Pressure Measurement

Pressure is one of the most important variable that affects most of the processes. Many other properties of systems are affected by the operating pressure. For example, in I.C. Engine cylinder, the pressure varies continuously with time and determines the power output of the engine. Chemical reactions affected by the operating pressure.

Pressure is not a primary quantity, but its derived from force and area. They are in turn functions of mass, length and time. Pressure is measured in static systems and in moving fluid systems.

Following are the reasons why pressure has to be closely measured in processes:

- Pressure is an important quantity that describes a thermodynamic system.
- Pressure is invariably an important process parameter.
- Pressure difference is used many a time as a means of measuring the flow rate of a fluid.

Before we look at the various pressure measuring devices let us look at some of the pressure measuring quantities:

- 1 Pascal or 1 Pa = 1 N/m^2
- 1 atmosphere or 1 atm =760 mm mercury column = 1.013×10^5Pa
- 1mm mercury column = 1 Torr
- 1 Torr = 1.316×10^{-3} atm= 133.3Pa
- 1 bar = 10^5 Pa

The gauge pressure scale is measured relative to some absolute reference pressure, which is defined in a manner convenient to the measurement. The relation between an absolute pressure, P_{abs}, and its corresponding gauge pressure, P_{gauge}, is given by

$$P_{gauge} = P_{abs} - P_o$$

where P_o is a reference pressure. A commonly used reference pressure is the local absolute atmospheric pressure. Absolute pressure is a positive number. Gauge

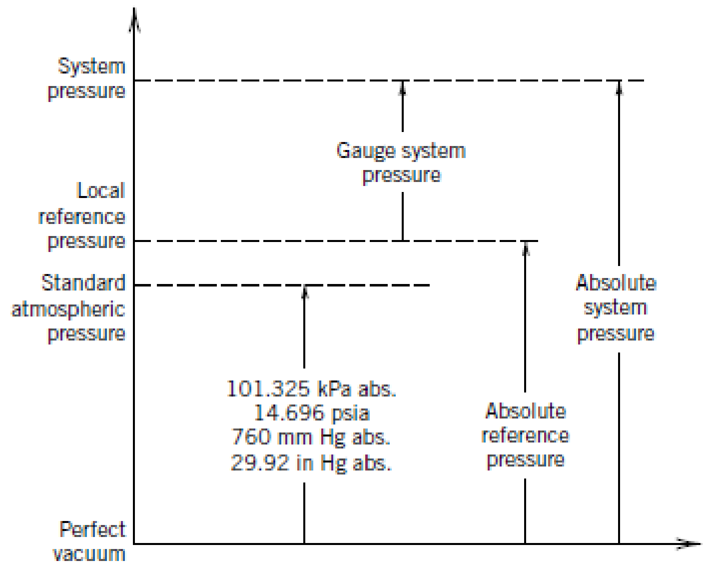
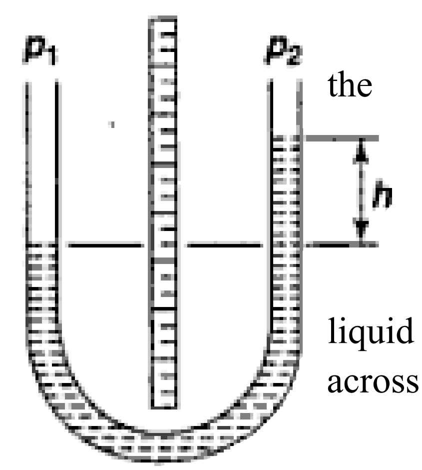


Figure 1:Relative pressure scale

pressure can be positive or negative depending on the value of measured pressure relative to the reference pressure. A differential pressure, such as P_1 - P_2, is a relative measure of pressure.

U-Tube Manometers

The simplest of the gauges that is used for measuring pressure is a U-tube manometer. The U-tube which has a uniform bore is vertically oriented and the acceleration due to gravity is assumed to be known. The height difference 'h', between the levels of the manometer liquid in the two limbs of the U-tube is the measured quantity. The quantity to be measured, the pressure , is thus converted to the measure of length, the height of the liquid column. The pressure to be measured is that of a system that involves a fluid(liquid or a gas) different from the manometer. Let the density of the fluid whose pressure being measured be ρ_m. Equilibrium of the manometer liquid requires that there be the same force in the two limbs across the plane A-A. We then have



U-tube manometer

$$p + \rho_f gh = p_a + \rho_m gh$$

This may be re-arranged to read

$$p - p_a = (\rho_m - \rho_f)gh$$

Even though mercury is a common liquid used in manometers, other liquids are also used. A second common liquid used is water. When measuring pressures close to the atmospheric pressure in gases, the fluid density may be quite negligible in comparison with the manometer liquid density. One may then use the appropriate expression.

$$p - p_a \sim \rho_m gh$$

The manometer liquid is chosen based on its density with respect to the density of the fluid whose pressure is being measured. Indeed small pressure difference are measured using mater or some organic liquid as the manometer liquid such that the height h measured is sufficiently large and hence estimated with sufficient precision.

The desirable properties of manometric fluid are

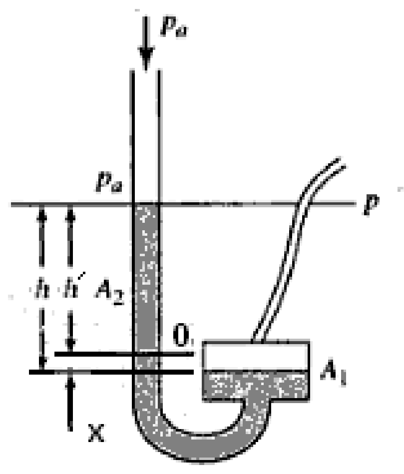
i. It should be non-corrosive and not have any chemical reaction with the fluid of which pressure is being measured. It should not absorb the gas of which pressure is being measured.
ii. It should have low viscosity and thus gives faster response to pressure change. It should move freely in the limbs of the manometer.
iii. It should have negligible surface tension and capillary effects. It should not wet the walls of tubes and wells.
iv. It should have reasonably high density so that the pressure balancing column stays within a desirable limit.
v. The manometric fluid should not be compressible.

Sources of error in manometers

a. Capillary effect due to surface tension may give wrong readings.
b. Thermal expansion of the fluid as well as readout scale may cause error.

c. Compressible fluid may change calibration (air bubble in the fluid may introduce compressibility).
d. Evaporated fluid at low pressure and/or high temperature can introduce inaccuracy

Well type manometer



Well-type manometer.

A well type manometer is used instead of a U- tube manometer. The advantage of the well type manometer is that it has a single vertical tube of small bore being provided with a large quantity of manometer liquid in a reservoir, referred to as the "well". The height reading is taken using a scale attached to the vertical tube, with respect to an unchanging datum which corresponds to the level when the pressure difference between the well side and the tube side is zero.

The zero line indicates the datum with reference to which the manometer height is measured. The advantage of a well type design is that relatively large pressure differences may be measured with enough manometer liquid being available for doing so.

$$h' . A_2 = x . A_1$$

$$= (h - h'). A_1$$

Using expression $p_1 - p_2 = hg\,(\rho_m - \rho_f)$ for this manometer.

$$p - p_a = h'(A_2/A_1 + 1)\, g.(\rho_m - \rho_f)$$

Inclined Tube Manometer

Inclined tube manometer is another device which is sensitive and convenient to use. It is essentially a U tube manometer with one tube leg inclined at an angle, typically 10-30^o relative to horizontal.

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

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

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

$$A_1 h_1 = A_2 l$$
$$h_2 = l \sin \theta$$

- From the above equations we get

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

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

$$p_1 - p_2 = \rho g l \sin \theta = \rho g h_2$$

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

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

$$A_1 h_1 = A_2 l$$
$$h_2 = l \sin \theta$$

- If q = 30^o then l=2h_2 and thus it would be more accurate to read l rather than h_2 as the output

- Since A_1>>A_2 the reading on one side only viz. l is required.

- Thus the change in pressure equivalent to deflection of height h in a U tube manometer would bring about a change in position of meniscus in the inclined leg of l (=h/sinq). This provides increased sensitivity over the conventional U tube manometer by a factor of 1/sinq

Micromanometers

- For increased accuracy in reading the output of the manometer the liquid levels can be measured with manometer heads. The contact between the micrometer movable points and the liquid may be sensed visually or electrically.

- A variation of this in order to minimise capillary and meniscus errors is movable tube type micromanometer. These special purpose manometers are used to measure very small differential pressures, down to 0.005 mm H_2O. In this device manometer well is moved up or down until the level of the manometer fluid within the well is at the same level as a set mark checked with magnifying sight glass. At this point manometer meniscus is at set mark this position serves as a reference position.

- Changes in the pressure bring about fluid displacement so that the well must be moved up or down to bring the meniscus back to set mark. The amount of repositioning is equal to the change in equivalent pressure head. The position of the reservoir (well) is controlled by micrometer so that relative changes in pressure can be measured with a high resolution.

- Other calibrated displacement measurement device can also be used in place of micrometer.

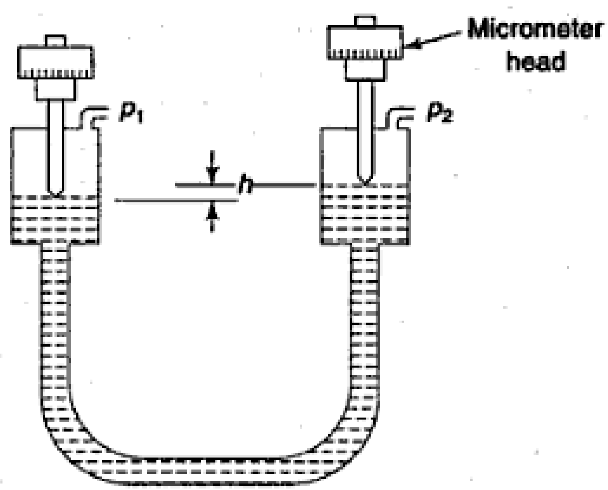
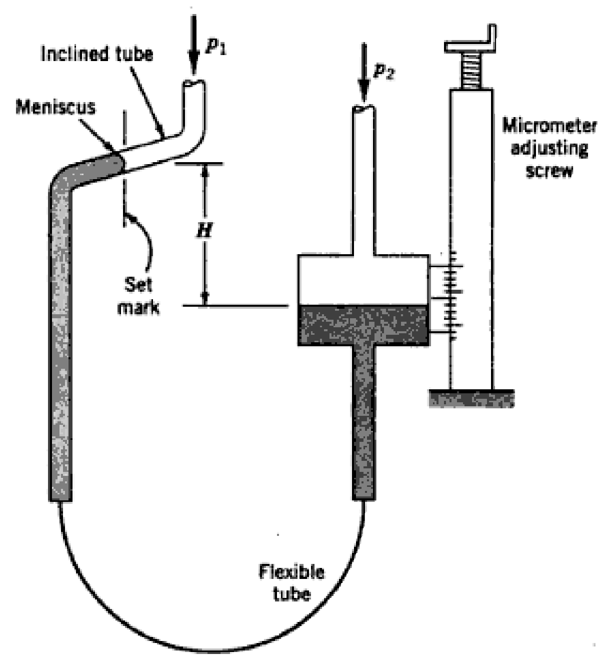


Fig. *Micrometer type manometer*



Micromanometer.

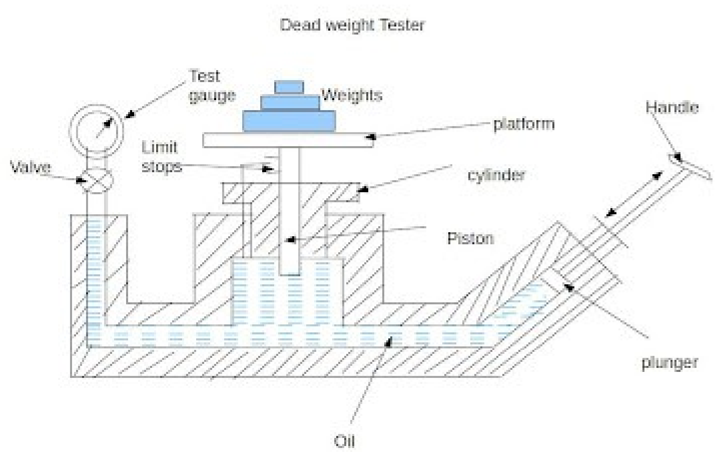
Dead Weight Tester

Description

The dead weight tester apparatus consists of a chamber which is filled with oil free impurities and a piston – cylinder combination is fitted above the chamber as shown in diagram. The top portion of the piston is attached with a platform to carry weights. A plunger with a handle has been provided to vary the pressure of oil in the chamber. The pressure gauge to be tested is fitted at an appropriate plate.

Operation

The dead weight tester is basically a pressure producing and pressure measuring device. It is used to calibrate pressure gauges. The following procedure is adopted for calibrating pressure gauges. Calibration of pressure gauge means introducing an accurately known sample of pressure to the gauge under test and then observing the response of the gauge. In order to create this accurately known pressure, the following steps are followed.



The valve of the apparatus is closed.
A known weight is placed on the platform.
Now by operating the plunger, fluid pressure is applied to the other side of the piston until enough force is developed to lift the piston-weight combination. When this happens, the piston weight combination floats freely within the cylinder between limit stops.

In this condition of equilibrium, the pressure force of fluid is balanced against the gravitational force of the weights puls the friction drag.

$$\text{Therefore, } P_A = Mg + F$$

$$\text{Hence : } P = Mg + F / A$$

where, P = pressure
M = Mass; Kg
g = Acceleratoion due to gravity ; m/s^2

F = Friction drag; N
A = Eqivalent area of piston – cylinder combination; m^2

Thus the pressure P which is caused due to the weights placed on the platform is calculated.

After calculating P , the plunger is released.

Now the pressure gauge to be calibrated is fitted at an appropriate place on the dead weight tester. The same known weight which was used to calucate P is placed on the platform. Due to the weight, the piston moves downwards and exerts a pressure P on the fluid. Now the valve in the apparatus is opened so that the fluid pressure P is transmitted to the gauge, which makes the gauge indicate a pressure value. This pressure value shown by the gauge should be equal to the known input pressure P. If the gauge indicates some other value other than p the gauge is adjusted so that it reads a value equal to P. Thus the gauge is calibrated.

Applications:

It is used to calibrate all kinds of pressure gauges such as industrial pressure gauges, engine indicators and piezoelectric transducers.

Advantages:

- It is simple in construction and easy to use.
- It can be used to calibrate a wide range of pressure measuring devices. Fluid pressure can be easily varied by adding weights or by changing the piston cylinder combination.

Limitations:

- The accuracy of the dead weight tester is affected due to the friction between the piston and cylinder, and due to the uncertainty of the value of gravitational constant 'g'.

Bourdon Gauge

Where indication of the static pressure is required, a Bourdon tube gauge is used. They cannot be used for measuring other than slowly changing pressures; for pulsating pressures, a pressure transducer with electronic instrumentation must be used.

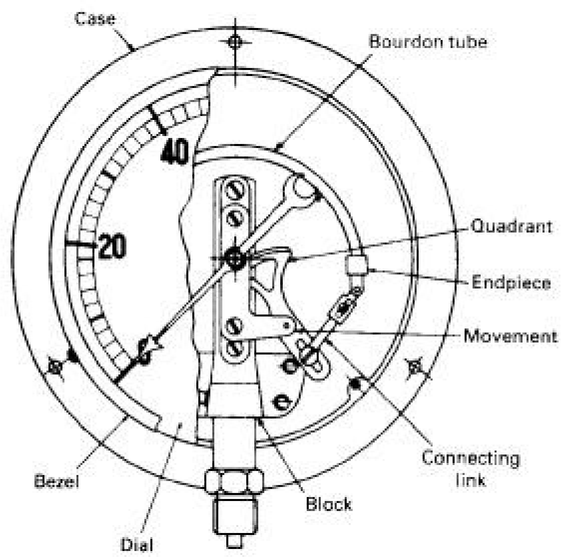


FIGURE 1 – Typical arrangement of Bourdon gauge.

The basic element is a thin walled tube, slightly flattened in section and bent into a ‘C’ shape. Under pressure the flattened section tends to become circular and the tube straightens. One end of the tube is fixed and the free end is sealed and attached to a mechanical linkage. Application of internal pressure to the tube causes it to straighten by an amount directly proportional to the internal pressure. The resulting movement of the free end is transmitted via a mechanical linkage to rotate a pointer associated with a graduated dial. This mechanical movement involves multiplication so that about 300 ° of pointer rotation is achieved over the working pressure range of the gauge.

The accuracy achieved with a Bourdon tube gauge is better than +2.5% of the full scale deflection. Greatest accuracy is achieved at the upper end of the scale. Thus selection of a gauge of this kind should be based on a pressure range where the normal reading point will be near the upper end of the scale; bear in mind that the actual pressure is likely to exceed the nominal system pressure through the operation of the compressor. The gauge should always be chosen so that its maximum pressure is in excess of any relief valve in the system. Consistency of performance is related to the fatigue characteristics of the tube material and some drift with time is inevitable. Pressure gauges need regular checking and re-calibration where necessary using a dead weight calibration method.

Bourdon tube gauges are susceptible to mechanical shock and pressure surges; they should be protected against both of these. A simple method of protection against pressure surges is to fit a snubber or restriction in the feed line. In severe cases, mechanical throttling or a shut off device responding directly to any sudden increase in pressure may be employed.

Another source of trouble is blocking of the tube by contaminants in the air. This can be overcome by incorporating a flexible diaphragm in the line to the gauge. The tube can then be filled with a clean fluid which is separated from the air by the diaphragm . The fluid used must be stable at the operating temperature. Commonly used fluids are glycerine and ethylene glycol. The principle can be extended by using the diaphragm unit as a transmitter, separated from the gauge by a length of tubing. The advantage of this is that the gauge can be some distance from the transmitter without affecting the readings.

Pressure Transducers

- Pressure tube with Bonded strain gauge
- Diaphragm/Bellows type transducer
- Capacitance Pressure transducer
- Piezo-electric transducer

Pressure tube with Bonded strain gauge

The principle of a pressure tube with bonded strain gauge. The pressure to be measured is communicated to the inside of a tube of suitable wall thickness, one end of which is closed with a thick plate. Because the end plate is very thick it undergoes hardly any strain. The tube experiences a hoop strain due to internal pressure. A strain gauge mounted on the tube wall experiences the hoop strain. The quantity to be measured, the pressure , is thus converted to the measurement of a change in length of a strain element. The strain gauge element itself responds to the strain in a material on which it is attached.

Strain gauge consists of a resistance element whose resistance is a function of its size. A wire subject to strain undergoes a deformation. Electrical resistance of a wire of Length L, area of cross section A and made of a material of specific resistance ρ is given by

$$R=\frac{\rho L}{A}$$

Logarithmic differential gives,

$$\frac{dR}{R}= \frac{d\rho}{\rho} + \frac{dL}{L} - \frac{dA}{A}$$

The specific resistance is a strong function of temperature but a weak function of pressure. Since the rate of change of density is small we can neglect it.

$$\frac{dR}{R}= \frac{dL}{L} - \frac{dA}{A}$$

Let us consider the wire is of circular cross section. Then $A=\Pi r^2$.

$$\frac{dA}{A} = 2\frac{dr}{r}$$

Poisson's ratio is defined as the ratio of lateral strain to longitudinal strain. Hence we have,

$$\frac{dA}{A} = 2\frac{dr}{r} = -2\frac{v.dL}{L}$$

Hence, we get,

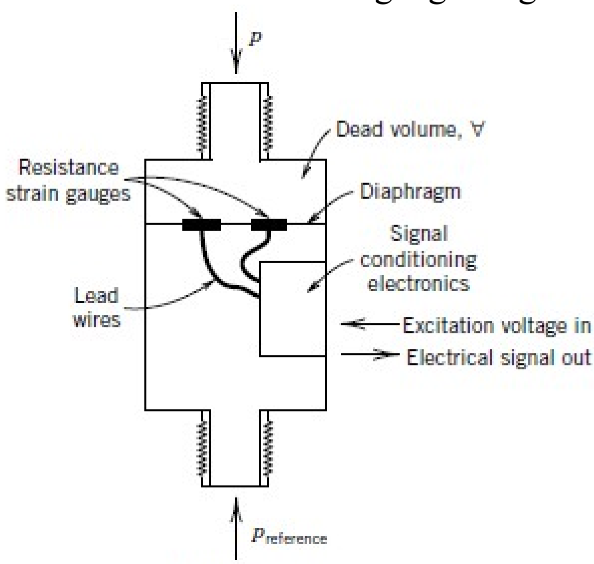
$$\frac{dR}{R}= (1+2v)\frac{dL}{L} = (1+2v)\,e$$

The ratio of fractional resistance change of the wire to the longitudinalstrain is called the gauge factor (GF) or sensitivity of the strain gauge.

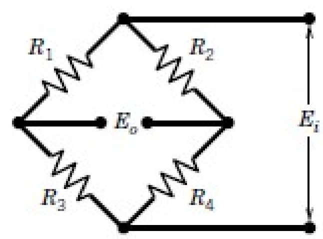
$$G.F = \frac{1}{e}\frac{dR}{R} = (1+2v)$$

Construction

The strain gauge is a serpentine metal layer obtained by etching , mounted on to the surface whose strain needs to be measured. When a force is applied to this direction the serpentine metal layer opens up like a spring and hence does not undergo any strain in the material. When the lengths of the metal foil changes the resistance is the measured quantity. Connecting wires are used to connect the strain gauge to the external circuit. By making the element in the form of a serpentine foil the actual length of the element is several times the length of longer side of the element. The gauge length may vary from 0.2 to 100mm.



(a) Sensing scheme



(b) Bridge–strain gauge circuit for pressure diaphragms.

Diaphragm / Bellows type transducer

Pressure signal is converted to a displacement in the case of diaphragm / bellows type pressure gauge. The diaphragm or bellows acts as a spring element that undergoes a displacement under the action of pressure. Here Linear Variable Differential transformer (LVDT) is used as a displacement transducer- a transducer that measures displacement by cinverting it to an electrical signal.

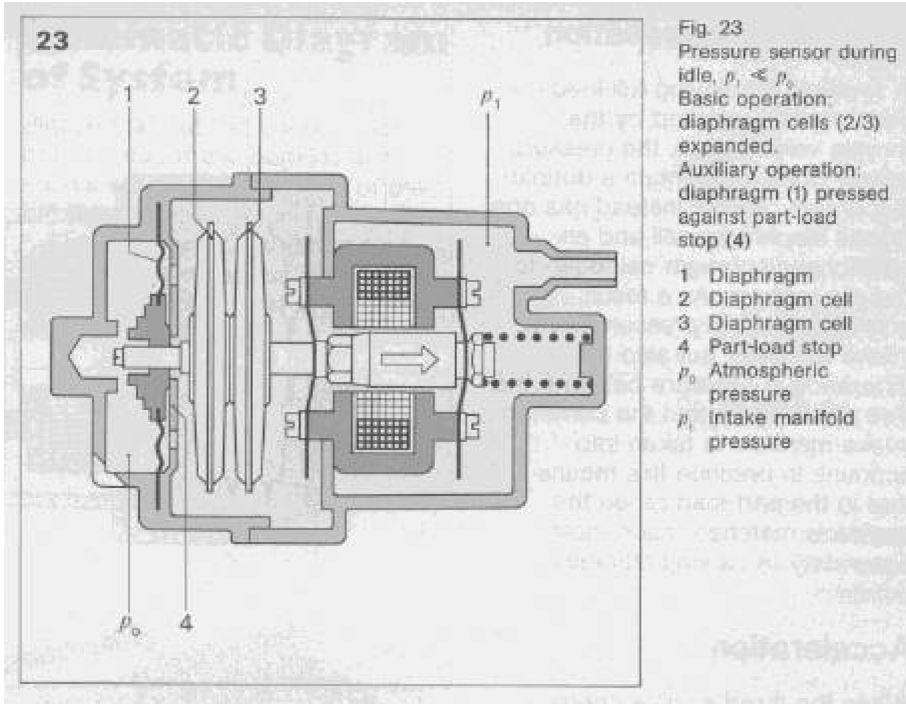
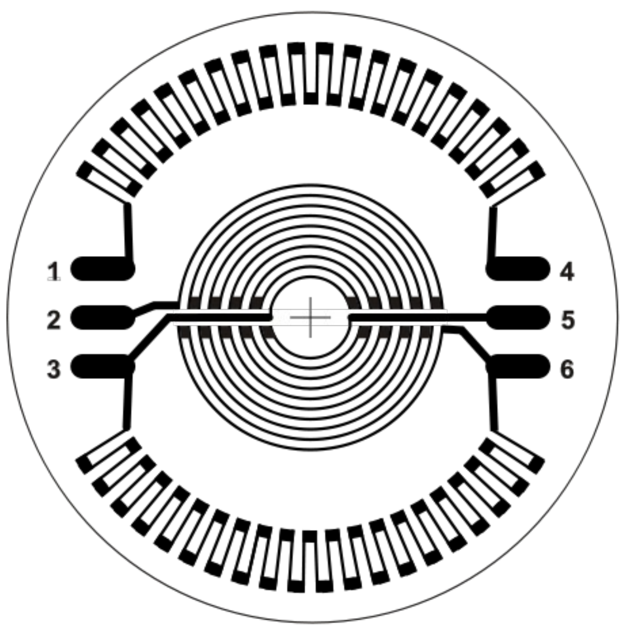


Fig. 23
Pressure sensor during idle, $p_i \ll p_0$
Basic operation: diaphragm cells (2/3) expanded.
Auxiliary operation: diaphragm (1) pressed against part-load stop (4)

1 Diaphragm
2 Diaphragm cell
3 Diaphragm cell
4 Part-load stop
p_0 Atmospheric pressure
p_i Intake manifold pressure

Diaphragm pressure gauge with strain gauges

In case of diaphragm type gauge one may also use a strain gauge for measuring the strain in the diaphragm by fixing it at a suitable position on the diaphragm.



Strain Gauge mounted on the diaphragm

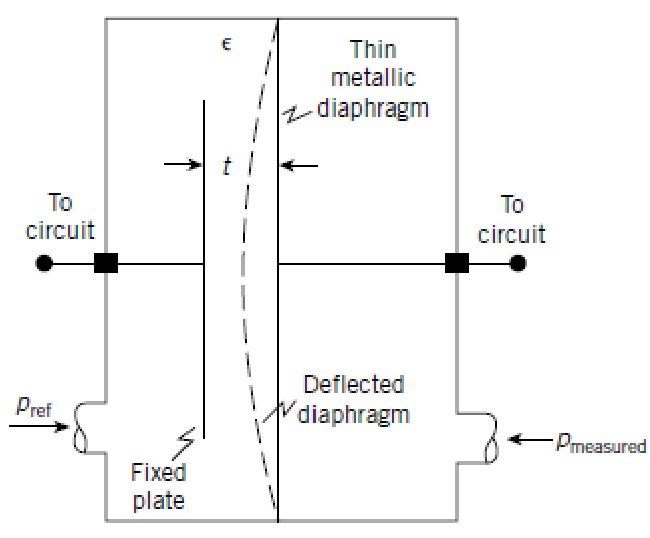
Capacitance Type diaphragm Gauge

Another common method to convert diaphragm to a measurable signal is capacitance sensor. One version uses a thin metallic diaphragm as one plate of capacitor paired with a fixed plate to complete the capacitor. The diaphragm is exposed to the process pressure on one side and to a reference pressure on the other or to a differential pressure. When pressure changes, so as to deflect the diaphragm, the gap between the plates changes, which causes a change in capacitance.

The capacitance C developed between two parallel plates separated by average gap t is determined by

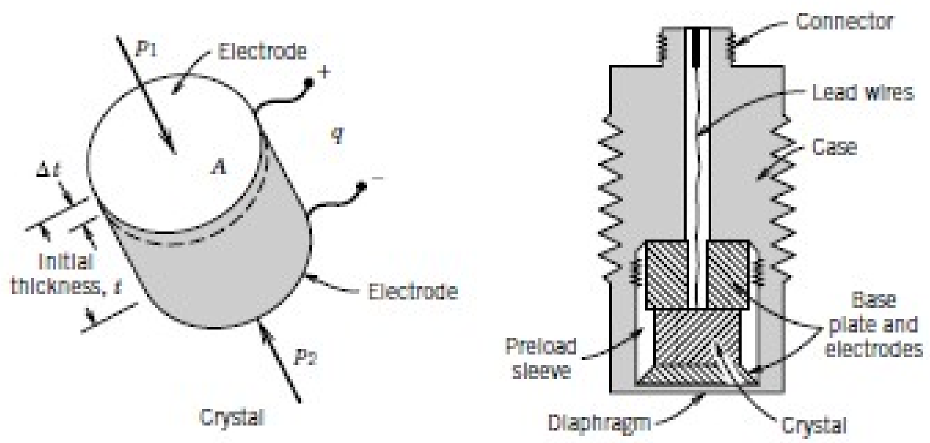
$$C = c.\varepsilon.A/t$$

Where the product c. ε is the permittivity of the material between the plays relative to a vacuum ($\varepsilon = 8.85 \times 10^{-12}$F/m; c= di-electric constant), and A is overlapping area of the two plates. The di-electric constant depends on the material in the gap, which for air is c=1 but for water is c = 80. The capacitance responds to an instantaneous change in the area-averaged plate gap separation from which the time- dependent pressure is determined. However, the capacitance change is small relative to the absolute capacitance. Oscillator and bridge circuits are commonly used to operate the circuit and to measure the small capacitance change providing an output voltage E_o.



Piezoelectric Pressure Transducer

Piezoelectric crystals form effective secondary elements for dynamic pressure measurements. Under the action of compression, tension, or shear, a piezoelectric crystal deforms and develops a surface charge “q”, which is proportional to the force acting to bring about the deformation. In a piezoelectric pressure transducer, a pre-loaded crystal is mounted to the diaphragm sensor. Pressure acts normal to the crystal and changes the crystal thickness t by a small amount Δt.



Piezoelectric Pressure transducer

This sets up a charge, $q=K_q pA$, where p is the pressure acting over the electrode area A and K_q is the crystal charge sensitivity, a material property. A charge amplifier is used to convert charge to voltage so that the voltace developed across the electrodes is

$$E_o = q/C$$

Where C is the capacitance of the crystal- electrode combination.

$$E_o=K_q\ tp/c\varepsilon = Kp$$

Where K is the overall transducer gain. The crystal sensitivity for quartz, the most common material used is $K_q=2.2 \times 10^{-9}$ coulombs/N.

- **Electrostatic PZT**: Electrostatic charge is developed across piezoelectric crystal, proportional to the force applied on it. This can be used to measure pressure as pressure is force per unit area. However the static charge decays rapidly and hence the signal. Therefore electrostatic PZT sensors are unsuitable for measurement of static pressure, but they can be used for dynamic measurement.

  The electrostatic PZT sensors are small and rugged. The pressure can be applied in longitudinal or transverse direction. In either case high output voltage, proportional to pressure is generated. Their high speed response make them suitable for measuring transient phenomena like rapidly changing pressures from explosions or other sources of shock and vibrations.

- **Piezoresistive PZT:** The resistivity of silicon depends on the force applied on it. The Piezoresistive pressure sensors operate on this principle of measurement of resistivity of silicon. In a piezoresistive sensor four pairs of silicon resistors are bonded onto a diaphragm similar to strain gauge, but the difference is in the construction. Here the diaphragm itself is a silicon wafer and sensing resistors are diffused into it during growth of the wafer.

  Piezo resistive sensors can be used to measure pressure between 21 kPa to 100 MPa. Since piezoresistivity does not decay with time, one can measure static pressure with these sensors.

- **Resonant PZT:** These sensors utilize the variation of the resonant frequency of PZT crystals when force is applied to them. The sensor can be in the form of a suspended beam, can be made to oscillate through the inverse piezoelectric effect by applying an oscillating electric field. The change in resonant frequency is related to the applied pressure.

  These transducers can be used to measure pressure between 0 MPa and 6 MPa in different spans.

- **Advantages of PZT :-**

  - Small in size, lightweight and very rugged
  - Electrostatic PZT may cover dynamic pressure range of $1:10^5$ and frequency range from 2 Hz to 1 MHz

– Outputs are quite large
– Special units operate up to 350ºC

- **Disadvantages of PZT :-**
  – The electrostatic type cannot measure static pressure for more than a few seconds.
  – All types are temperature sensitive and need temperature compensation.

Vibrating Element Transducer

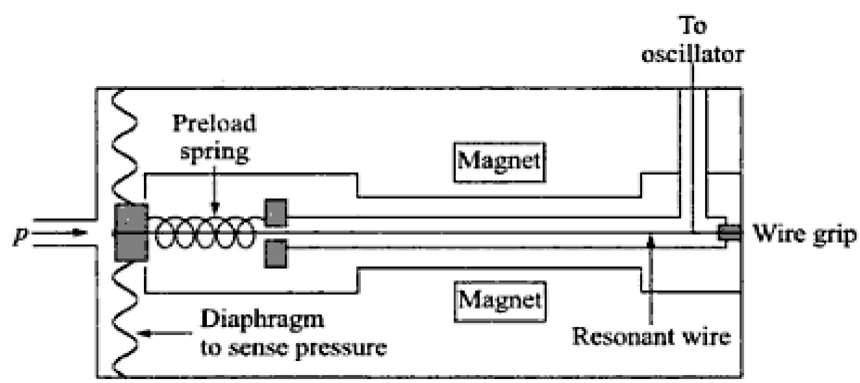


Fig. Resonant wire secondary pressure transducer.

- The vibrating element used in this transducer would be a wire or a cylinder, which resonates at the frequency.

$$\nu = \frac{1}{2\pi}\sqrt{\frac{T}{m}}$$

Where n is the frequency of vibration, T is the tension and m is mass per unit length of the wire. As a secondary transducer for pressure measurement, the tension in wire is altered by the pressure signal by means of a primary elastic element sensor like diaphragm. An oscillating voltage supplied by an oscillator is fed to the wire which is placed between the pole pieces of a magnet. This causes wire to vibrate. The oscillator frequency is tuned to cause a resonant vibration. A change in the pressure, sensed by the diaphragm changes the wire tension, which in turn changes the resonant frequency of the wire. A digital counter can detect the frequency shift and the same is calibrated in terms of the pressure change.

Measurement of vacuum

Pressure below the atmospheric pressure is referred to as vacuum pressure. The gauge pressure is negative when we specify vacuum pressure. It is possible to use, U-tube manometers, bourdon gauges for measurement of vacuum as long as it is not high vacuum. In the case of a U-tube with mercury as the manometer liquid we can practically go all the way down to -760 mm mercury but there is no way of using it to measure vacuum pressures involving a fraction of a mm of mercury. A U-tube manometer can thus be used for rough measurement of vacuum. A Bourdon gauge capable of measuring vacuum pressure will have the zero somewhere in the middle of the dial with the pointer going below zero while measuring vacuum, and the pointer going above zero, while measuring pressures above the atmosphere.

McLeod gauge

McLeod gauge is basically a manometric method of measuring a vacuum pressure that is useful between0.01 and 100μm of mercury column.

A known volume (V) of gas at vacuum pressure(p), given by the volume of the capillary , the bulb and the bottom tube up to the opening, is trapped by lowering the movable reservoir down to the appropriate extent. It is then slowly raised till the level of the manometer liquid in the movable reservoir is in line with the reference level marked on the stem of the forked tube. This operation compresses the trapped gas to a pressure (p_c) equivalent to the head y. The corresponding volume of the gas is given by the clear volume of the capillary V_c=ay where a is the area of cross section of the capillary. The gauge is exposed to the ambient and hence remains at the ambient temperature throughout this operation.

Since, the entire process is isothermal Boyle's law holds and hence we have

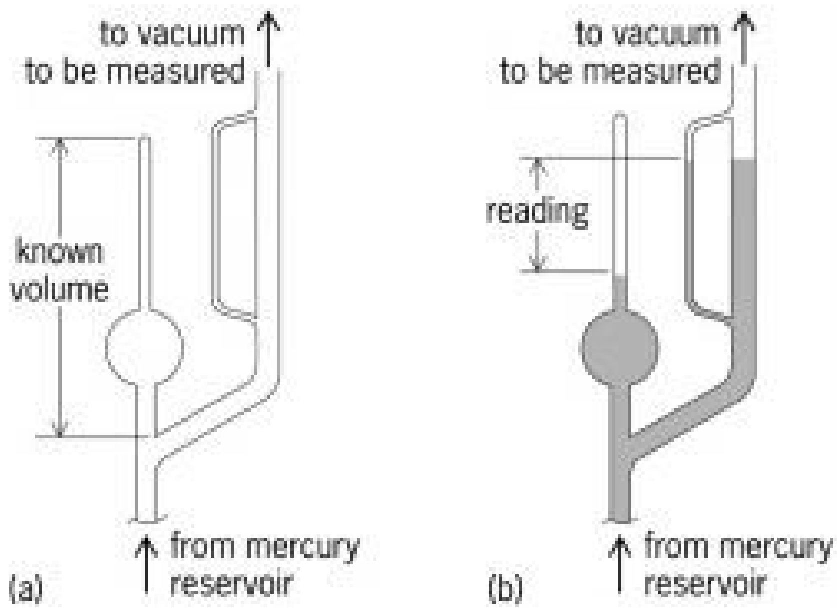
$$pV = p_c V_c = p_c a y$$

Manometer gives,

$$p_c - p = y$$

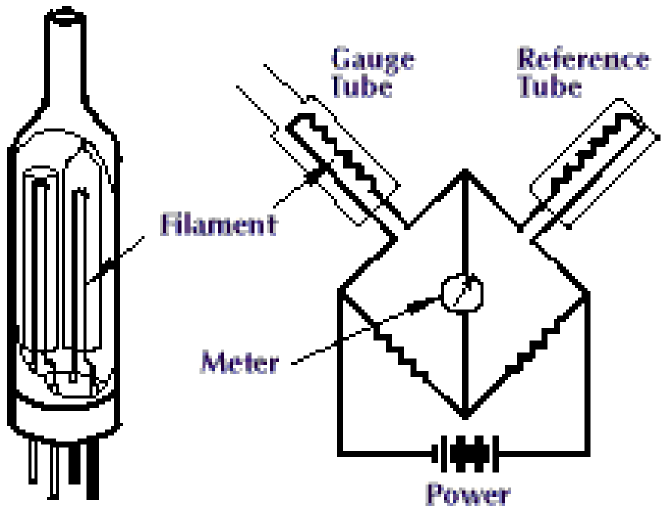
Eliminating p_c from the equation, we get,

$$p = \frac{ay^2}{V-ay} = \frac{ay^2}{V}$$

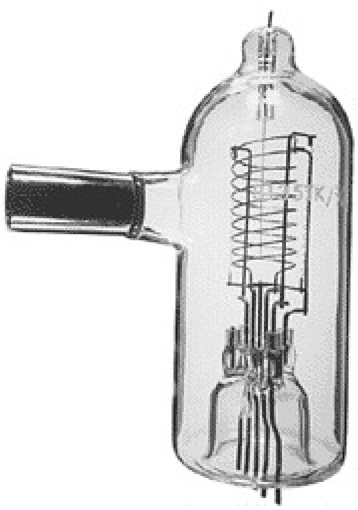


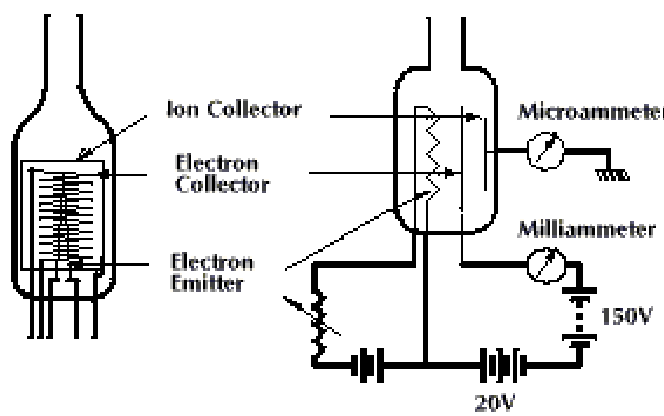
Pirani Gauge

Another gauge for measuring vacuum is the Pirani gauge. The temperature of a heated resistance increases with a reduction of the background pressure. This is due to the reduction of rate of heated transfer from the filament to the environment. The rise in temperature changes its resistance just as we found in the case of RTD. The pirani gauge consists of two resistance connected in one arm of the bridge. One of the resistors is sealed in after evacuating its container while the other is exposed to the vacuum space whose pressure is to be measured. Ambient conditions will affect both the resistors alike and hence the gauge will respond to only the changes in the vacuum space whose pressure is to be measured. The Pirani gauge is calibrated such that the imbalance current of the bridge is directly related to vacuum pressure being measured. The range of this gauge is from 1µ m mercury to 1mm mercury that corresponds to 0.1-100 Pa absolute pressure range.



Ionization Gauge



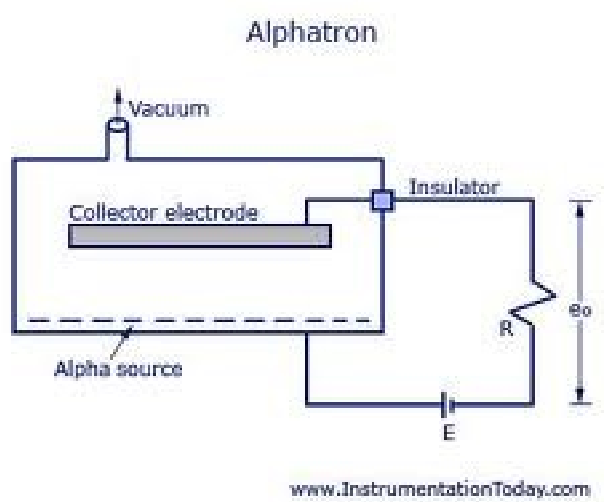


Very high vacuum pressures are measured using an ionization gauge. The ion gauge is similar to a triode valve which was used in radio reciever built with respect to the cathode. The high speed electrons suffer collisions with the molecules of the residual gas in the bulb and ionizes thses gas modules. The electrons move towards the grid and manifest in the form of grid i_g. The positive ions move towards the plate that is maintained at a potential negative with respect to the grid. These ions are neutralized at the plate and consequently we have the plate current i_p. The pressure in the bulb is then given by

$$p = \frac{1}{S}\frac{i_p}{i_g}$$

Here S is a proportionality called the ionization gauge sensitivity. S has typical value of 200 $Torr^{-1}$. Or 2.67 kPa^{-1}. The gauge cannot be used when the pressure is greater than about 10^{-3} Torr since the filament is likely to burn off.

Alphatron Gauge



In the alphatron gauge, ionization of the residual gas is brought about by alpha particles that are emitted by a radioactive material. The gauge is similar to a common smoke detector in its operation. Since there is no hot cathode as in the case of ion gauge considered earlier, the gauge may be exposed to the atmospheric pressure without any fear of losing a filament. The rate of ion production is dependent on the residual pressure is the same as the vacuum pressure that is being measured. A collector electrode is maintained at a positive potential. The ion current produces a potential drop V_o across the load resistor and this is indicative of the pressure. The output is fairly linear over the entire range from1 milliTorr to the atmospheric pressure or 0.1 to 10^5Pa