Unit – V: Measurement of Power and Temperature

Measurement of Power and Temperature

Technical Terms

- **Force:** The mechanical quantity which changes or tends to change the motion or shape of a body to which it is applied
- **Load Cells:** Load cells are devices for the force measurement through indirect methods
- **Torque:** Torque can be defined as a measure of the tendency of a force to rotate the body on which it acts about an axis.
- **Thermocouple:** When two dissimilar metals are joined together, it will create an emf it is primarily a function of the junction temperature.
- **Flow meter:** Flow meter is a device that measures the rate of flow or quantity of a moving fluid in an open or closed conduit.
- **Thermometry**: Thermometry is the science and practice of temperature measurement. Any measurable change in a thermometric probe can be used to mark temperature levels that should later be calibrated against an internationally agreed unit if the measure is to be related to other thermodynamic variables.
- **Resistance Temperature Detectors:** RTD as the name implies, are sensors used to measure temperature by correlating the resistance of the RTD element with temperature.
- **Dynamometer:** A dynamometer or "dyno" for short is a device used to measure power and torque produced by an engine.

3.1 Measurement of Force

The mechanical quantity which changes or tends to change the motion or shape of a body to which it is applied is called force. Force is a basic engineering parameter, the measurement of which can be done in many ways as follows:

- Direct methods
- Indirect methods

Direct methods, it involves a direct comparison with a known gravitational force on a standard mass, say by a balance.

Indirect methods, It involves the measurement of effect of force on a body, such as acceleration of a body of known mass subjected to force.

Devices to measure Force

- Scale and balances
  a. Equal arm balance
  b. Unequal arm balance
  c. Pendulum scale
- Elastic force meter (Proving ring)
- Load cells
  a. Strain gauge load cell
  b. Hydraulic load cell
  c. Pneumatic load cell

3.1.1 Scale and balances

a. Equal arm balance

An equal arm balance works on the principle of moment comparison. The beam of the equal arm balance is in equilibrium position.

when, Clockwise rotating moment = Anti-clockwise rotating moment

$M2L2 = M1L1$

That is, the unknown force is balanced against the known gravitational force.

Description

The main parts of the arrangement are a follows:

- A beam whose centre is pivoted and rests on the fulcrum of a knife edge. Either side of the beam is equal in length with respect to the fulcrum
- A pointer is attached to the center of the beam. This pointer will point vertically downwards when the beam is in equilibrium.
- A Provision to place masses at either end of the beam.

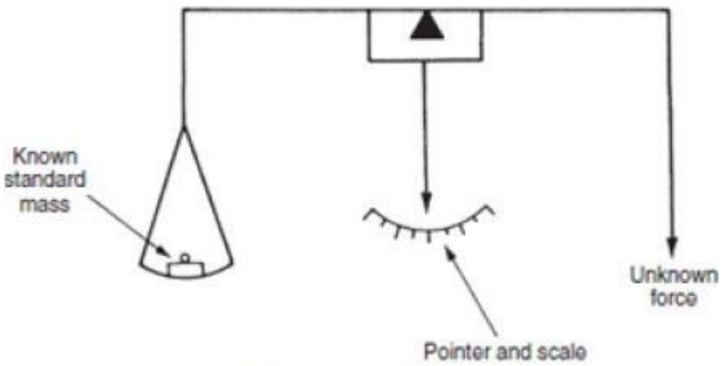


Fig: Equal Arm Balance

Operation

- A known standard mass (m1) is placed at one end of the beam and an unknown mass (m2) is placed at its other end.
- Equilibrium condition exists when, clockwise rotating moment = Anti- clockwise rotating moment Moreover at a given location, the earth's attraction will act equally on both the masses (m1 and m2) and hence at equilibrium condition. W1=W2. That is, the unknown force (weight) will be equal to the known force (weight).

b. Unequal arm balance

An unequal arm balance works on the principle of moment comparison. The beam of the unequal arm balance is in equilibrium position.

when, Clockwise rotating moment = Anti-clockwise rotating moment

$$F \times L2 = Fx \times L1$$

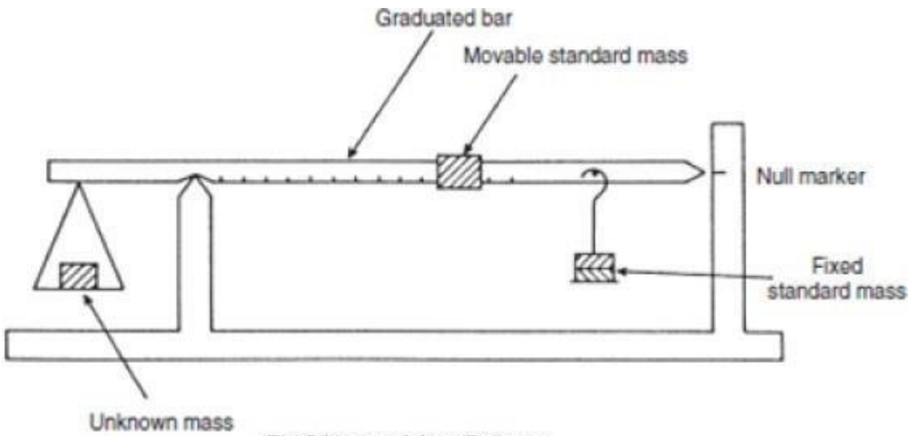


Fig 2 Unequal Arm Balance

Description

The main parts of the arrangements are as follows:

- A graduated beam pivoted to a knife edge “Y”
- A leveling pointer is attached to the beam
- A known mass “m” is attached to the right side of the beam. This creates an unknown force “F”. This mass “m” can slide on the right side of the beam.
- Provisions are made to apply an unknown force “Fx” on the left side of the beam.

Operation

- An unknown force “Fx” is applied on the left side of the beam through knife edge “Z” as shown
- Now the position of mass “m” on the right side of the beam is adjusted until the leveling pointer reads null balance position. When the leveling pointer is in null balance position, the beam is in equilibrium.

Clock wise rotating moment = Anti-clock wise rotating moment

$$Fx.L1 = F.\ L2$$

$$Fx = Mg.L2/L1$$

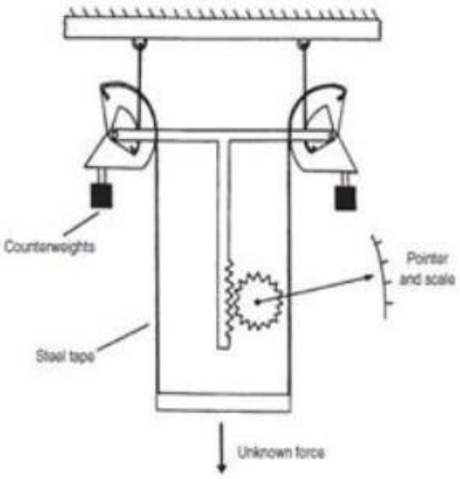
- Thus the unknown force “Fx” is proportional to the distance “L2” of the mass “m” from the knife edge “Y”
- The right hand side of the beam which is graduated is calibrated to get a direct measure of “Fx”

c. Pendulum Scale(Multi-lever Type)

It is a moment comparison device. The unknown force is converted to torque which is then balanced by the torque of a fixed standard mass arranged as a pendulum.

Description

- The scale’s frames carry support ribbons. These support ribbons are attached to the sectors. The loading ribbons are attached to the sectors and the load rod a shown. The load rod is inturn attached to the weighing platform.
- The two sectors are connected on either side of an equalizer beam. The sectors carry counter weighs. To the center of the equalizer beam is attached a rack and pinion arrangement.
- A pointer is attached to the pinion which sweeps over a weight (force) calibrated scale.



Operation

- The unknown force is applied to the load rod. Due to this force, the loading tapes are pulled downwards. Hence the loading tapes rotate the sectors.
- As the sectors rotate about the pivots, it moves the counter weights outwards, This movements increases the counter weight effective moment until the torque produced by the force applied to the load rod and the moment produced by the counter weight balance each other, thereby establishing an equilibrium.
- During the process of establishing equilibrium, the equalizer beam would be displaced downwards. As the rack is attached to the equalizer beam, the rack also is displaced downwards rotating the pinion.
- As the pointer is attached to the pinion, the rotation of the pinion makes the pointer to assume a new position on the scale. The scale is calibrated to read the weight directly. Thus the force applied on the load rod is measured.

3.1.2 Elastic force meter (Proving Ring)

When a steel ring is subjected to a force across its diameter, it deflects. This deflection is proportional to the applied force when calibrated. Description A steel ring attached with external bosses to apply force. A precision micrometer with one of its ends mounted on a vibrating reed.

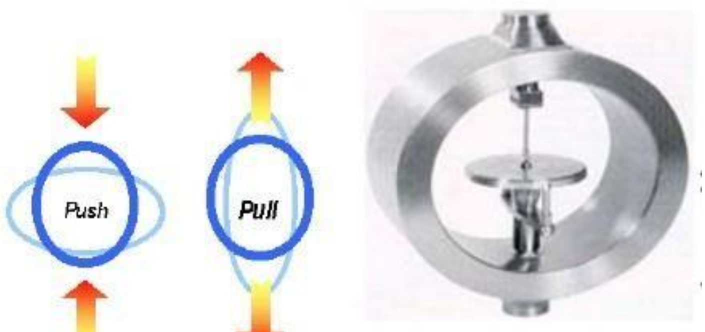


Fig. Proving Ring

Operation

- The force to be measured is applied to the external bosses of the proving ring. Due to the applied force, the ring changes in diameter. This deflection of the ring is proportional to the applied force.

- At this stage, the reed is plucked to obtain a vibrating motion. When the reed is vibrating, the micrometer wheel is turned until the micrometer contact moves forward and makes a noticeable damping of the vibrating reed.
- Now the micrometer reading is noted which is a measure of deflection of the ring. The device is calibrated to get a measure of force in terms of deflection of the proving ring.

3.1.3 Load cells

a. Strain gauge load cell

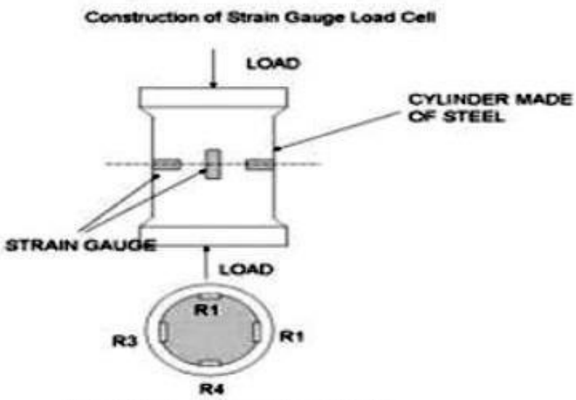


Fig. Strain Gauge Load Cell

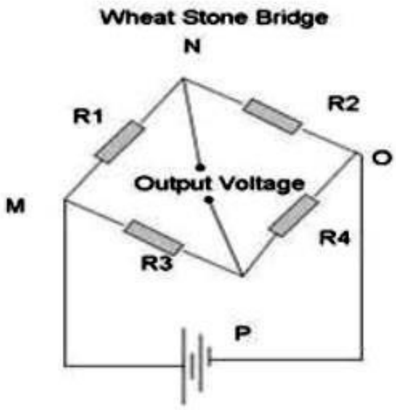


Fig. Wheat Stone Bridge

- When a steel cylinder is subjected to a force, it tends to change in dimension. On this cylinder if strain gauges are bonded, the strain gauge also is stretched or compressed, causing a change in its length and diameter.
- This change in dimension of the strain gauge causes its resistance to change. This change in resistance of the strain gauge becomes a measure of the applied force.

Description

- A cylinder made of steel on which four identical strain gauges are mounted.
- Out of the four strain gauges, two of them (R1 and R4) are mounted along the direction of the applied load(Vertical gauges)
- The other two strain gauges (R2 and R3 horizontal gauges) are mounted circumferentially at right angles to gauges R1 and R4.
- The four gauges are connected to the four limbs of wheat stone bridge. Operation
- When there is no load on the steel cylinder, all the four gauges will have the same resistance. As the terminals N and P are at the same potential, the wheat stone bridge is balanced and hence the output voltage will be zero.
- Now the force to be measured is applied on the steel cylinder. Due to this, the vertical gauges R1 and R4 will undergo compression and hence there will be a decrease in resistance. At the same time, the horizontal gauges R2 and R3 will undergo tension and there will be an increase in resistance. Thus when strained, the resistance of the various gauges change.
- Now the terminals N and P will be at different potential and the change in output voltage due to the applied load becomes a measure of the applied load when calibrated.

b. Hydraulic Load Cell

- When a force is applied on liquid medium contained in a confined space, the pressure of the liquid increases. This increase in pressure of the liquid is proportional to the applied force. Hence a measure of the increase in pressure of the liquid becomes a measure of the applied force when calibrated.

- The force to be measure is applied to the piston
- The applied force moves the piston down wards and deflects the diaphragm and this deflection of the diaphragm increase the pressure in the liquid medium.
- This increase in pressure of the liquid medium is proportional to the applied force. This increase in pressure is measured by the pressure gauge which is connected to the liquid medium.
- The pressure is calibrated in force units and hence the indication in the pressure gauge becomes a measure of the force applied on the piston.

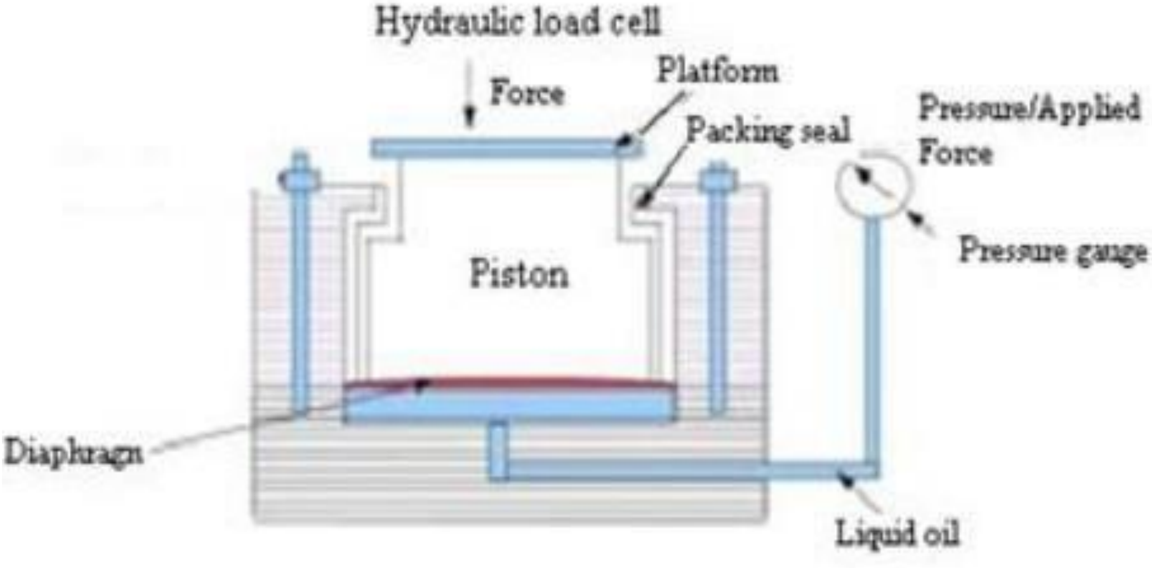


Fig. Hydraulic Load Cell

c. Pneumatic load cells

- If a force is applied to one side of a diaphragm and an air pressure is applied to the other side, some particular value of pressure will be necessary to exactly balance the force. This pressure is proportional to the applied force.
- The force to be measured is applied to the top side of the diaphragm. Due to this force, the diaphragm deflects and causes the flapper to shut-off the nozzle opening.
- Air supply is provided at the bottom of the diaphragm. As the flapper closes the nozzle opening, a back pressure results underneath the diaphragm.
- This back pressure acts on the diaphragm producing an upward force. Air pressure is regulated until the diaphragm returns to the pre-loaded position which is indicated by air which comes out of the nozzle.
- At this stage, the corresponding pressure indicated by the pressure gauge becomes a measure of the applied force when calibrated.

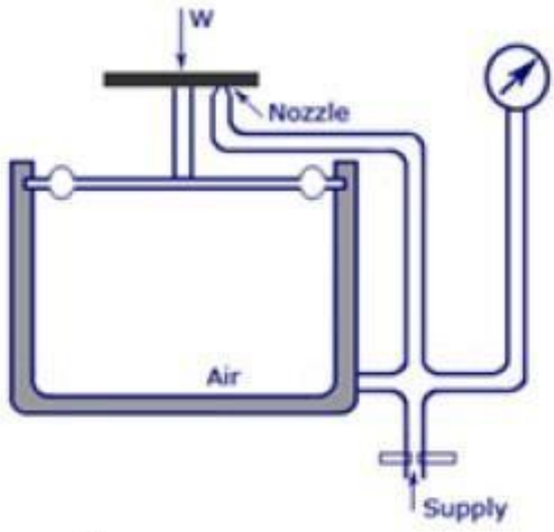


Fig. Pneumatic Load Cell

3.2 Torque Measurement

- Measurement of applied torques is of fundamental importance in all rotating bodies to ensure that the design of the rotating element is adequate to prevent failure under shear stresses.
- Torque measurement is also a necessary part of measuring the power transmitted by rotating shafts.
- The four methods of measuring torque consist of
  1. Measuring the strain produced in a rotating body due to an applied torque
  2. An optical method
  3. Measuring the reaction force in cradled shaft bearings
  4. Using equipment known as the Prony brake.

3.2.1 Measurement of Induced Strain

Measuring the strain induced in a shaft due to an applied torque has been the most common method used for torque measurement in recent years. The method involves bonding four strain gauges onto a shaft as shown in Figure, where the strain gauges are arranged in a d.c. bridge circuit. The output from the bridge circuit is a function of the strain in the shaft and hence of the torque applied.

It is very important that positioning of the strain gauges on the shaft is precise, and the difficulty in achieving this makes the instrument relatively expensive. This technique is ideal for measuring the stalled torque in a shaft before rotation commences.

However, a problem is encountered in the case of rotating shafts because a suitable method then has to be found for making the electrical connections to the strain gauges. One solution to this problem found in many commercial instruments is to use a system of slip rings and brushes for this, although this increases the cost of the instrument still further.

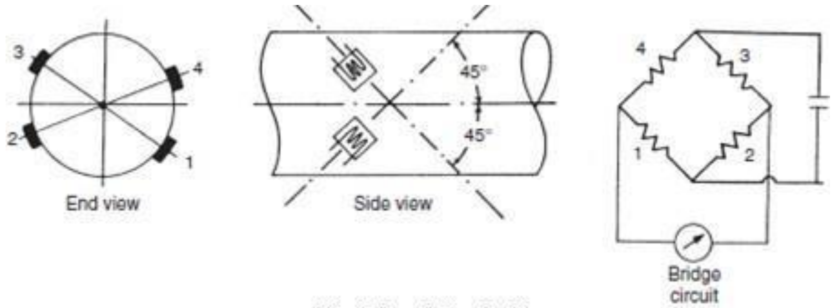


Fig. Induced Strain Gauge

3.2.2. Optical Torque Measurement

Optical techniques for torque measurement have become available recently with the development of laser diodes and fiber-optic light transmission systems. One such system is shown in Figure. Two black-and-white striped wheels are mounted at either end of the rotating shaft and are in alignment when no torque is applied to the shaft.

Light from a laser diode light source is directed by a pair of fiber-optic cables onto the wheels. The rotation of the wheels causes pulses of reflected light, which are transmitted back to a receiver by a second pair of fiber-optic cables. Under zero torque conditions, the two pulse trains of reflected light are in phase with each other. If torque is now applied to the shaft, the reflected light is modulated.

Measurement by the receiver of the phase difference between the reflected pulse trains therefore allows the magnitude of torque in the shaft to be calculated. The cost of such instruments is relatively low, and an additional advantage in many applications is their small physical size.

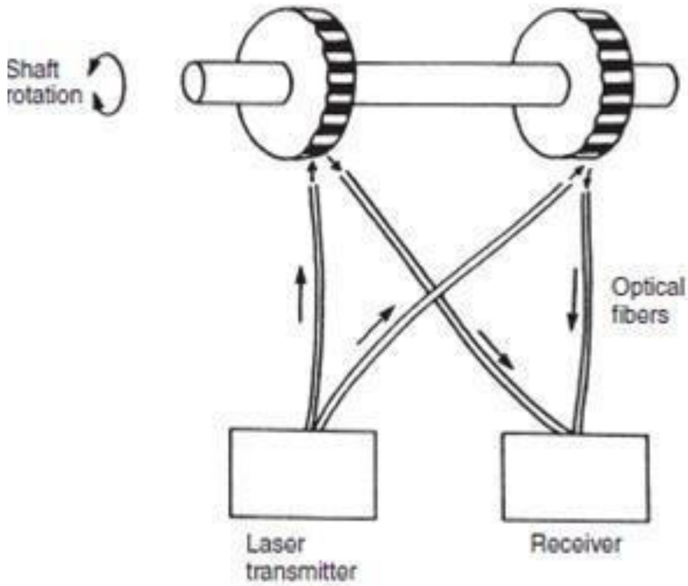


Fig. Optical Torqu Measurement

3.2.3. Reaction Forces in Shaft Bearings

Any system involving torque transmission through a shaft contains both a power source and a power absorber where the power is dissipated. The magnitude of the transmitted torque can be measured by cradling either the power source or the power absorber end of the shaft in bearings, and then measuring the reaction force, F, and the arm length, L, as shown in Figure.

The torque is then calculated as the simple product, FL. Pendulum scales are used very commonly for measuring the reaction force. Inherent errors in the method are bearing friction and windage torques. This technique is no longer in common use.

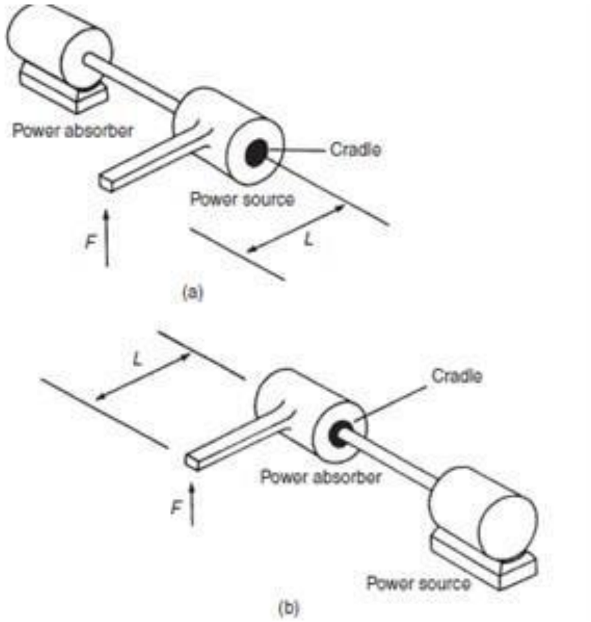


Fig. Measuring Reaction forces in cradled shaft bearing

3.2.4. Prony Brake

The Prony brake is another torque- measuring system that is now uncommon. It is used to measure the torque in a rotating shaft and consists of a rope wound round the shaft, as illustrated in Figure. One end of the rope is attached to a spring balance and the other end carries a load in the form of a standard mass, m.

If the measured force in the spring balance is Fs, then the effective force, Fe, exerted by the rope on the shaft is given by

$$Fe = mg - Fs$$

If the radius of the shaft is Rs and that of the rope is Rr, then the effective radius, Re, of the rope and drum with respect to the axis of rotation of the shaft is given by

$$Re = Rs + Rr$$

The torque in the shaft, T, can then be calculated as

$$T = FeRe$$

While this is a well-known method of measuring shaft torque, a lot of heat is generated because of friction between the rope and shaft, and water cooling is usually necessary.

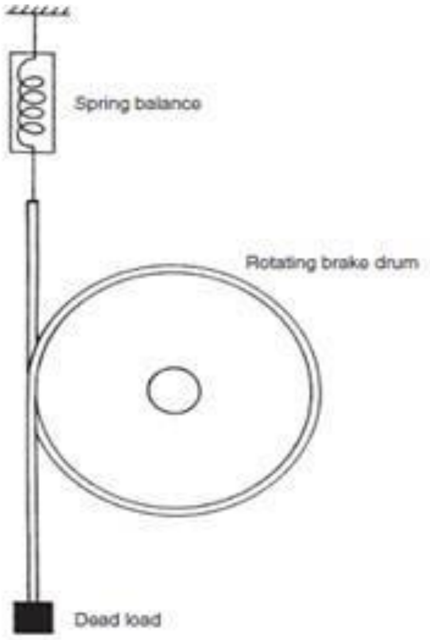


Fig. Prony Brake

3.3 Measurement of Power

Torque is exerted along a rotating shaft. By measuring this torque which is exerted along a rotating shaft, the shaft power can be determined. For torque measurement dynamometers are used.

$T = F.r$ $P = 2\pi NT$

Where,

T – Torque,

F – Force at a known radius r,

P – Power

Types of dynamometers

- Absorption dynamometers
- Driving dynamometers
- Transmission dynamometers

3.3.1 Absorption dynamometers

The dynamometer absorbs the mechanical energy when torque is measured. It dissipates mechanical energy (heat due to friction) when torque is measured. Therefore, dynamometers are used to measure torque/power of power sources like engine and motors.

3.3.2 Mechanical Dynamometers

In prony brake, mechanical energy is converted into heat through dry friction between the wooden brake blocks and the flywheel (pulley) of the machine. One block carries a lever arm. An arrangement is provided to tighten the rope which is connected to the arm. Rope is tightened so as to increase the frictional resistance between the blocks and the pulley. Power dissipated, $P = 2\pi NT/60$ The capacity of proney brake is limited due to wear of wooden blocks, friction coefficient varies. So, it is unsuitable for large powers when it is used for long periods.

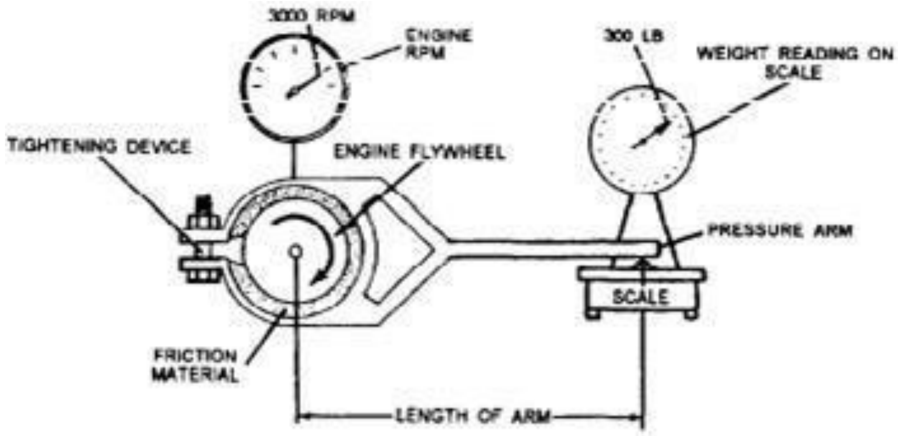


Fig. Mechanical Dynamometer

3.3.3 Eddy Current Dynamometer

Basically an electrical dynamometer of absorption type, used to measure power from a source such as engine or a motor. When a conducting material moves through a magnetic flux field, voltage is generated, which causes current to flow. If the conductor is a wire forming, a part of a complete circuit current will be caused to flow through that circuit and with some form of commutating device a form of A.C or D.C generator may result. An eddy current dynamometer is shown above.

It consists of a metal disc or wheel which is rotated in the flux of a magnetic field. The field if produced by field elements or coils is excited by an external source and attached to the dynamometer housing which is mounted in trunnion bearings. As the disc turns, eddy currents are generated. Its reaction with the magnetic field tends to rotate the complete housing in the trunnion bearings. Water cooling is employed.

3.3.4 Hydraulic or Fluid Friction Dynamometer

A rotating disk that is fixed to the driving shaft, Semi-elliptical grooves are provided on the disc through which a stream of water flows. There is a casting which is stationary and the disc rotates in this casing. When the driving shaft rotates, water flow is in a helical path in the chamber. Due to vortices and eddy-currents setup in the water, the casting tends to rotate in the same direction as that of the driving shafts. By varying the amount of water, the braking action is provided. Braking can also be provided by varying the distance between the rotating disk and the casting. The absorbing element is constrained by a force-measuring device placed at the end of the arm of radius r

3.4 Flow Measurements

The flow rate of a fluid flowing in a pipe under pressure is measured for a variety of applications, such as monitoring of pipe flow rate and control of industrial processes. Differential pressure flow meters, consisting of orifice, flow nozzle, and venturi meters, are widely used for pipe flow measurement and are the topic of this course.

All three of these meters use a constriction in the path of the pipe flow and measure the difference in pressure between the undisturbed flow and the flow through the constriction. That pressure difference can then be used to calculate the flow rate. Flow meter is a device that measures the rate of flow or quantity of a moving fluid in an open or closed conduit. Flow measuring devices are generally classified into four groups. They are

1. Mechanical type flow meters

Fixed restriction variable head type flow meters using different sensors like orifice plate, venturi tube, flow nozzle, pitot tube, dall tube, quantity meters like positive displacement meters, mass flow meters etc. fall under mechanical type flow meters.

2. Inferential type flow meters

Variable area flow meters (Rotameters), turbine flow meter, target flow meters etc.

3. Electrical type flow meters

Electromagnetic flow meter, Ultrasonic flow meter, Laser doppler Anemometers etc. fall under electrical type flow meter.

4. Other flow meters

Purge flow regulators, Flow meters for Solids flow measurement, Cross- correlation flow meter, Vortex shedding flow meters, flow switches etc.

3.4.1 Orifice Flow Meter

An Orifice flow meter is the most common head type flow measuring device. An orifice plate is inserted in the pipeline and the differential pressure across it is measured.

Principle of Operation

The orifice plate inserted in the pipeline causes an increase in flow velocity and a corresponding decrease in pressure. The flow pattern shows an effective decrease in cross section beyond the orifice plate, with a maximum velocity and minimum pressure at the venacontracta.

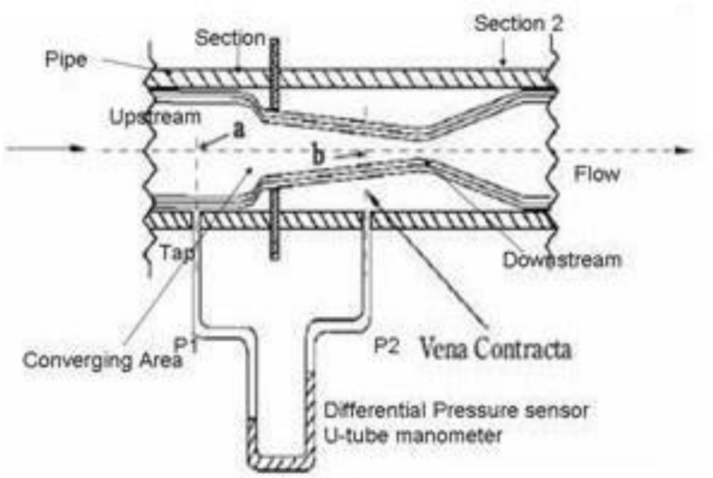


Fig.Orifice Meter

The flow pattern and the sharp leading edge of the orifice plate which produces it are of major importance. The sharp edge results in an almost pure line contact between the plate and the effective flow, with the negligible fluid-to-metal friction drag at the boundary.

Types of Orifice Plates The simplest form of orifice plate consists of a thin metal sheet, having in it a square edged or a sharp edged or round edged circular hole. There are three types of orifice plates namely

a. Concentric, b.Eccentric and c. Segmental type.

The concentric type is used for clean fluids. In metering dirty fluids, slurries and fluids containing solids, eccentric or segmental type is used in such a way that its lower edge coincides with the inside bottom of the pipe. This allows the solids to flow through without any obstruction. The orifice plate is inserted into the main pipeline between adjacent flanges, the outside diameters of the plate being turned to fit within the flange bolts. The flanges are either screwed or welded to the pipes.

Applications

- The concentric orifice plate is used to measure flow rates of pure fluids and has a wide applicability as it has been standardized
- The eccentric and segmental orifice plates are used to measure flow rates of fluids containing suspended materials such as solids, oil mixed with water and wet steam.

Advantages

- It is very cheap and easy method to measure flow rate
- It has predictable characteristics and occupies less space
- Can be used to measure flow rates in large pipes

Limitations

- The vena-contracta length depends on the roughness of the inner wall of the pipe and sharpness of the orifice plate. In certain case it becomes difficult to tap the minimum pressure due the above factor
- Pressure recovery at downstream is poor, that is, overall loss varies from 40 to 90% of the differential pressure.
- In the upstream straightening vanes are a must to obtain laminar flow conditions.
- The orifice plate gets corroded and due to this after sometime, inaccuracy occurs. The coefficient of discharge is low.

3.4.2 Venturi Meter

Venturi tubes are differential pressure producers, based on Bernoulli's Theorem. General performance and calculations are similar to those for orifice plates. In these devices, there is a continuous contact between the fluid flow and the surface of the primary device. It consists of a cylindrical inlet section equal to the pipe diameter, a converging conical section in which the cross sectional area decreases causing the velocity to increase with a corresponding increase in the velocity head and a decrease in the pressure head; a cylindrical throat section where the velocity is constant so that the decreased pressure head can be measured and a diverging recovery cone where the velocity decreases and almost all of the original pressure head is recovered. The unrecovered pressure head is commonly called as head loss.

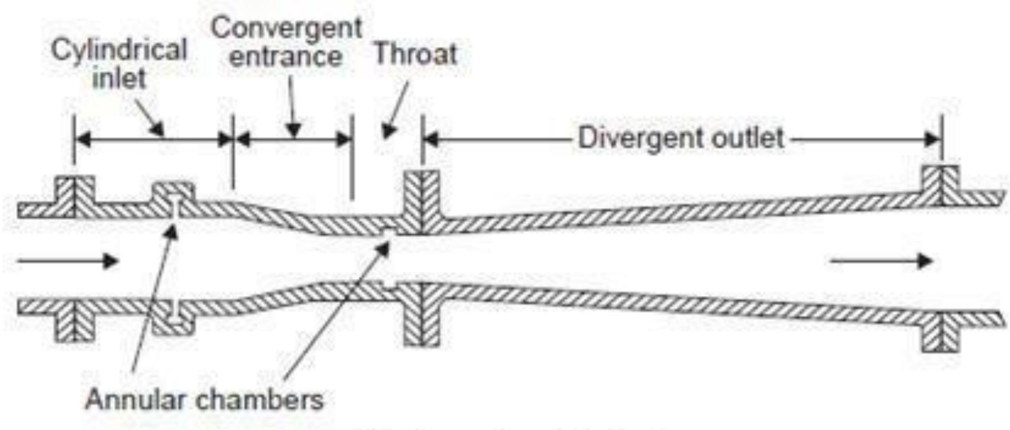


Fig. Long form Venturi

$$\frac{p_1}{\rho} + \frac{v_1^2}{2} = \frac{p_2}{\rho} + \frac{v_2^2}{2}$$

where

p is pressure (N/m^2)
v is velocity (m/s)
ρ is the density of the liquid (kg/m^3).

$$\therefore \dot{Q} = \frac{a_1 a_2}{\sqrt{(a_1^2 - a_2^2)}} \sqrt{\frac{2}{\rho}(p_1 - p_2)} \text{ m}^3/\text{s}$$

$$\dot{Q} = a_2 \sqrt{\frac{2(p_1 - p_2)}{\rho(1 - \beta^4)}}$$

β is the ratio : $\frac{\text{throat diameter}}{\text{pipe diameter}}$

Limitations

This flow meter is limited to use on clean, non- corrosive liquids and gases, because it is impossible to clean out or flush out the pressure taps if they clog up with dirt or debris.

3.4.3 Short Form Venturi Tubes

In an effort to reduce costs and laying length, manufactures developed a second generation, or short-form venturi tubes shown in Figure.

There were two major differences in this design. The internal annular chamber was replaced by a single pressure tap or in some cases an external pressure averaging chamber, and the recovery cone angle was increased from 7 degrees to 21 degrees. The short form venture tubes can be manufactured from cast iron or welded from a variety of materials compatible with the application.

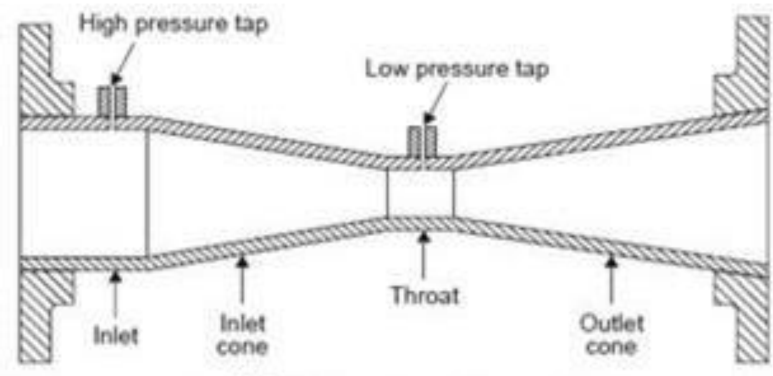


Fig .Short-form Venturi Tube

The pressure taps are located one-quarter to one-half pipe diameter upstream of the inlet cone and at the middle of the throat section. A piezometer ring is sometimes used for differential pressure measurement. This consists of several holes in the plane of the tap locations. Each set of holes is connected together in an annular ring to give an average pressure. Venturis with piezometer connections are unsuitable for use with purge systems used for slurries and dirty fluids since the purging fluid tends to short circuit to the nearest tap holes. Piezometer connections are normally used only on very large tubes or where the most accurate average pressure is desired to compensate for variations in the hydraulic profile of the flowing fluid. Therefore, when it is necessary to meter dirty fluids and use piezometer taps, sealed sensors which mount flush with the pipe and throat inside wall should be used. Single pressure tap venturis can be purged in the normal manner when used with dirty fluids. Because the venturi tube has no sudden changes in contour, no sharp corners, and no projections, it is often used to measure slurries and dirty fluids which tend to build up on or clog of the primary devices.

3.4.3 Flow Nozzle

Flange Type Flow Nozzle

The Flow nozzle is a smooth, convergent section that discharges the flow parallel to the axis of the downstream pipe. The downstream end of a nozzle approximates a short tube and has the diameter of the venacontracta of an orifice of equal capacity. Thus the diameter ratio for a nozzle is smaller or its flow coefficient is larger. Pressure recovery is better than that of an orifice. Figure shows a flow nozzle of flange type.

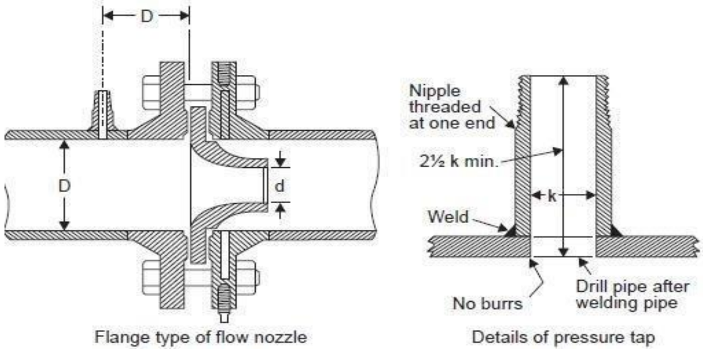


Fig. Flow Nozzle

Advantages

1. Permanent pressure loss lower than that for an orifice plate.

2. It is suitable for fluids containing solids that settle.

3. It is widely accepted for high pressure and temperature steam flow.

Disadvantages

1. Cost is higher than orifice plate.

2. It is limited to moderate pipe sizes, it requires more maintenance.

3.4.4 Pitot tube

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

Principle

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

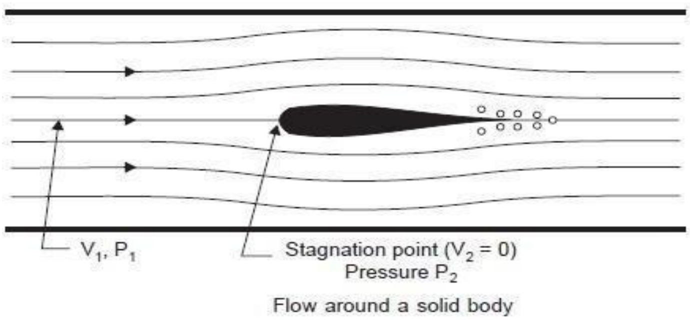


Fig. Flow through solid body

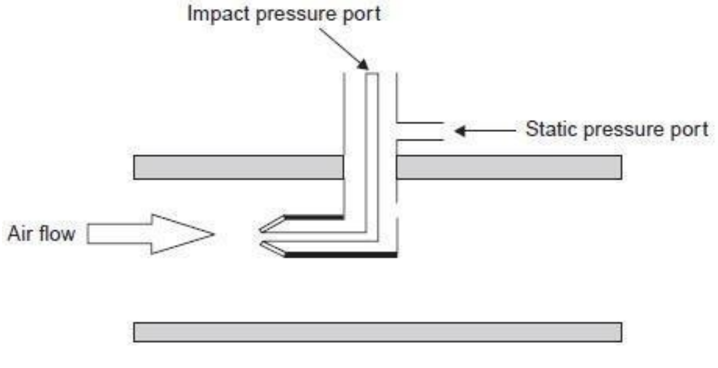


Fig. Pitot tube

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

$$v = C_p\sqrt{2gh}$$

Advantages

1. No pressure loss.
2. It is relatively simple.
3. It is readily adapted for flow measurements made in very large pipes or ducts

Disadvantages

1. Poor accuracy.
2. Not suitable for dirty or sticky fluids and fluids containing solid particles.
3. Sensitive to upstream disturbances.

3.4.5 Rotameter

The orifice meter, Venturimeter and flow nozzle work on the principle of constant area variable pressure drop. Here the area of obstruction is constant, and the pressure drop changes with flow rate. On the other hand Rotameter works as a constant pressure drop variable area meter. It can be only be used in a vertical pipeline. Its accuracy is also less (2%) compared to other types of flow meters. But the major advantages of rotameter are, it is simple in construction, ready to install and the flow rate can be directly seen on a calibrated scale, without the help of any other device, e.g. differential pressure sensor etc. Moreover, it is useful for a wide range of variation of flow rates (10:1).

The basic construction of a rotameter is shown in figure. It consists of a vertical pipe, tapered downward. The flow passes from the bottom to the top. There is cylindrical type metallic float inside the tube. The fluid flows upward through the gap between the tube and the float. As the float moves up or down there is a change in the gap, as a result changing the area of the orifice. In fact, the float settles down at a position, where the pressure drop across the orifice will create an upward thrust that will balance the downward force due to the gravity. The position of the float is calibrated with the flow rate.

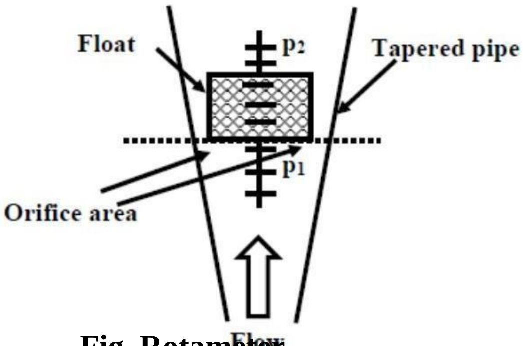


Fig. Rotameter

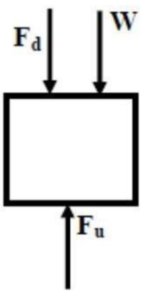


Fig. Force acting on float

γ_1= Specific weight of the float

γ_2= specific weight of the fluid ν= volume of the float A_f= Area of the float.

A_t= Area of the tube at equilibrium (corresponding to the dotted line)

$$Q = \frac{C_d A_2}{\sqrt{1-(\frac{A_2}{A_1})^2}} \sqrt{\frac{2g}{\gamma_2}(p_1 - p_2)}$$

F_d = Downward thrust on the float F_u = Upward thrust on the float

The major source of error in rotameter is due to the variation of density of the fluid. Besides, the presence of viscous force may also provide an additional force to the float.

Applications

- Can be used to measure flow rates of corrosive fluids
- Particularly useful to measure low flow rates

Advantages

- Flow conditions are visible
- Flow rate is a linear function(uniform flow scales)
- Can be used to measure flow rates of liquids, gases and vapour
- By changing the float, tapered tube or both, the capacity of the rotameter can be changed.

Limitations

- They should be installed vertically
- They cannot be used for measurements in moving objects
- The float will not be visible when coloured fluids are used, that is, when opaque fluid are used.
- For high pressure and temperature fluid flow measurements, they are expensive
- They cannot be used for fluids containing high percentage of solids in suspension.

3.5 Temperature Measurement

Temperature is one of the most measured physical parameters in science and technology; typically for process thermal monitoring and control. There are many ways to measure temperature, using various principles.

Four of the most common are:

- Mechanical (liquid-in-glass thermometers, bimetallic strips, etc.)
- Thermojunctive (thermocouples)
- Thermoresistive (RTDs and thermistors)
- Radiative (infrared and optical pyrometers)

Mechanical Temperature Measuring Devices

A change in temperature causes some kind of mechanical motion, typically due to the fact that most materials expand with a rise in temperature. Mechanical thermometers can be constructed that use liquids, solids, or even gases as the temperature-sensitive material. The mechanical motion is read on a physical scale to infer the temperature.

3.5.1 Bimetallic strip thermometer

- Two dissimilar metals are bonded together into what is called a bimetallic strip, as sketched to the right.
- Suppose metal A has a smaller coefficient of thermal expansion than does metal B. As temperature increases, metal B expands more than does metal A, causing the bimetallic strip to curl upwards as sketched.
- One common application of bimetallic strips is in home thermostats, where a bimetallic strip is used as the arm of a switch between electrical contacts. As the room temperature changes, the bimetallic strip bends as discussed above. When the bimetallic strip bends far enough, it makes contact with electrical leads that turn the heat or air conditioning on or off.
- Another application is in circuit breakers High temperature indicates over-current, which shuts off the circuit.
- Another common application is for use as ven, wood burner, or gas grill thermometers. These thermometers consist of a bimetallic strip wound up in a spiral, attached to a dial that is calibrated into a temperature scale.

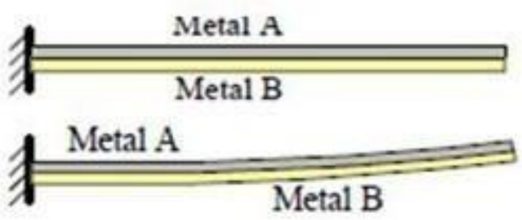
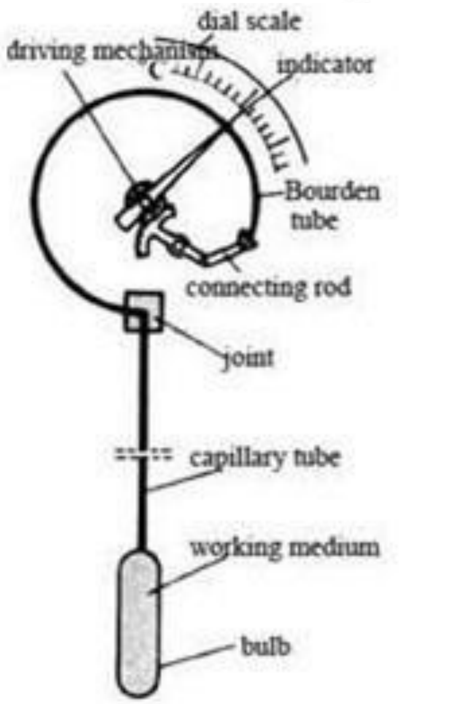


Fig.Bimetallic Strip

3.5.2 Pressure thermometer

- A pressure thermometer, while still considered mechanical, operates by the expansion of a gas instead of a liquid or solid. There are also pressure thermometers that use a liquid instead of a gas
- Suppose the gas inside the bulb and tube can be considered an ideal gas. The ideal gas law is PV = mRT, where P is the pressure, V is the volume of the gas, m is the mass of the gas, R is the gas constant for the specific gas (not the universal gas constant),and T is the absolute temperature of the gas.
- Specific gas constant R is a constant. The bulb and tube are of constant volume, so V is a constant. Also, the mass m of gas in the sealed bulb and tube must be constant (conservation of mass).
- A pressure thermometer therefore measures temperature indirectly by measuring pressure.
- The gage is a pressure gage, but is typically calibrated in units of temperature instead.
- A common application of this type of thermometer is measurement of outside temperature from the inside of a building. The bulb is placed outside, with the tube running through the wall into the inside.
- The gauge is on the inside. As *T* increases outside, the bulb temperature causes a corresponding increase in pressure, which is read as a temperature increase on the gauge.

$$e_0 = C_1(T_1 - T_2) + C_2(T_1^2 - T_2^2)\ \mu v$$



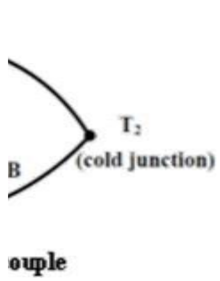


Fig.Pressure Thermometer

3.5.3 Thermocouples (Thermo-junctive temperature measuring devices)

Thomas Johan Seeback discovered in 1821 that thermal energy can produce electric current. When two conductors made from dissimilar metals are connected forming two common junctions and the two junctions are exposed to two different temperatures, a net thermal emf is produced, the actual value being dependent on the materials used and the temperature difference between hot and cold junctions. The thermoelectric emf generated, in fact is due to the combination of two effects: Peltier effect and Thomson effect. A typical thermocouple junction is shown in fig. 5. The emf generated can be approximately expressed by the relationship: Where, T_1 and T_2 are hot and cold junction temperatures in K. C_1 and C_2 are constants depending upon the materials. For Copper/ Constantan thermocouple, C_1=62.1 and C_2=0.045.

Thermocouples are extensively used for measurement of temperature in industrial situations. The major reasons behind their popularity are:

They are rugged and readings are consistent

(i) They can measure over a wide range of temperature

(ii) Their characteristics are almost linear with an accuracy of about 0.05%. However, the major shortcoming of thermocouples is low sensitivity compared to other temperature measuring devices (e.g. RTD, Thermistor).

3.5.4. Thermocouple Materials

Table-1 Thermocouple materials and Characteristics

Type	Positive lead	Negative lead	Temperature range	Temperature coeff.variation μv/°C	Most linear range and sensitivity in the range
R	Platinum-Rhodium (87% Pt, 13% Rh)	Platinum	0-1500°C	5.25-14.1	1100-1500°C 13.6-14.1 μv/°C
S	Platinum-Rhodium (90% Pt, 10% Rh)	Platinum	0-1500°C	5.4-12.2	1100-1500 °C 13.6-14.1 μv/°C
K	Chromel (90%Ni, 10% Cr)	Alumel ($Ni_{94}Al_2$ Mn_3Si)	-200-1300°C	15.2-42.6	0-1000 °C 38-42.9 μv/°C
E	Chromel	Constantan (57%Cu, 43%Ni)	-200-1000°C	25.1-80.8	300-800 °C 77.9-80.8 μv/°C
T	Copper	Constantan	-200-350°C	15.8-61.8	nonlinear
J	Iron	Constantan	-150-750°C	21.8-64.6	100-500 °C 54.4-55.9

Theoretically, any pair of dissimilar materials can be used as a thermocouple. But in practice, only few materials have found applications for temperature measurement. The choice of materials is influenced by several factors, namely, sensitivity, stability in calibration, inertness in the operating atmosphere and reproducibility (i.e. the thermocouple can be replaced by a similar one without any recalibration).

Table-I shows the common types of thermocouples, their types, composition, range, sensitivity etc. The upper range of the thermocouple is normally dependent on the atmosphere where it has been put. For example, the upper range of Chromel/ Alumel thermocouple can be increased in oxidizing atmosphere, while the upper range of Iron/ Constantan thermocouple can be increased in reducing atmosphere.

Laws of Thermocouple

The Peltier and Thompson effects explain the basic principles of thermoelectric emf generation. But they are not sufficient for providing a suitable measuring technique at actual measuring situations. For this purpose, we have three laws of thermoelectric circuits that provide us useful practical tips for measurement of temperature. These laws are known as law of homogeneous circuit, law of intermediate metals and law of intermediate temperatures. These laws can be explained using figure

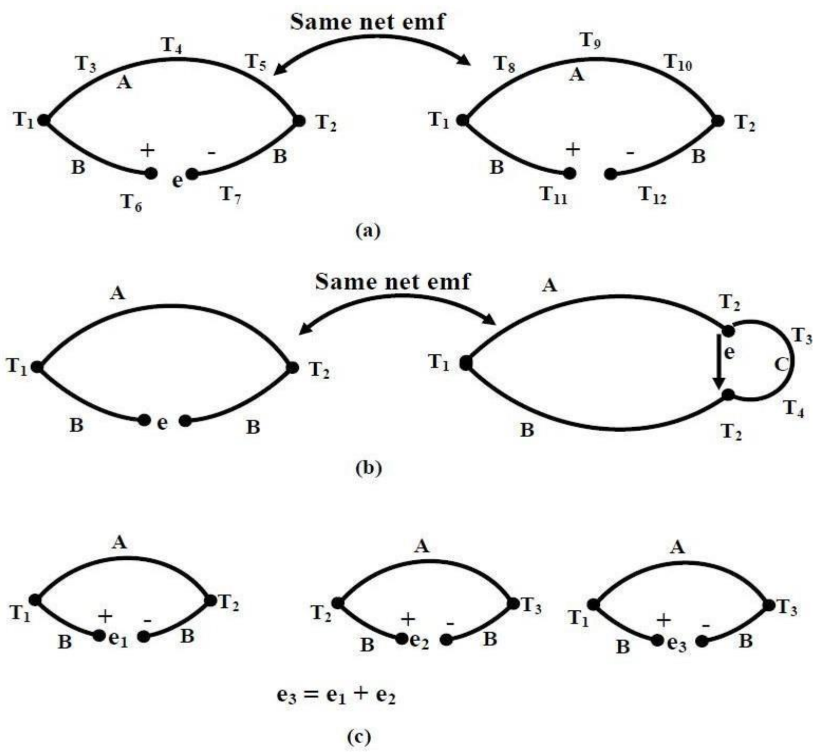
The first law can be explained using figure

(a). It says that the net thermo-emf generated is dependent on the materials and the temperatures of two junctions only, not on any intermediate temperature.

According to the second law, if a third material is introduced at any point (thus forming two additional junctions) it will not have any effect, if these two additional junctions remain at the same temperatures (figure b). This law makes it possible to insert a measuring device without altering the thermo-emf.

The third law is related to the calibration of the thermocouple. It says, if a thermocouple produces emf e_1, when its junctions are at T_1 and T_2, and e_2 when its junctions are at T_2 and T_3; then it will generate emf e_1+e_2 when the junction temperatures are at T_1 and T_3 (figure c).

The third law is particularly important from the point of view of reference junction compensation. The calibration chart of a thermocouple is prepared taking the cold or reference junction temperature as 0 C. But in actual measuring situation, seldom the reference junction temperature is kept at that temperature, it is normally kept at ambient temperature. The third law helps us to compute the actual temperature using the calibration chart.



3.5.5 Thermo Resistive Temperature Measuring Devices

Principle of operation

- A change in temperature causes the electrical resistance of a material to change.
- The resistance change is measured to infer the temperature change.
- There are two types of thermoresistive measuring devices: resistance temperature detectors and thermistors, both of which are described here.

Resistance temperature detectors

A resistance temperature detector (abbreviated RTD) is basically either a long, small diameter metal wire (usually platinum) wound in a coil or an etched grid on a substrate, much like a strain gauge.

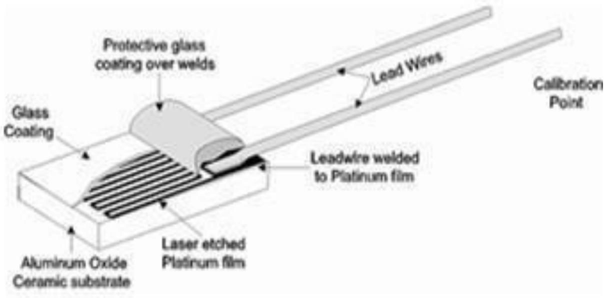
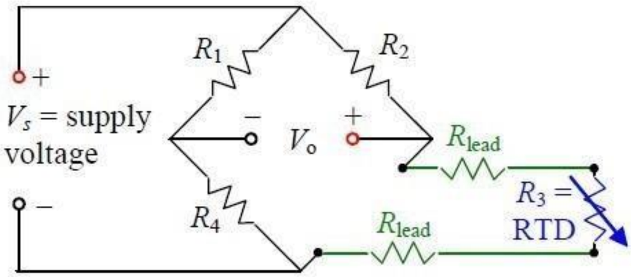


Fig 5.28 RTD

The resistance of an RTD increases with increasing temperature, just as the resistance of a strain gage increases with increasing strain. The resistance of the most common RTD is 100 Ω at 0ºC.



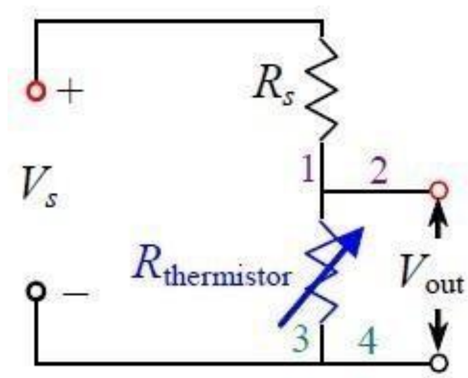
If the temperature changes are large, or if precision is not critical, the RTD resistance can be measured directly to obtain the temperature. If the temperature changes are small, and/or high precision is needed, an electrical circuit is built to measure a change in resistance of the RTD, which is then used to calculate a change in temperature. One simple circuit is the quarter bridge Wheatstone bridge circuit, here called a two-wire RTD bridge circuit

R_{lead} represents the resistance of one of the wires (called lead wires) that run from the bridge to the RTD itself. Lead resistance is of little concern in strain gage circuits because R_{lead} remains constant at all times, and we can simply adjust one of the other resistors to zero the bridge.

For RTD circuits, however, some portions of the lead wires are exposed to changing temperatures. Since the resistance of metal wire changes with temperature, R_{lead} changes with T and this can cause errors in the measurement. This error can be non-trivial changes in lead resistance may be misinterpreted as changes in RTD resistance, and therefore give a false temperature measurement

3.5.6 Thermistors

A thermistor is similar to an RTD, but a semiconductor material is used instead of a metal. A thermistor is a solid state device. Resistance thermometry may be performed using thermistors. Thermistors are many times more sensitive than RTD's and hence are useful over limited ranges of temperature. They are small pieces of ceramic material made by sintering mixtures of metallic oxides of Manganese, Nickel, Cobalt, Copper and Iron etc.



Resistance of a thermistor decreases non-linearly with temperature. Thermistors are extremely sensitive but over a narrow range of temperatures. A thermistor has larger sensitivity than does an RTD, but the resistance change with temperature is nonlinear, and therefore temperature must be calibrated with respect to resistance. Unlike RTDs, the resistance of a thermistor decreases with increasing temperature. The upper temperature limit of thermistors is typically lower than that of RTD. However, thermistors have greater sensitivity and are typically more accurate than RTDs or thermocouples. A simple voltage divider, where V_s is the supply voltage and R_s is a fixed (supply) resistor. R_s and V_s can be adjusted to obtain a desired range of output voltage V_{out} for a given range of temperature. If the proper value of R_s is used, the output voltage is nearly (but not exactly) linear with temperature. Some thermistors have 3 or 4 lead wires for convenience in wiring – two wires are connected to one side and two to the other side of the thermistor (labeled 1, 2 and 3, 4 above).