a suitable property for the non-contact and non-intrusive measurement of temperature. Instruments for temperature measurement by radiation are called **radiation thermometers**.

There are **four principal techniques** for the measurement of temperature by the radiation from a hot body:

1. Total radiation
2. Pyroelectric
3. Photo-electric
4. Optical

Instruments using the first three of these techniques are normally constructed in the same general physical form.

Radiation thermometers can "see" the temperature of a surface from a distance. What they are seeing is the color of the invisible infrared IR(infrared radiation) light given off by the object. A detector is located inside the instrument that senses the infrared light waves. A change in the IR light's color occurs as a result of temperature changes, which results in a change in the electrical output of the detector. A small integrated circuit converts that electrical output into a displayed temperature. The detector is from the object, the surface color, and its reflectivity all affect the accuracy of the temperature reading. The most accurate reading is obtained when the object whose temperature is being read is a black dull surface. IR thermometer is generally not useful for measuring air, liquid, shiny metal objects, or small objects.

Sensor location considerations

To obtain accurate temperature measurement careful consideration must be given to the siting of temperature sensing probes. Frequently in industrial applications temperature measuring equipment does not live up to the expectations of the plant design engineer. The measurement error is not infrequently ten or even twenty times the error tolerance quoted by the instrument manufacturer.

Large measurement errors in service may be due to the wrong choice of instrument but more frequently the error is due to incorrect location of the measurement points. Unfortunately the location of temperature sensors is dictated by the mechanical design of the plant rather than by measurement criteria.

- ***Immersion probes***

To minimize errors in the measurement of the temperature of process fluids, whether liquid or gas, it is preferable to insert the sensor so that it is directly immersed in the fluid. The probe may be directly dipped into liquid in an open vessel, inserted through the wall of the vessel or inserted into a pipe.

- ***Probes in pipes or ducts***

There is frequently a requirement to measure the temperature of a fluid flowing in a pipe. This is usually straightforward, but there are still points to watch out for. Figure 6.18 shows three possible configurations for insertion into a pipe. The most satisfactory arrangement is to insert the thermometer probe into the pipe at a bend or elbow. Figure 6.18(a) shows this arrangement. Points to note are:

(a) To ensure that the probe is inserted far enough for the sensitive length to be wholly immersed and far enough into the fluid to minimize thermal conduction from the sealing coupling to the sensor(S) To insert the probe into the direction of flow as indicated. The reasons for this are to keep the sensor ahead of the turbulence at the bend, which could cause an error due to local heating, and to remove the effects of cavitation that could occur at the tip of a trailing probe. Figure 6.18(b) shows the problem that can arise in small pipes where the probe can cause serious obstruction to the flow.

Where it is not possible to put the thermometer at a bend in the pipe it can be inserted radially provided the pipe is big enough. Great care should be taken to ensure complete immersion of the sensitive portion of the probe. Figure 6.18(c) illustrates this problem. A better solution is diagonal1 insertion as shown at (d). Again the probe should point into the direction of flow. When measuring temperature in large pipes or ducts it must be remembered that the temperature profile across the pipe may not be constant. This is especially true for large flue stacks and air-conditioning ducts. The center liquid or gas is usually hotter (or colder in refrigerated systems) than that at the duct wall. In horizontal ducts carrying slow moving air or gas the gas at the top of the duct will be significantly hotter than that at the bottom of the duct. In these circumstances careful consideration must be given as to how a representative measurement can be obtained; it may well be necessary to make several measurements across the duct and average the readings.

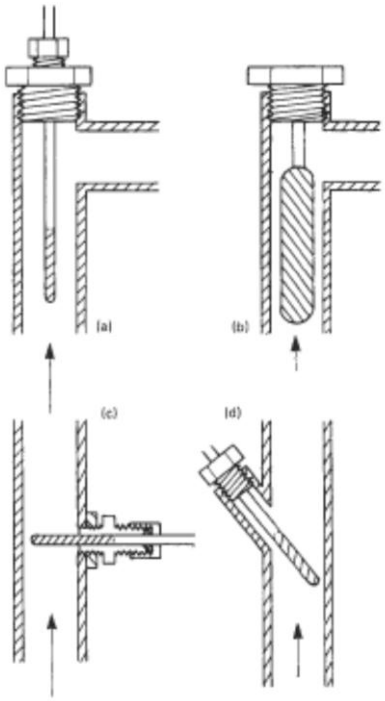
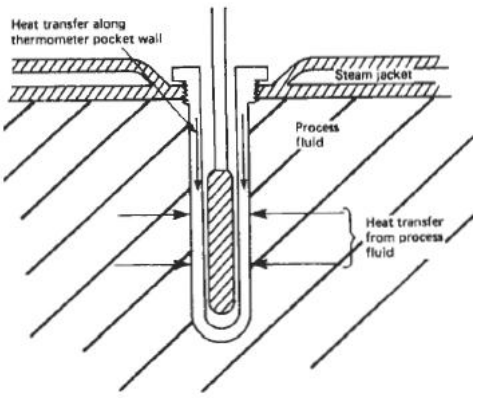


Figure 6.18 probe in pipe

- ***Thermometer pockets, thermo wells***

The direct immersion of temperature sensing probes into process fluid, while being the optimum way to get an accurate measurement, has its disadvantages. First, it has disadvantages from the maintenance point of view: normally the sensing probe cannot be removed while the plant is on stream. Second, in the case of corrosive process streams special corrosion-resistant materials may need to be used. Standard temperature gauges are normally only available in a limited range of materials, typically brass, steel, stainless steel, or ceramic, so a sheath or thermometer pocket or thermo-well can be used to protect the temperature sensing probe. The use of a thermometer pocket does degrade the measurement accuracy of the instrumentation. Figure shows a thermometer pocket mounted in the wall of a steam-jacketed process vessel. The thermometer probe receives heat from the wall of the pocket by conduction where it touches it and by radiation at other places. The inner wall of the pocket receives heat from the process fluid and by conduction in this case from the steam jacket of the vessel. In the case of a short pocket the heat conducted along the pocket can cause a significant measurement error, causing too high a reading. In the situation where the outer jacket of the vessel is used for cooling the vessel, for example, a cooling water jacket, the heat flow will be away from the sensing probe and consequently the error will be a low measurement. This conduction error is only significant where the



thermometer pocket is short or where the pocket is inserted into a gas stream. To minimize the error the length of the pocket should be at least three times the length of the sensitive area of the probe.

- ***Effect of process fluid flow rate:***

Two sources of error in temperature measurement are clearly identified. *Fractional heating* where the process fluid flows past a probe at high velocity there is, especially in the case of gases, a frictional heating effect. The magnitude of the effect is not easily evaluated but it is advisable if possible to site the probe at a location where the fluid velocity is low. Resistance thermometers and thermistors depend for their operation on an electric current flowing through them. This current causes a small heating effect in the sensor. When such a sensor is used for liquid temperature measurement the relatively high specific heat of most liquids ensures that this heat is removed and the sensor temperature is that of the liquid. However, in gas measurement the amount of heat removed is a function of the gas velocity and thus a variable source of error can arise dependent on flow rate. In a well-designed instrument this error should be very small but it is a potential source of error to be borne in mind.

- ***Cavitation***

Liquid flowing past a thermometer probe at high speed is liable to cause cavitation at the downstream side of the probe. Apart from any heating effect of the high flow rate the cavitation will generate noise and cause vibration of the probe. This vibration is likely in due course to cause deterioration or premature catastrophic failure of the probe.

- ***Surface temperate measurement***

Where the temperature of a surface is to be measured this can be done either a temperature probe cemented or clamped to the surface or where a spot measurement is to be made a sensor can be pressed against the surface. In the former arrangement, which is likely to be a permanent installation, the surface in the region of the sensor itself can be protected from heat loss by lagging with thermally insulating material. Provided heat losses are minimized the measurement error can be kept small. Errors can be further reduced where the sensor is clamped to the surface by coating the surface and the sensor with heat-conducting grease. This grease is normally silicone grease heavily loaded with finely ground alumina. Grease loaded with beryllium oxide has better heat transfer properties. However, since beryllium oxide is very toxic this grease must be handled with the greatest of care.

MEASUREMENT OF PRESSURE

What is pressure?

When a fluid is in contact with a boundary it produces a force at right angles to that boundary. The force per unit area is called the pressure. There are three categories of pressure measurements, namely:

1- The absolute pressure is the difference between the pressure at a particular point in a fluid and the absolute zero of pressure, i.e., a complete vacuum. **A** barometer is one example of an absolute pressure gauge because the height of the column of mercury measures the difference between the atmospheric pressure and the "zero" pressure of the Torricelli an vacuum that exists above the mercury column.

2- Gauge pressure the pressure-measuring device measures the difference between the unknown pressure and local atmospheric pressure.

3- Differential pressure When the pressure-measuring device measures the difference between two unknown pressures, neither of which is atmospheric pressure, then the measurement is known as the.

pressure units:

Pascal	**Pa**	**1**
Bar	**bar**	**10^{-5}**
Standard atmosphere	**atm**	**9.86923×10^{-6}**
Kilogram force per square cm	**Kg_f/cm^2**	**1.01972×10^{-5}**
Pound force per square inch	**lb/in^2**	**1.45038×10^{-4}**
Torr		**7.50062×10^{-3}**
Millimeter of water	**mmH_2O**	**1.01972×10^{-1}**
Millimeter of Mercury	**mmHg**	**7.50062×10^{-3}**
Inch of water	**inH_2O**	**4.01463×10^{-3}**
Inch of Mercury	**In Hg**	**2.95300×10^{-4}**

Pressure measurement

There are three basic methods for pressure measurement.

1- The simplest method involves balancing the unknown pressure against the pressure produced by a column of liquid of known density.

2- The second method involves allowing the unknown pressure to act on a known area and measuring the resultant force either directly or indirectly.

3- The third method involves allowing the unknown pressure to act on an elastic member (of known area) and measuring the resultant stress or strain.

pressure measurement devices types:

Pressure measurements by balancing a column of liquid of known density:

The simplest form of instrument for this type of measurement is the U-tube. Consider a simple U tube containing a liquid of density *p* as shown in Figure 5.2. The points **A** and **B** are at the same horizontal level, and the liquid at *C* stands at a height *h* mm above **B**.

Then the pressure at **A** =the pressure at **B**

= atmospheric pressure + pressure due to liquid at column **BC**

= atmospheric pressure + *hp*

If the liquid is water the unit of measure is mmH_2Q, and if the liquid is mercury then the unit of measure is mmHg. The corresponding SI unit is the Pascal and

1 mmH_2O = 9.80665 Pa

1 mmHg = 133.322 Pa

For a system such as this it must be assumed that the density of the fluid in the left-hand leg of the manometer (Figure 6.1) is negligible compared with the manometer liquid.

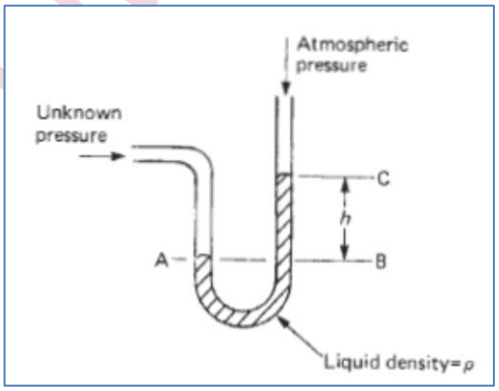


Figure 7.1 U tube manometer.

Pressure measurements by allowing the unknown pressure to act on a known area and measuring the resultant force:

Dead-weight testers

The simplest technique for determining a pressure by measuring the force that is generated when it acts on a known area is illustrated by the dead-weight tester, but this system is used for calibrating instruments rather than measuring unknown pressures. The basic system is shown diagrammatically in Figure 7.2.

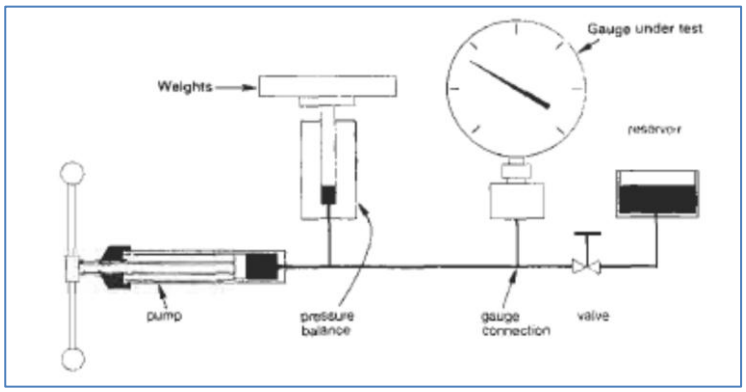


Figure 7.2 dead weight calibration test.

Pressure measurement by allowing the unknown pressure to act on a flexible member and measuring the resultant motion:

The great majority of pressure gauges utilize a Bourdon, tube, stacked diaphragms, or a bellows to sense the pressure. The applied pressure causes a change in the shape of the sensor that is used to move a pointer with respect to a scale.

Bourdon tubes:

The simplest form of Bourdon tube comprises a tube of oval cross-section bent into a circle. One end is sealed and attached via an adjustable connecting link to the lower end of a pivoted quadrant. The upper part of the quadrant is the toothed segment that engages in the teeth of the central pinion which carries the pointer that moves with respect to a fixed scale. Backlash between the quadrant and pinion is minimized by a delicate hairspring. The other end of the tube is open so that the pressure to be measured can be applied via the block to which it is fixed and which also carries the pressure connection and provides the datum for measurement of the deflection. If the internal pressure exceeds the external pressure the shape of the tube changes from oval towards circular with the result that it becomes straighter. The movement of the free end drives the pointer mechanism so that the pointer moves with respect to the scale. If the internal pressure is less than the external pressure, the free end of the tube moves towards the block, causing the pointer to move in the opposite direction. The material from which the tube is formed must have stable elastic properties and be selected to suit the fluid whose pressure is to be measured. Phosphor bronze, beryllium copper, and stainless steel are used most widely but for applications involving particularly corrosive fluids, alloys are used. The thickness of the tube and the material from which it is to be fabricated are selected according to the pressure range. But the actual dimensions of the tube determine the force available to drive the pointer mechanism. The construction of a typical gauge is shown in Figure 7.3.

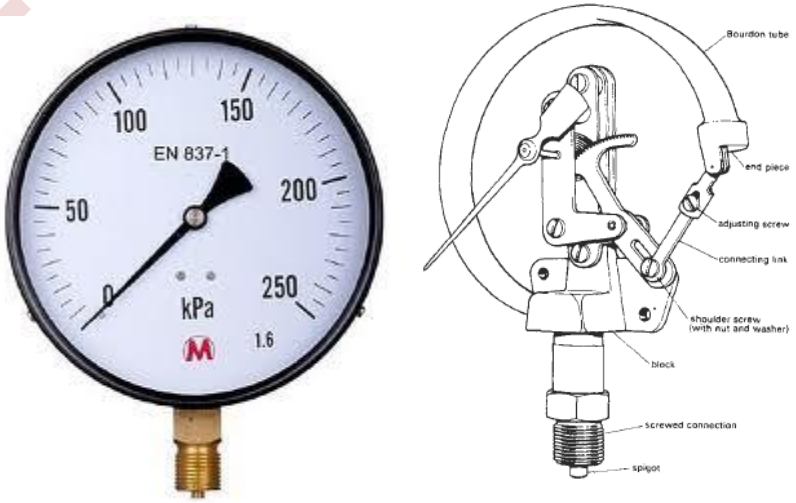


Figure 7.3

The performance of pressure gauges of this type varies widely, not only as a result of their basic design and materials of construction, but also because of the conditions under which they are used. The principal sources of error are hysteresis in the Bourdon tube, changes in its sensitivity due to changes of temperature, frictional effects, and backlash in the pointer mechanism.

Spiral und helical Bourdon tubas

The amount of the movement of the free end of a Bourdon tube varies inversely as the wall thickness and is dependent on the cross-sectional shape. It also varies directly with the angle subtended by the arc through which the tube is formed. By using a helix or spiral to increase the effective angular length of the tube, the movement of the free end is similarly increased and the need for further magnification is reduced.

Examples of these constructions are shown in Figures 7.4 and 7.5. They avoid the necessity for the toothed quadrant with the consequent reduction of backlash and frictional errors. In general, the spiral configuration is used for low pressures and the helical form for high pressures.

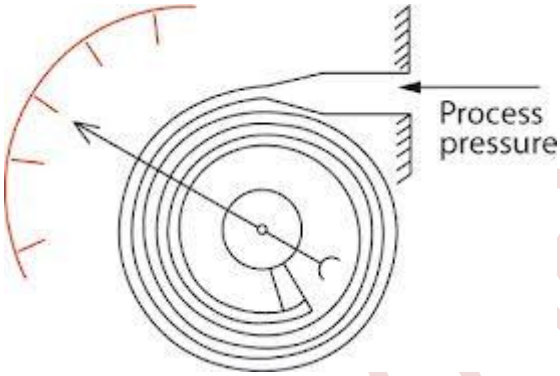


Figure 7.4 spiral gauge

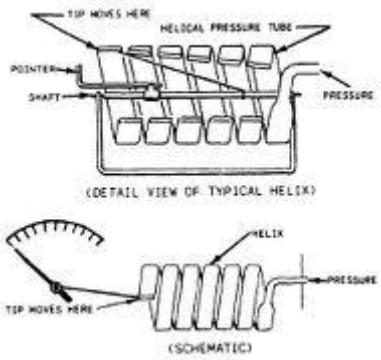


Figure 7.5 Helical gauge

Diaphragm pressure elements:

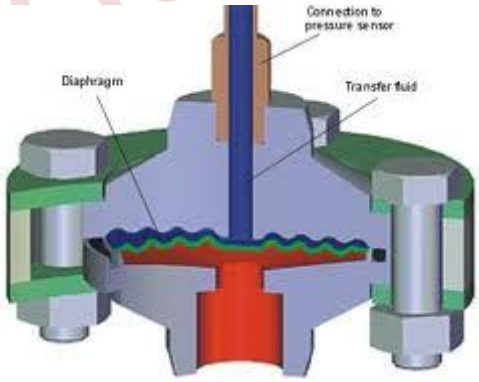
The diaphragm, shown schematically in Figure 7.6, is one of three types of elastic-element pressure transducers. Applied pressure causes displacement of the diaphragm and this movement is measured by a displacement transducer. Different versions of diaphragm sensors can measure both absolute pressure (up to 50 bar) and gauge pressure (up to 2000 bar) according to whether the space on one side of the diaphragm is, respectively, evacuated or open to the atmosphere. A diaphragm can also be used to measure differential pressure (up to 2.5 bar) by applying the two pressures to the two sides of the diaphragm. The diaphragm can be plastic, metal alloy, stainless steel, or ceramic. Plastic diaphragms are the least expensive, but metal diaphragms give better accuracy. Stainless steel is normally used in high temperature or corrosive environments.

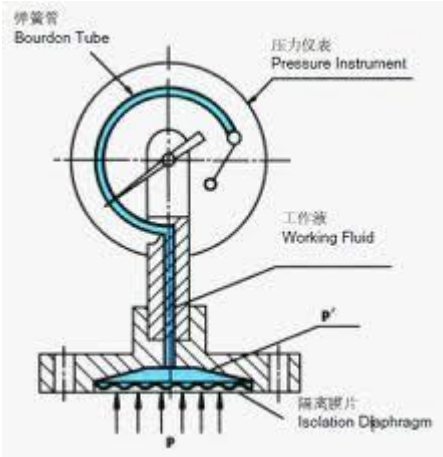
Ceramic diaphragms are resistant even to strong acids and alkalis and are used when the operating environment is particularly harsh. The name aneroid gauge is sometimes used to describe this type of gauge when the diaphragm is metallic.

The typical magnitude of diaphragm displacement is 0.1 mm, which is well suited to a strain gauge type of displacement-measuring transducer; although other forms of displacement measurements are also used in some kinds of diaphragm-based sensors. If the displacement is measured with strain gauges, it is normal to use four strain gauges arranged in a bridge circuit configuration. The output voltage from the bridge is a function of the resistance change due to the strain in the diaphragm. This arrangement automatically provides compensation for environmental temperature changes

.

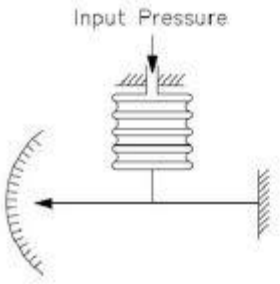
Figure 7.6





Bellows elements:

Bellows, illustrated schematically in Figure 7.7, are another elastic-element type of pressure sensor that operate on very similar principles to the diaphragm pressure sensor. Pressure changes within the bellows, which are typically fabricated as a seamless tube of either metal or metal alloy, produce translational motion of the end of the bellows that can be measured by capacitive, inductive (LVDT), or potentiometric transducers. Different versions can measure either absolute pressure (up to 2.5 bars) or gauge pressure (up to 150 bar). Double-bellows versions also exist that are designed to measure differential pressures of up to 30 bar. Bellows have a typical measurement uncertainty of only _0.5%, but have a relatively high manufacturing cost and are prone to failure. Their principle attribute in the past has been their greater measurement sensitivity compared with diaphragm sensors. However, advances in electronics mean that the high-sensitivity requirement can usually be satisfied now by diaphragm-type devices, and usage of bellows is therefore falling.



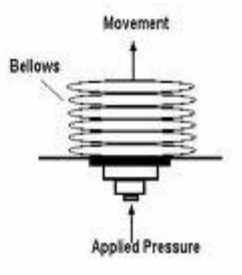


Figure 7.7

Low pressure range elements (vacuum)

McLeod gauge

Figure 7.8 shows the general form of a McLeod gauge in which low-pressure fluid is compressed to a higher pressure that is then read by manometer techniques. In essence, the gauge can be visualized as a U-tube manometer that is sealed at one end and where the bottom of the U can be blocked at will. To operate the gauge, the piston is first withdrawn. This causes the level of mercury in the lower part of the gauge to fall below the level of junction J between the two tubes marked Y and Z in the gauge. Fluid at unknown pressure Pu is then introduced via the tube marked Z, from where it also flows into the tube of cross-sectional area A marked Y. Next, the piston is pushed in, moving the mercury level up to block junction J. At the stage where J is just blocked, the fluid in tube Y is at pressure Pu and is contained in a known volume, Vu. Further movement of the piston compresses the fluid in tube Y and this process continues until the mercury level in tube Z reaches a zero mark. Measurement of the height (h) above the mercury column in tube Y then allows calculation of the compressed volume of the fluid. Although the smallest inaccuracy achievable with McLeod gauges is _1%, this is still better than that achievable with most other gauges available for measuring pressures in this range. Therefore, the McLeod gauge is often used as a standard against which other gauges are calibrated. The minimum pressure normally measurable is 10^{-1} mbar, although lower pressures can be measured if pressure-dividing techniques are applied.

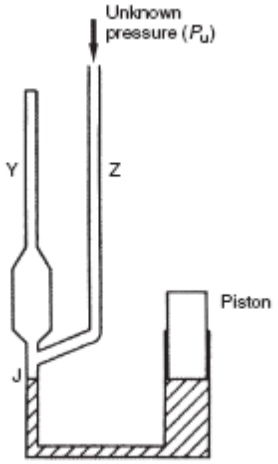


Figure 7.8

Ionization Gauge

The ionization gauge is a special type of instrument used for measuring very low pressures in the range 10^{-10} to 1 mbar. Normally, they are only used in laboratory conditions because their calibration is very sensitive to the composition of the gases in which they operate, and use of a mass spectrometer is often necessary to determine the gas composition around them. They exist in two forms known as a hot cathode and a cold cathode. The hot cathode form is shown schematically in Figure 7.9. In this, gas of unknown pressure is introduced into a glass vessel containing free electrons discharged from a heated filament, gas pressure is determined by measuring the current flowing between an anode and a cathode within the vessel. This current

is proportional to the number of ions per unit volume, which in turn is proportional to the gas pressure. Cold cathode ionization gauges operate in a similar fashion except that the stream of electrons is produced by a high voltage electrical discharge.

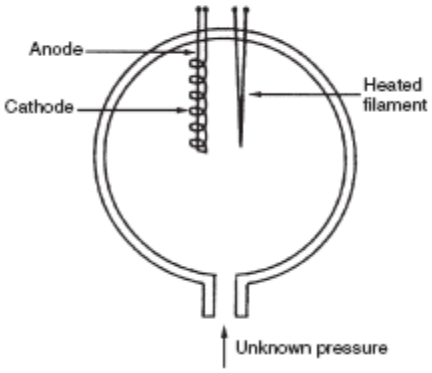


Figure 7.9

Thermistor Gauge:

This is used to measure the temperature of the metal strip rather than a thermocouple figure 7.10. It is commonly marketed under the name electronic vacuum gauge in a form that includes a digital light-emitting diode display and switchable output ranges.

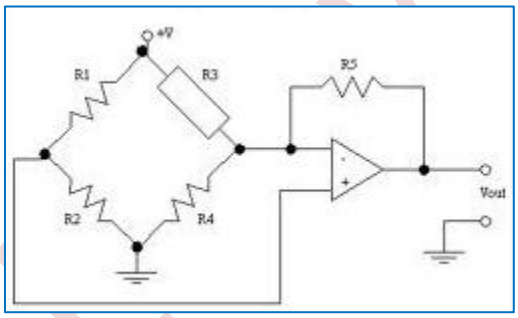


Figure 7.10

Bourbon gauge:

Electronic Pressure Gauges

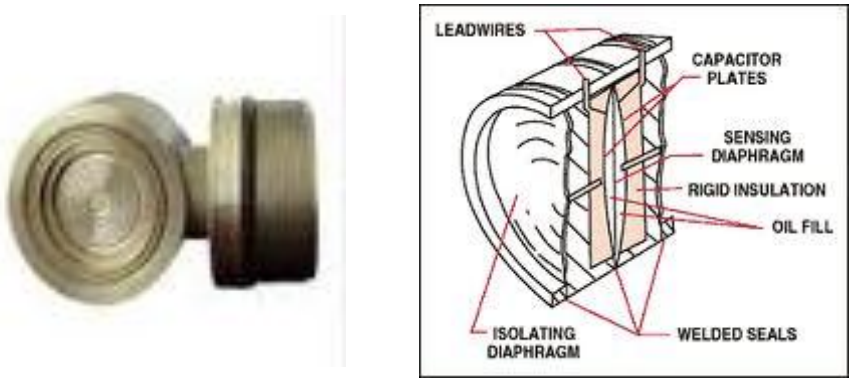
This section is included because many instrument manufacturers' catalogues have a section entitled "electronic pressure gauges." However, in reality, electronic pressure gauges are merely special forms of the pressure gauges described earlier in which electronic techniques are applied to improve performance. All of the following commonly appear in instrument catalogues under the heading "electronic pressure gauges."

- **Piezoresistive pressure transducer**: This diaphragm-type sensor uses piezoresistive strain gauges to measure diaphragm displacement.
- **Piezoelectric pressure transducer**: This diaphragm-type sensor uses a piezoelectric crystal to measure diaphragm displacement.
- **Magnetic pressure transducer**: This class of diaphragm-type device measures diaphragm displacement magnetically using inductive, variable reluctance, or eddy current sensors.
- **Capacitive pressure transducer**: This diaphragm-type sensor measures variation in capacitance between the diaphragm and a fixed metal plate close to it.
- **Fiber-optic pressure sensor**: Known alternatively as an optical pressure sensor, this uses a fiber-optic sensor to measure the displacement of either a diaphragm or a Bourdon tube pressure sensor.
- **Potentiometric pressure sensor**: This is a device where the translational motion of a bellows-type pressure sensor is connected to the sliding element of an electrical potentiometer
- **Resonant pressure transducer**: This is a form of resonant wire pressure-measuring device in which the pressure-induced frequency change is measured by electronics integrated into the device.

Capacitive Pressure transducer:

A capacitive pressure transducer figure 7.11 is simply a diaphragm-type device in which diaphragm displacement is determined by measuring the capacitance change between the diaphragm and a metal plate that is close to it. Such devices are in common use and are sometimes known as *Baratron gauges*. It is also possible to fabricate capacitive elements in a silicon chip and thus form very small micro sensors. These have a typical measurement uncertainty of $\pm 0.2\%$.

Figure 7.11



Calibration of Pressure Sensors

Different types of reference instruments are used according to the range of the pressure measuring instrument being calibrated. In the midrange of pressures from 0.1 mbar to 20 bars, U-tube manometers, dead-weight gauges, and barometers can all be used as reference instruments for calibration purposes. The vibrating cylinder gauge also provides a very accurate reference standard over part of this range. At high pressures above 20 bars, a gold–chrome alloy resistance reference instrument is normally used. For low pressures in the range of 10^{-1} to 10^{-3} mbar, both the McLeod gauge and various forms of micro manometers are used as a pressure-measuring standard. At even lower pressures below 10^{-3} mbar, a pressure-dividing technique is used to establish calibration. This involves setting up a series of orifices of an accurately known pressure ratio and measuring the upstream pressure with a McLeod gauge or micro manometer.

The limits of accuracy with which pressure can be measured by presently known techniques are as follows:

10_7	mbar	±4%
10_5	mbar	±2%
10_3	mbar	±1%
10_1	mbar	±0.1%
1	bar	±0.001%
10$_4$	bar	±0.1%

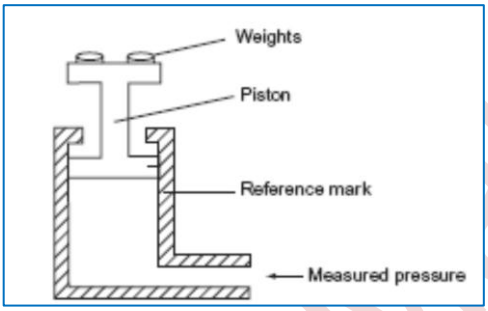
Reference Calibration Instruments

Dead-weight gauge (pressure balance) the dead-weight gauge, also known by the alternative names of piston gauge and pressure balance. It is a null-reading type of measuring instrument in which weights are added to the piston platform until the piston is adjacent to a fixed reference mark, at which time the downward force of the weights on top of the piston is balanced by the pressure exerted by the fluid beneath the piston. The fluid pressure is therefore calculated in terms of the weight added to the platform and the known area of the piston. The instrument offers the ability to measure pressures to a high degree of accuracy and is widely used as a reference instrument against which other pressure-measuring instruments are calibrated in the midrange of pressures. Unfortunately, its mode of measurement makes it inconvenient to use and is therefore rarely used except for calibration duties. Special precautions are necessary in the manufacture and use of dead-weight gauges. Friction between the piston and the cylinder must be reduced to a very low level, as otherwise a significant measurement error would result. Friction reduction is accomplished by designing for a small clearance gap between the piston and the cylinder by machining the cylinder to a slightly greater diameter than the piston. The piston and cylinder are also designed so that they can be turned relative to one another, which reduce friction still further. Unfortunately, as a result of the small gap between the piston and the cylinder, there is a finite flow of fluid past the seals. This produces a viscous shear force, which partly

balances the dead weight on the platform. A theoretical formula exists for calculating the magnitude of this shear force, suggesting that exact correction can be made for it. In practice, however, the piston deforms under pressure and alters the piston/cylinder gap and so shear force calculation and correction can only be approximate.

Despite these difficulties, the instrument gives a typical measurement inaccuracy of only ±0.01%. It is normally used for calibrating pressures in the range of 20 mbar up to 20 bars. However, special versions can measure pressures down to 0.1 mbar or up to 7000 bar.

Dead-weight gauge



U-tube manometer

In addition to its use for normal process measurements, the U-tube manometer is also used as a reference instrument for calibrating instruments measuring midrange pressures. Although it is a deflection rather than null type of instrument, it manages to achieve similar degrees of measurement accuracy to the dead-weight gauge because of the error sources noted in the latter. The major source of error in U-tube manometers arises out of the difficulty in estimating the meniscus level of the liquid column accurately. There is also a tendency for the liquid level to creep up the tube by capillary action, which creates an additional source of error.

U tubes for measuring high pressures become unwieldy because of the long lengths of liquid column and tube required. Consequently, U-tube manometers are normally used only for calibrating pressures at the lower end of the mid pressure range.

Barometers

The most commonly used type of barometer for calibration duties is the Fortin barometer. This is a highly accurate instrument that provides measurement inaccuracy levels of between ±0.03 and ±0.001% of full-scale reading depending on the measurement range. To achieve such levels of accuracy, the instrument has to be used under very carefully controlled conditions of lighting, temperature, and vertical alignment. It must also be manufactured to exacting standards and is therefore very expensive to buy. Corrections have to be made to the output reading according to ambient temperature, local value of gravity, and atmospheric pressure. Because of its expense and difficulties in using it, the barometer is not normally used for calibration other than as a primary reference standard at the top of the calibration chain.

McLeod gauge

The McLeod gauge can be used for the calibration of instruments designed to measure low pressures between 10^{-4} and 0.1 mbar (10^{-7} to 10^{-4} bar).

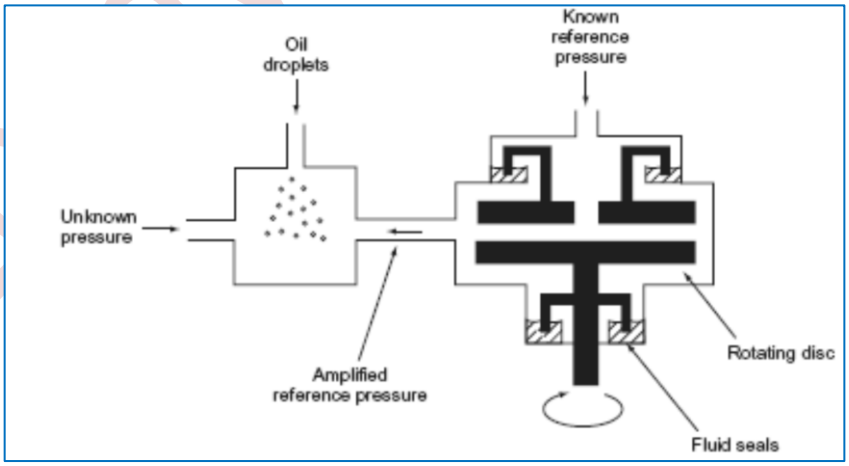
Ionization gauge

An ionization gauge is used to calibrate instruments measuring very low pressures in the range 10^{-13} to 10^{-3} bar. It has the advantage of having a straight-line relationship between output reading and pressure. Unfortunately, its inherent accuracy is relatively poor and specific points on its output characteristic have to be calibrated against a McLeod gauge.

Micro manometers

Micro manometers are instruments that work on the manometer principle but are specially designed to minimize capillary effects and meniscus reading errors. The centrifugal form of a micro manometer, shown schematically in Figure 7.12, is the most accurate type for use as a calibration standard down to pressures of 10^{-3} mbar. In this, a rotating disc serves to amplify a reference pressure, with the speed of rotation being adjusted until the amplified pressure just balances the unknown pressure. This null position is detected by observing when oil droplets sprayed into a glass chamber cease to move. Measurement inaccuracy is $\pm$1%. Other types of micro manometers also exist, which give similar levels of accuracy, but only at somewhat higher pressure levels. These can be used as calibration standards at pressures up to 50 mbar.

Figure 7.12 micro manometer



Procedures for Calibration:

Pressure calibration requires the output reading of the instrument being calibrated to be compared with the output reading of a reference standard instrument when the same pressure is applied to both. This necessitates designing a suitable leak proof seal to connect the pressure measuring chambers of the two instruments.

The calibration of pressure transducers used for process measurements often has to be carried out in situ in order to avoid serious production delays. Such devices are often remote from the nearest calibration laboratory and to transport them there for calibration would take an unacceptably long time. Because of this, portable reference instruments have been developed for calibration at this level in the calibration chain. These use a standard air supply connected to an accurate pressure regulator to provide a range of reference pressures. An inaccuracy of _0.025% is achieved when calibrating midrange pressures in this manner. Calibration at higher levels in the calibration chain must, of course, be carried out in a proper calibration laboratory maintained in the correct manner. However, irrespective of where calibration is carried out, several special precautions are necessary when calibrating certain types of instrument, as described in the following paragraphs.

U-tube manometers must have their vertical alignment set up carefully before use. Particular care must also be taken to ensure that there are no temperature gradients across the two halves of the tube. Such temperature differences would cause local variations in the specific weight of the manometer fluid, resulting in measurement errors. Correction must also be made for the local value of g (acceleration due to gravity). These comments apply similarly to the use of other types of manometers and micro manometers.

The existence of one potentially major source of error in Bourdon tube pressure measurement has not been widely documented, and few manufacturers of Bourdon tubes make any attempt to warn users of their products appropriately. This problem is concerned with the relationship between the fluid being measured and the fluid used for calibration. The pointers of Bourdon tubes are normally set at zero during manufacture, using air as the calibration medium.

However, if a different fluid, especially a liquid, is subsequently used with a Bourdon tube, the fluid in the tube will cause a nonzero deflection according to its weight compared with air, resulting in a reading error of up to 6% of full-scale deflection.

This can be avoided by calibrating the Bourdon tube with the fluid to be measured instead of with air. Alternatively, correction can be made according to the calculated weight of the fluid in the tube. Unfortunately, difficulties arise with both of these solutions if air is trapped in the tube, as this will prevent the tube being filled completely by the fluid. Then, the amount of fluid actually in the tube, and its weight, will be unknown. To avoid this problem, at least one manufacturer now provides a bleed facility in the tube, allowing measurement uncertainties of less than 0.1% to be achieved.

When using a McLeod gauge, care must be taken to ensure that the measured gas does not contain any vapor. This would be condensed during the compression process, causing a measurement error. A further recommendation is insertion of a liquid-air cold trap between the gauge and the instrument being calibrated to prevent the passage of mercury vapor into the latter.

Pressure transmitters:

In the process industries, it is often necessary to transmit the measurement signal from a sensor over a substantial distance so that it can be used to implement a control function or can be combined with other measurement signals in a more complex scheme. The initial development of such transmission systems was required for the petroleum and petro-chemical industries where pneumatic control schemes were used most widely, because they could be installed in plants where explosive or hazardous conditions could arise and the diaphragm actuator provided a powerful and fast acting device for driving the final operator. It followed that the first transmission systems to be evolved were pneumatic and were based on the standardized signal range (3 to 15 psig) 20 to 100 kPa.

Early transmitters utilized a motion-balance system, i.e., in which the primary element produces a movement proportional to the measured quantity, such as a Bourdon tube, in which movement of the free end is proportional to the applied pressure. However, these transmitters were rather sensitive to vibration and have, in general, been superseded by force-balance systems. But pneumatic transmission itself is unsuitable when the distance involved exceeds a few hundred meters, because of the time delay and response lag which occur.

Consequently, an equivalent electronic system has been evolved. In this, a current in the range 4 to 20 mA d.c. and proportional to the span of the measured quantity is generated by the sensor and transmitted over a two-wire system. The advantage of this system is that there is virtually no delay or response lag, and the transmitted signal is not affected by changes in the characteristic of the transmission line. Also there is sufficient power below the live zero (i.e., 4mA) to operate the sensing device. Such systems have the additional advantage that they are more easily configured in complex control schemes than the corresponding pneumatic transmitters.

The growth in digital computers and control systems has generated a need for intelligent, digital output pressure transmitters. Since 1994, many pressure transmitters have been installed that use for their primary means of communication some form of digital fieldbus, such as Provirus or Foundation Fieldbus. It is expected that these intelligent transmitters will eventually supersede the 4-20 mA d.c. standard (ISA S50) and the remaining pneumatic transmitters in use.

Pneumatic motion-balance pressure transmitters

Figure 7.13 shows the arrangement of a typical pneumatic motion-balance transmitter in which the sensor is a spiral Bourdon tube. Changes in the measured variable, which could be pressure, or temperature in the case system, cause the free end of the Bourdon tube to move. This movement is transmitted via a linkage to the

lever that pivots about the axis **A.** The free end of this lever bears on a second lever that is pivoted at its center so that the movement is thus transmitted to a third lever that is free to pivot about the axis C.

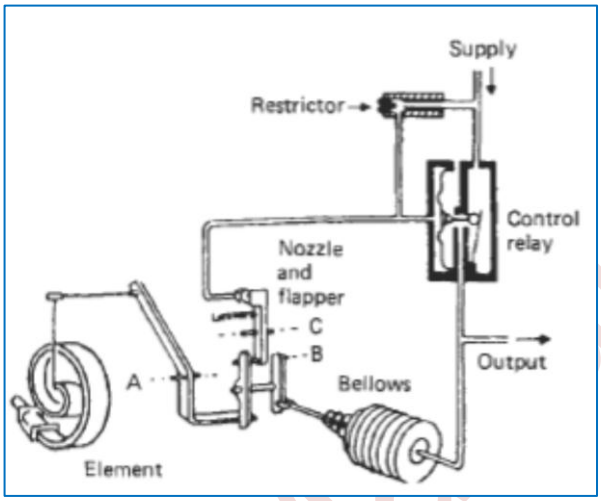


Figure 7.13

Pneumatic force-balance pressure transmitters

There are many designs of pneumatic force-balance transmitters, but in Invensys Inc. design the same force-balance mechanism is used in all the pressure and differential pressure transmitters. It is shown in Figure 7.14, and its basic function is to convert a force applied to its input point into a proportional pneumatic signal for transmission, such as 20 to 100 kPa.

The force to be measured may be generated by a Bourdon tube, a bellows, or a diaphragm assembly and applied to the free end of the force bar. This is pivoted at the diaphragm seal; which in some instruments also provides the interface between process fluid and the force-ba1ance mechanism, so that an initial displacement arising from the applied force appears amplified at the top of the force bar where it is transmitted via the flexure connector to the top of the range rod.

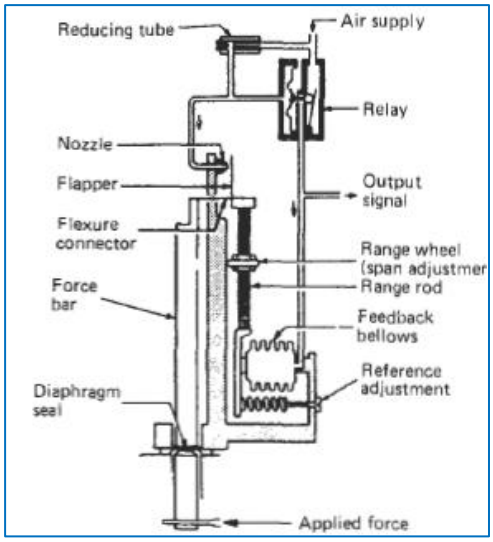
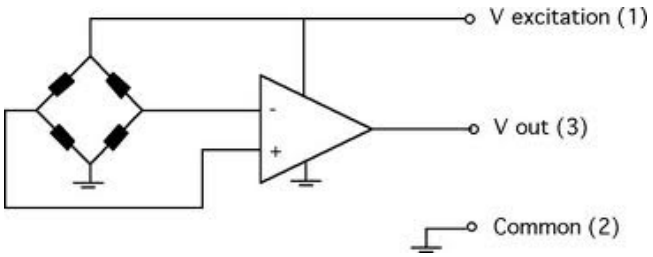
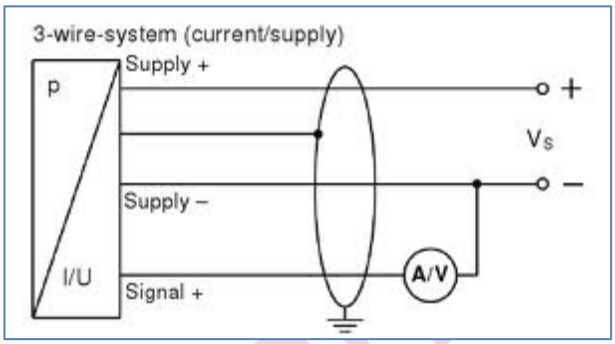


Figure 7.14

Digital pressure transmitter:





MEASUREMENT OF VELOCITY

Definition: Linear Velocity is distance/time **(mm/time, cm/time, m/time, km/hr)** $v = \frac{s}{t}$

Principles of fluid mechanics:

Shear stress and viscosity

There are three states of matter: solid, liquid and gas. Liquids and gases are different in many respects but behave in the same way under the action of a deforming force. Liquids and gases, i.e. fluids, flow under the action of a deforming force, whereas a solid retains its shape. The effect is illustrated in Figure 8.1(a), which shows the effect of a shear force *F* on a rectangular block. The corresponding shear stress τ is the force per unit area *F*/*A*, where *A* is the area of the base of the block.

The effect of τ is to deform the block as shown, and the resulting *shear strain* is quantified by the angle Ø. In a solid Ø will be constant with time and of magnitude proportional to τ. In a fluid Ø will increase with time and the fluid will flow.

Figure 8.1(b) shows a fluid flowing over a solid boundary, e.g. a flat plate. The fluid in contact with the plate surface at $y = 0$ has zero velocity. As we move away from the plate, i.e. as y increases, the velocity v of the layers increases, until well away from the plate the layers have the free stream velocity v_0. The layers between the free stream and the boundary are called *boundary layers* and are characterized by a velocity gradient d*v*/d*y*. From fihure [8.1] we see that frictional shear stresses are present in these boundary layers.

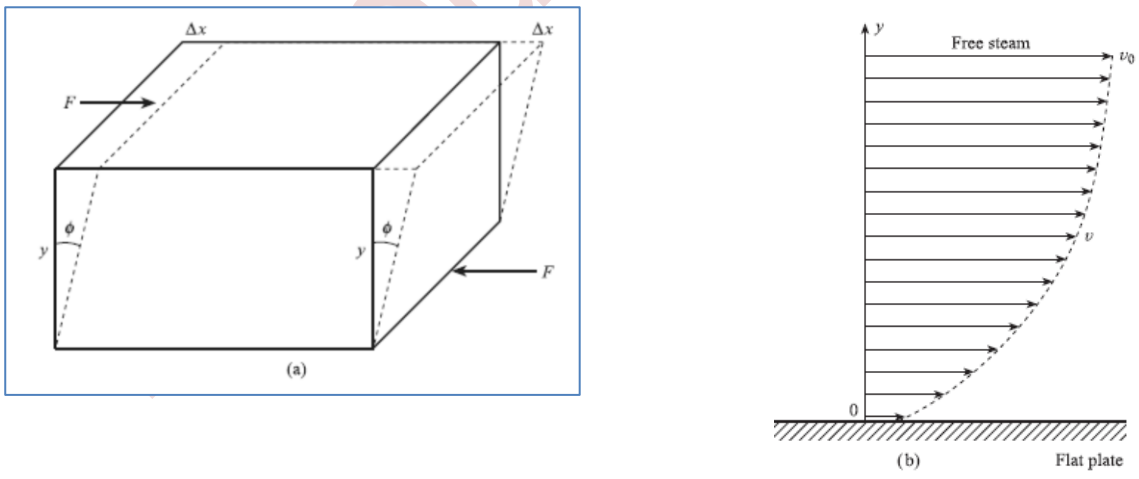


Figure 8.1 Shear stress and viscosity: (a) Deformation caused by shearing forces (b) Velocity distribution in boundary layers.

Liquids and gases:

Although liquids and gases have the common properties of fluids, they have distinctive properties of their own. A liquid is difficult to compress, i.e. there is a very small decrease in volume for a given increase in pressure, and it may be regarded as incompressible, i.e. density ρ is independent of pressure (but will depend on temperature). Gases are easy to compress, and density depends on both pressure and temperature.

For an ideal gas we have:

$P=\rho.R.T$ Equation of state for ideal gas

For real gases the above equation must be corrected by introducing an experimental compressibility factor or gas law deviation constant.

The amount of heat required to raise the temperature of a gas by a given amount depends on whether the gas is allowed to expand, i.e. to do work, during the heating process. A gas therefore has two specific heats: specific heat at constant volume C_V and specific heat at constant pressure C_P. If the expansion or contraction of a gas is carried out **adiabatically**, i.e.

Laminar and turbulent flow: Reynolds number

Experimental observations have shown that two distinct types of flow can exist.

The first is **laminar flow**, or viscous or streamline flow; this is shown for a circular pipe in Figure 8.2(a). Here the particles move in a highly ordered manner, retaining the same relative positions in successive cross-sections. Thus laminar flow in a circular pipe can be regarded as a number of annular layers: the velocity of these layers increases from zero at the pipe wall to a maximum at the pipe center with significant viscous shear stresses between each layer. Figure 12.2(a) shows the resulting velocity profile; this is a graph of layer velocity *v* versus distance *r* of layer from center, and is parabolic in shape.

The second type of flow, **turbulent flow**, is shown in Figure 8.2(b). This is highly disordered; each particle moves randomly in three dimensions and occupies different relative positions in successive cross-sections. As a result, the velocity and pressure at a given point in the pipe are both subject to small random fluctuations with time about their mean values. The viscous friction forces which cause the ordered motion in laminar flow are much smaller in turbulent flow. Figure 8.2(b) shows a typical velocity profile for turbulent flow in a circular pipe. It is obtained by taking a point *r* in the pipe and measuring the time average *v* of the velocity component, along the direction of flow at that point.

The **Reynolds number** tells us whether the flow in a given situation is laminar or turbulent. It is the dimensionless number:

$Re=\rho.U.d/\mu$

The Reynolds number represents the ratio of inertial forces (proportional to ρ.U.d) to viscous forces (proportional to η); thus a low value of *Re* implies laminar flow and a high value turbulent flow. The following is an approximate guide:

$Re < 2 \times 10^3$ – laminar flow

$2 \times 10^3 < Re < 10^4$ – transition region

$Re > 10^4$ – turbulent flow

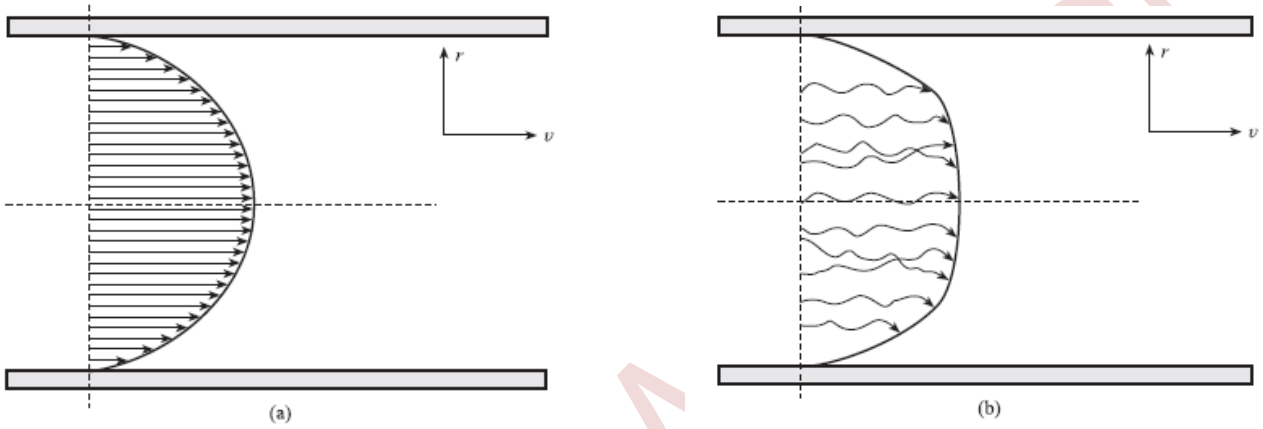


Figure 8.2 Types of flow and velocity profiles in a circular pipe: (a) Laminar (b) Turbulent

Continuity: conservation of mass and volume flow rate:

Figure 7.3 shows a stream tube through which there is a steady flow; since conditions are steady the principle of conservation of mass means that:

Mass of fluid entering in unit time = mass of fluid leaving in unit time

Conservation of mass flow rate: $\dot{m}=\rho.U.A$

Conservation of volume flow rate: Q=U.A

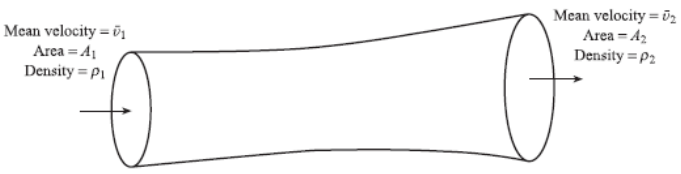


Figure 8.3 Conservation of mass flow rate in a stream tube.

Total energy and conservation of energy

Potential energy given by: Potential energy = $m.g.z$

Kinetic energy given by: Kinetic energy = 1/2 (mv^{-2})

Flow work is often referred to as **pressure energy**; this is the energy possessed by a fluid when moving under pressure as part of a continuous stream. The *total energy* of a flowing fluid is the sum of pressure, kinetic and potential energies, so that:

Fluid energy: Total energy/unit mass $= \frac{p}{\rho} + \frac{1}{2} \cdot v^{-2} + gz$

Conservation of energy – incompressible fluid:

Measurement of velocity at a point in a fluid

This is important in investigational work, such as studies of the velocity distribution around an aerofoil in a wind tunnel, or measurement of the velocity profile in a pipe prior to the installation of a permanent flow meter. There are two main methods.

Pitot-static tube

An obstruction type primary element used mainly for fluid velocity measurement is the Pitot tube.

Principle

Consider Fig. 8.4 which shows flow around a solid body. When a solid body is held centrally and stationary in a pipeline with a fluid streaming down, due to the presence of the body, the fluid while approaching the object starts losing its velocity till directly in front of the body, where the velocity is zero. This point is known as the stagnation point. As the kinetic head is lost by the fluid, it gains a static head. By measuring the difference of pressure between that at normal flow line and that at the stagnation point, the velocity is found out. This principle is used in Pitot tube sensors.

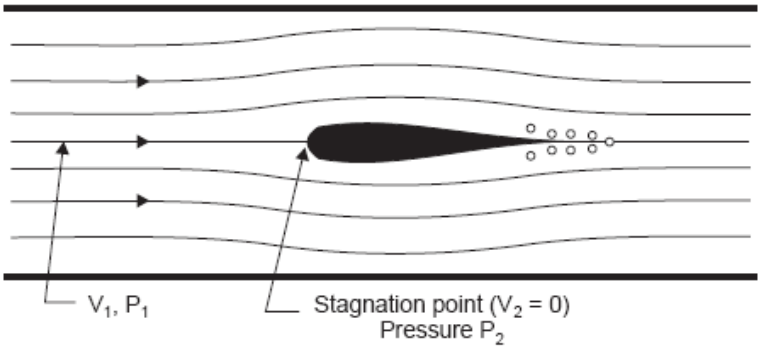


Figure 8.4 Flow around a solid body

The simplest Pitot tube consists of a tube with an impact opening of 3.125 mm to 6.35 mm diameter pointing towards the approaching fluid. This measures the stagnation pressure. An ordinary upstream tap can be used for measuring the line pressure.

A common industrial type of Pitot tube consists of a cylindrical probe inserted into the air stream, as shown in Fig. 8.4. Fluid flow velocity at the upstream face of the probe is reduced substantially to zero. Velocity head is converted to impact pressure, which is sensed through a small hole in the upstream face of the probe. A corresponding small hole in the side of the probe senses static pressure. A pressure instrument measures the differential pressure, which is proportional to the square of the stream velocity in the vicinity of the impact pressure sensing hole. The velocity equation for the Pitot tube is given by:

$$v = C_{pitot} \cdot \sqrt{2gh}$$

Where C_{pitot} is the Pitot tube constant.

Figure 8.5 shows a typical Pitot tube which also shows the taps for sensing static pressure. The total pressure developed at the point where the flow is stagnated is assumed to occur at the tip of a Pitot tube or at a specific point on a bluff body immersed in the stream.

The Pitot tube causes practically no pressure loss in the flow stream. It is normally installed through a nipple in the side of the pipe. It is frequently installed through an isolation valve, so that it can be moved back and forth across the stream to establish the profile of flow velocity.

Certain characteristics of Pitot tube flow measurement have limited its industrial application. For true measurement of flow, it is essential to establish an average value of flow velocity. To obtain this with a Pitot tube, it is necessary to move the tube back and forth across the stream to establish the velocity at all points and then to take an average. For high-velocity flow streams, it is required to provide necessary stiffness and strength.

A tube inserted in a high-velocity stream has a tendency to vibrate and get broken. As a result, Pitot tubes are generally used only in low-to-medium flow gas applications where high accuracy is not required.

Figure 8.5 Typical Pitot tube

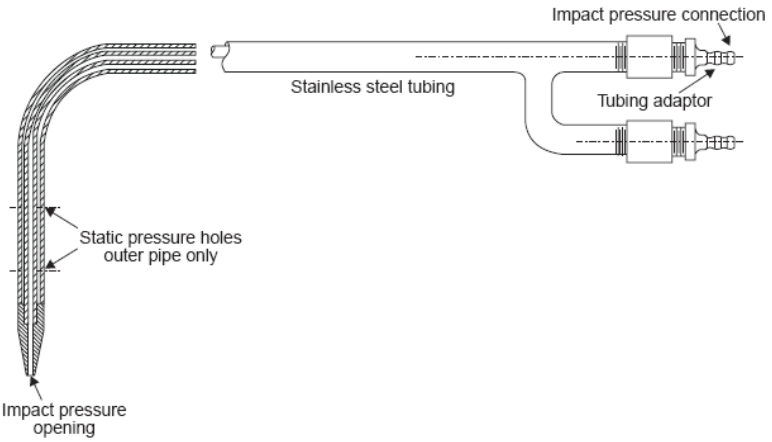


Figure 8.6 shows the Pitot - static tube. At the impact hole part of the fluid is brought to rest; this part has therefore no kinetic energy, only pressure energy. At the static holes the fluid is moving and therefore has both kinetic and pressure energy. This creates a pressure difference $P_I - P_S$ which depends on velocity v.

Applying the incompressible equation to air at standard temperature (20 °C) and pressure ($PS = 10^5$ Pa), with $\rho = 1.2$ kg m^{-3}, gives $\Delta P = 0.6v^2$. Thus at $v = 5$ m s^{-1} we have $\Delta P = 15$ Pa, $\Delta P/PS = 1.5 \times 10^{-4}$; and at $v = 100$ m s^{-1}, $\Delta P = 6 \times 10^3$ Pa, $\Delta P/PS = 6 \times 10^{-2}$. The small $\Delta P/PS$ ratio means that for $v < 100$ m s−1, the difference in density between the air at the impact and static holes is negligible; the error introduced by using the incompressible equation is within 1%.

The above very low differential pressures mean that special pressure transmitters must be used. One such transmitter uses a linear variable differential transformer to sense the deformation of a diaphragm capsule with a large area; this gives a 4 to 20 mA current output proportional to input differential pressure in the range 0 to 250 Pa. Figure 7.6 shows a computer-based measurement system incorporating this transmitter for measuring air velocities in the range 0 to 20 m s−1. The amplifier converts the transmitter output to a voltage signal between 0.51 and 2.55 V. The analogue-to-digital converter gives an 8-bit parallel digital output signal corresponding to decimal numbers D between 51 and 255.

The above system is only suitable for measuring the time average of the velocity at a point in a fluid. The system frequency response is insufficient for it to measure the rapid random velocity fluctuations present in turbulent flow.

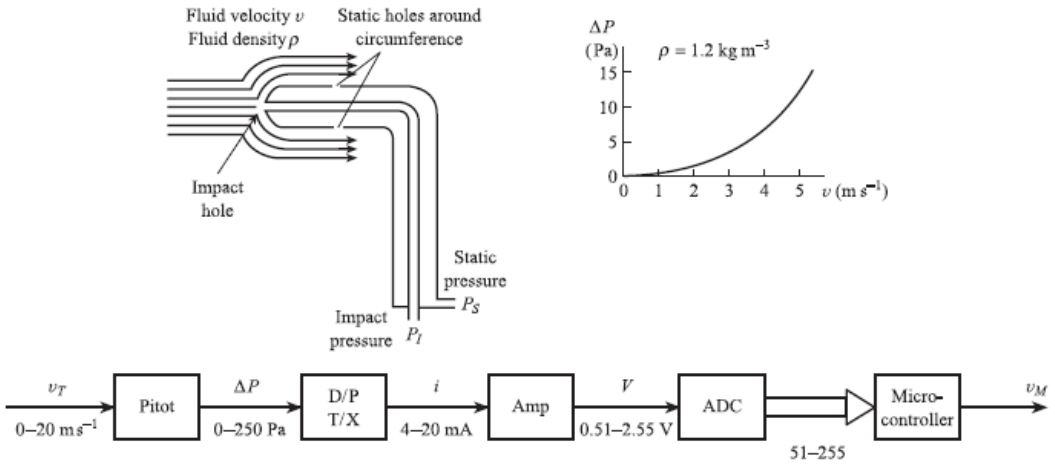


Figure 8.6 Pitot-static tube.

Hot Wire probes

INTRODUCTION

The hot-wire anemometer has been used extensively for many years as a research tool in fluid mechanics. hot-wire anemometry will refer to the use of a small, electrically heated element exposed to a fluid medium for the purpose of measuring a property of that medium. Normally, the property being measured is the velocity. Since these elements are sensitive to heat transfer between the element and its environment, temperature and composition changes can also be sensed.

Figure 8.7 shows a hot-wire anemometer probe. Typical dimensions of the wire sensor are 0.00015 to 0.0002 inches (0.0038 to 0.005 mm) in diameter and 0.040 to 0.080 inches (1.0 to 2.0 mm) long. This is the type of hot wire that has been used for such measurements as turbulence levels in wind tunnels, flow patterns around models and blade wakes in radial compressors. The film type of sensor is shown in Figure 7.8. The hot film is used in regions where a hot wire probe would quickly break such as in water flow measurements.

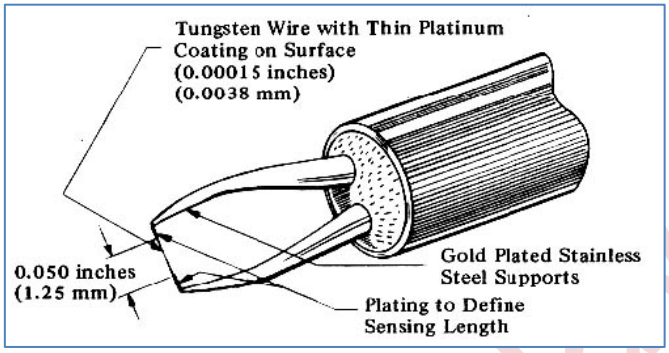


Figure 8.7 hot wire

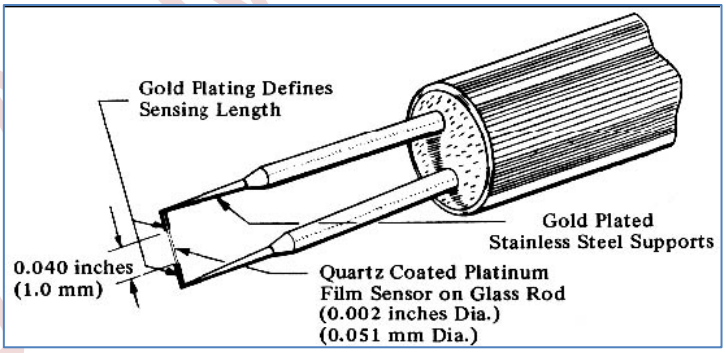


Figure 8.8 hot film hot wire

Modes of anemometer operation:

- **Constant Current (CCA)**
- **Constant Temperature (CTA)**

Hot wire can be using as a **Constant Temperature Anemometer (CTA)**. It works based on the fact that the probe's resistance will be proportional to the temperature of the hot wire. The bridge circuit shown in Figure 8.9 below is set up by setting the adjustable resistor to the resistance you wish the probe and its leads to have during operation. (The other two legs of the bridge have identical resistance.) The servo amplifier tries to keep the error voltage zero (meaning the resistances of the two lower legs of the bridge match). It will adjust the bridge voltage such that the current through the probe heats it to the temperature which gives the selected resistance. When we put the probe in a flow, the air (or water) flowing over it will try to cool it. In order to maintain the temperature (resistance) constant, the bridge voltage will have to be increased. A very fine hot

wire by itself cannot respond to changes in fluid velocity at frequencies above about 500 Hz. By compensating for frequency lag with a non-linear amplifier this response can be increased to values of 300 to 500 kHz.

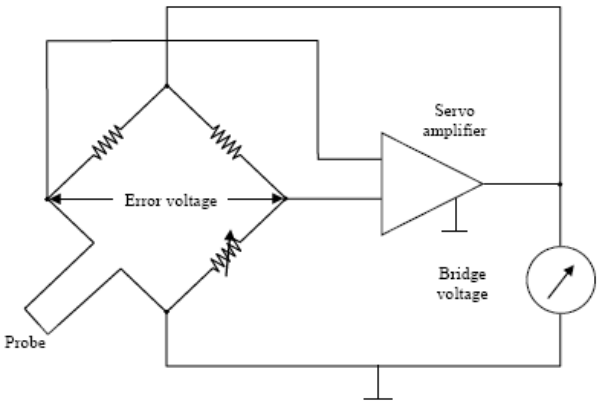


Figure 8.9 Constant Temperature Anemometer (CTA)

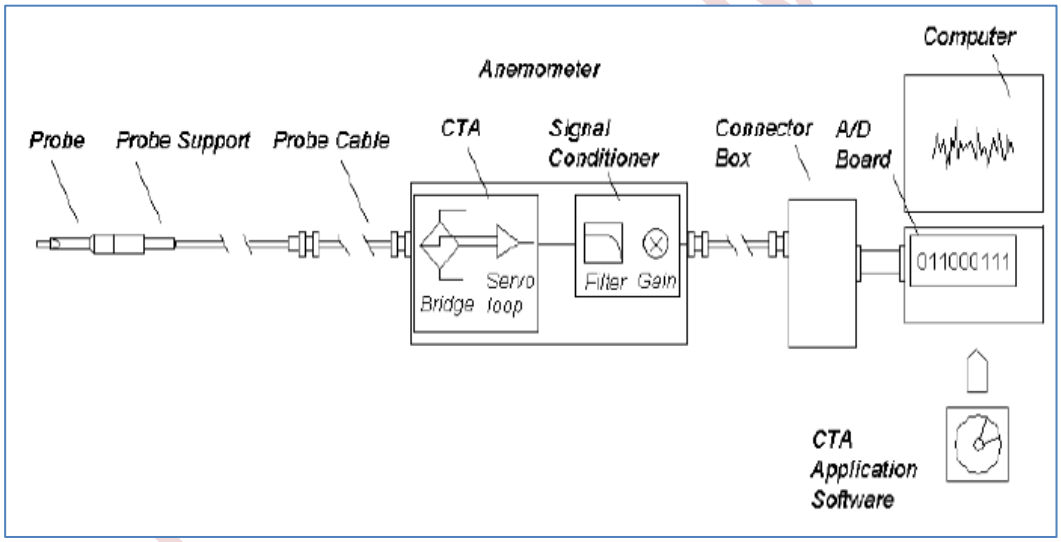


Figure 8.10 Basic CTA Measuring Chain

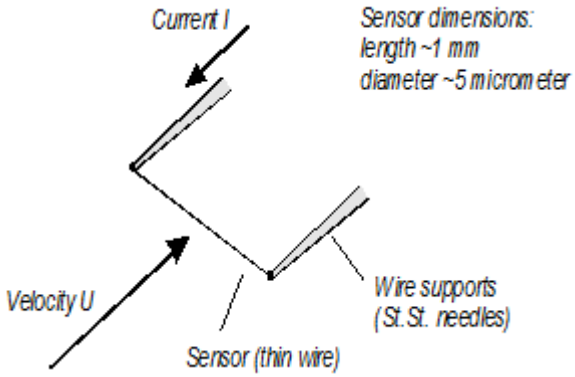
Features

- Measures velocities from a few cm/s to supersonic.
- High temporal resolution: fluctuations up to several hundred kHz.
- High spatial resolution: eddies down to 1 mm or less.
- Measures all three velocity components simultaneously.
- Provides instantaneous velocity information.

Principles of operation:

Consider a thin wire mounted to supports and exposed to a velocity *U*. When a current is passed through wire, heat is generated (I^2R_w). In equilibrium, this must be balanced by heat loss (primarily convective) to the surroundings.

If velocity changes, convective heat transfer coefficient will change, wire temperature will change and eventually reach a new equilibrium.



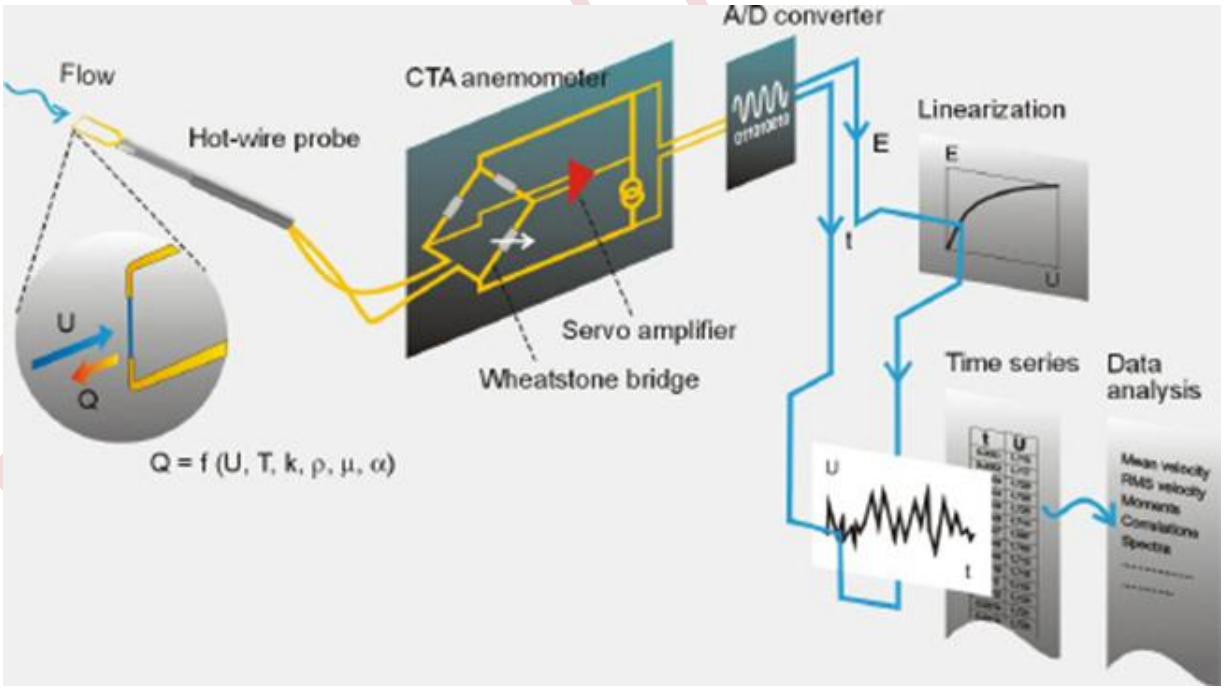


Figure 8.11

PROBE TYPES

Hot-Wire Sensors

A hot-wires type sensor must have two characteristics to make it a useful device:

- A high temperature coefficient of resistance
- An electrical resistance such that it can be easily heated with an electrical current at practical voltage and current levels.

The most common wire materials are ***tungsten, platinum and a platinum-iridium alloy***. Tungsten wires are strong and have a high temperature coefficient of resistance, (0.004/°C). However, they cannot be used at high temperatures in many gases *because of poor oxidation resistance*. Platinum has good oxidation resistance, has a good temperature coefficient (0.003/°C), but is very weak, particularly at high temperatures. The platinum-iridium wire is a compromise between tungsten and platinum with good oxidation resistance, and more strength than platinum, but it has a low temperature coefficient of resistance (0.00085/oC). Tungsten is presently the more popular hot wire material. A thin platinum coating is usually applied to improve bond with the plated ends and the support needles.

Hot-Film Sensors

The hot-film sensor is essentially a conducting film on a ceramic substrate. The sensor shown in Figure 7.8 is a quartz rod with a platinum film on the surface. **Gold plating on the ends** of the rod isolates the sensitive area and provides a heavy metal contact for fastening the sensor to the supports. When compared with hot wires the cylindrical hot-film sensor has the following advantages:

- Better frequency response (when electronically controlled) than a hot wire of the same diameter because the sensitive part of the sensor is distributed on the surface rather than including the entire cross section as with a wire. Although hot wires are typically much smaller in diameter.
- Lower heat conduction to the supports (end loss) for a given length to diameter ratio due to the low thermal conductivity of the substrate material. A shorter sensing length can thus be used.
- More flexibility in sensor configuration. Wedge, conical, parabolic and flat surface shapes are available.
- Less susceptible to fouling and easier to clean. A thin quartz coating on the surface resists accumulation of foreign material. Fouling tends to be a direct function of size.

The metal film thickness on a typical film sensor is less than 1000 Angstrom units, causing the physical strength and the effective thermal conductivity to be determined almost entirely by the substrate material. Most films are made of platinum due to its good oxidation resistance and the resulting long-term stability. The ruggedness and stability of film sensors have led to their use for many measurements that have previously been very difficult with the more fragile and less stable hot wires.

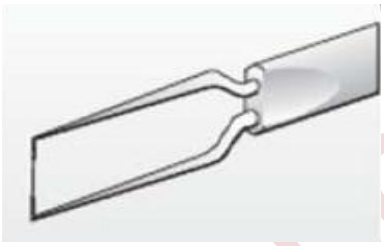
Due to the fact that ***hot film probes are typically of a much larger diameter than wires***, *they will not respond as quickly as a typical wire and therefore will not measure turbulent fluctuations at as high a frequency as hot wires*.

Advantages:

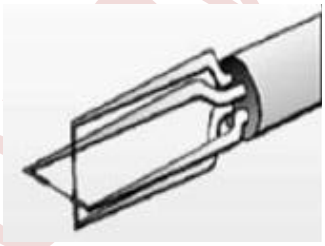
- Good Frequency response: Measurements to several hundred kHz possible, 1 MHz also feasible.
- Velocity Measurement: measures magnitude and direction of velocity and velocity fluctuations, Wide velocity range
- Temperature Measurements
- Two Phase Flow: Measurements in flows containing continuous turbulent phase and distributed bubbles.
- Signal to noise ratio: have low noise levels. Resolution of1 part in 10000 is accomplished.
- Signal Analysis: Output is continuous analogue signal, both time domain and frequency domain analysis can be carried out. Output can also be processed by digital systems.
- Measurement of turbulent quantities like vorticity, dissipation rate etc.

Classification of Hot Wire Probes

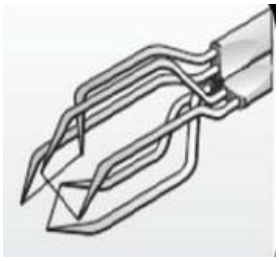
On the basis of number of sensors:



Single Sensor Probe



Dual Sensor Probe



Triple Sensor Probe

Problem Sources:

- Bubbles in Liquids: Effect of bubbling on portion of typical calibration curve
- Eddy shedding: from cylindrical sensors occurs at Re ~50. Vibrations from prongs and probe supports causes vibrate due to eddy shedding from them or due induced vibrations.
- Temperature Variations.

Anemometer

These anemometers have been used to measure air and gas flows in a variety of applications.

They are also used to measure the velocity of wet and dry gases.

Designs of Mechanical Anemometers:

1. Vane anemometer
2. three-cup anemometer
3. Impeller anemometer.

Vane Anemometer

Fig. 8.12 shows the vane-design. In this type, the vanes rotate in response to airflow with the angular velocity of the vanes being proportional to the wind speed. When a portable unit is required or when the local readout is satisfactory, vane motion is passed to the indicator through a gear and spring assembly. If the reading is to be remote, a magnetically coupled or capacitive coupled pickup can be used to generate a transmission signal.

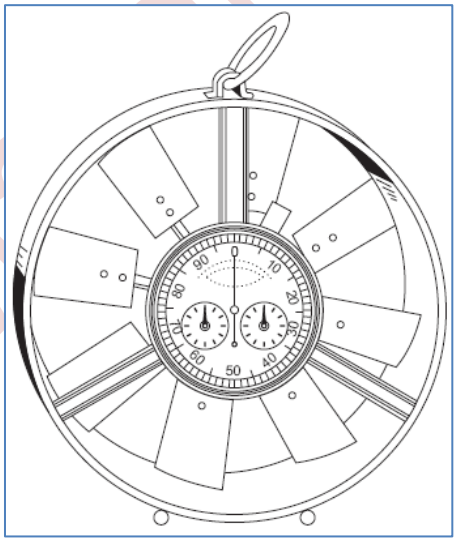


Figure 8.12

Three-Cup Anemometer

Fig. 8.13 shows a three-cup anemometer. This type of anemometer is not sensitive to the direction of the fluid. In this design the shaft drives a direct current tachometer generator with an output voltage that is proportional to the wind speed. This signal may be used to drive a remote mounted indicator recorder.

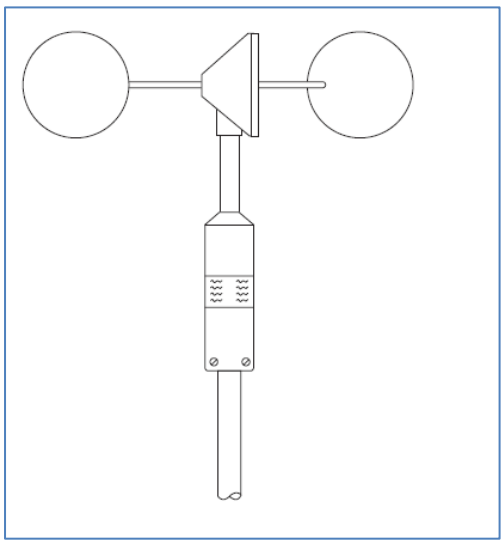


Figure 8.13

Impeller Anemometer

The impeller design is shown in Fig. 8.14. This anemometer also has a shaft-driven tachometer. Since the tail on the impeller design always keep the impellers pointed into the wind, this instrument can be used to detect both wind speed and wind direction. The speed of response for anemometer is given in meters of wind and is known as distance constant.

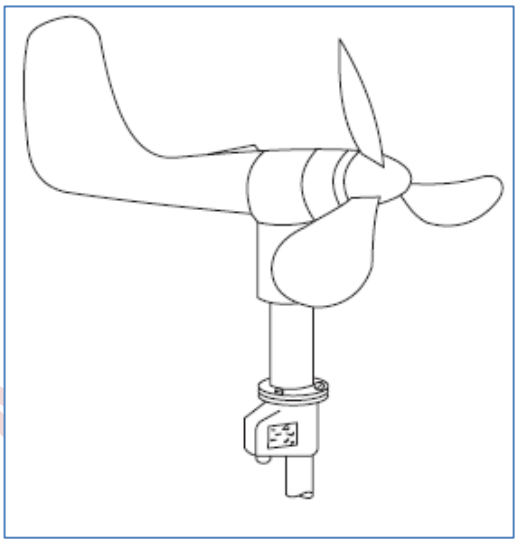
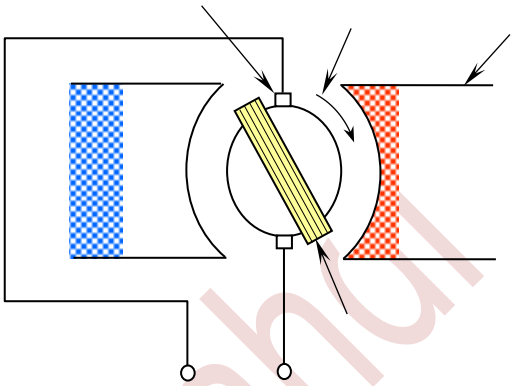


Figure 8.14

Angular velocity:

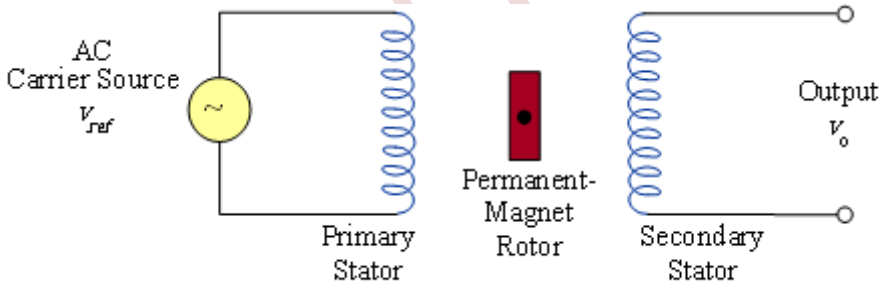
Definition: Angular Velocity is turn/time (r.p.m): $\omega = \frac{\theta}{t}$

DC Tachometer (Angular Velocity):



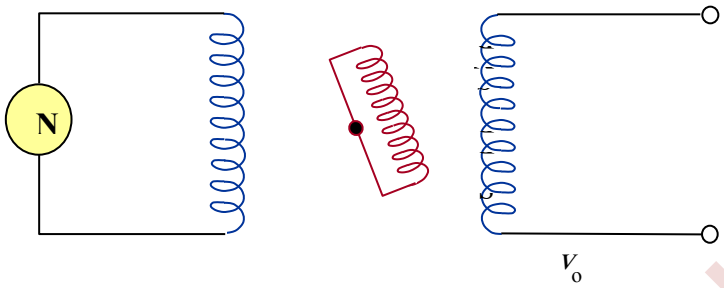
- The rotor is directly connected to the rotating object.
- The output signal that is induced at the rotating coil is picked up using a commutator device (consists of low resistance carbon brushes)
- Commutator is stationary but makes contact with the split slip rings
- Generated voltage is (Faraday's Law)

Permanent Magnet AC Tachometer:



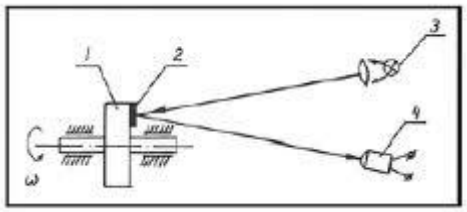
- When the rotor is stationary or moving in a quasi-static manner the output voltage will be constant.
- As the rotor moves, an additional voltage, proportional to the speed of the rotor will be induced.
- The output is an amplitude modulated signal proportional to the rotor speed and demodulation is necessary.
- Direction is obtained from the phase angle.
- Main advantage of AC tachometers is that they have no slip rings or brushes.
- For low frequency applications (~5Hz), supply with 60Hz is adequate.
- Sensitivity is in the range 50 – 100mV/rad/s.

AC Induction Tachometer:



- Similar in construction to an induction motor. Rotor windings are shorted.
- The induced voltage in the rotor windings is a modulated signal of the supply. Modulation is due to the speed of the rotor.
- The output voltage on the secondary is a result of primary and rotor windings and is supply modulated by the speed.
- Main advantage of AC tachometers is that they have no slip rings or brushes

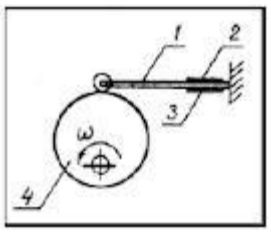
Photoelectric Tachometer:



Structure: A disk with reflecting markings attached to the shaft.
A light source and a light detector.

Output: a train of pulses whose frequency is proportional to shaft's RPM.

Strain Gauge Tachometer:

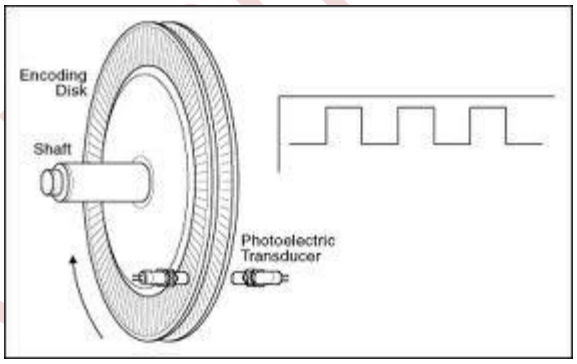


Structure: A thin rod with a bonded strain gauge attached. The end of the rod has a small wheel that rests on the dist. attached to the shaft.

Output: A sinusoidal waveform whose frequency is proportional to the RPM.

Optical Sensor:

Structure: A light emitter and a light detector**.**



MEASUREMENT OF FLOW

Introduction:

The material which is in a liquid or gaseous state, flow can be quantified as either the ***mass flow rate*** or the ***volume flow rate***, with the latter being the volume of material that flows in one unit of time. Of the two, a flow measurement in terms of mass flow rate is preferred if very accurate measurement is required. The greater accuracy of mass flow measurement arises from the fact that mass is invariant whereas volume is a variable quantity.

Mass Flow Rate:

The method used to measure mass flow rate is determined by whether the measured quantity is in a solid, liquid, or gaseous state, as different techniques are appropriate for each.

Conveyor-Based Methods:

Conveyor-based methods are appropriate for measuring the flow of solids in the form of powders or small granular particles. Such powders and particles are produced commonly by crushing or grinding procedures in process industries, and a conveyor is a very suitable means of transporting materials in this form. Transporting materials on a conveyor allows the mass flow rate to be calculated in terms of the mass of material on a given length of conveyor multiplied by the speed of the conveyor.

Coriolis Flow meter

As well as sometimes being known by the alternative name of inertial flow meter, the Coriolis flow meter is often referred to simply as a mass flow meter because of its dominance in the mass flow meter market. Coriolis meters are used primarily to measure the mass flow rate of liquids, although they have also been used successfully in some gas-flow measurement applications. The flow meter consists either of a pair of parallel vibrating tubes or as a single vibrating tube that is formed into a configuration that has two parallel sections. The two vibrating tubes (or the two parallel sections of a single tube) deflect according to the mass flow rate of the measured fluid that is flowing inside. Tubes are made of various materials, of which stainless steel is the most common. They are also manufactured in different shapes, such as B shaped, D shaped, U shaped, triangular shaped, helix shaped, and straight. These alternative shapes are sketched in Figure 9.1a, and a U-shaped tube is shown in more detail in Figure 9.1b. The tubes are anchored at two points. An electromechanical drive unit, positioned midway between the two anchors, excites vibrations in each tube at the tube resonant frequency. Vibrations in the two tubes, or the two parallel sections of a single tube, are 180 degrees out of phase.

The vibratory motion of each tube causes forces on the particles in the flowing fluid. These forces induce motion of the fluid particles in a direction that is orthogonal to the direction of flow, which produces a Coriolis force. This Coriolis force causes a deflection of the tubes that is superimposed on top of the vibratory motion. Coriolis meters give excellent accuracy, with measurement uncertainties of $\pm 0.2\%$ being typical. They also have low maintenance requirements. However, apart from being expensive (typical cost is $6000), they suffer from a number of operational problems. Failure may occur after a period of use because of mechanical fatigue in the tubes. Tubes are also subject to both corrosion caused by chemical interaction with the measured fluid and abrasion caused by particles within the fluid. Diversion of the flowing fluid around the flow meter causes it to suffer a significant pressure drop, although this is much less evident in straight tube designs.

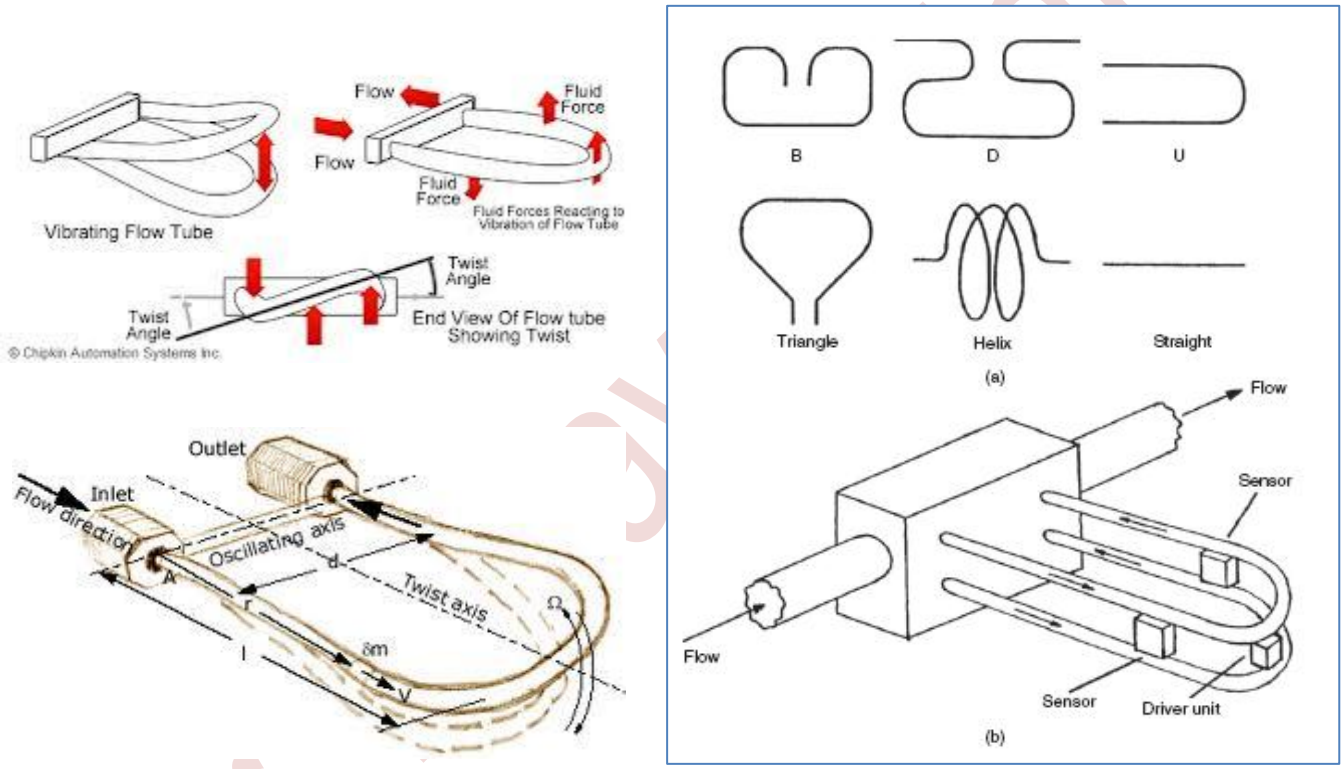
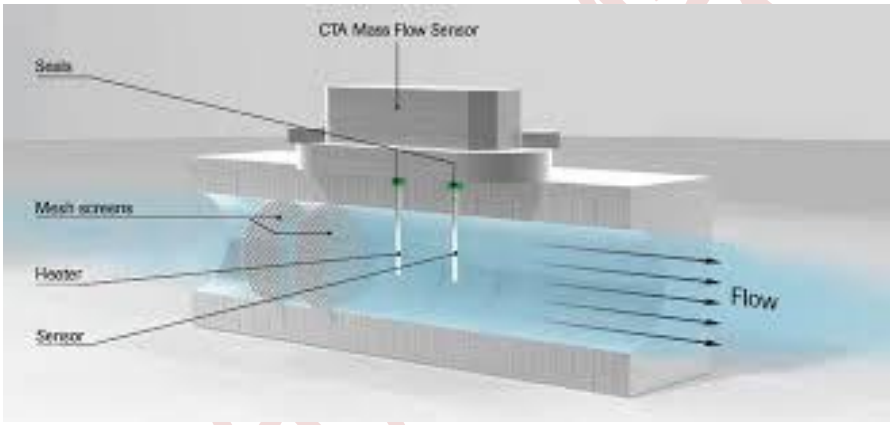


Figure 9.1

Thermal Mass Flow Measurement

Thermal mass flow meters are used primarily to measure the flow rate of gases. The principle of operation is to direct the flowing material past a heated element. The mass flow rate is inferred in one of two ways: (a) by measuring the temperature rise in the flowing material or (b) by measuring the heater power required to achieve a constant set temperature in the flowing material. In both cases, the specific heat and density of the flowing fluid must be known. Typical measurement uncertainty is $\pm$2%. Standard instruments require the measured gas to be clean and noncorrosive. However, versions made from special alloys can cope with more aggressive gases. Tiny versions of thermal mass flow meters have been developed that can measure very small flow rates in the range of nano liters (10-9 liters) or microliters (10-6 liters) per minute.



Volume flow rate:

Volume flow rate is an appropriate way of quantifying the flow of all materials that are in a gaseous, liquid, or semiliquid slurry form (where solid particles are suspended in a liquid host), although measurement accuracy is inferior to mass flow measurement as noted earlier. Materials in these forms are usually carried in pipes, and various instruments can be used to measure the volume flow rate as described later. As noted in the introduction, these all assume laminar flow. In addition, flowing liquids are sometimes carried in an open channel, in which case the volume flow rate can be measured by an open channel flow meter.

Variable Area Flow meters (Rotameters)

In the variable area flow meter (which is also sometimes known as a rotameter), the differential pressure across a variable aperture is used to adjust the area of the aperture. The aperture area is then a measure of the flow rate. The instrument is reliable, inexpensive, and used extensively throughout industry, accounting for about 20% of all flow meters sold. Normally, because this type of instrument only gives a visual indication of flow rate, it is of no use in automatic control schemes. However, special versions of variable area flow meters are now available that incorporate fiber optics. In these, a row of fibers detects the position of the float by sensing the reflection of light from it, and an electrical signal output can be derived from this.

In its simplest form, shown in Figure 9.2, the instrument consists of a tapered glass tube containing a float that takes up a stable position where its submerged weight is balanced by the up thrust due to the differential pressure across it. The position of the float is a measure of the effective annular area of the flow passage and hence of the flow rate. The inaccuracy of the least expensive instruments is typically ±5%, but more expensive versions offer measurement inaccuracies as low as±0.5%.

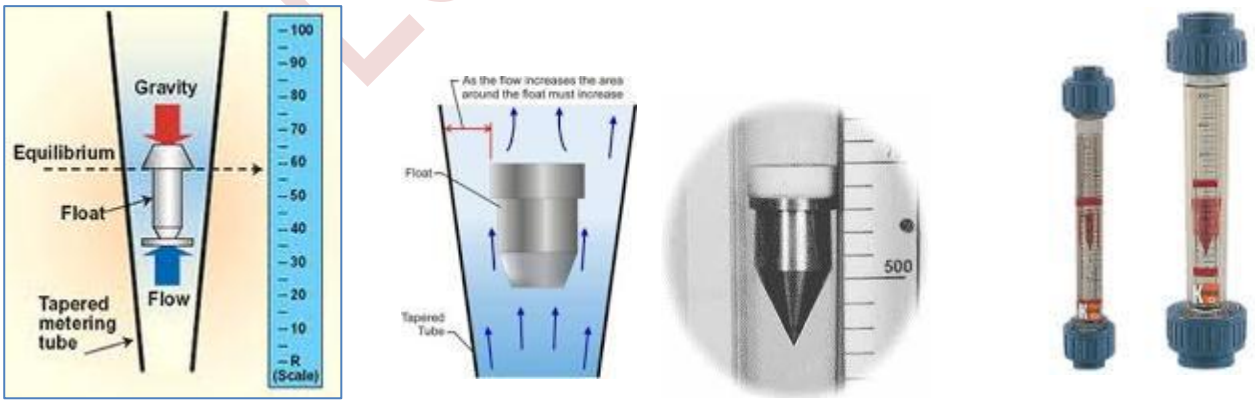


Figure 9.2

Differential Pressure (Obstruction-Type) Meters

Differential pressure meters involve the insertion of some device into a fluid-carrying pipe that causes an obstruction and creates a pressure difference on either side of the device. Such meters are sometimes known as obstruction-type meters or flow restriction meters. Devices used to obstruct the flow include the orifice plate, Venturi tube, flow nozzle, and Dall flow tube, as illustrated in Figure 9.3. When such a restriction is placed in a pipe, the velocity of the fluid through the restriction increases and the pressure decreases. The volume flow rate is then proportional to the square root of the pressure difference across the obstruction. The manner in which this pressure difference is measured is important. Measuring the two pressures with different instruments and calculating the difference between the two measurements is not satisfactory because of the large measurement error that can arise when the pressure difference is small. Therefore, the normal procedure is to use a differential pressure transducer, which is commonly a diaphragm-type device.

The Pitot static tube is another device that measures flow by creating a pressure difference within a fluid-carrying pipe. However, in this case, there is negligible obstruction of flow in the pipe. The Pitot tube is a very thin tube that obstructs only a small part of the flowing fluid and thus measures flow at a single point across the cross section of the pipe. This measurement only equates to average flow velocity in the pipe for the case of uniform flow. The an nubar is a type of multiport Pitot tube that measures the average flow across the cross section of the pipe by forming the mean value of several local flow measurements across the cross section of the pipe.

All applications of this method of flow measurement assume laminar flow by ensuring that the flow conditions upstream of the obstruction device are in steady state; a certain minimum length of straight run of pipe ahead of the flow measurement point is specified to achieve this. The minimum lengths required for various pipe diameters are specified in standards tables. However, a useful rule of thumb widely used in process industries is to specify a length of 10 times the pipe diameter. If physical restrictions make this impossible to achieve, special flow-smoothing vanes can be inserted immediately ahead of the measurement point.

Flow restriction-type instruments are popular because they have no moving parts and are therefore robust, reliable, and easy to maintain. However, one significant disadvantage of this method is that the obstruction causes a permanent loss of pressure in the flowing fluid. The magnitude and hence importance of this loss depend on the type of obstruction element used, but where the pressure loss is large, it is sometimes necessary to recover the lost pressure by an auxiliary pump further down the flow line. This class of device is not normally suitable for measuring the flow of slurries, as the tappings into the pipe to measure the differential pressure are prone to blockage, although the Venturi tube can be used to measure the flow of dilute slurries.

Figure 9.3

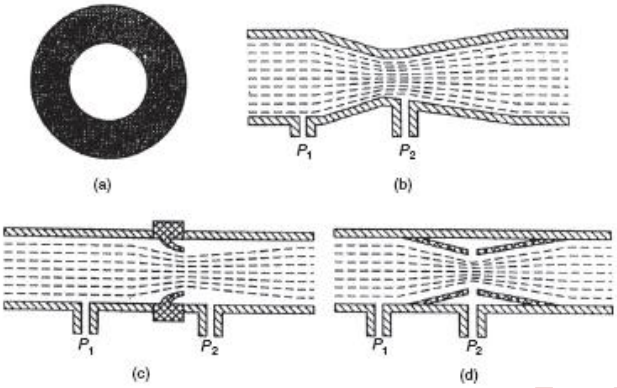
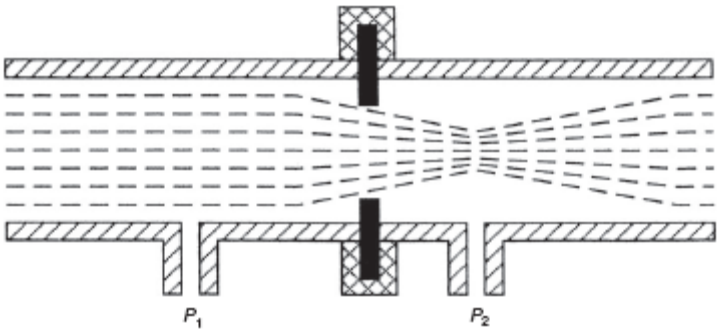


Figure 9.4 illustrates approximately the way in which the flow pattern is interrupted when an orifice plate is inserted into a pipe. Other obstruction devices also have a similar effect to this, although the magnitude of pressure loss is smaller. Of particular interest is the fact that the minimum cross-sectional area of flow occurs not within the obstruction but at a point downstream of there.

Figure 9.4



Orifice plate

The orifice plate is a metal disc with a concentric hole in it, which is inserted into the pipe carrying the flowing fluid. Orifice plates are simple, inexpensive, and available in a wide range of sizes. In consequence, they account for almost 50% of the instruments used in industry for measuring volume flow rate. One limitation of the orifice plate is that its inaccuracy is typically at least $\pm$2% and may approach$\pm$5%. Also, the permanent pressure loss caused in the measured fluid flow is between 50 and 90% of the magnitude of the pressure difference, (P1-P2). Other problems with the orifice plate are a gradual change in the discharge coefficient over a period of time as the sharp edges of the hole wear away and a tendency for any particles in the flowing fluid to stick behind the hole, thereby reducing its diameter gradually as the particles build up. The latter problem can be minimized by using an orifice plate with an eccentric hole. If this hole is close to the bottom of

the pipe, solids in the flowing fluid tend to be swept through, and buildup of particles behind the plate is minimized.

A very similar problem arises if there are any bubbles of vapor or gas in the flowing fluid when liquid flow is involved. These also tend to build up behind an orifice plate and distort the pattern of flow. This difficulty can be avoided by mounting the orifice plate in a vertical run of pipe.

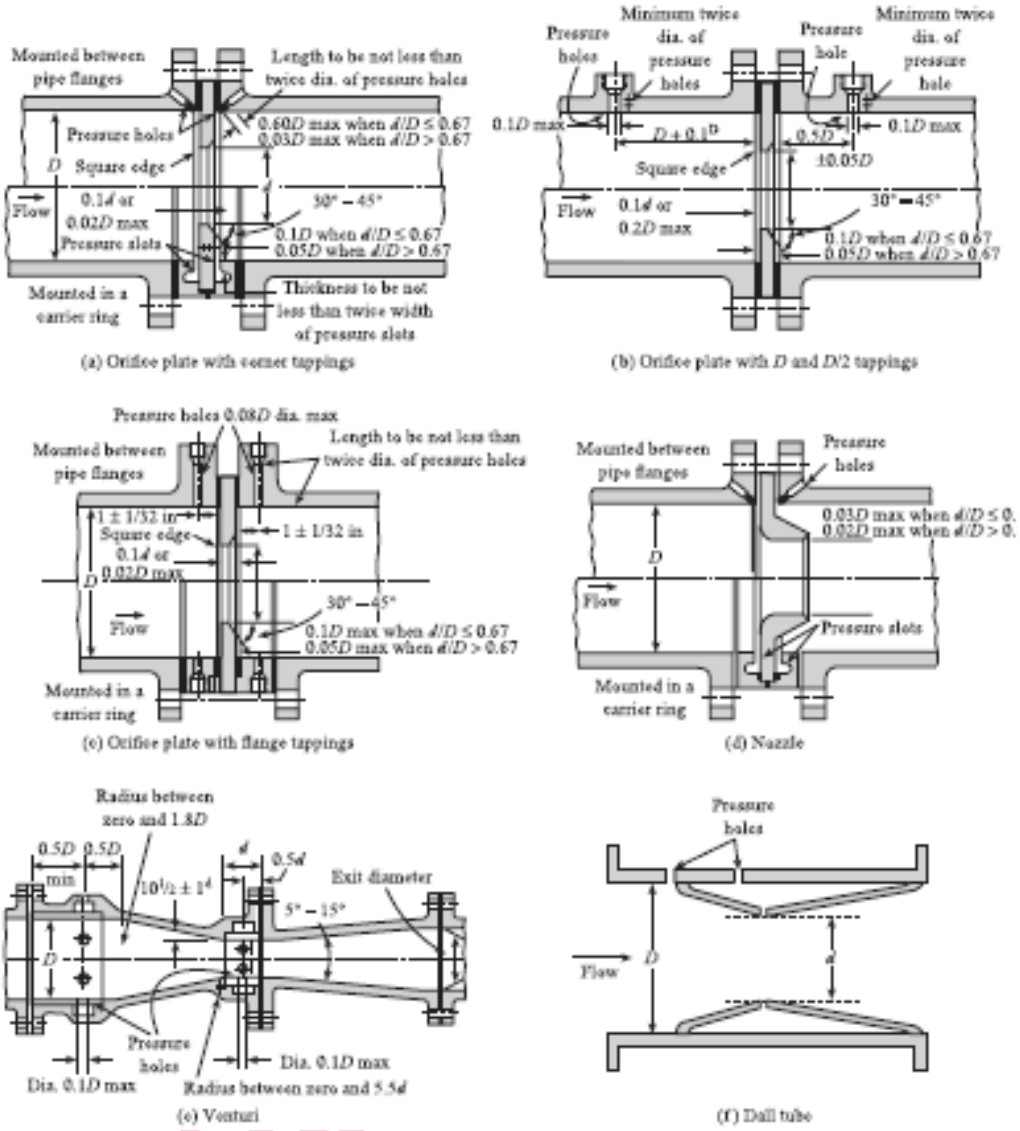
Venturis and similar devices

A number of obstruction devices are available that are specially designed to minimize pressure loss in the measured fluid. These have various names such as Venturi, flow nozzle, and Dall flow tube. They are all much more expensive than an orifice plate but have better performance. The smooth internal shape means that they are not prone to solid particles or bubbles of gas sticking in the obstruction, as is likely to happen in an orifice plate. The smooth shape also means that they suffer much less wear and, consequently, have a longer life than orifice plates. They also require less maintenance and give greater measurement accuracy.

Venturi: The Venturi has a precision-engineered tube of a special shape. This offers measurement uncertainty of only$\pm$1%. However, the complex machining required manufacturing it means that it is the most expensive of all the obstruction devices discussed. Permanent pressure loss in the measured system is 10-15% of the pressure difference (P1-P2) across it.

Dall flow tube: The Dall flow tube consists of two conical reducers inserted into a fluid carrying pipe. It has a very similar internal shape to the Venturi, except that it lacks a throat. This construction is much easier to manufacture, which gives the Dall flow tube an advantage in cost over the Venturi, although the typical measurement inaccuracy is a little higher ($\pm$1.5%). Another advantage of the Dall flow tube is its shorter length, which makes the engineering task of inserting it into the flow line easier. The Dall tube has one further operational advantage in that the permanent pressure loss imposed on the measured system is only about 5% of the measured pressure difference (P1-P2).

Flow nozzle: This nozzle is of simpler construction still and is therefore less expensive than either a Venturi or a Dall flow tube, but the pressure loss imposed on the flowing fluid is 30-50% of the measured pressure difference (P1-P2) across the nozzle.



Differential pressure flow meter according to British standard Institution.

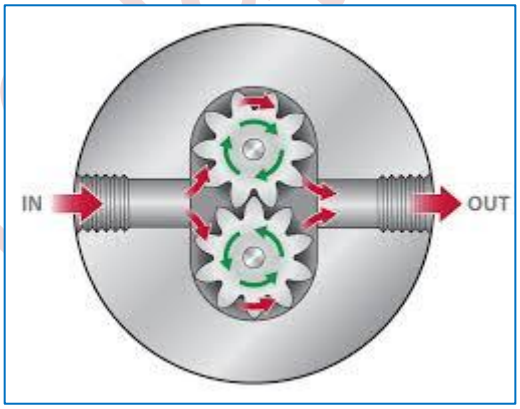
Pitot static tube

The Pitot static tube is used mainly for making temporary measurements of flow, although it is also used in some instances for permanent flow monitoring. It measures the local velocity of flow at a particular point within a pipe rather than the average flow velocity as measured by other types of flow meters. This may be very useful where there is a requirement to measure local flow rates across the cross section of a pipe in the case of non-uniform flow. Multiple Pitot tubes are normally used to do this.

Positive Displacement Flow meters

Positive displacement flow meters account for nearly 10% of the total number of flow meters used in industry and are used in large numbers for metering domestic gas and water consumption. The least expensive instruments have a typical inaccuracy of about $\pm$2%, but the inaccuracy in more expensive ones can be as low as $\pm$0.5%. These higher quality instruments are used extensively within the oil industry; as such applications can justify the high cost of such instruments.

All positive displacement meters operate using mechanical divisions to displace discrete volumes of fluid successively. While this principle of operation is common, many different mechanical arrangements exist for putting the principle into practice. However, all versions of positive displacement meters are low friction, low maintenance, and long life devices, although they do impose a small permanent pressure loss on the flowing fluid. Low friction is especially important when measuring gas flows, and meters with special mechanical arrangements to satisfy this requirement have been developed.



Turbine Meters

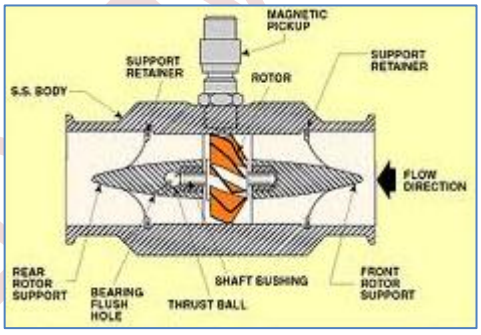
A turbine flow meter consists of a multi-bladed wheel mounted in a pipe along an axis parallel to the direction of fluid flow in the pipe, as shown in Figure 9.5. The flow of fluid past the wheel causes it to rotate at a rate proportional to the volume flow rate of the fluid. This rate of rotation has traditionally been measured by constructing the flow meter such that it behaves as a variable reluctance tachogenerator. This is achieved by

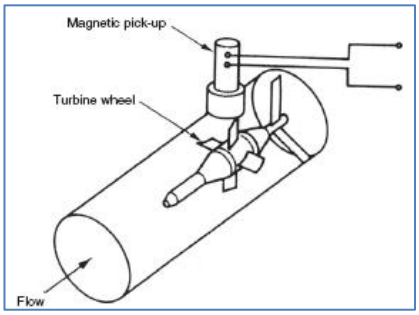
fabricating the turbine blades from a ferromagnetic material and placing a permanent magnet and coil inside the meter housing. A voltage pulse is induced in the coil as each blade on the turbine wheel moves past it, and if these pulses are measured by a pulse counter, the pulse frequency and hence flow rate can be deduced. In recent instruments, fiber optics are also now sometimes used to count the rotations by detecting reflections off the tip of the turbine blades.

Provided that the turbine wheel is mounted in low-friction bearings, measurement inaccuracy can be as low as ±0.2%. However, turbine flow meters are less rugged and reliable than flow restriction-type instruments and are affected badly by any particulate matter in the flowing fluid. Bearing wear is a particular problem, which also imposes a permanent pressure loss on the measured system. Turbine meters are particularly prone to large errors when there is any significant second phase in the fluid measured. For instance, using a turbine meter calibrated on pure liquid to measure a liquid containing 5% air produces a 50% measurement error. As an important application of the turbine meter is in the petrochemical industries, where gas/oil mixtures are common, special procedures are being developed to avoid such large measurement errors.

Turbine meters have a similar cost and market share to positive displacement meters and compete for many applications, particularly in the oil industry. Turbine meters are smaller and lighter than the latter and are preferred for low-viscosity, high-flow measurements. However, positive displacement meters are superior in conditions of high viscosity and low flow rate.

Figure 9.5



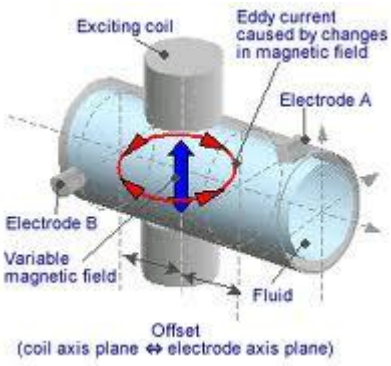


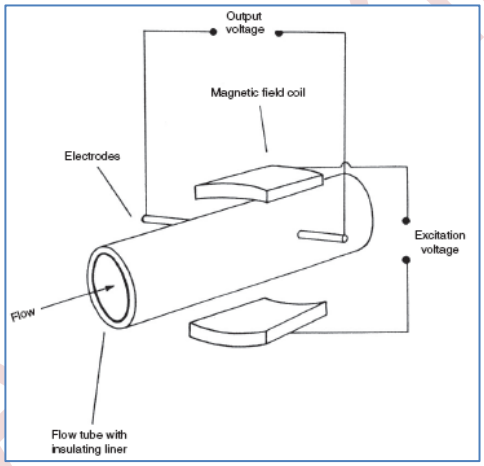
Electromagnetic Flow meters:

Electromagnetic flow meters, sometimes known just as magnetic flow meters, are limited to measuring the volume flow rate of electrically conductive fluids. A typical measurement inaccuracy of around ±1% is acceptable in many applications, but the instrument is expensive both in terms of the initial purchase cost and in running costs, mainly due to its electricity consumption. A further reason for its high cost is the need for careful calibration of each instrument individually during manufacture, as there is considerable variation in the properties of the magnetic materials used.

The instrument, shown in Figure 9.6, consists of a stainless-steel cylindrical tube fitted with an insulating liner, which carries the measured fluid. Typical lining materials used are neoprene, polytetrafluoroethylene, and polyurethane. A magnetic field is created in the tube by placing mains-energized field coils either side of it, and the voltage induced in the fluid is measured by two electrodes inserted into opposite sides of the tube. The ends of these electrodes are usually flush with the inner surface of the cylinder. The electrodes are constructed from a material that is unaffected by most types of flowing fluids, such as stainless steel, platinum–iridium alloys, Hastelloy, titanium, and tantalum. In the case of rare metals in this list, the electrodes account for a significant part of the total instrument cost.

Figure 9.6





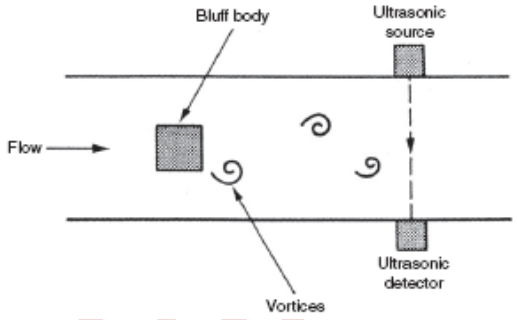
Vortex-Shedding Flow meters

The vortex-shedding flow meter is used as an alternative to traditional differential pressure meters in many applications. The operating principle of the instrument is based on the natural phenomenon of vortex shedding, created by placing an un stream lined obstacle (known as a bluff body) in a fluid-carrying pipe, as indicated in Figure 9.7. When fluid flows past the obstacle, boundary layers of viscous, slow-moving fluid are formed along the outer surface. Because the obstacle is not streamlined, the flow cannot follow the contours of the body on the downstream side, and the separate layers become detached and roll into eddies or vortices in the low-pressure region behind the obstacle. The shedding frequency of these alternately shed vortices is proportional to the fluid velocity past the body. Various thermal, magnetic, ultrasonic, and capacitive vortex detection techniques are employed in different instruments.

Such instruments have no moving parts, operate over a wide flow range, have low power consumption, require little maintenance, and have a similar cost to measurement using an orifice plate. They can measure both liquid and gas flows, and a common inaccuracy value quoted is $\pm$1% of full-scale reading, although this can

be seriously downgraded in the presence of flow disturbances upstream of the measurement point and a straight run of pipe before the measurement point of 50 pipe diameters is recommended. Another problem with the instrument is its susceptibility to pipe vibrations, although new designs are becoming available that have a better immunity to such vibrations.

Figure 9.7



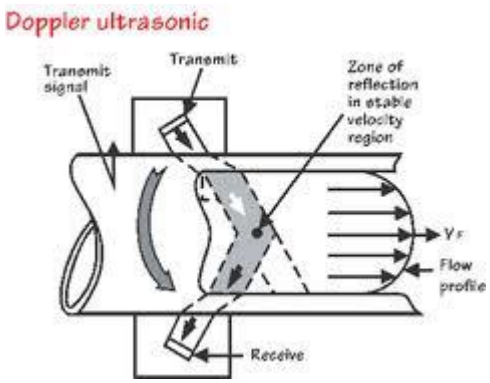
Ultrasonic Flow meters

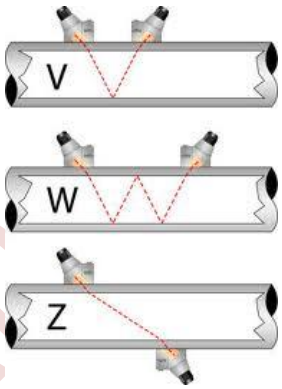
The ultrasonic technique of volume flow rate measurement is, like the magnetic flow meter as show in figure 9.8, a noninvasive method. It is not restricted to conductive fluids, however, and is particularly useful for measuring the flow of corrosive fluids and slurries. In addition to its high reliability and low maintenance requirements, a further advantage of an ultrasonic flow meter over an electromagnetic flow meter is that the instrument can be clamped externally onto existing pipework instead of being inserted as an integral part of the flow line. As the procedure of breaking into a pipeline to insert a flow meter can be as expensive as the cost of the flow meter itself, the ultrasonic flow meter has enormous cost advantages. Its clamp-on mode of operation also has significant safety advantages in avoiding the possibility of personnel installing flow meters coming into contact with hazardous fluids, such as poisonous, radioactive, flammable, or explosive ones. Also, any contamination of the fluid being measured (e.g., food substances and drugs) is avoided. Ultrasonic meters are still less common than differential pressure or electromagnetic flow meters, although usage continues to expand year by year.

Two different types of ultrasonic flow meter exist that employ distinct technologies—one based on Doppler shift and the other on trans it time. In the past, the existence of these alternative technologies has not always been readily understood and has resulted in ultrasonic technology being rejected entirely when one of these two forms has been found to be unsatisfactory in a particular application.

This is unfortunate because the two technologies have distinct characteristics and areas of application, and many situations exist where one form is very suitable and the other is not. To reject both, having only tried out one, is therefore a serious mistake. Ultrasonic flow meters have become available that combine both Doppler shift and transit time technologies. Particular care has to be taken to ensure a stable flow profile in ultrasonic flow meter applications.

It is usual to increase the normal specification of the minimum length of straight pipe run prior to the point of measurement, expressed as a number of pipe diameters, from a value of 10 up to 20 or, in some cases, even 50 diameters. Analysis of the reasons for poor performance in many instances of ultrasonic flow meter application has shown failure to meet this stable flow profile requirement to be a significant factor. figure 8.8





Choice between Flow meters for Particular Applications

The number of relevant factors to be considered when specifying a flow meter for a particular application is very large. These include the temperature and pressure of the fluid, its density, viscosity, chemical properties and abrasiveness, whether it contains particles, whether it is a liquid or gas, etc. This narrows the field to a subset of instruments that are physically capable of making the measurement. Next, the required performance factors of accuracy, range ability, acceptable pressure drop, output signal characteristics, reliability, and service life must be considered. Accuracy requirements vary widely across different applications, with measurement uncertainty of $\pm$5% being acceptable in some and less than $\pm$0.5% being demanded in others. Finally, economic viability must be assessed, which must take into account not only the purchase cost, but also reliability, installation difficulties, maintenance requirements, and service life.

Where only a visual indication of flow rate is needed, the variable area meter is popular. Where a flow measurement in the form of an electrical signal is required, the choice of available instruments is very large. The orifice plate is used extremely commonly for such purposes and accounts for almost 50% of instruments currently in use in industry. Other forms of differential pressure meters and electromagnetic flow meters are used in significant numbers. Currently, there is a trend away from rotating devices, such as turbine meters and positive displacement meters. At the same time, usage of ultrasonic and vortex meters is expanding.

Calibration of Flow meters

The first consideration in choosing a suitable way to calibrate flow-measuring instruments is to establish exactly what accuracy level is needed so that the calibration system instituted does not cost more than necessary. In some cases, such as handling valuable fluids or where there are legal requirements as in petrol pumps, high accuracy levels (e.g., error $\pm 0.1\%$) are necessary and the expensive procedures necessary to achieve these levels are justified. However, in other situations, such as in measuring additives to the main stream in a process plant, only low levels of accuracy are needed (e.g., error $\pm 5\%$ is acceptable) and relatively inexpensive calibration procedures are sufficient.

The accuracy of flow measurement is affected greatly by the flow conditions and characteristics of the flowing fluid. Therefore, wherever possible, process flow-measuring instruments are calibrated on-site in their normal measuring position. This ensures that calibration is performed in the actual flow conditions, which are difficult or impossible to reproduce exactly in a laboratory. To ensure the validity of such calibration, it is also normal practice to repeat flow calibration checks until the same reading is obtained in two consecutive tests. However, it has been suggested that even these precautions are inadequate and that statistical procedures are needed.

If on-site calibration is not feasible or is not accurate enough, the only alternative is to send the instrument away for calibration using special equipment provided by instrument manufacturers or other specialist calibration companies. However, this is usually an expensive option. Furthermore, the calibration facility does not replicate the normal operating conditions of the meter tested, and appropriate compensation for differences between calibration conditions and normal use conditions must be applied.

The equipment and procedures used for calibration depend on whether mass, liquid, or gaseous flows are being measured. Therefore, separate sections are devoted to each of these cases. It must also be stressed that all calibration procedures mentioned in the following paragraphs in respect to fluid flow only refer to flows of single phase fluids (i.e., liquids or gases).

Where a second or third phase is present, calibration is much more difficult and specialist advice should be sought from the manufacturer of the instrument used for measurement.

Calibration Equipment and Procedures for Mass Flow-Measuring Instruments

Where the conveyor method is used for measuring the mass flow of solids in the form of particles or powders, both mass-measuring and velocity-measuring instruments are involved. In the case of Coriolis and thermal mass flow meters, the usual method of calibrating these while in situ in their normal measurement position is to provide a diversion valve after the meter. During calibration procedures, the valve is opened for a measured time period to allow some of the fluid to flow into a container that is subsequently weighed. Alternatively, the meter can be removed for calibration using special test rigs normally provided by the instrument manufacturer.

Calibration Equipment and Procedures for Instruments Measuring Volume Flow Rate of Liquids:

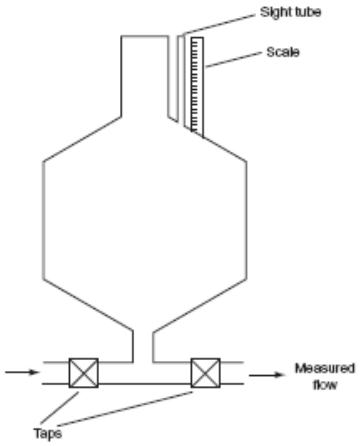
Calibrated tank

Probably the simplest piece of equipment available for calibrating instruments measuring liquid flow rates is the calibrated tank. This consists of a cylindrical vessel, as shown in Figure 9.9, with conical ends that facilitate draining and cleaning of the tank. A sight tube with a graduated scale is placed alongside the final, upper, cylindrical part of the tank, which allows the volume of liquid in the tank to be measured accurately. Flow rate calibration is performed by measuring the time taken, starting from an empty tank, for a given volume of liquid to flow into the vessel.

Because the calibration procedure starts and ends in zero flow conditions, it is not suitable for calibrating instruments affected by flow acceleration and deceleration characteristics. This therefore excludes instruments such as differential pressure meters (orifice plate, flow nozzle, Venturi, Dall flow tube, Pitot tube), turbine flow meters, and vortex-shedding flow meters.

The technique is further limited to the calibration of low-viscosity liquid flows, although lining the tank with an epoxy coating can allow the system to cope with somewhat higher viscosities. The limiting factor in this case is the drainage characteristics of the tank, which must be such that the residue liquid left after draining has an insufficient volume to affect the accuracy of the next calibration.

Figure 9.9



Orifice plate

A flow line equipped with a certified orifice plate is sometimes used as a reference standard in flow calibration, especially for high flow rates through large-bore pipes. While measurement uncertainty is of the order of±1% at best, this is adequate for calibrating many flow-measuring instruments.

Turbine meter

Turbine meters are also used as a reference standard for testing flow meters. Their main application, as for orifice plates, is in calibrating high flow rates through large-bore pipes. Measurement uncertainty down to ±0.2% is attainable.