



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 $1.0132 \times 10^5 \text{ N.m}^{-2}$ (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 $1.0132 \times 10^5 \text{ N.m}^{-2}$. 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 Alexandria 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 expanded 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.

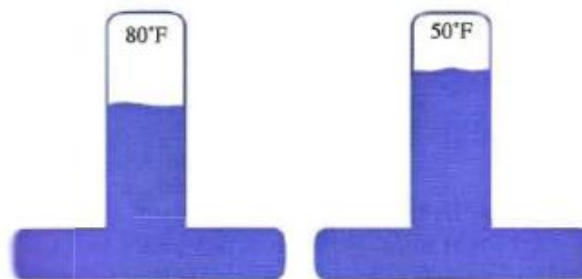


Figure 6.1

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.

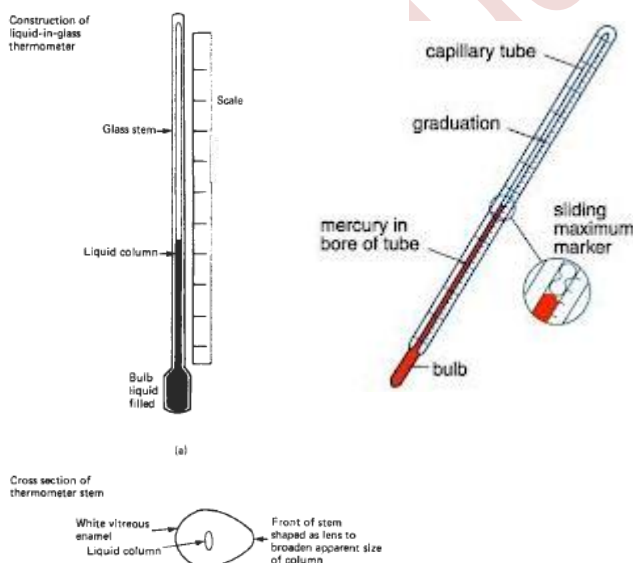


Figure 6.3 Mercury-in-glass thermometer. (a) thermometer and scale, (b) cross-section of thermometer stem.

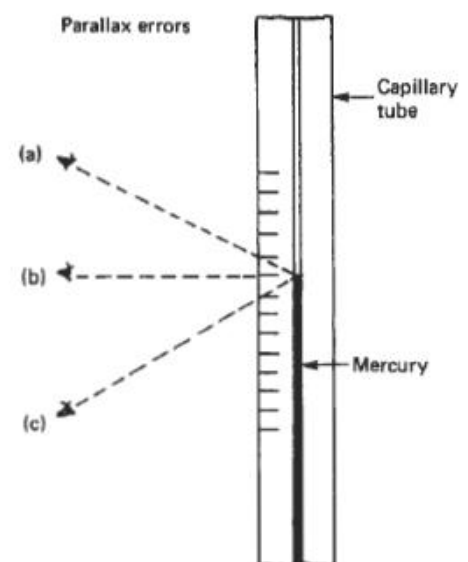


Figure 6.4 Parallax errors when reading glass thermometer.

- **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 mark 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°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

<i>Liquid</i>	<i>Temperature range (°C)</i>
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 °C and 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

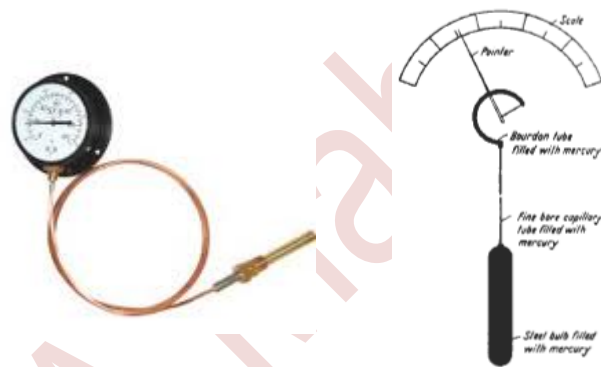
- Mercury-in-steel thermometer

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.

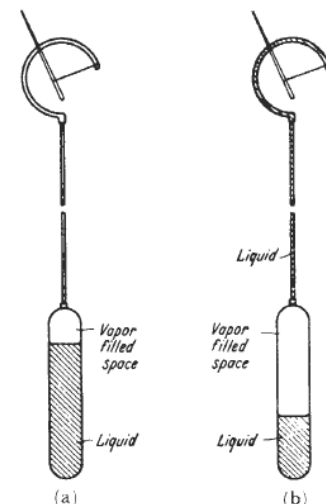


Figure 6.6 saturated vapor pressure thermometer.

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. Day-to-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	$\pm \frac{1}{2} \%$ of range to 320 °C $\pm \%$ of range above 320°C.	$\pm 1 \%$ of differential rage of the instrument if the temperature of the capillary and Bourdon tube does not vary too much.	$\pm 1 \%$ 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.

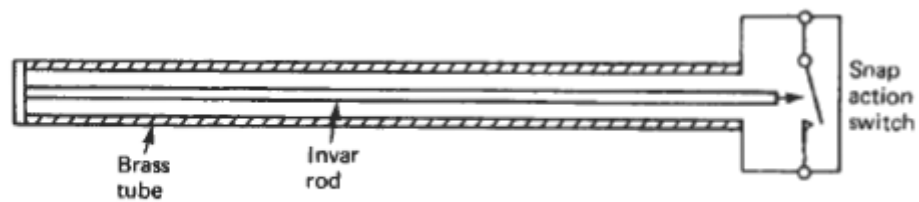


Figure 6.7 Rod thermostat.

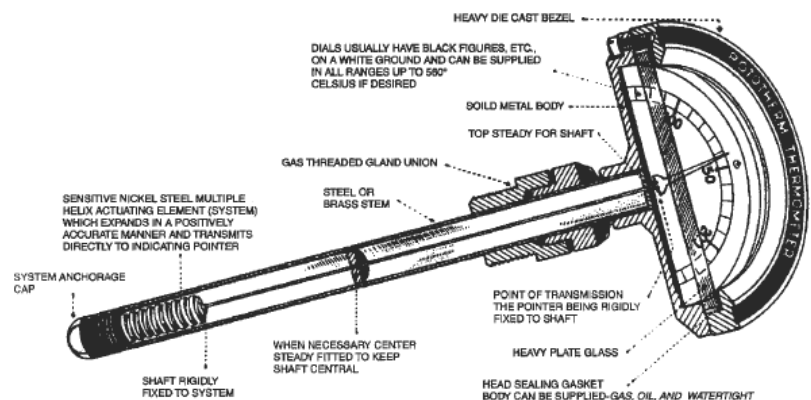


Figure 6.8 Dial thermometer.

- 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.

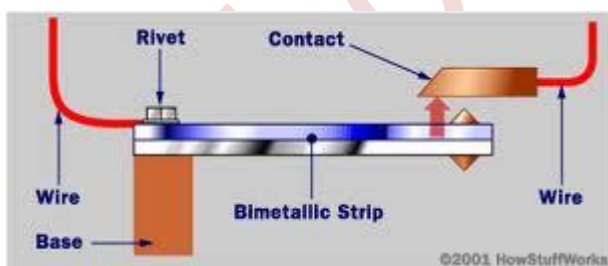


Figure 6.9 Action of bimetal strip

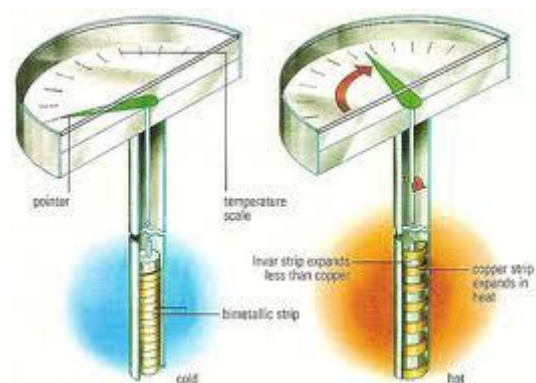


figure 6.10 helical bimetal strip.

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 $+300^{\circ}\text{C}$. 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.

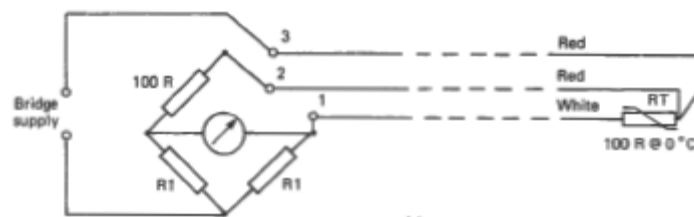


Figure 6.11 Connections for compensation of resistance thermometer leads.

These devices are manufactured to fine tolerances and are interchangeable with an error of less than ± 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.

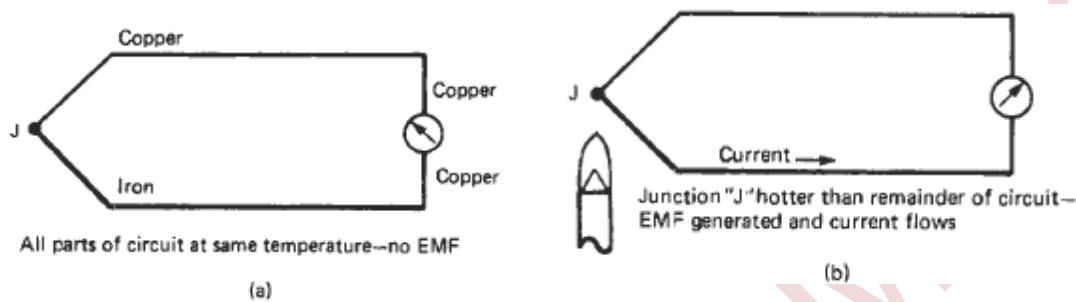


Figure 6.12 Basic thermocouple circuit.

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.**

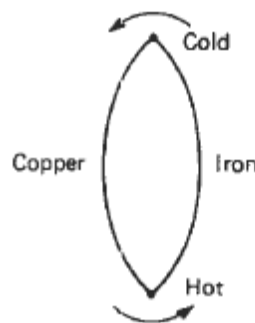


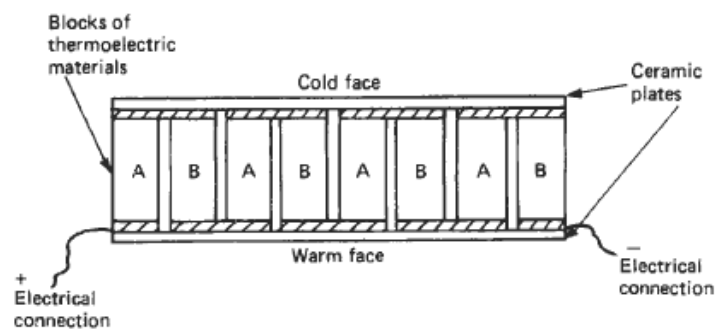
Figure 6.13 simple thermocouple.

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.

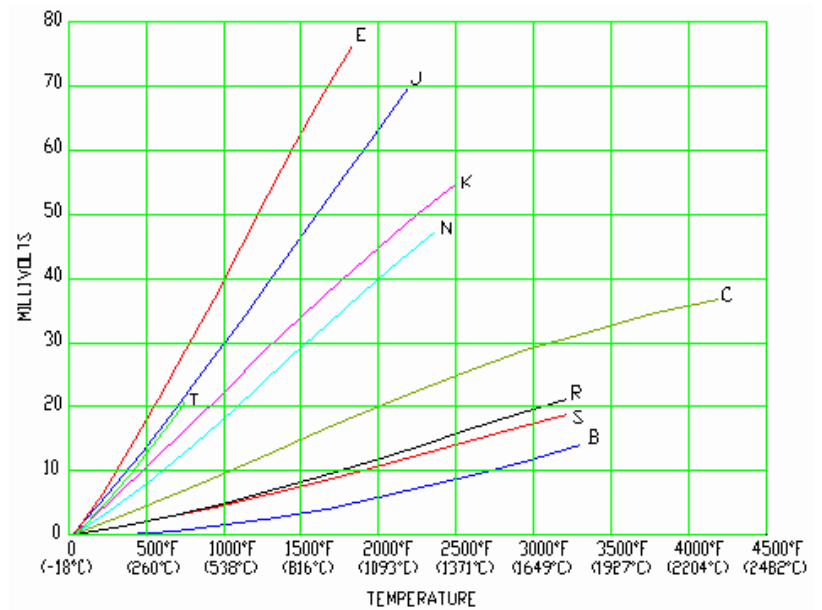
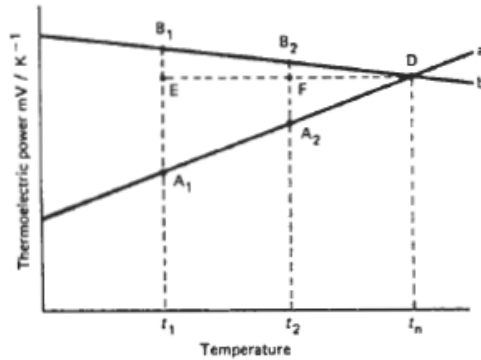


Figure 6.15 behaviour of the pair metal of thermocouple Figure 5.16 behaviour of the pair metal of thermocouples

Thermocouple connecting diagram:

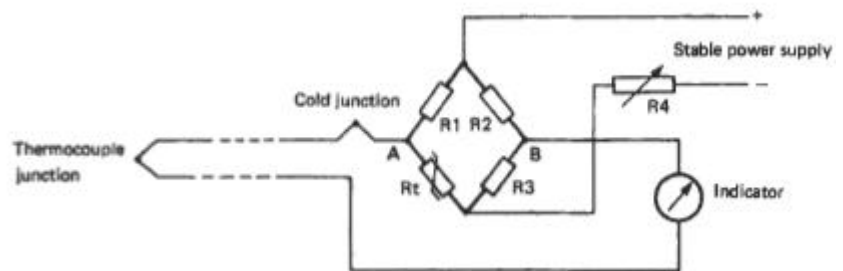


Figure 6.17 show the electric connection diagram for the thermocouples.

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 $\pm 3^{\circ}\text{C}$	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 $\pm 3^{\circ}\text{C}$ 333 to 900°C $\pm 0.75\%$	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 $\pm 2.5^{\circ}\text{C}$ 300 to 750°C $\pm 0.75\%$	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 $\pm 2.5^{\circ}\text{C}$ 333 to 1200°C $\pm 0.75\%$	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 $\pm 2.5^{\circ}\text{C}$ 333 to 1200°C $\pm 0.75\%$	2.774mV at 100°C	0-1100°C (-270°C to +1300°C). Alternative to type K.
R	Platinum: 13% Rhodium/platinum	Part 2: 1973 (1981)	0 to 600°C $\pm 1.5^{\circ}\text{C}$ 600 to 1600°C $\pm 0.25\%$	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 to 600°C $\pm 1.5^{\circ}\text{C}$ 600 to 1600°C $\pm 0.25\%$	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 $\pm 1^{\circ}\text{C}$	4.277mV at 100°C	-250 to 400°C (500°C). High resistance to corrosion by water.

Recommended colors of thermocouples wire:

	United States Color Codes  ANSI MC96.1 1982		IEC 60584-3 Color Coding 		Redundant national color coding for insulation of thermocouple cables			
	Thermocouple Grade	Extension Grade	Thermocouple Grade	Intrinsically Safe	British to BS1843 	German to DIN 13711 	French to NFC 42324 	Japanese to JIS C 1610-1981 
Type K Thermocouple	KK 	KX 						
Type T Thermocouple	TT 	TX 						
Type J Thermocouple	JJ 	JX 						
Type N Thermocouple	NN 	NX 						
Type E Thermocouple	EE 	EX 						
Type S Thermocouple	None Established	SX 						
Type R Thermocouple	None Established	RX 						
Type B Thermocouple	None Established	BX 						

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:

- Water path calibration instrumentation**
- 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 diagonal 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.

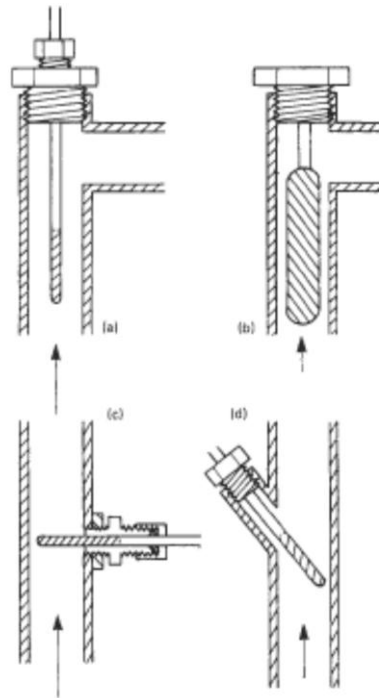
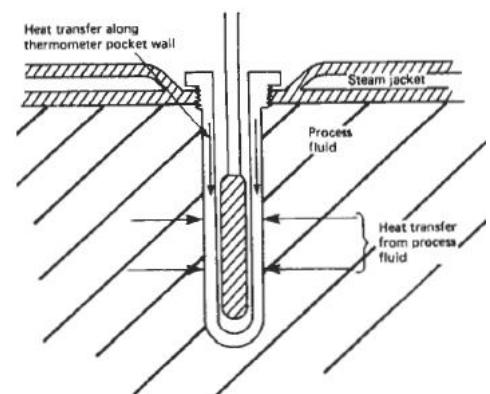


Figure 6.18 probe in pipe

- **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/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 ρ 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 + $h\rho$

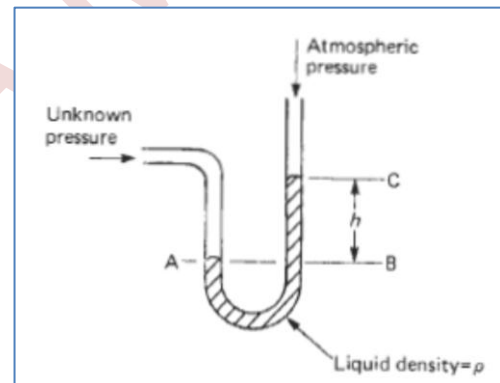
If the liquid is water the unit of measure is mmH₂O, and if the liquid is mercury then the unit of measure is mmHg. The corresponding SI unit is the Pascal and

$$1 \text{ mmH}_2\text{O} = 9.80665 \text{ Pa}$$

$$1 \text{ mmHg} = 133.322 \text{ Pa}$$

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.

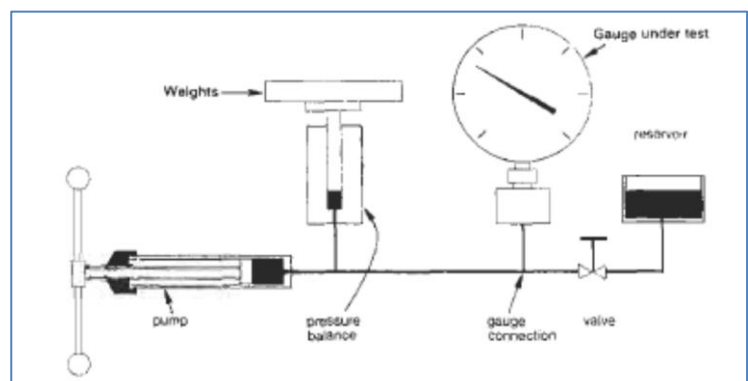


Pressure measurements by allowing the unknown pressure to act on a known area and measuring the resultant force:

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.



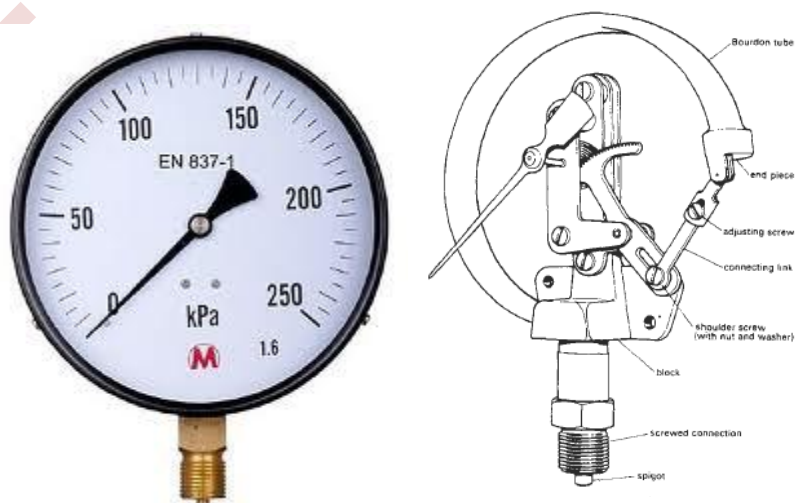
Pressure measurement by allowing the unknown pressure to act on a flexible member and measuring the resultant motion:

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 and helical Bourdon tubes

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.

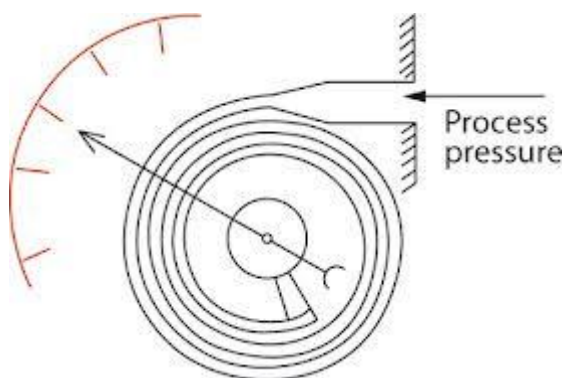


Figure 7.4 spiral gauge

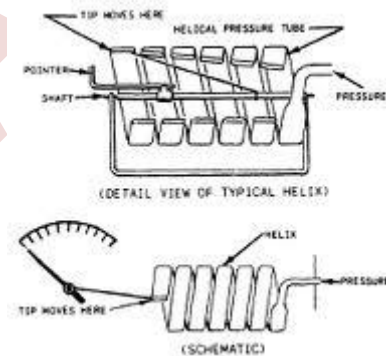


Figure 7.5 Helical gauge

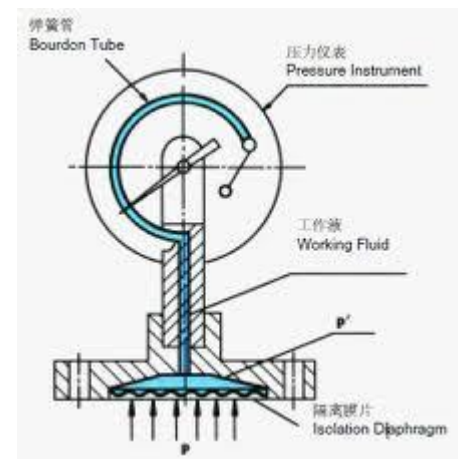
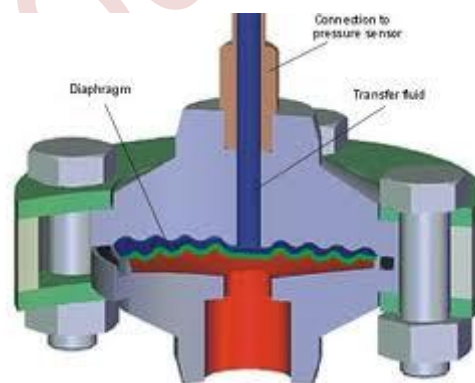
Diaphragm pressure elements:

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

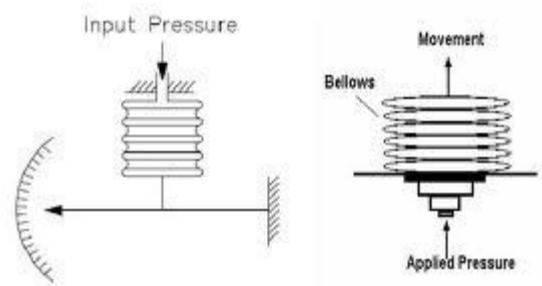


Bellows elements:

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 $\pm 0.5\%$, 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

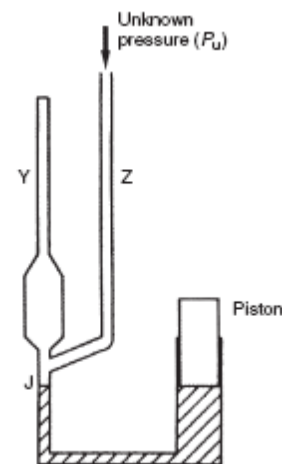


Low pressure range elements (vacuum)

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 P_u 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 P_u and is contained in a known volume, V_u . 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 $\pm 1\%$, 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.

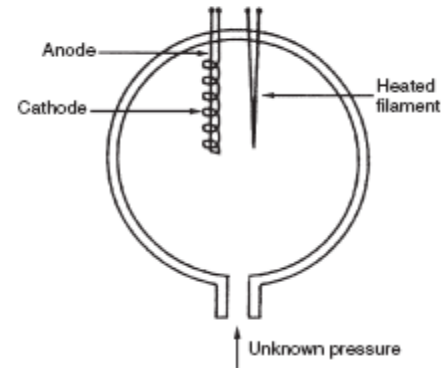


Figure 7.9

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.

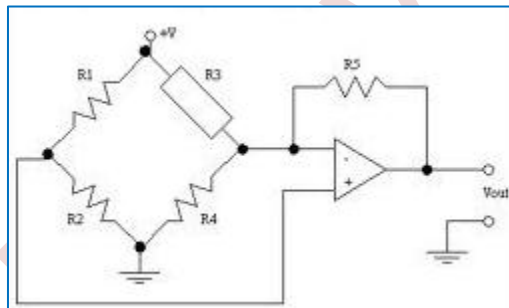


Figure 7.10



Bourbon gauge:



Electronic Pressure Gauges

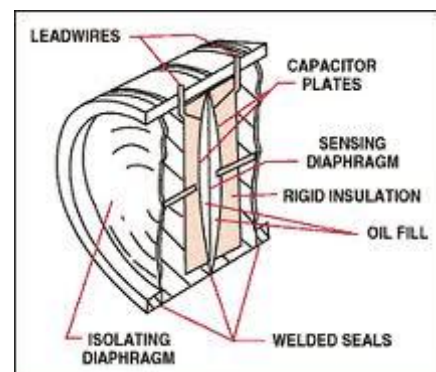
This section is included because many instrument manufacturers' catalogues have a section entitled "electronic pressure gauges." However, in reality, electronic pressure gauges are merely special forms of the pressure gauges described earlier in which electronic techniques are applied to improve performance.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

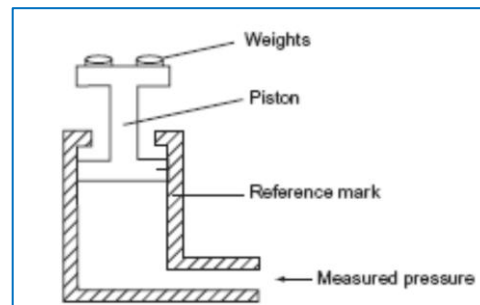
Reference Calibration Instruments

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 $\pm 0.01\%$. 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 $\pm 0.001\%$ 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

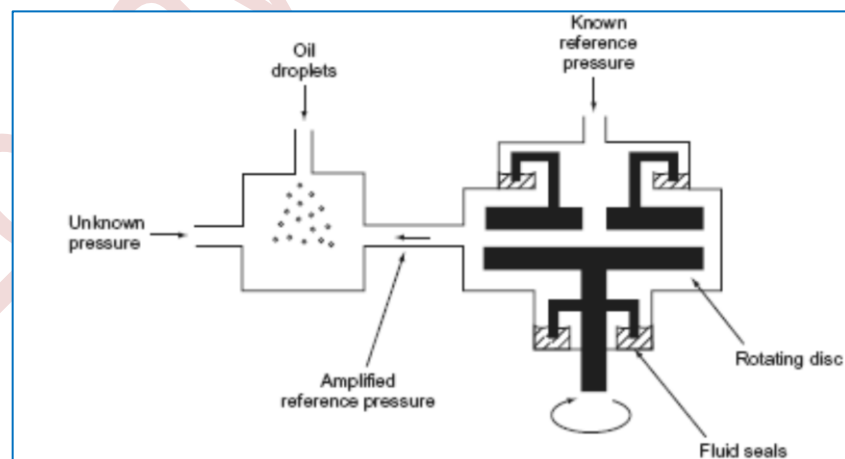
An ionization gauge is used to calibrate instruments measuring very low pressures in the range 10^{-13} to 10^{-3} bar. It has the advantage of having a straight-line relationship between output reading and pressure.

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 $\pm 0.025\%$ 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.

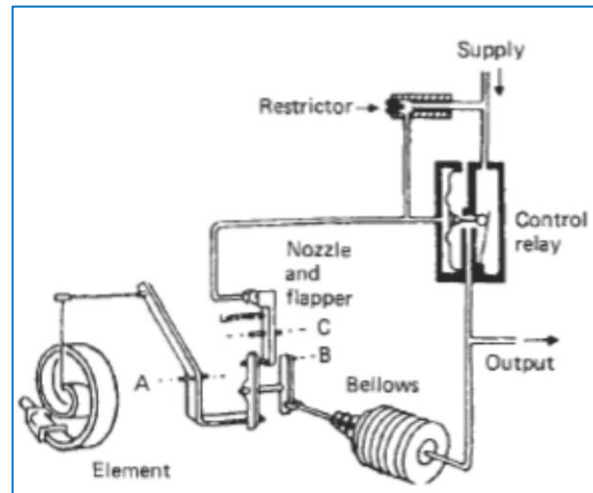
The growth in digital computers and control systems has generated a need for intelligent, digital output pressure transmitters. Since 1994, many pressure transmitters have been installed that use for their primary means of communication some form of digital fieldbus, such as Provisus or Foundation Fieldbus. 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

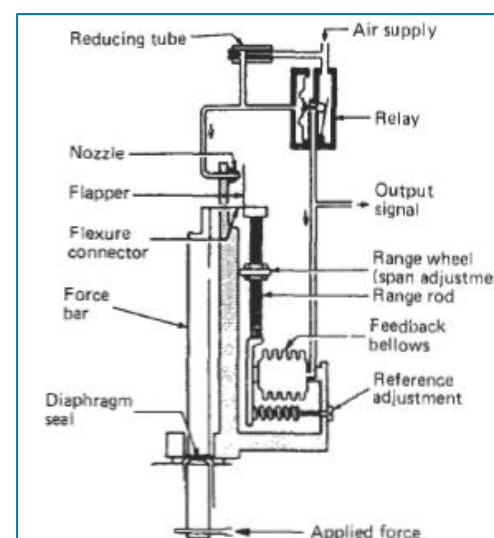


Pneumatic force-balance pressure transmitters

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-balance 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:

