CHAPTER

11 Pressure Measurement

LEARNING OBJECTIVES

After learning this chapter, the reader should be able to

LO 1: Define pressure and the terms gauge pressure and absolute pressure

LO 2: Describe moderate pressure measurements with manometers and elastic elements

LO 3: Describe high pressure measurement Bridgeman gauge

LO 4: Discuss various types of low pressure (vacuum) measuring devices

LO 5: Explain the calibration and testing of pressure measuring devices

LO 6: Explain the pressure measuring range of various pressure and vacuum gauges.

INTRODUCTION LO 1

Pressure means force per unit area, exerted by a fluid on the surface of the container. Absolute pressure means the fluid pressure above the reference value of a perfect vacuum or the absolute zero pressure. Gauge pressure represents the value of pressure above the reference value of atmospheric pressure. It is the difference between the absolute and local atmospheric pressures. The atmospheric pressure, at sea level, is nearly 14.7 lb/in^2. (psi) or 1.013×10^5 N/m^2 (Pa) or 1.013 bar (1 bar = 10^5 N/m^2) or 760 mm of Hg. Figure 11.1 shows the various terms used to express pressure. Vacuum represents the amount by which the atmospheric pressure exceeds the absolute pressure. Thus, from Fig. 11.1, it can be seen that the *gauge pressure*, $(p_1)_{gauge}$ corresponding to absolute pressure $p_1 = (p_1 - p_{atm})$ and *vacuum pressure*, $(p_2)_{gauge}$ corresponding to absolute pressure $p_2 = (p_2 - p_{atm})$.

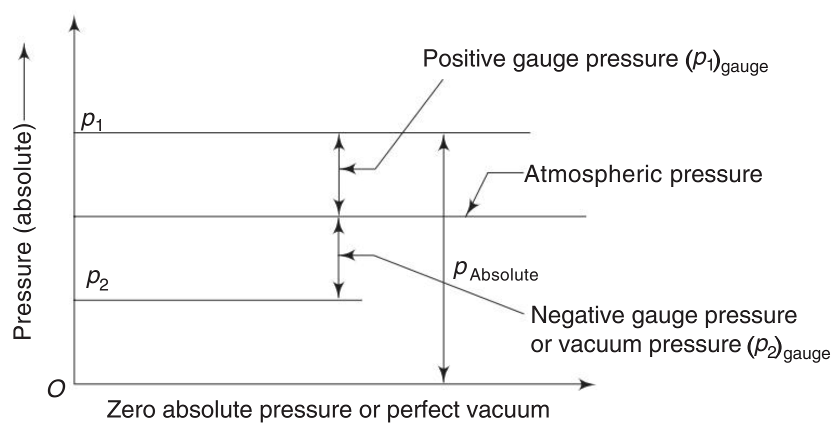

Fig. 11.1 Pressure diagram indicating various pressure terms

The techniques for pressure measurements are quite varied, depending on whether the pressure is moderate, very high or very low and also whether it is static or dynamic. Pressures higher than 1000 atm are usually regarded as very high while those of the order of 1 mm of Hg or below are regarded as very low.

For dynamic pressure measurements, like those in reciprocating compressors or engines, it is usual to convert it into displacement by an elastic element and then use one of the electromechanical transducers for an electrical output. The accuracy of measurements, in the case of dynamic pressures, is influenced by the characteristics of the elastic elements, the electromechanical transducer as well as those of the fluid.

11.1 MODERATE PRESSURE MEASUREMENT TECHNIQUES LO 2

Essentially, there are two types of devices, which can be included in this category:

1. Manometers, and
2. Others using elastic elements.

Manometers are meant for measuring static pressures, while devices using elastic elements may be used for both static and dynamic measurements.

11.1.1 Manometers

A manometer is the simplest device for measuring static pressure. A simple U-tube manometer (Fig. 11.2) uses water, mercury or any other suitable fluid. The difference in levels h between the two limbs is an indication of the pressure difference $(p_1 - p_2)$ between the two limbs. If one of the pressures, say that applied to limb 2, is atmospheric, the difference gives the gauge pressure applied to limb 1.

$$h = (p_1 - p_2)/(\rho g) \tag{11.1}$$

ρ being the mass density of the liquid used in the manometer.

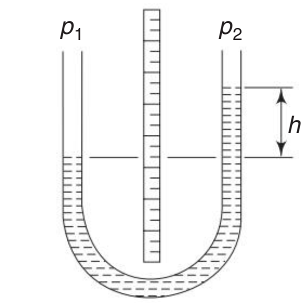

Fig. 11.2 U-tube manometer

The desirable characteristics of a manometer fluid are:

1. It should be non-corrosive and not have any chemical reaction with the fluid whose pressure is being measured.
2. It should have low viscosity and thus ensures quick adjustment with pressure change.
3. It should have negligible surface tension and capillary effects.

Several types of modified manometers are available which have the advantages of ease in use and high sensitivity.

One such device that is convenient to use is the *cistern* or *well type manometer*, shown in Fig. 11.3. In this type, the well area is large compared to that of the tube. Thus, only a single leg reading may be noted and the change in level in the well may be ignored. If p_1 and p_2 are absolute pressures applied as shown, force equilibrium gives:

$$p_1 A - p_2 A = Ah\rho g$$

ρ being mass density of the liquid.

$$\frac{p_1 - p_2}{\rho g} = h$$

If p_2 is atmospheric, h is a measure of the gauge pressure applied at the well.

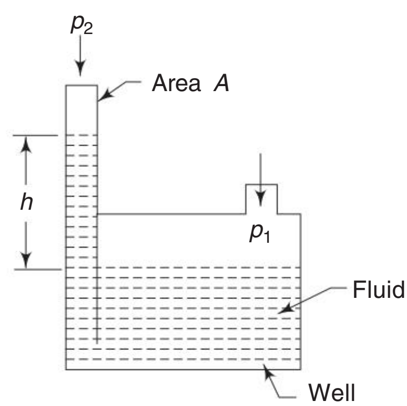

Fig. 11.3 Cistern or well type manometer

An *inclined tube manometer* (Fig. 11.4) is another device, which is sensitive and convenient to use. In such a manometer, the length l along the inclined tube is read as a measure of the pressure difference $(p_1 - p_2)$. The relation between $(p_1 - p_2)$ and l is derived as follows:

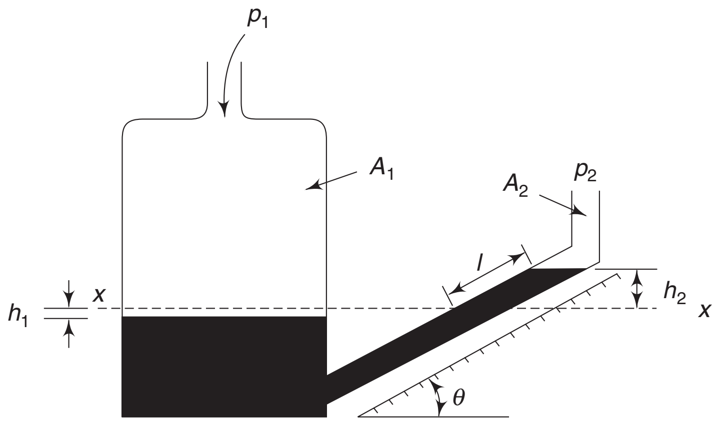

Fig. 11.4 Inclined tube manometer

When pressures in the two limbs are the same, the levels of the liquid are at equilibrium position xx. On application of pressures p_1 and p_2, difference in levels between the two limbs is

$$h_1 + h_2 = \frac{p_1 - p_2}{\rho g} \tag{11.2}$$

If A_1 and A_2 are the respective areas of the two limbs,

$$A_1 h_1 = A_2 l \tag{11.3}$$

$$h_2 = l \sin \theta \tag{11.4}$$

From Eqs. (11.2)–(11.4), we get

$$p_1 - p_2 = \rho g l \left(\frac{A_2}{A_1} + \sin \theta \right) \tag{11.5}$$

If $A_1 \gg A_2$ or A_2/A_1 is negligible,

$$p_1 - p_2 = \rho g l \sin \theta = \rho g h_2 \tag{11.6}$$

If $\theta = 30°$, $l = 2h_2$ and thus it would be more accurate to read l rather than h_2 as the output. Since $A_1 \gg A_2$, the reading on one side only, viz. l is required.

For increased accuracy in reading the output of the manometer, i.e., liquid displacements, can be measured with micrometer heads (Fig. 11.5). The contact between the micrometer movable points and the liquid may be sensed electrically or visually.

In order to minimise capillary and meniscus errors, the meniscus is returned to a reference position marked on the inclined transparent portion of the manometer tube (Fig. 11.6). This is done by a motorised screw (Fig. 11.7), whose rotation is converted to a digital read-out. This type of manometer is quite sensitive, accurate and easy to use.

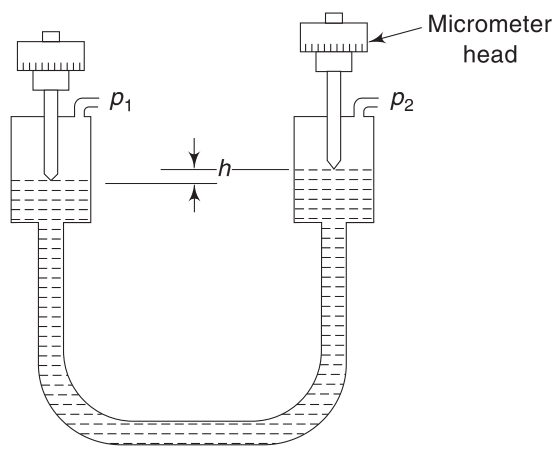

Fig. 11.5 Micrometer type manometer

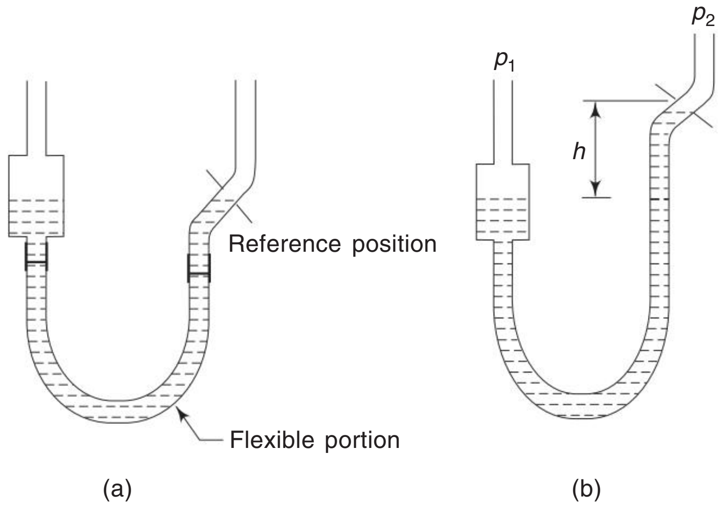

Fig. 11.6 Movable tube type micromanometer

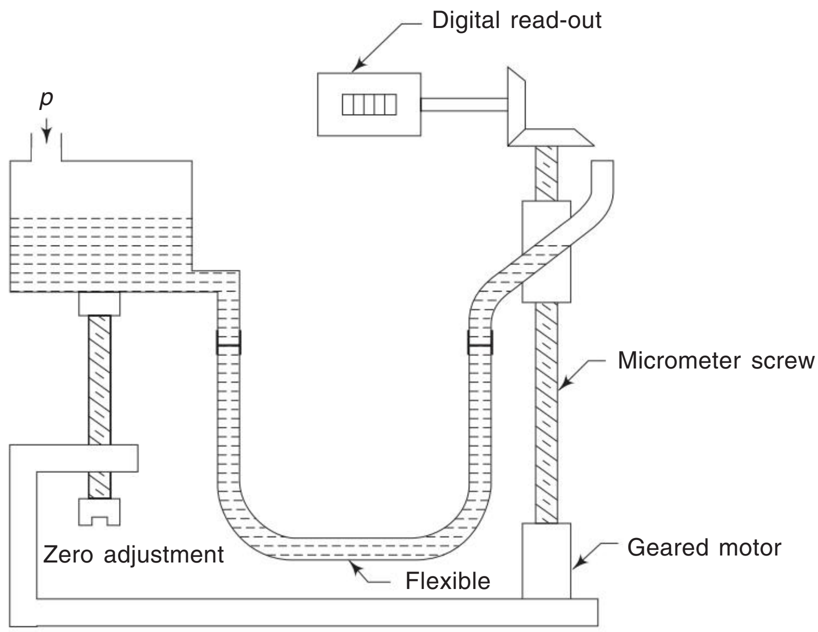

Fig. 11.7 Micromanometer with motor drive and digital read-out

Under dynamic conditions, manometers can be modelled as second order systems as discussed in Chapter 3. These are, however, used for static measurements as the dynamic response is not satisfactory due to, the inertia of the liquid.

Problem 11.1 A mercury manometer of the type shown in Fig. 11.8 is to have a float in the left-hand chamber. An electromechanical transducer is used to measure the motion of the fluid. The float motion is 5 mm for a gauge pressure of 50 kN/m^2. If the diameter of the float chamber is 40 mm, find the required diameter for the right-hand chamber. For mercury, density ρ = 13600 kg/m^3. Assume that the other end of the manometer is open to the atmosphere.

Solution If due to pressure differential Δp, the displacements from equilibrium position in the two chambers are y_1 and y_2

$$y_1 A_1 = y_2 A_2 \qquad (11.7)$$

where A_1 and A_2 are the respective chamber areas. Also,

$$\Delta p = \rho g(y_1 + y_2) \qquad (11.8)$$

Substituting

$$A_1 = \frac{\pi}{4}\,(0.04)^2 \text{ m}^2$$

$$y_1 = 0.005 \text{ m}$$

$$\Delta p = 50\,000 \text{ Pa}$$

and ρ = 13600 kg/m^3, we get from Eqs. (11.7) and (11.8)

$$A_2 = 1.7 \times 10^{-5} \text{ m}^2$$

which gives a diameter 4.65 mm for the right-hand chamber.

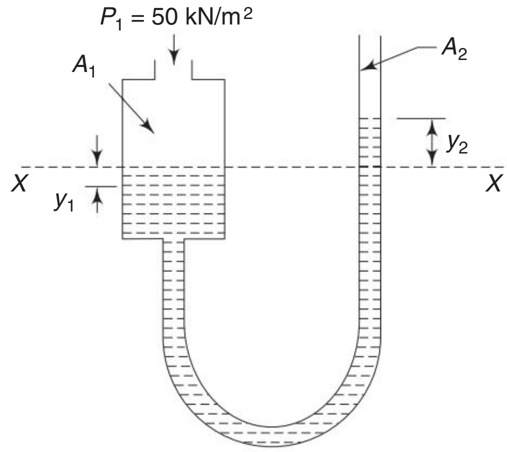

Fig. 11.8 Figure for Problem 11.1

11.1.2 Elastic Transducers

Elastic elements, when subjected to pressure, get deformed. The deformation, when measured, gives an indication of the pressure. These elements may be in the form of diaphragms, capsules, bellows, Bourdon or helical tubes (Fig. 11.9). The deformation may be measured by mechanical or electrical means. These devices are convenient to use and can cover a wide range of pressures, depending on the design of the elastic elements.

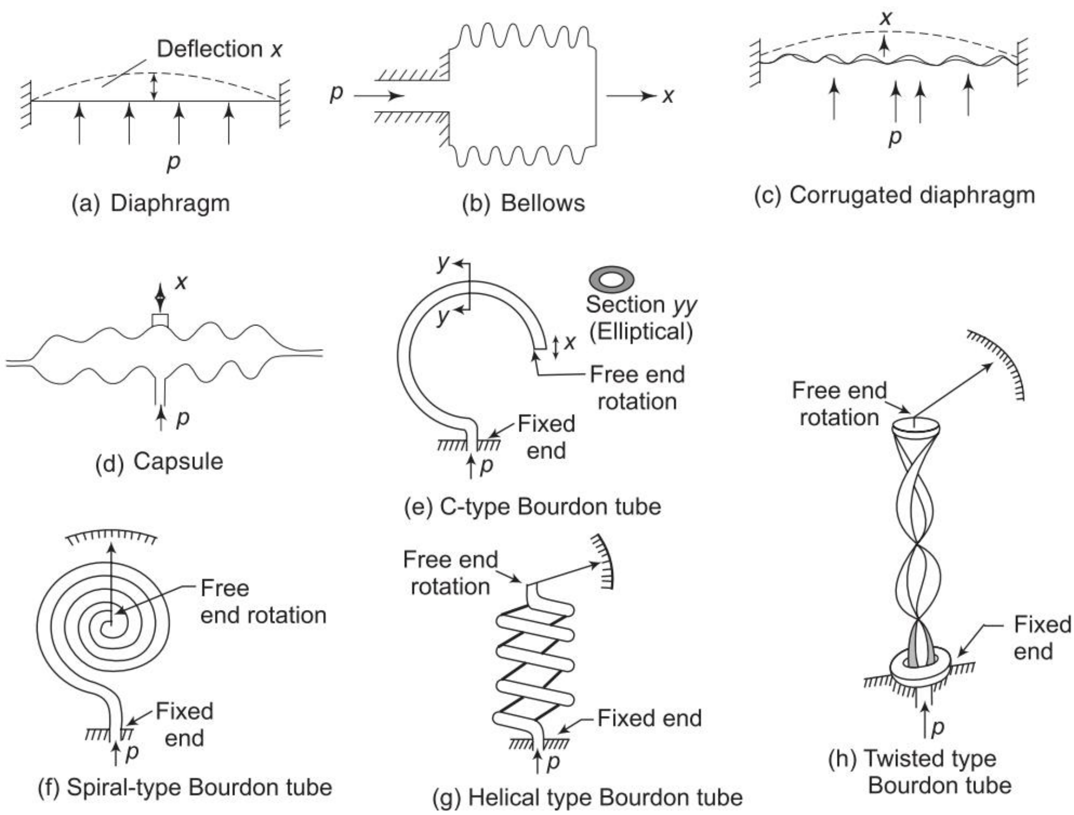

Fig. 11.9 Elastic elements used for pressure measurements

Bourdon Pressure Gauge Bourdon pressure gauge is one of the most common devices for the measurement of medium pressure up to 70 MPa as well as low pressures up to 10 mm of Hg (vacuum). The schematic diagram of this gauge is shown in the Fig. 11.10. The transducer element, known as Bourdon tube, in most cases is C-type of hollow elastic tube, which is elliptical in shape. Alternatively, in some gauges the transducer element may be in the form of hollow tube of non-circular section of either spiral type or helical type or twisted tube type (See Fig. 11.9). One end of the transducer element is fixed type and the pressure to be measured, is applied at this end. With the application of pressure, the elliptical cross-section of the C-tube, tends to expand to become round shaped and also tends to uncoil. This way, there is an output of small movement of the tube at the free end of the tube, which caused by the applied pressure. The mechanical linkages attached to this free end cause the motion of toothed sector and pinnion and their gear ratio amplifies the small displacement of the free end of the Bourdon tube. This movement is further amplified by the length of pointer attached to the pinion shaft.

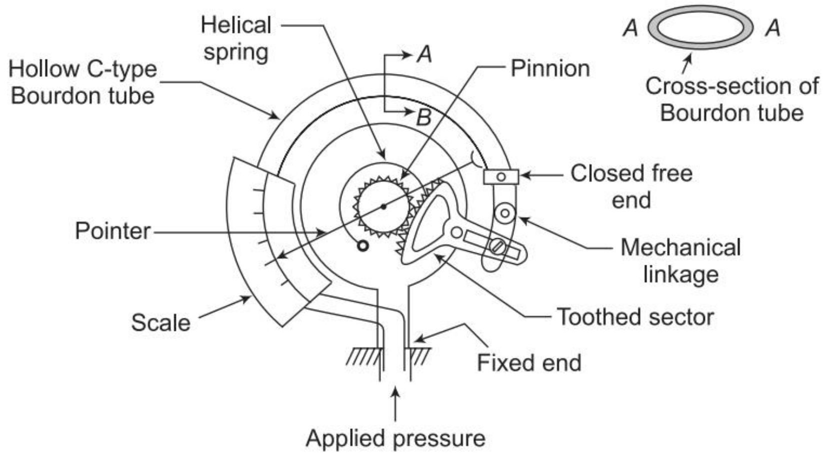

Fig. 11.10 Schematic diagram of the Bourdon pressure gauge

A small helical spring is attached to the pinion shaft to provide the restoring torque. The position of the pointer on the circular scale indicates the balance between the torque developed by the linkages of the Bourdon tube on the pinion shaft with that of the restoring torque of the helical spring. This gauge is then calibrated and after that, it indicates the measured pressure in appropriate units on a circular scale.

Bourdon gauges are available in several different ranges, i.e., from 0.1 to 70 MPa. In addition, they can be used to measure vacuum pressures up to the order of 10 Torr (10 mm of Hg vacuum), by sensing the movement of the free end of the pressure gauge in the reverse direction.

Advantages

1. It is purely a mechanical device with good accuracy and good sensitivity.
2. It is simple in construction and not very expensive.
3. It is rugged in nature and also does not require any maintenance.
4. It can be easily calibrated by means of a Dead Weight Tester.
5. It can be converted into an electro-mechanical device by incorporating additional transducer like inductive or capacitive or potentiometeric transducers for obtaining the electrical output.

Limitations

1. The gauge is not suitable for measuring the dynamic pressures.
2. It is not suitable for measurements in the shock and vibration conditions.
3. It exhibits hysteresis effects in measurements.

Electromechanical Devices Usually, an electromechanical transducer is used along with the elastic element, especially when dynamic pressures are to be measured (Fig. 11.11). The output voltage can be indicated or recorded by a suitable instrument like an oscilloscope or a recorder. Figure 11.12 shows a linear variable differential transducer (LVDT) type of pressure transducer, the principle of which has already been discussed in Ch. 4. The motion of the bellows is communicated to the core, whose motion gives an output voltage proportional to it. Since the bellows motion is proportional to pressure p, the output voltage is also proportional to p. Similarly output of the free end of Bourdon tube can be fed to LVDT to obtain electrical output [Fig. 11.12(b)].

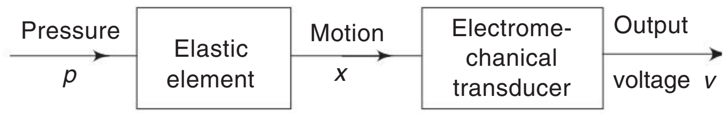

Fig. 11.11 Pressure measurement using an elastic element and an electromechanical transducer

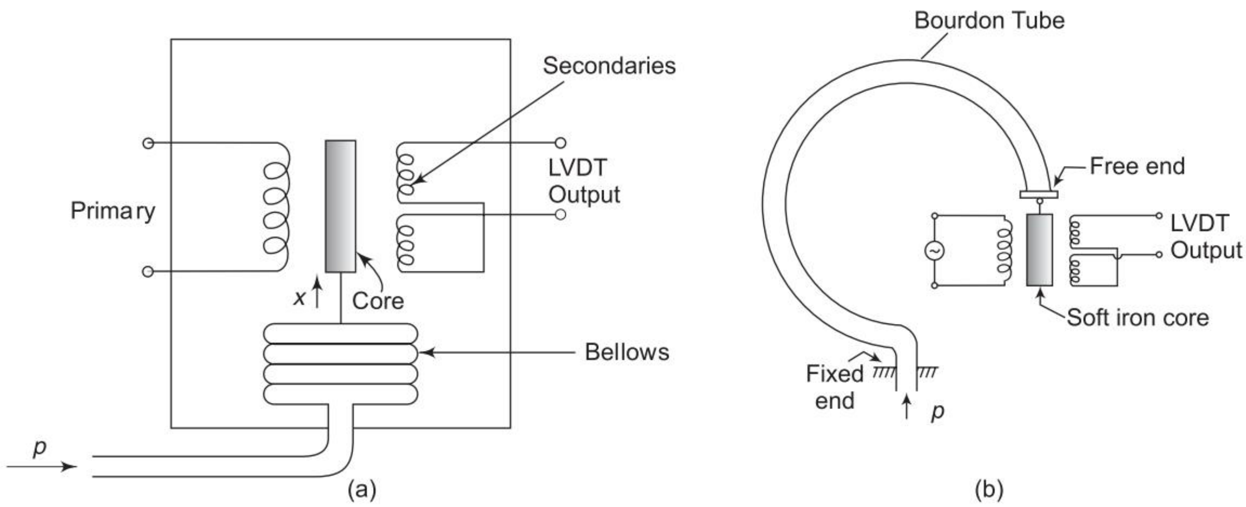

Fig. 11.12 Schematic diagram of LVDT-type pressure transducer using (a) bellows and (b) Bourdon tube

Figure 11.13 shows a variable capacitance type pressure transducer. Due to a pressure p, the elastic diaphragm deflects, changing the capacitance between it and the fixed electrode. The output of the bridge is proportional to the pressure p. Similarly, a piezo-electric crystal can be used (Fig. 11.14) for measuring the dynamic pressure. A voltage is developed between A and B, according to the pressure p applied. As discussed earlier, static variables cannot be measured with this type of transducer.

Three types of pressure transducers, using resistance gauges are shown in Figs. 11.15, 11.17 and 11.18. In Fig. 11.15, resistance gauges R_1 and R_3 are bonded, so as to measure radial strain near the outer radius of the diaphragm while R_2 and R_4 are bonded near the centre and measure tangential strains, Expressions for radial stress σ_r and tangential stress σ_t at a radius r are

$$\sigma_r = \frac{3pR^2\nu}{8t^2}\left(\frac{1}{\nu}+1\right)-\left(\frac{3}{\nu}+1\right)\left(\frac{r}{R}\right)^2$$

$$\sigma_t = \frac{3pR^2\nu}{8t^2}\left(\frac{1}{\nu}+1\right)-\left(\frac{1}{\nu}+3\right)\left(\frac{r}{R}\right)^2 \tag{11.9}$$

t being the diaphragm thickness, ν the Poisson's ratio of diaphragm material and p the pressure on the diaphragm. A plot of radial and tangential stresses (Fig. 11.16) shows that stresses in R_1 and R_3 would

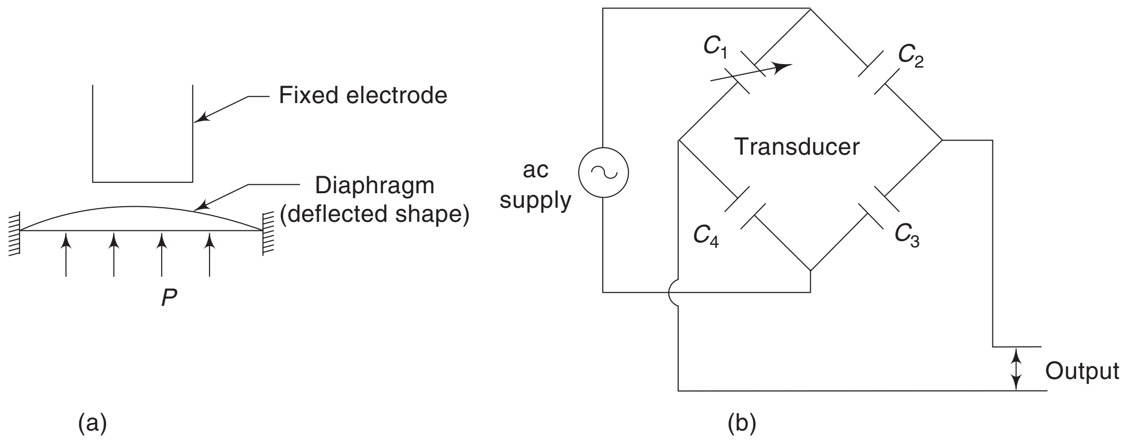

Fig. 11.13 Capacitance-type pressure transducer

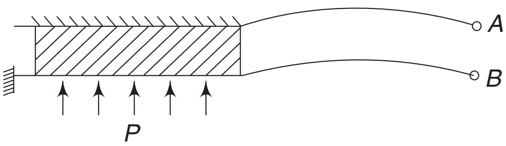

Fig. 11.14 Piezeo-electric type pressure transducer

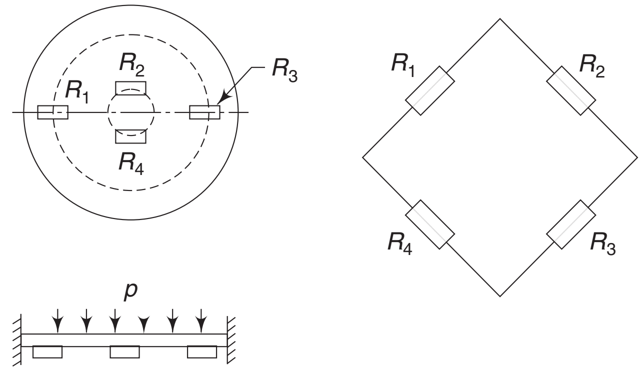

Fig. 11.15 Diaphragm type strain gauge pressure transducer

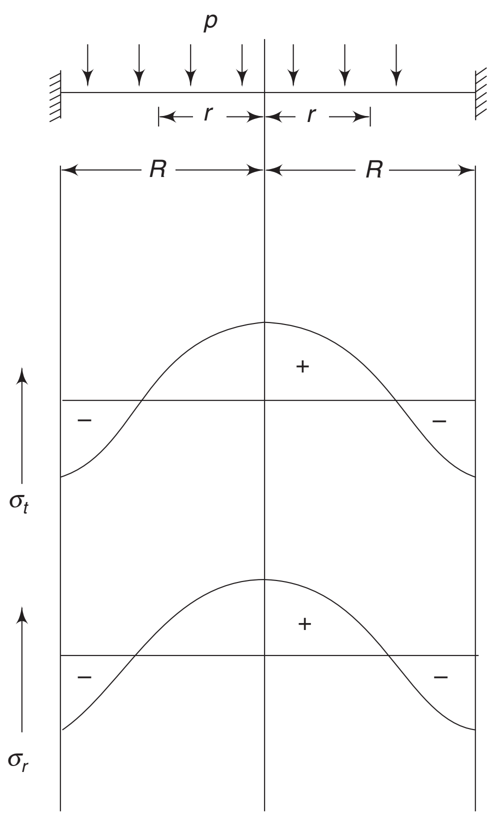

Fig. 11.16 Plot of radial and tangential stresses

be opposite in nature to those in R_2 and R_4. Figure 11.17 shows a strain gauge pressure transducer in which the resistance gauges are bonded on a member which are strained longitudinally. This type of transducer can be used for high pressures. Figure 11.18 shows a strain gauge pressure transducer, meant for measuring the pressure of a fluid in a pipe, without disturbing the fluid. Strain gauge R_1 measures the hoop strain in the pipe due to the pressure of the fluid.

Except for the pizeo-electric type, other transducers discussed here can be used for both static and dynamic measurements. The advantage of the piezo-electric type transducer lies in its increased sensitivity and thus higher output for a given pressure change.

Elastic Element Characteristics Elastic elements used for pressure transducers have to be carefully designed for

1. deflection due to pressure, and
2. dynamic considerations.

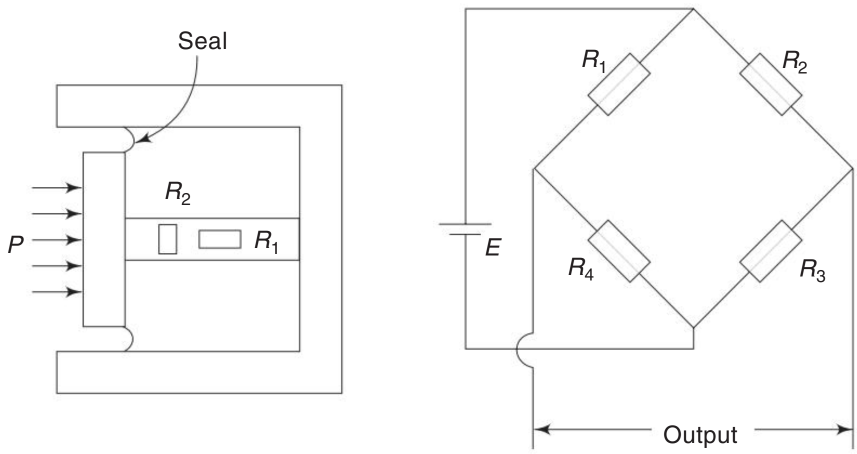

Fig. 11.17 Piston type strain gauge pressure transducer

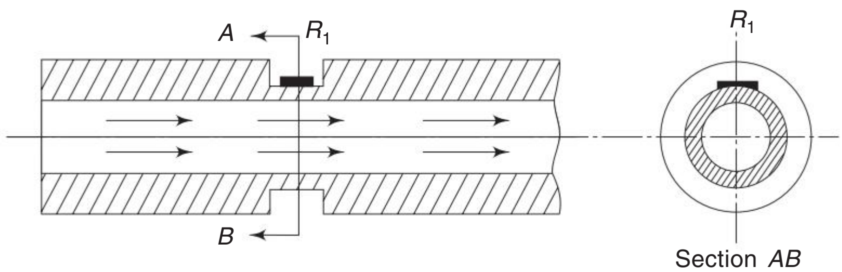

Fig. 11.18 Strain gauge pressure transducer for measuring fluid pressure in a pipe

It is known that an elastic diaphragm would remain linear for small deflections only and for this purpose, maximum deflection y should be $< t/3$, t being the diaphragm thickness.

From strength and elasticity of materials, it is seen that deflection y at radius r of a circular diaphragm clamped at its outer periphery (Fig. 11.19) is given by

$$y = \frac{3}{16} p \frac{(1-\nu^2)}{Et^3} (R^2 - r^2)^2 \tag{11.10}$$

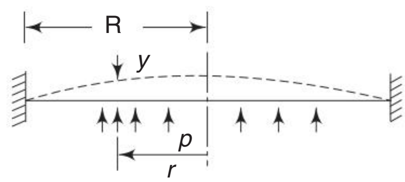

Fig. 11.19 Configuration of a deflected diaphragm

where p is the pressure on the diaphragm of radius R and thickness t, E being Young's modulus of the diaphragm material and ν its Poisson's ratio.

Thus

$$y_{\max} \text{ (at } r = 0) = \frac{3}{16} \frac{p}{Et^3} R^4 (1 - \nu^2) \tag{11.11}$$

For dynamic considerations, it is important to check that the fundamental frequency of vibrations of the elastic element is higher than the exciting frequency due to fluctuating pressure. For a circular diaphragm fixed at its periphery, the fundamental bending natural frequency is given by

$$\omega_n = \frac{10.21}{R^2} \sqrt{\frac{Et^2}{12(1-\nu^2)\rho}} \text{ rad/s} \tag{11.12}$$

ρ being the mass density of the diaphragm material. Remaining symbols have been defined earlier.

It may be further seen that the dynamic characteristics of a pressure measuring system are dependent not only on the characteristics of the elastic transducing element but also upon the characteristics of the pressure transmitting fluid, and the connecting tubing. As seen from Fig. 11.20, the effective mass of the moving system depends on the mass of the fluid that moves with deflected elastic diaphragm. Similarly, the damping action depends on the fluid friction. A consideration of the above factors for predicting the dynamic response is thus desirable.

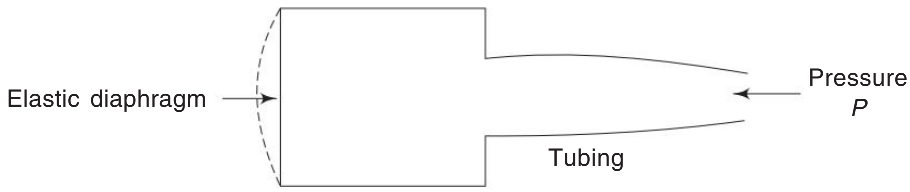

Fig. 11.20 Elastic diaphragm with chamber and tubing

Problem 11.2 Figure 11.21 shows a pressure transducer, using a clamped diaphragm. Strain gauges 2 and 4 are meant to measure the tangential strain while gauges 1 and 3 measure the radial strain. Find the open circuit sensitivity in mV/Pa.

Resistance of each gauge = 120 Ω, gauge factor = 2, radius R = 7 cm, r_0 = 1 cm and r_i = 6 cm. Thickness t of the diaphragm = 1 mm.

Young's modulus $E = 2.07 \times 10^5$ N/mm^2
Poisson's ratio $\nu = 0.25$

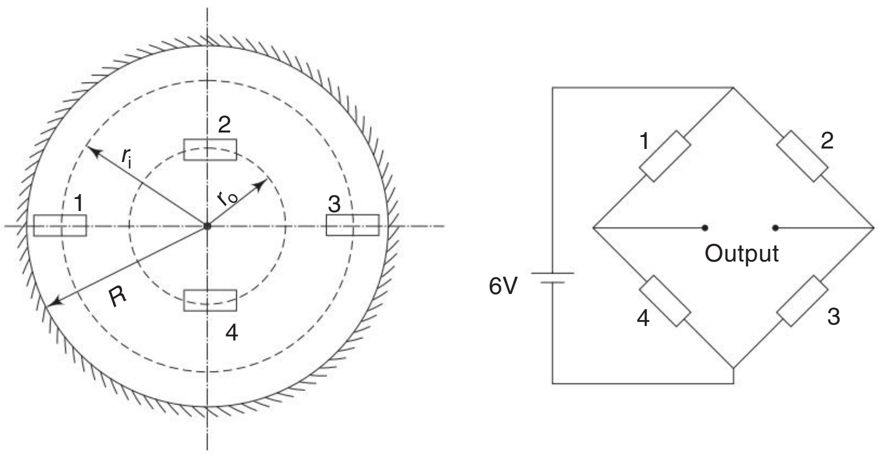

Fig. 11.21 Figure for Problem 11.2

Solution Radial strain e_r at any radius r is

$$\varepsilon_r = \frac{\sigma_r - \nu\sigma_t}{E} \tag{11.13}$$

σ_r and σ_t being the radial and tangential stresses, respectively, at radius r. Similarly, tangential strain e_t is

$$\varepsilon_t = \frac{\sigma_t - \nu\sigma_r}{E} \tag{11.14}$$

Expressions for σ_r and σ_t are given in Eq. (11.9) and are:

$$\sigma_r = \frac{3pR^2\nu}{8t^2}\left[\left(\frac{1}{\nu}+1\right)-\left(\frac{3}{\nu}+1\right)\left(\frac{r}{R}\right)^2\right]$$

$$\sigma_t = \frac{3pR^2\nu}{8t^2}\left[\left(\frac{1}{\nu}+1\right)-\left(\frac{1}{\nu}+3\right)\left(\frac{r}{R}\right)^2\right]$$

For r = 60 mm, using Eqs. (11.9) and (11.13) and taking $E = 2.07 \times 10^{11}$ N/m^2

$$\sigma_r = -2090.6p$$

$$\sigma_t = -65.6p$$

$$\varepsilon_r = -1.002 \times 10^{-8}\, p = \varepsilon_1 = \varepsilon_3 \tag{11.15}$$

ε_1 and ε_3 are strains in resistance gauges 1 and 3, respectively. For r = 10 mm, using Eqs. (11.9) and (11.15)

$$\sigma_r = 2175p$$

$$\sigma_t = 2231.25p$$

$$\varepsilon_t = 8.15 \times 10^{-9}\, p = \varepsilon_2 = \varepsilon_4 \tag{11.16}$$

where ε_2 and ε_4 are strains in resistance gauges 2 and 4, respectively. Open circuit output voltage expression, as deduced earlier

$$e_o = \frac{E_b F}{4}\ [\varepsilon_2 + \varepsilon_4 - \varepsilon_1 - \varepsilon_3] \tag{11.17}$$

E_b being the battery voltage, given as 6 V and F the gauge factor. Substituting from Eqs. (11.15) and (11.16) in Eq. (11.17) and taking p = 1 Pa

Output voltage = 1.086×10^{-7} V

or Sensitivity of diaphragm type pressure gauge = 1.086×10^{-7} V/Pa

Problem 11.3 A variable capacitance pressure gauge (Fig. 11.22) has the following specifications: diameter of clamped diaphragm = 20 mm, diameter of fixed electrode = 15 mm, thickness of diaphragm = 1 mm, Young's modulus E of diaphragm material = 2.07×10^5 N/mm^2, Poisson's ratio ν = 0.3, and initial air gap = 1 mm. The variable capacitance C due to change of air gap, forms a part of circuit of Fig. 11.22(b). Find the sensitivity (V/Pa) of the instrument, given V = 12 V and $R = 10^5 \Omega$.

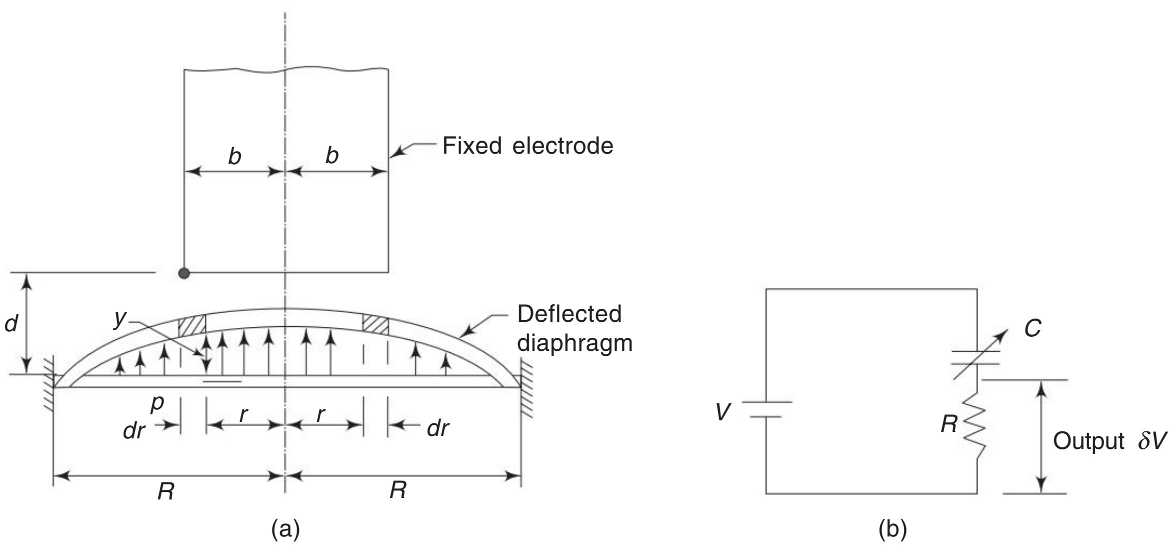

Fig. 11.22 Figure for Problem 11.3

Solution As seen from Fig. 11.22(a), the change in the gap between the diaphragm and the fixed electrode, due to pressure p is not uniform but is a function of the radius r.

With initial air gap d, initial capacitance C_0 between the diaphragm and the fixed electrode is obtained using Eq. (4.1) as

$$C_0 = b^2/(3.6d) \tag{11.18}$$

A being the area of the electrode (cm^2) = πb^2 and d the air gap (cm).

After application of pressure p, as seen from Fig. 11.22(a), gap at radius $r = d - y$, y being the deflection of diaphragm, given by Eq. (11.10), viz.

$$y = B(R^2 - r^2)^2 \tag{11.19}$$

$$B = \frac{3}{16}\frac{p(1-\nu^2)}{Et^3}$$

The capacitance C between the diaphragm and the fixed electrode is

$$C = \int_0^b \frac{2\pi r dr}{3.6\pi(d-y)}$$

$$\approx \frac{1}{1.8d}\int_0^b \left(1+\frac{y}{d}\right) r dr \qquad \text{(for } y/d \text{ being small).} \tag{11.20}$$

Substituting from Eq. (11.19) in Eq. (11.20) and integrating

$$C = \frac{b^2}{3.6d} + \frac{0.0174(1-\nu^2)p}{Ed^2t^3}[b^6 + 3R^2b^2(R^2 - b^2)] \tag{11.21}$$

From Eqs. (11.18) and (11.21)

$$\frac{\delta C}{C_0} = \frac{C - C_0}{C_0} = \frac{0.0625(1-\nu^2)p}{Edt^3}[b^4 + 3R^2(R^2 - b^2)] \tag{11.22}$$

where δC is the change is capacitance due to pressure p. For the circuit of Fig. 11.22(b), as proved in Chapter 4,

$$\frac{\delta V}{V} \approx \frac{\delta C}{C_0} \tag{11.23}$$

Using Eqs. (11.20) and (11.23) and substituting the values of the various quantities,

Sensitivity of capacitive type pressure gauge = $\dfrac{\delta V}{p}$ = 5.36×10^{-12} V/Pa

11.1.3 Dynamic Effect of Connecting Tubing

Usually, a connecting tube is used between the pressure measuring instrument and the location where the fluid pressure is to be measured (Fig. 11.23). Such a tubing would cause a lag under dynamic conditions. The lag may be determined as below. The inertia effect due to fluid motion is ignored.

Referring to Fig. 11.23, in which a manometer is the measuring instrument, it is seen that the mass rate of fluid flow in the tubing would be affected due to

1. change of fluid density due to pressure change, and
2. change of volume of fluid as a result of change of liquid level of the manometer.

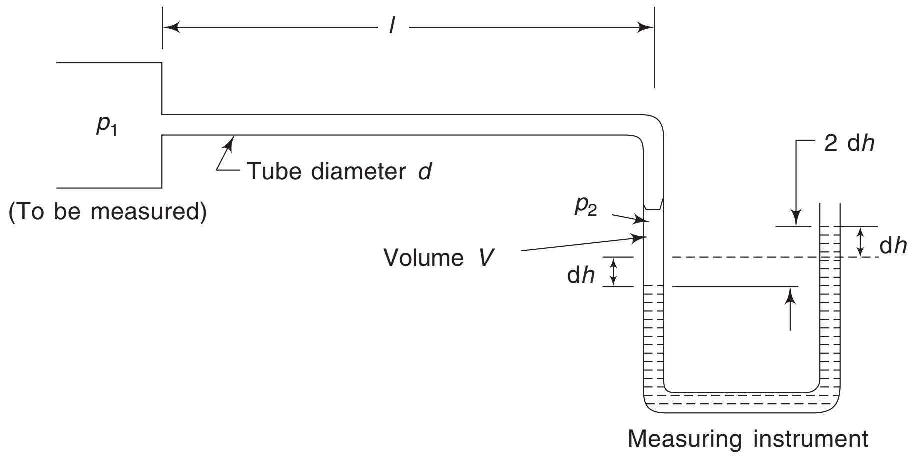

Fig. 11.23 Effect of connecting tubing

Effect 1 would be absent in the case of liquids while both effects 1 and 2 would be involved in case of gases.

If p_1 and p_2 are absolute pressures at the beginning and end of the tubing respectively, using Eq. (3.15) for pressure loss in the tubing, viz.

$$p_1 - p_2 = \frac{128\,\mu l Q}{\pi d^4},$$

μ being viscosity of the fluid and Q the volume flow rate. Mass flow rate of the fluid through the tubing

$$\rho Q = \frac{\rho \pi d^4\,(p_1 - p_2)}{128\,\mu l} \tag{11.24}$$

ρ being the mass density of the fluid mass. Flow rate is also equal to d/dt (ρV), V being the volume of space

$$= \frac{\rho \mathrm{d}V}{\mathrm{d}t} + \frac{V \mathrm{d}\rho}{\mathrm{d}t} \tag{11.25}$$

The first term on RHS of Eq. (11.25) is due to volume change of fluid as a result of the motion of the liquid in the manometer while the second term is due to change of mass density due to pressure change. Now,

$$\mathrm{d}V = A\mathrm{d}h$$

A being area of cross-section of the manometer tube and dh the liquid motion in the manometer arm. Also,

$$2\mathrm{d}h = \frac{\mathrm{d}p_2}{\rho_0 g}$$

ρ_0 being mass density of liquid in manometer. Thus,

$$\mathrm{d}V = \frac{A}{2\,\rho_0 g}\,\mathrm{d}p_2$$

or

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{A}{2\,\rho_0 g}\,\frac{\mathrm{d}p_2}{\mathrm{d}t} \tag{11.26}$$

Further, due to pressure change dp_2,

$$d\rho = \left(\frac{\rho}{p_2}\right) dp_2$$

or

$$\frac{d\rho}{dt} = \frac{\rho}{p_2}\frac{dp_2}{dt} \tag{11.27}$$

Equating Eqs. (11.24) and (11.25) and substituting from Eqs. (11.26) and (11.27), we get

$$\tau \frac{dp_2}{dt} + p_2 = p_1 \tag{11.28}$$

where

$$\tau = \frac{128\,\mu l}{\pi d^4}\left[\frac{A}{2\,\rho_0\, g} + \frac{V}{p_2}\right]$$

τ is the time constant of the first order relation representing the lag of the system. In order to reduce τ; l, A and V should be small and d should be large.

11.2 HIGH PRESSURE BRIDGEMAN GAUGE — LO 3

For pressures above 1000 atm, special techniques have to be used. One such technique is based on the electrical resistance change of a manganin (alloy of Cu, Ni, Mn) or gold chrome wire, with hydrostatic pressure, due to bulk compression effect. Figure 11.24 shows an outline diagram of this type of device known as *Bridgeman gauge*. Usually, the coil is enclosed in a flexible bellows (not shown in the figure) filled with kerosene, for transmitting the pressure to be measured to the coil. The change in the resistance of the wire between *A* and *B* is measured by usual methods like Wheatstone bridge, etc.

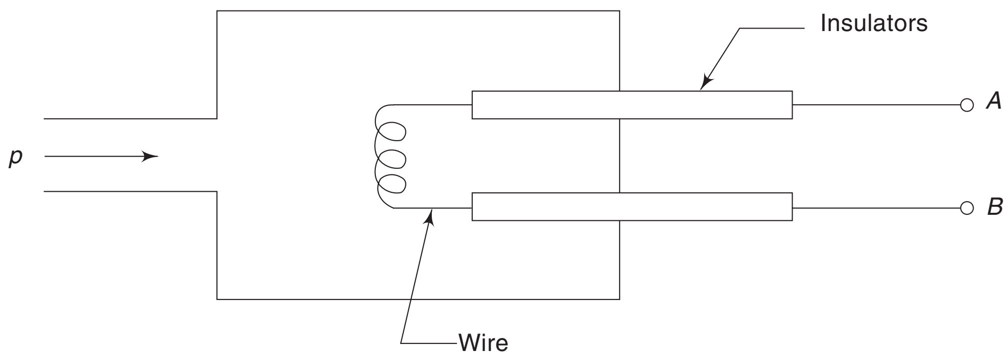

Fig. 11.24 Schematic diagram of High-wire pressure type Bridgeman gauge

For manganin, the sensitivity is 2.5×10^{-11} Ω/Ω-Pa while for gold–chrome, the same is 9.85×10^{-12} Ω/Ω-Pa. Even though gold–chrome is less sensitive, it is preferred to manganin, since the former is less temperature sensitive than the latter.

An expression for sensitivity for the arrangement of Fig. 11.24 may be deduced as under: For a wire of diameter D and length L, the resistance

$$R = \frac{4\,\rho L}{\pi D^2}$$

ρ being resistivity constant. From the above, we can write

$$\frac{dR}{R} = \frac{dL}{L} - \frac{2\,dD}{D} + \frac{d\rho}{\rho} \tag{11.29}$$

Relations between strains ε_x, ε_y and ε_z in the three perpendicular directions, in terms of stresses σ_x, σ_y and σ_z are

$$\varepsilon_x = \frac{1}{E}\ [\sigma_x - \nu(\sigma_y + \sigma_z)]$$

$$\varepsilon_y = \frac{1}{E}\ [\sigma_y - \nu(\sigma_x + \sigma_z)]$$

$$\varepsilon_z = \frac{1}{E}\ [\sigma_z - \nu(\sigma_x + \sigma_y)] \tag{11.30}$$

ν being Poisson's ratio and E Young's modulus.

The wire in the arrangement of Fig. 11.24 is subjected to a bi-axial state of stress as the ends will not be subjected to pressure.

Thus, taking $\sigma_x = \sigma_y = -p$ and $\sigma_z = 0$ we get from Eq. (11.30)

$$\varepsilon_x = \varepsilon_y = \frac{dD}{D} = -\frac{p}{E}\ (1 - \nu)$$

$$\varepsilon_z = \frac{dL}{L} = \frac{2\nu p}{E}$$

Substituting in Eq. (11.29)

$$\frac{dR}{R} = \frac{2p}{E} + \frac{dp}{\rho}$$

Thus, sensitivity of Bridgeman gauge $= \dfrac{dR/R}{p} = \dfrac{2}{E} + \dfrac{d\rho/\rho}{p}$ (11.31)

11.3 LOW PRESSURE (VACUUM) MEASUREMENT — LO 4

Units of vacuum measurements are Torr and micron. One Torr is a pressure equivalent of 1 mm of Hg while 1 micron is 10^{-3} Torr.

Manometer and elastic element gauges can be used to about 10 Torr. Below these ranges, other types of vacuum gauges are needed.

11.3.1 McLeod Vacuum Pressure Gauge

This gauge is used for the measurement of vacuum pressures between 10^{-4} and 10^{-1} Torr. This is, in fact, a modified mercury manometer. Further, it is considered as vacuum standard because the measured vacuum pressure can be computed from the dimensions of the gauge. The principal of operation of this gauge is the gradual compression of the low pressure trapped gas isothermally to a pressure value, which can be conveniently read with a simple mercury manometer.

The unknown pressure from a vacuum source is connected to the McLeod gauge, as shown in the Fig. 11.25. The moveable mercury reservoir is moved downwards till the level of mercury is just below the opening O. At this point, the vacuum pressure source fills the volume V above opening O. This volume V includes three volumes, namely, a small portion of volume of connecting length just below the McLeod gauge bulb, McLeod gauge bulb B and the volume of the measuring capillary. The moveable mercury reservoir is then, moved slowly upwards and this in turn seals the opening and starts compressing the trapped gas. This upward movement of the mercury reservoir is continued till the level of mercury visible in the reference capillary reaches the level of top end of the measuring capillary, which is termed as the reference level. At this point the initial trapped volume V at low vacuum pressure gets compressed and confined in the capillary space at a relatively high pressure p_c (say). This pressure can be conveniently measured with the usual manometric equation.

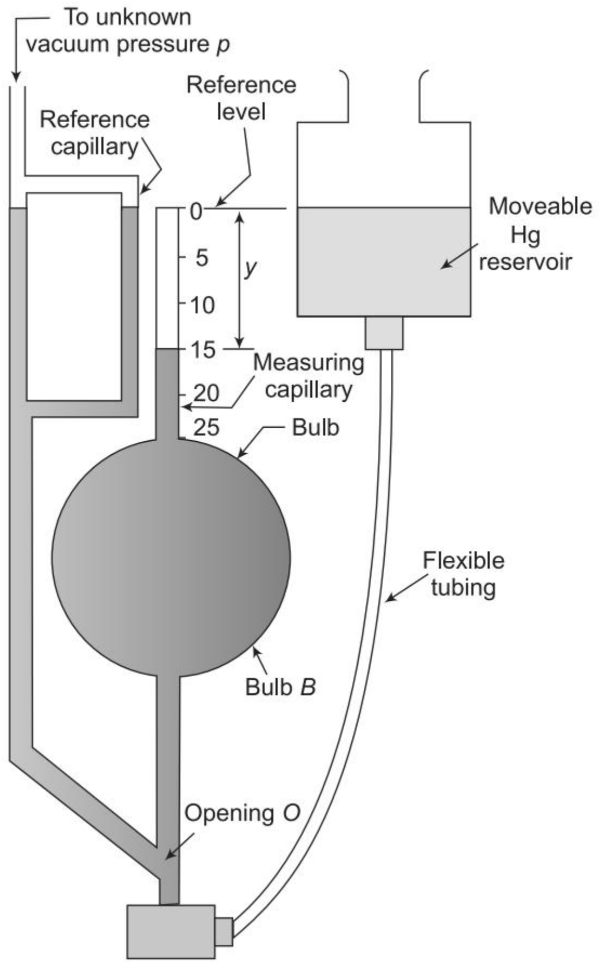

Fig. 11.25 McLeod vacuum gauge (Non-linear operation)

The final volume remaining in the capillary can be read directly from the scale marked in millimeters on the length of the capillary. Further, the difference in height y shown in the Fig. 11.25 is the measure of difference in pressure p_c and vacuum pressure p in mm of mercury (i.e., $y = p_c - p$).

If p = unknown vacuum pressure in mm of Hg,

A_c = area of cross-section of the measuring capillary,

v_c = final volume of the gas compressed in the capillary space $= A_c y$

p_c = pressure of the gas in the measuring capillary after compression, and

V = initial volume of gas when the mercury level had reached the mark O.

Now, applying the Boyle's law for isothermal compression of gas from initial volume V to final volume v_c, we get,

$$p = \frac{p_c v_c}{V} \qquad \text{where } y = P_c - p \tag{11.32}$$

Substituting the value of p and simplifying we get,

$$p = \frac{A_c y^2}{(V - A_c y)} \tag{11.33}$$

Usually, the term $A_c y$ (i.e., the term v_c) is extremely small as compared to the value V and, therefore, neglecting this value, the approximate formula of vacuum pressure measurement in McLeod Gauge becomes:

$$p = \frac{A_c y^2}{V} \tag{11.34}$$

In Eq. (11.34), since the values of A_c and V are constant, therefore, the capillary tube length can be directly calibrated in measured vacuum pressures.

Advantages

1. It is a simple mechanical device employing the simple manometric principle in the measurements of unknown vacuum pressures.
2. The gauge is not very expensive and does not need skilled operations.
3. It is considered vacuum standard as the unknown pressures can be evaluated from the gauge dimensions. For this reason, it is employed for the calibration of other vacuum gauges.
4. The capillary tube length can be directly calibrated in terms of vacuum pressure values either in Torr or Pascals.

Limitations

1. It is not suitable for the measurements of dynamic pressures.
2. The gauge cannot measure vacuum pressures below 10^{-4} Torr because of the interferences caused due to the formation of mercury vapors at those pressures.
3. The scale of the gauge is non-linear, i.e., of the square law type.

11.3.2 Linearization of Pressure Scale of McLeod Gauge

The McLeod gauge Eq. (11.37) for the measurement of vacuum pressures is parabolic in nature. This indicates that sensitivity of the instrument is not same in the whole measurement range. However, this scale can be conveniently linearized by means of adopting a small variation in the measurement technique. In this case, instead of raising the mercury reservoir level up to the reference mark, namely the top end of the measuring capillary, it is only moved to a height, such that the trapped volume V at the opening O, in each measurement is compressed to a known constant volume of gas v_c, up to reference marked on the capillary (see Fig. 11.26).

The height of mercury level in the reference capillary above the reference mark on the capillary represents the difference in pressure 'p_c' and vacuum pressure 'p' in mm of mercury (i.e., $z = p_c - p$).

If p = unknown pressure in mm of Hg,

v_c = Final volume of the gas in the capillary space up to reference mark

p_c = Pressure of the gas in the measuring capillary after compression, and

V = Initial volume of gas when the mercury level had reached the mark O.

Now, applying the Boyle's law for isothermal compression of gas from initial volume V to final volume v_c, we get,

$$pV = (p_c)(v_c) \qquad \text{where } z = p_c - p \qquad (11.35)$$

Substituting the value of 'p' and simplifying we get,

$$p = \frac{v_c}{(V - v_c)} z \qquad (11.36)$$

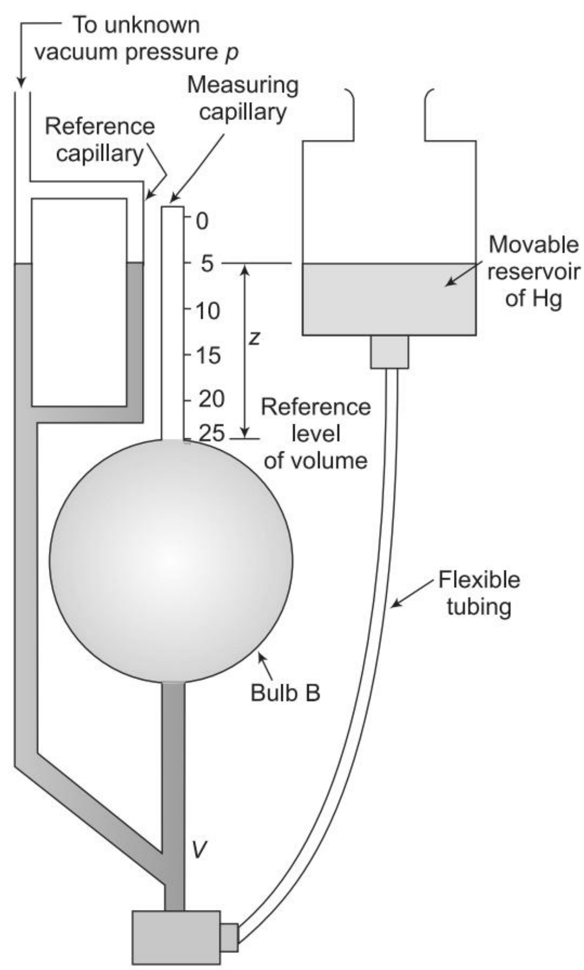

Fig. 11.26 McLeod vacuum gauge (Linear operation)

Usually, $(v_c) << V$ and therefore, approximate governing equation of the McLeod gauge becomes:

$$p = \frac{v_c}{V} z \tag{11.37}$$

Thus the operation of the McLeod gauge becomes *linear*. In other words, knowing the values of (v_c) and (V), the measured vacuum pressure is linearly related to the value of height of mercury column z above the reference mark of the capillary tube.

11.3.3 Thermocouple Vacuum Gauge

Figure 11.27 shows the schematic diagram of thermocouple type of vacuum gauge. It consists of a sealed container of either glass or metal which is connected to the vacuum system. It has a heating element, which is heated up to a temperature of 100°C to 400°C, by supplying a constant current. Its central portion is connected to a thermocouple and its output is fed to a micro-voltmeter.

It may be noted that the thermal conductivity a gas decreases with decrease in vacuum pressures. Further, the heat loss from the heating element to the surroundings is dependent on the thermal conductivity of the gas. Thus, with lowering of vacuum pressure, the thermal conductivity decreases and this in turn decreases, the heat loss from the heating element, for a given energy input. Consequently, this results in the increase of the temperature of the heating element, which is then, indicated by the corresponding increase in the thermocouple output. This output of thermocouple is directly calibrated to indicate the vacuum pressures. This gauge can measure vacuum pressures from 10^{-4} Torr to 1 Torr. Further, the calibration of the gauge is different for different gases. This is because the variation of thermal conductivity at vacuum pressures is not same for different gases. Typical variations of thermocouple output versus vacuum pressure obtained for different gases in the calibration of the thermocouple gauge are shown in Fig. 11.28.

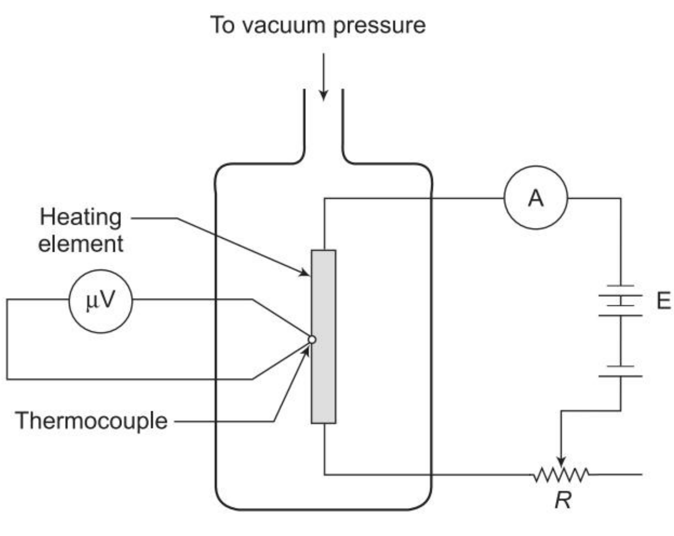

Fig. 11.27 Thermocouple vacuum gauge

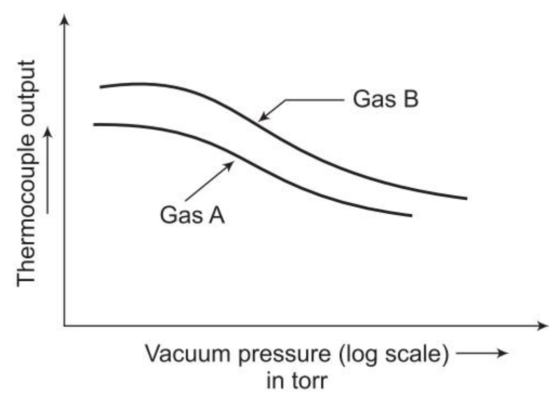

Fig. 11.28 Vacuum pressure vs voltage characteristic of thermocouple gauge

The main advantage of thermocouple gauge is that it is simple in construction and operation and also it is quite inexpensive. Further, its output is electrical.

However, the main limitation of this gauge is that it needs to be calibrated before it can be put in use. Further, the calibration of the gauge is gas specific, i.e., it is not the same for all gases. In addition, the changes in ambient temperatures may cause small error in measurements. Lastly, the transient response of this gauge is poor. This is because, it takes several minutes to arrive at the equilibrium conditions.

11.3.4 Pirani Thermal Conductivity Gauge

The principle of operation of the Pirani thermal conductivity gauge is the variation of thermal conductivity of a gas at low pressures. Lower the measured pressure, lower is the thermal conductivity the gas and this results in lowering of heat loss to the surroundings from the heated resistive element of the gauge. Consequently, there is increase in the temperature of the resistive element, which in turn increases its resistance value, which is sensed by the associated Wheatstone bridge circuitry.

Figure 11.29 shows the schematic diagram of Pirani gauge, in the form of half-bridge type of Wheatstone bridge circuit. The two adjacent arms of the bridge consist of two identical bulbs, each containing a filament of either platinum or tungsten. One of the bulb is a measuring bulb and is connected to the vacuum pressure to be measured. While, the other bulb is evacuated to a low pressure (vacuum pressure) and sealed. This forms a compensating bulb, also known as dummy bulb, which minimizes the effects of the variations of ambient temperatures in the vacuum measurements.

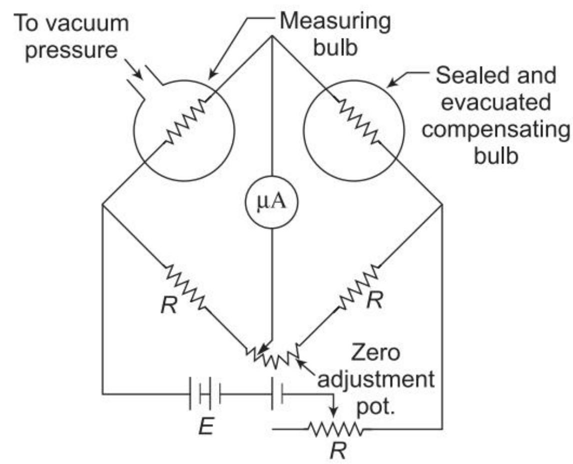

Fig. 11.29 Schematic diagram of Pirani gauge in half Wheatstone bridge configuration

The Wheatstone bridge is initially balanced using the bridge top zero balance potentiometer. After that, the measuring bulb is connected to the vacuum pressure. The currents flowing in the Pirani gauge bridge circuit, change with the application of measured vacuum pressure. This disturbs the balance in the Wheatstone bridge circuit. Consequently, this results in the form of the bridge output which is function of the measured vacuum pressure. This gauge when calibrated for a particular gas gives electrical output with accuracy of the order of ±2%. It has a wide measuring range i.e., from 10^{-6} Torr to 1 Torr.

Some manufacturers of this gauge also give option of the operation of Pirani gauge in full bridge Wheatstone configuration. In this case, we have four identical bulbs having either platinum or tungsten filament. Out of the four bulbs two are measuring bulbs and the other two are evacuated type of compensating bulbs. The measuring bulbs are connected to the vacuum pressure and they form two opposite arms of the Wheatstone bridge. Further, the compensating bulbs form the other two opposite arms of this bridge. (see Fig. 11.30). This way the output of the Pirani gauge become twice the output of the half bridge circuit.

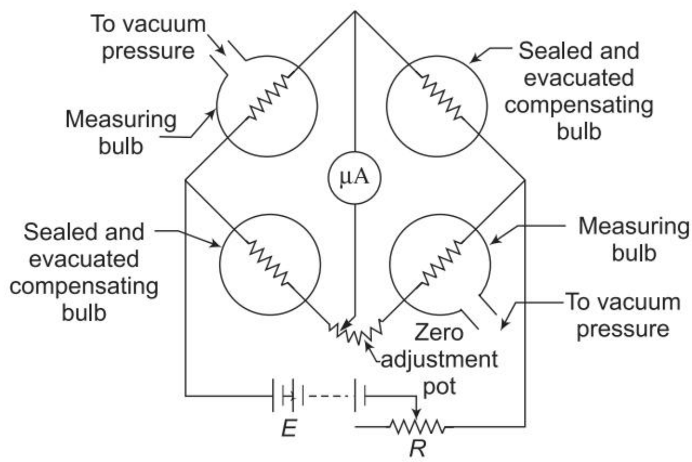

Fig. 11.30 Schematic diagram of Pirani gauge in full Wheatstone bridge configuration

Typical variation of bridge output in Pirani gauge versus vacuum pressure for different gases in the calibration of Pirani thermal conductivity gauge are shown in Fig. 11.31. It may be noted that the of the gauge needs to be calibrated for each individual gas as thermal conductivity of different gases is not the same.

Advantages

1. This gauge is more accurate than that of 'Thermocouple' gauge. This is because, the compensating gauge minimizes to great extent the effects of variations of ambient temperatures in the vacuum measurements.
2. It has a wide measuring range i.e., from 10^{-6} Torr to 1 Torr.
3. The gauge is compact type and portable.
4. The output of the gauge is electrical.

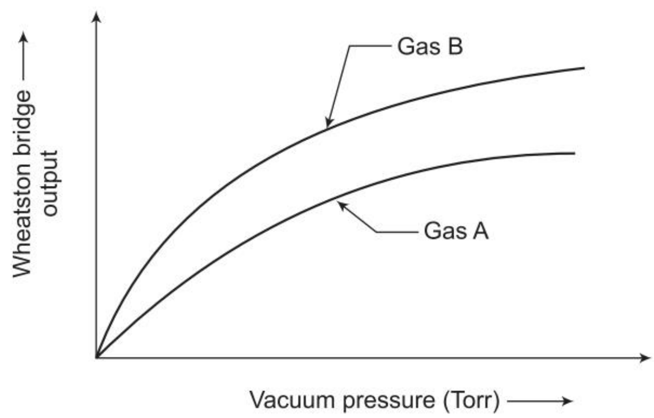

Fig. 11.31 Vacuum pressure vs Pirani gauge output characteristics

Limitations

1. It needs to be calibrated before for each individual gas as the thermal conductivity varies from one gas to another.
2. The calibration is non-linear type.
3. Its calibration gets badly affected by organic vapours because the filament gets coated with deposits and its heat transfer ability gets changed.

11.3.5 Ionization Gauge

This gauge is used for the measurement of very low vacuums of the order of 10^{-8} Torr. The gauge is very similar to the triode electronic tube, which was earlier used in the radio circuits and is shown in Fig. 11.32. The high strength ceramic tube encloses the basic elements of this gauge which are, heated cathode filament, positively biased grid and negatively biased plate. Further, the gauge is evacuated by connecting it to the vacuum pressure to be measured.

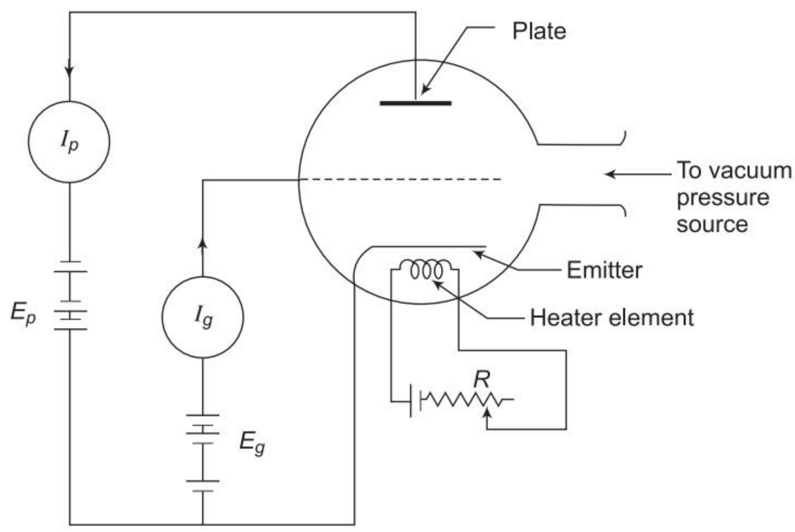

Fig. 11.32 Schematic diagram of an ionization gauge

The heated cathode emits electrons which are accelerated by the positively charged grid. As the electrons move towards the grid, they collide with the gas molecules and in this process ionize them. The ionization process knocks off secondary electrons from the gas molecules and produce positively charged ions. The negatively biased plate attracts these positively charged ions and produces a current I_p in the error due unknown emissivity is usually not known. To reduce such uncertainties, pyrometers calibrated from time to time in actual use.

In view of the troubles due to filtering and emissivity, the total radiation pyrometer is not a very accurate temperature indicator. However, it can be used to good advantage in fixed locations where the emissivity and optical paths are well known and constant. A typical use is a large furnace in metal industries. The signal is electrical and therefore can be used for control applications.

12.6.2 Selective Radiation Pyrometer

The principle of this instrument is based on Planck's law which states that the energy level in the radiations from a hot body are distributed in the different wavelengths. As the temperature increases, the emissive power shifts to shorter wavelengths. The planck's distribution equation is:

$$W = \frac{c_1 \lambda^{-5}}{\left(e^{c_2/\lambda T} - 1\right)} \tag{12.14}$$

where $c_1 = 3.740 \times 10^{-12}$ (W–cm^2)
$c_2 = 1.4385$ (cm –°C)
λ = wavelength (cm)
T = absolute temperature in (K)
W = energy level associated with wavelength at temperature T (W/cm^3)

The classical form of this optical pyrometer is the *disappearing filament optical pyrometer* (or the monochromatic brightness radiation pyrometer). It is most accurate of all radiation pyrometers; however, its use is limited to temperatures greater than about 700°C since it requires visual brightness match by a human operator. This instrument is used to realise the International Practical Temperature Scale above 1064°C.

It is obvious from Planck's distribution equation that for a given wavelength, the radiant intensity (brightness) varies with the temperature. In the disappearing filament instrument shown in the Fig. 12.13, an image of the target is superimposed on the heated filament. The tungsten lamp, which is very stable, is previously calibrated so that when the current through the filament is known, the brightness temperature of the filament is also known. A red filter that passes only a narrow band of wavelengths around

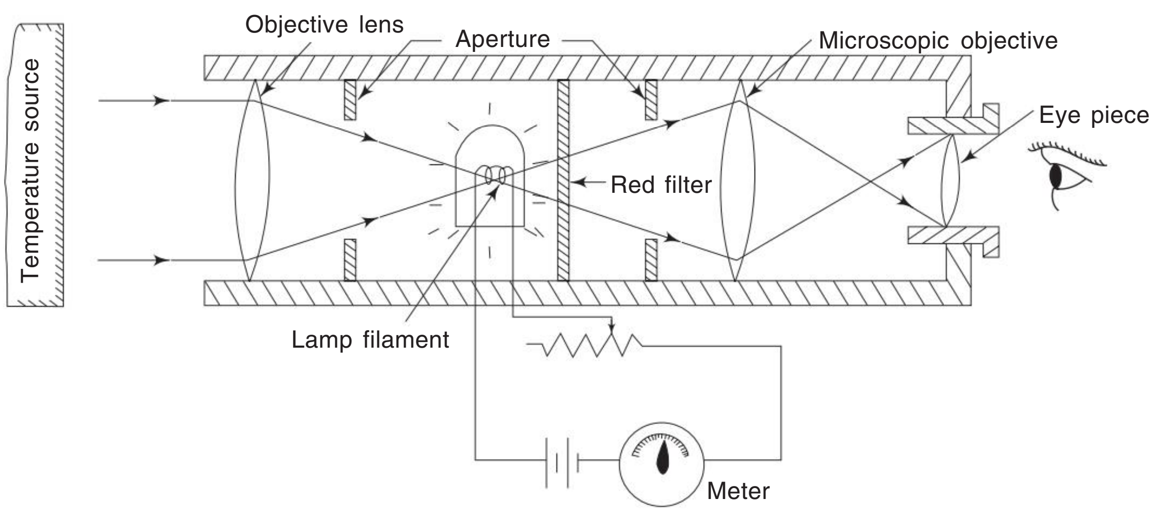

Fig. 12.13 Schematic of the disappearing filament type of optical pyrometer

The Knudsen gauge gives an absolute measurement of pressure p, which is independent of gas composition. It can cover a range of pressure from 10^{-8} to 10^{-2} Torr.

Problem 11.4 A McLeod gauge has volume of bulb, capillary and tube down to its opening equal to 90 cm^3 and a capillary diameter of 1 mm. Calculate the pressure indicated by a reading of 3 cm on the capillary tube.

Solution In the McLeod gauge, the capillary volume v_c is extremely small as compared to the volume of bulb V. Therefore, the vacuum pressure p can be evaluated using Eq. (11.34), which is as follows

$$p = \frac{A_C\, y^2}{V}$$

Substituting V = 90,000 mm^3, $A_C = \dfrac{\pi}{4}(1)^2 = 0.785$ mm^2 and y = 30 mm, we get

$$p = 7.85 \times 10^{-3} \text{ mm of Hg.}$$

Problem 11.5 A vacuum gauge is to use a differential transformer combination, which has a resolution of 2.5 microns. The diaphragm is to be constructed of steel ($\rho = 7.9 \times 10^{-6}$ kg/mm^3, $E = 2.07 \times 10^5$ N/mm^2, $\nu = 0.3$), with a diameter of 15 cm. Calculate the diaphragm thickness so that the maximum deflection does not exceed one-third of its thickness. Also find the lowest vacuum, which may be sensed and the frequency limit of the instrument.

Solution Using Eq. (11.11), viz.

$$y_{\max} = \frac{3}{16}\frac{p}{Et^3} R^4 (1 - \nu^2), \text{ } R \text{ being the radius of diaphragm} \tag{11.40}$$

Also $$y_{\max} = \frac{t}{3}, \text{ where '}t\text{' is the diaphragm thickness} \tag{11.41}$$

p corresponding to $y_{\max}$ can have a maximum value equal to the atmospheric pressure, since in the vacuum gauge the end of diaphragm would be subjected to atmospheric pressure and the other end to the vacuum to be measured.

Taking $p = 1.013 \times 10^5$ N/m^2 and using Eqs. (11.38) and (11.39), we get, t = 1.68 mm. Thus, $y_{\max}$ = 0.56 mm.

Lowest vacuum, that can be sensed, would correspond to the resolution of the instrument, viz $y = 2.5 \times 10^{-3}$ mm. Thus,

$$\text{Lowest vacuum} = \frac{1.013 \times 10^5}{0.56} \times 2.5 \times 10^{-3}$$

$$= 452 \text{ N/m}^2 = 3.40 \text{ mm of Hg}$$

The frequency limit of the instrument is given by the fundamental frequency of bending vibrations of the diaphragm, which is given by Eq. (11.12).

Using Eq. (11.12), and putting R = 0.075 m, $E = 2.07 \times 10^{11}$ N/m^2, $\rho = 7.9 \times 10^3$ kg/m^3

and $$t = 1.68 \times 10^{-3} \text{ m, we get}$$

$$\omega_n = 3644.3 \text{ rad/s} = 580 \text{ Hz}$$

11.4 CALIBRATION OF PRESSURE GAUGES LO 5

Calibration of pressure measuring instruments can be checked against monometers. These can be used for moderate pressures. Further, the static calibration of pressure measuring devices, a dead weight tester can also be employed for relatively higher ranges of moderate pressures. For low pressures, McLeod gauge can be used. Special methods have to be used for very low or very high pressures.

The calibration techniques described in Sections 11.4.1 and 11.4.2 are the *primary standards* for *static calibration* of the pressure gauges. These are conveniently achievable at laboratory level.

11.4.1 Manometric Method

Manometric measurements give direct values of the measured gauge pressure and can be used as primary method for calibrating the pressure gauges in the lower ranges of pressures. Figure 11.34 shows the schematic diagram of test rig for the calibration of the pressure gauge. A pipe line connected to an air pressure tank is fitted with a needle valve for controlling the pressure to be supplied to the pressure gauge under test A precision manometer is connected in series with test gauge in same pipe line. In addition, a second needle valve is fitted just before the test pressure gauge. This is employed for releasing the pressure to the atmosphere, so as to adjust different values of test pressures. In practice, generally, a U-tube manometer in deflection mode, as shown in the figure, is employed for calibration of the test pressure gauge. Alternatively, a moving reservoir-type manometer may be used. These manometers are provided with anti parallax and vernier devices for accurate measurements of the heights of liquid columns of the manometer.

It may be noted that the manometric method can be used for the static calibration of lower range pressure gauges from 0 to 200 kN/m^2 with a high accuracy of the order of 0.01%. For higher range of pressures, a 'Dead Weight Tester' is commonly used, which has been discussed in the following section.

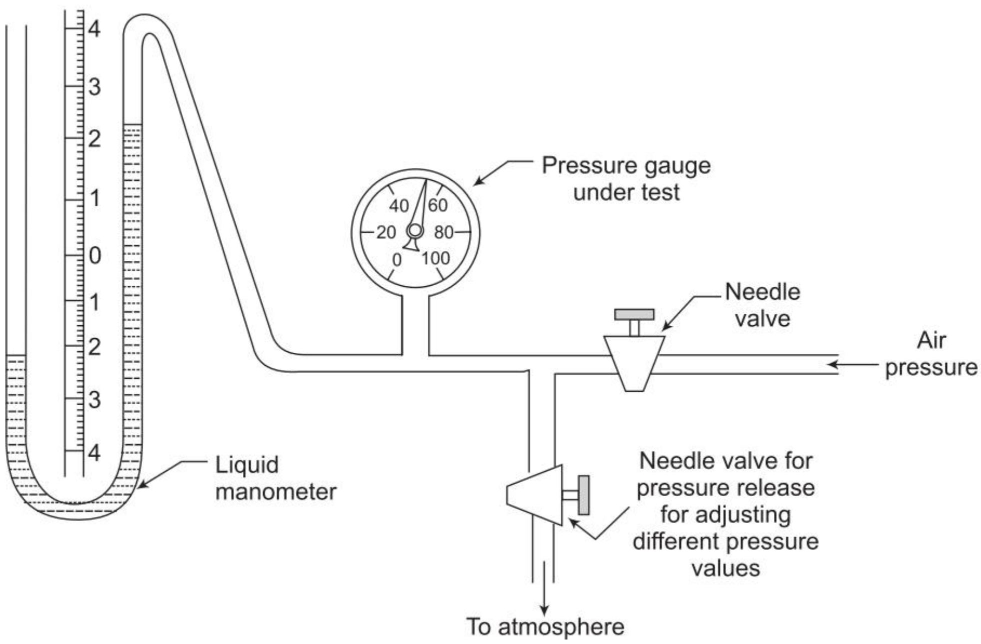

Fig. 11.34 Schematic diagram of Manometer method of calibration of pressure gauge

11.4.2 Dead Weight Tester

A dead weight tester is a commonly used device for the static calibration of pressure gauges in the medium pressure range up from 0 to 4.0 MPa. However, with special designs and techniques, it can be used up to 7.0 MPa (i.e., 70 bars). It utilizes the fundamental definition of pressure as force per unit area, for the generation of calibration pressures. It may be noted that this device is only used for the static calibration of the pressure gauges. In practice, it is not suitable for the direct measurement of pressures.

Figure 11.35 shows the schematic diagram of the 'Dead Weight Tester'. It has an oil chamber, which is filled with a liquid, which is generally a clean mineral oil. It is provided with an accurately machined and close-fitting piston and cylinder arrangement with a provision of a top platform. Dead weights available with test kit, can be placed on this platform and they have markings in terms of pressure which they would produce on the upper side of the piston. The pressure in the oil chamber is built up by the compression of liquid by moving the screw type of plunger. This pressure acts on the lower side of the piston. The same pressure acts on the test pressure gauge, when the valve in the calibration port, shown in the figure just below the test pressure gauge, is opened.

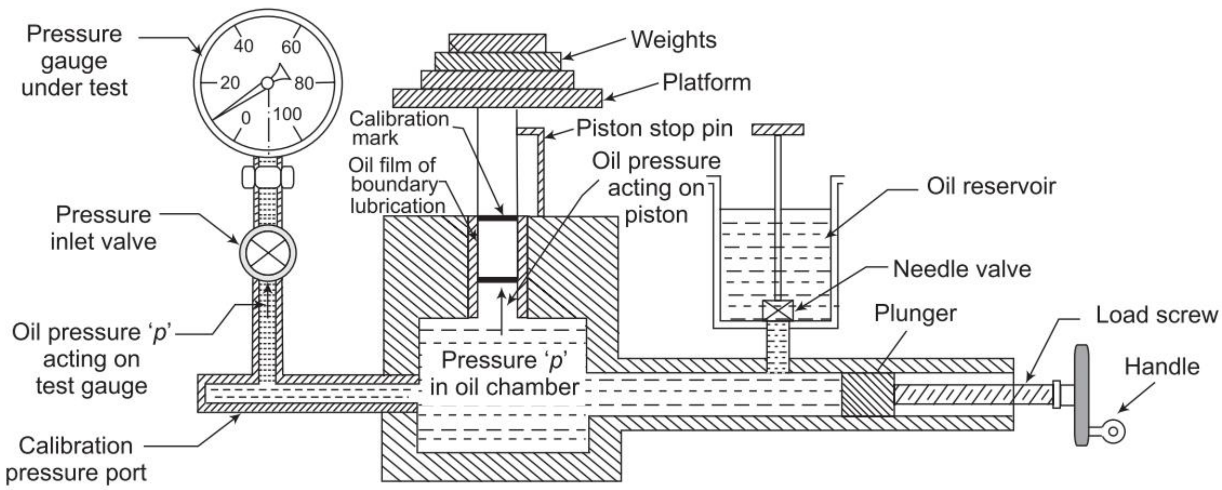

Fig. 11.35 Schematic diagram of dead weight tester for calibration of pressure gauges

In the calibration procedure, the pressure in the oil chamber is gradually increased by moving the handle, which pushes the plunger. It is continued till, the required pressure is generated which lifts the piston dead weight combination up to a calibration mark. To reduce, the viscous effects of oil, the piston-dead weight combination is given a rotational motion. This condition corresponds to a free-floating condition, which ensures that the frictional effects due to the viscosity of oil are minimal. At this condition, the calibration pressure is equal to the dead weight divided by the piston area.

Dead weight tester is a *primary* standard for pressure measurements. Further, it is suitable for pressure calibrations up to 7 MPa (i.e., 70 bars) with an accuracy of 0.01 %.

The main advantage of this gauge is that it is inexpensive, compact and rugged type of mechanical device. Further, it is simple in operation and does not need as skilled operator. However, it is not suitable for dynamic pressure calibrations.

11.4.3 Dynamic Calibration of Pressure Gauges

Dynamic calibration of pressure measuring instruments is quite involved. In order to determine the use-fulness of these instruments under dynamic conditions, special testers based on the frequency response or transient types of tests, have to be used. Figure 11.37 shows a harmonic steady state test apparatus. The shaker, which may be of electrodynamic or mechanical type, is used to create sinusoidal variations in pressure at desired frequencies. The reference transducer should have a flat frequency response over the test frequencies and the performance of the test transducer can be compared against the same.

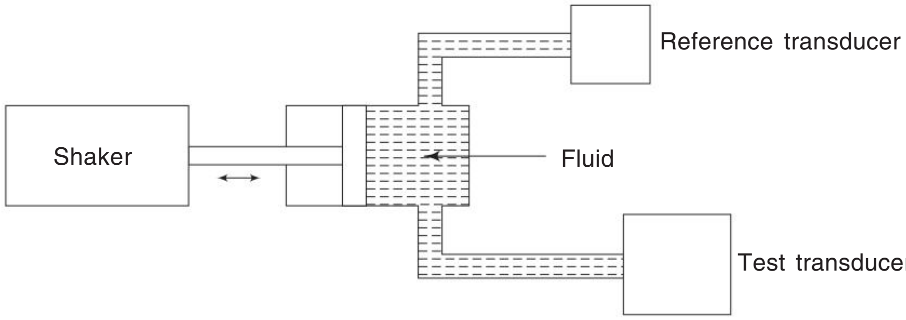

Fig. 11.37 Frequency response tester

Transient tests can be carried out using a shock tube or by using steel balls, dropped on to the elastic member of the pressure transducer. In a shock tube (Fig. 11.38) the bursting of a thin diaphragm, subjected to gas pressure, creates a nearly step pressure. The diaphragm is burst by either pressure differential or an external probe.

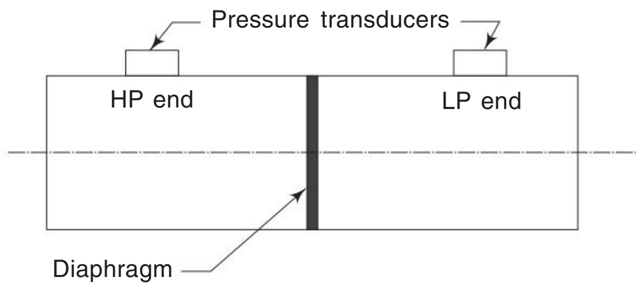

Fig. 11.38 Shock tube

11.5 SUMMARY OF PRESSURE RANGES OF VARIOUS PRESSURE AND VACUUM GAUGES — LO 6

Table 11.1 gives the approximate range for various types of pressure measuring devices discussed in this chapter.

Table 11.1 *Approximate range for different pressure measuring devices*

Type of measuring device	*Pressure range*
Manometer	10 to 10^6 Pa
Bourdon gauge	10^3 to 7×10^8 Pa
Elastic diaphragm with LVDT or capacitance or resistance strain gauge transducer	100 to 10^8 Pa
Piezo-electric transducer	10^4 to 10^8 Pa
Hydrostatic compression gauge	100 to 10^5 atm
McLeod gauge	10^{-5} to 1 Torr
Pirani gauge	10^{-4} to 1 Torr
Ionisation gauge	10^{-8} to 10^{-3} Torr
Knudsen gauge	10^{-8} to 10^{-2} Torr

Review Questions

11.1 Indicate true or false against each of the following:

(a) Fluid pressure is independent of momentum exchange between the molecules of the fluid and a containing wall.

(b) Pressure readings can be negative if measurements are taken in 'gauge pressure' scale.

(c) In a U-tube manometer, the location of the pressure source does not affect the pressure measurements.

(d) In a well type manometer, the ratio of cross-sectional areas of the well and the tube is not the factor that determines the scale of the manometer.

(e) Accuracy of a manometer is affected by the shape or size of the tubes.

(f) In Bourdon pressure gauge, incorrect readings may be encountered due to hysteresis.

(g) For dynamic pressure measurement, the natural frequency of an elastic diaphragm should be lower than the frequency of the pressure signal.

(h) A piezo-electric pressure transducer can be used for measuring both static and dynamic pressures.

(i) A resistance strain gauge type pressure transducer cannot be used for dynamic pressure measurement.

(j) Calibration of the McLeod gauge can be directly related to the physical dimensions of the gauge, independent of nature of the gas being used.

(k) Vacuum levels lower than 1 micron can be measured with an ionisation gauge.

(l) Pressures higher than 10 atm are usually regarded as very high.

(m) Pressures of the order of 1 mmHg or below are usually regarded as very low.

(n) An inclined tube manometer is more accurate if the inclination of the tube with the vertical is high.

(o) Any metallic coil may be used as a sensor for measuring high pressure.

(p) In a bulk compression effect type of the high-pressure measurement device, the sensitivity increases with the increase in Young's modulus of the wire.

(q) Knudsen vacuum gauge is used for measuring pressure of the order of 1 Torr.

11.2 A mercury manometer has one arm in the shape of a well and the other as a tube inclined at 30° to the horizontal. The well is 4 cm in diameter and the tube 5 mm in diameter. Find the percentage error if no area correction factor is used.

11.3 For a McLeod gauge, with a capillary of 1 mm diameter and effective bulb volume of 80 cm^3, find the reading as indicated by mercury column due to a pressure of 10 Pa.

11.4 A variable capacitance transducer is shown in Fig. 11.39. The housing is made of steel. Find the pressure sensitivity (μF/F per Pa), fundamental natural frequency of vibrations of the diaphragm and maximum allowable pressure for which the transducer may be used.

11.5 A very high-pressure gauge, using a manganin element is to measure a maximum pressure of 10^8 Pa. The wire diameter is 25 μm, length is 3 cm. Pressure sensitivity of wire material is 2.5×10^{-11} Ω/Ω-Pa, resistively 45×10^{-6} Ω-cm. The wire forms one arm of a Wheatstone bridge, with resistances of all arms being equal. If the supply voltage is 12 V, find the output voltage due to maximum pressure.

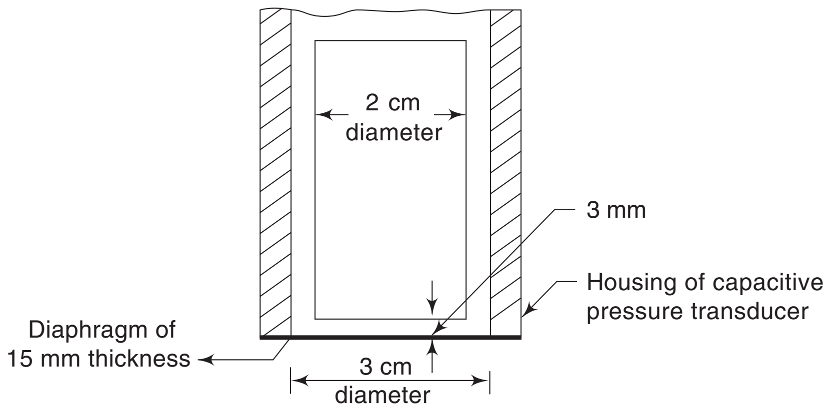

Fig. 11.39

11.6 A pressure tapping is taken from a measuring point by means of a tubing 50 cm long, 5 mm bore to a U-tube manometer using water as the working liquid. The tubes are of 10 mm bore. To start with, the water level is 30 cm below the top of the tube. Taking viscosity of air as 1.78×10^{-5} kg/m-s, find the time constant of the system if a small change occurs in the pressure which is around atmospheric.

11.7 Design a resistance strain gauge type pressure transducer, with the following specifications:
Maximum pressure, to be measured = 2 bar
Diameter of steel diaphragm = 8 cm
Size of resistance gauges used = 3 mm × 6 mm
Resistance of each gauge = 120 Ω
Gauge factor = 2
Find the thickness of the diaphragm, sensitivity of the transducer and other parameters of the transducer.

11.8 It is required to measure and plot the pressure in the cylinder of a single cylinder reciprocating air compressor, at several positions in a cycle. Suggest a suitable measuring system, and mention the type of sensor, signal conditioning and recording elements. Draw a sketch and suggest a calibration system.

Answers

11.1	(a) F	(b) T	(c) F	(d) F	(e) F
	(f) T	(g) F	(h) F	(i) F	(j) T
	(k) T	(l) F	(m) T	(n) T	(o) F
	(p) F	(q) F			

11.2 3.03%.
11.3 8.74 cm.
11.4 (a) 1.69×10^4 Hz
(b) 40.44 MPa
(c) 25.6 μF/(F–Pa)
11.5 7.5 mV
11.6 4.65×10^{-3} s
11.7 1.06 mm
1.135×10^{-9}/Pa