Chapter 7

Measurement and Instrumentation

Engineering is a creative and a learning profession. If engineers are to create, they must experiment and open the new frontiers of information. Experimentation is vital for progress in any field where information is lacking. There would thus be a need to measure the physical entities such as displacement, velocity, pressure, force, elapsed time, etc., in the operating devices and machines. Experimentation is considered to be the corner stone in the field of engineering design, research and development projects. In industry too, there is need for the measurement and control of the physical conditions required for mass production and high quality products. Similarly in commercial organizations, the measurement of water and electricity supplied to a consumer is a must.

The instruments for measurement, control and transmission find such a wide and varied use that they have become an essential feature of technological operations and modern day-to-day life. It would be difficult to think of any man-made article whose manufacture did not at some stage involve measurement. There are instruments to control the flight of man-made satellites, to probe the mysteries of outer space and to transmit the related information. Nearer at home, we use instruments to control the temperature of our homes and to preserve food in refrigerators and cold storages. Our automobiles are equipped with instruments to measure speed, condition of battery and the amount of gasoline in the fuel tank. The national security devices and the sophisticated war weapons too utilize instruments for their functioning. The division of engineering science which deals with measuring techniques, devices and their associated problems is called ***instrumentation.***

In this chapter on measurement and instrumentation, it is intended to describe the measuring instruments and devices with regard to their construction and operation.

7.1. MEASUREMENT AND INSTRUMENT

The word *measurement* is used to tell us the length, the weight, the temperature, the colour or the change in one of these physical entities of a material. Measurement is the result of an opinion formed by one more observer about the relative size or intensity of some physical quantity. The opinion is formed by the observer after comparing the object with a quantity of same kind chosen as a unit, called ***standard.*** The result of measurement is expressed by a number representing the ratio of the unknown quantity to the adopted standard. This number gives the value of the measured quantity. For example, 10 cm length of an object implies that the object is 10 times as large as 1 cm ; the unit employed in expressing length.

The measurement standard is the physical embodiment of the unit of measurement. This places a sizeable responsibility on the observer, he may be an engineer or a technician, to be certain that the standard used by him is accurately known and commonly accepted. Further, the procedure and apparatus employed for obtaining the comparison must be provable, *i.e.*, accuracy can be reproduced anywhere in the world. This is essential so that measurements obtained by him can be accepted with confidence. For consistence and quantitative comparison of physical parameters, certain standards of mass, length, time, temperature and electrical quantities have been established. These standards are internationally accepted and well-preserved under controlled environmental conditions.

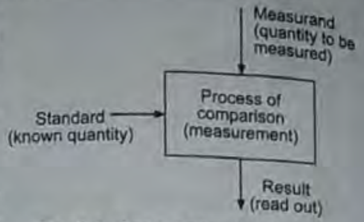


Fig. 7.1. Basic measuring process

The physical quantity or the characteristic condition which is the object of measurement in an instrumentation system is variously termed as *measurand, measurement variable, instrumentation variable and process variable*. The measurand may be a fundamental quantity (length, mass and time), a derived quantity (speed, velocity, acceleration, power, etc.) or a quality like pressure, temperature etc.

The human senses cannot provide exact quantitative information about the knowledge of events occurring in our environments. The stringent requirements of precise and accurate measurements in the technological fields have, therefore, led to the development of mechanical aids called ***instruments***. Scientific instruments allow the humans to observe and measure aspects of the physical universe beyond the range and precision of the unaided human senses. Instruments are the essential extensions of human sensing and perception without which scientific exploration of nature would be impossible. The instrument would sense a physical parameter (pressure, temperature, velocity, etc.), process and translate it into a format and range which can be interpreted by the observer.

The man-made instruments are not only accurate and sensitive in their response but also retain their characteristics for extended periods of time. Instruments may be quite simple, such as liquid-in-glass thermometer or extremely complex such as the device to sense the physiological reactions of a man during space flight.

7.2. MEASUREMENT METHODS

7.2.1. Direct and Indirect Measurements

Measurement is a process of comparison of the physical quantity with a reference standard. Depending upon the requirement and based upon the standards employed, there are two basic methods of measurement :

1. Direct Measurement : The value of the physical parameter (measurand) is determined by comparing it directly with reference standards. The physical quantities like mass, length and time are measured by direct comparison.

Direct measurements are not to be preferred because they involve human factors, are less accurate and also less sensitive. Further, the direct methods may not always be possible, feasible and practicable.

2. Indirect Measurement : The value of the physical parameter (measurand) is more generally determined by indirect comparison with secondary standards through calibration. The measurand is converted into an analogous signal which is subsequently processed and fed to the end device that presents the result of measurement. The indirect technique saves the primary or secondary standards from a frequent and direct handling.

The accuracy of each approach is apparently traceable to the primary standard via secondary standard and the calibration.

7.2.2. Primary, Secondary and Tertiary Measurements

The complexity of an instrument system depends upon the measurement being made and upon the accuracy level to which the measurement is needed. Based upon complexity of the measurement system, the measurements are generally grouped into three categories, namely, the primary, secondary and tertiary measurements.

In the ***primary mode***, the sought value of a physical parameter is determined by comparing it directly with reference standards. The requisite information is obtainable through senses of sight and touch. Examples are :

(*i*) matching of two lengths while determining the length of an object with a ruler.

(*ii*) matching of two colours while judging the temperature of red hot steel.

(*iii*) estimating the temperature difference between the contents of containers by inserting fingers.

(*iv*) use of beam balance to measure (actually compare) masses.

(*v*) measurement of time by counting the number of strokes of a clock.

The primary measurements provide subjective information only. That is, the observer can indicate only that the contents of one container are hotter than the contents of the other; one rod is longer than the other rod; one object contains more or less mass than the other.

In many technological activities, it is often difficult to make direct observation of the quantity being measured. The human senses are not equipped to make direct comparison of all the quantities with equal facility. Further, frequent measurements are extremely time consuming and tedius if taken directly. Accordingly, we use *indirect* methods in which the measurand is converted into some effect which is directly measurable. The indirect methods make comparison with a standard through use of a calibrated system, *i.e.*, an empirical relation is established between the measurement actually made and the results that are desired. For example, an indirect method may consist of developing an electrical voltage proportional to a physical variable to be measured, measuring that voltage and then converting the measured voltage back to the corresponding value of the original measurand. Electrical methods are preferred in the indirect methods due to their high speed of operation and simpler processing of the measured variable.

The indirect measurements involving one translation are called *secondary* measurements and those involving two conversions are called *tertiary* measurements.

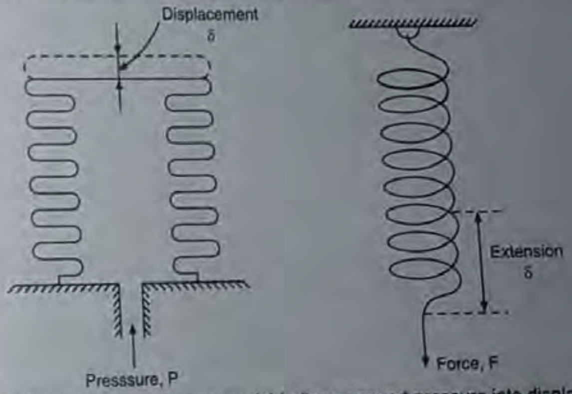


Fig. 7.2. Secondary measurements : (a) bellows convert pressure into displacement,
(b) springs convert force into displacement.

The conversion of presure into displacement by means of bellows (Fig. 7.2*a*) and the conversion of force into displacement by means of springs (Fig. 7.2*b*) are simple examples of secondary measurements. When a pressure above that of atmosphere is applied to the open end of the bellows, these expand and the resulting displacement is a measure of applied pressure. The displacement varies linerarly with applied pressure provided that the range of pressure variation is small. Likewise, a spring stretches when a vertical force is applied at its free end. Different forces give rise to different displacements and so a measure of the spring deflection gives a unique indication of the force.

The pressure measurement by manometers and the temperature measurement by mercury-in-glass thermometers are other examples of secondary measurements. In these instruments, the primary signal (pressure or temperature) is first transmitted to a transducer where its effect is translated into a length change. The secondary signal of length change is subsequently converted into equivalent pressure or temperature change through a calibration process.

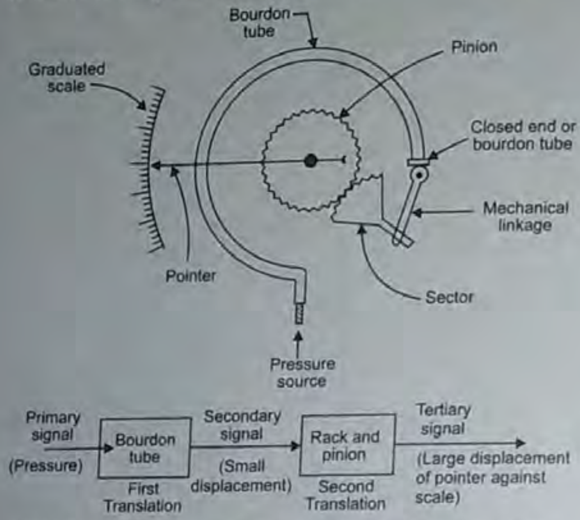


Fig. 7.3. Tertiary measurement : measurement of pressure by a bourdon tube pressure gauge

The measurement of static pressure by a bourdon tube pressure gauge (Fig. 7.3) is a typical example of tertiary measurement.

When the static pressure (input signal) is applied to bourdon tube, its free end deflects. The deflection which constitutes the secondary signal is very small and needs to be made larger for display and reading. The task is accomplished by an arrangement of lever, quadrant, gearing and the pointer. The amplified displacement constitutes the tertiary signal, and it is indicated by the movement of the pointer against a graduated scale.

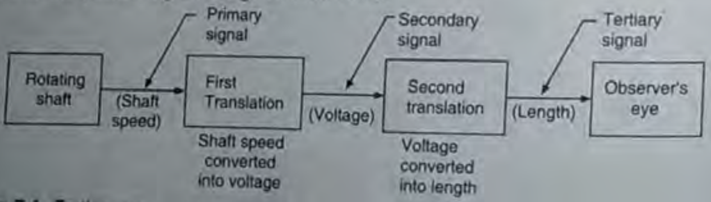


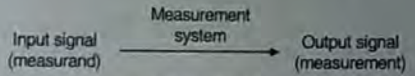
Fig. 7.4. Tertiary measurement : measurement of angular speed by an electric tachometer

The measurement of the speed of a rotating shaft by means of an electric tachometer (Fig. 7.4) is another typical example of tertiary measurement. The angular speed of the rotating shaft is first translated into an electrical voltage which is transmitted by a pair of wires to a voltmeter. In the voltmeter, the voltage moves a pointer on a scale, *i.e.*, voltage is translated into a length change. The tertiary signal of length change is a measure of the speed of the shaft and is transmitted to the observer.

The unit of a measuring system where translation of a measurand takes place is called the *transducer* or *translator*. The term is usually applied to an electromechanical device which converts the measurand into a proportional electrical output. The electrical, mechanical or any other variable which is actually measured is called the *measured signal*. In the example of a tertiary measurement cited above, the measured signal is the voltage which is an electrical analog of the speed of rotation of the unit coupled to the tachometer. In a thermocouple thermometer, the measured signal is an electromotive force which is the electrical analog of the temperature applied to the thermocouple. Likewise in a differential flowmeter, the measured signal would be the differential pressure which is the analog of the rate of flow through an orifice plate.

Needless to say, majority of measurement systems are tertiary systems and they include the whole range of mechanical, electrical, pneumatic, electro-mechanical and electro-pneumatic instruments.

Whereas the input to a measuring system is known as ***measurand***, the output is called ***measurement***.



For example, in a bourdon tube gauge, the applied pressure (input to the measurement system) is the measurand. The output from the system is the movement of the pointer against a calibrated scale, and this pointer movement becomes the measurement. Likewise in an electric tachometer, the angular speed is the measurand and the movement of pointer (length change) is the measurement.

7.2.3. Contact and Non-contact type Measurements

Measurements may also be described as (*i*) contact type where the sensing element of the measuring device has a contact with the medium whose characteristics are being measured and (*ii*) non-contact type where the sensor does not communicate physically with the medium. The optical, radio active and some of the electrical/electronic measurements belong to this category.

7.3. STATIC TERMS AND CHARACTERISTICS

Range and Span

The region between the limits within which an instrument is designed to operate for measuring, indicating or recording a physical quantity is called the *range* of the instrument. The range is expressed by stating the lower and upper values. *Span* represents the algebraic differences between the upper and lower range values of the instrument. For example,

Range	– 10° C to 80° C ;	Span	90°C
Range	5 bar to 100 bar ;	Span	95 bar
Range	0 volt to 75 volt ;	Span	75 volt

Accuracy, Error and Correction

No instrument gives an exact value of what is being measured. There is always some uncertainty in the measured value. This uncertainty is expressed in terms of accuracy and error. Accuracy of an indicated (measured) value may be defined as conformity with or closeness to an accepted standard value (true value). Accuracy of the measured signal depends upon the intrinsic accuracy of the instrument itself, variation of the signal being measured, accuracy of the observer and whether or not the quantity is being truly impressed upon the instrument. For example, the accuracy of a micrometer depends upon factors like error in screw, anvil shape, temperature difference, and the applied torque variations, etc.

In general, the result of any measurement differs somewhat from the true value of the quantity being measured. The difference between the measured value (V_m) and the true value (V_t) of the quantity represents *static error* or absolute error of measurement (E_s).

$$E_s = V_m - V_t \qquad \text{.....(7.1)}$$

The error may be either positive or negative. For positive static errors the instrument reads high and for negative static errors the instrument reads low.

From the experimentalist's view point, *static correction* or simply correction (C_s) is more important than the static error. The static correction is defined as the difference between the true value and the measured value of a quantity.

$$C_s = V_t - V_m \qquad \text{...(7.2)}$$

The correction of the instrument reading is of the same magnitude as the error, but opposite in sign, *i.e.*, $C_s = -E_s$.

EXAMPLE 7.1

A thermometer reads 73.5°C and the true value of the temperature is 73.15°C. Determine the error and the correction for the given thermometer.

Solution: Error E_s = measured value V_m – true value V_t

$= 73.5 - 73.15 = 0.35°\text{C}$

Correction $C_s = -E_s = -0.35°\text{C}$

EXAMPLE 7.2

A temperature transducer has a range of 0°C to 100°C and an accuracy of ±0.5 percent of full scale value. Find the error in a reading of 55°C.

Solution: Error $E_s = \pm 0.5°\text{C}$ percent of full scale value

$$= \pm \frac{0.5}{100} \times 100 = \pm 0.5°\text{C}$$

Thus a nominal reading of 55°C actually indicates a temperature in the range 54.5°C to 55.5°C.

EXAMPLE 7.3

(*a*) The accuracy of instrument has been specified as "accurate to within ± *x* for the prescribed or full range of the instrument". How do you interpret it?

(*b*) A thermometer is quoted as having the following specification :

Range and subdivision °C	**Maximum error**
-0.75 to $+37.5 \times 0.1$	0.25°C

How will you interpret this catalogue?

Solution: (*a*) The statement means that the instrument is accurate to within ± *x* at all points on the scale unless specified otherwise. This implies that irrespective of the indicated value, the error remains the same. For example, a given thermometer may be stated to read within ± 0.5°C between 100°C and 230°C. Likewise a scale of length may be read within ± 0.025 cm.

(*b*) The given specification implies that thermometer can be used for temperature measurement between – 0.75°C and + 37.5°C and has a scale which is subdivided into 0.1°C intervals. Further, the error has a temperature within a region bounded by plus or minus 0.25°C of the indicated value. Thus if meniscus of the mercury-in-glass thermometer were read at 28.5°C, the actual temperature would lie between (28.5 ± 0.25)°C.

Hysteresis and Dead Zone

The magnitude of output for a given input depends upon the direction of the change of input. This dependence upon previous inputs is called *hysteresis*. Hysteresis is the maximum difference for the same measured quantity (input signal) between the upscale and downscale readings during a full range traverse in each direction. Maximum difference is frequently specified as a percentage of full scale. Hysteresis results from the presence of irreversible phenomenon such as mechanical friction, slack motion in bearings and gears, elastic deformation, magnetic and thermal effects. Hysteresis may also occur in electronic systems due to heating and cooling effects which occur differentially under conditions of rising and falling input.

Dead zone is the largest range through which an input signal can be varied without initiating any response from the indicating instrument. Friction or play is the direct cause of dead zone or band.

Drift

It is an undesired gradual departure of instrument output over a period of time that is unrelated to changes in input, operating conditions or load. Wear and tear, high stress developing at some parts and contamination of primary sensing elements cause drift. It may occur in obstruction flow meters because of wear and erosion of the orifice plate, nozzle or venturimeter. Drift occurs in thermocouples and resistance thermometers due to the contamination of the metal and a change in its atomic or metallurgical structure. Drift occurs very slowly and can be checked only by periodic inspection and maintenance of the instrument.

Sensitivity

Sensitivity of an instrument or an instrumentation system is the ratio of the magnitude of the response (output signal) to the magnitude of the quantity being measured (input signal), *i.e.*,

$$\text{Static sensitivity, } K = \frac{\text{change of output signal}}{\text{change of input signal}} \qquad \text{...(7.3)}$$

Sensitivity has a wide range of units, and these depend upon the instrument or measurement system being investigated. For example, the operation of a resistance thermometer depends upon a change in resistance (output) to change in temperature (input) and as such its sensitivity will have units of ohms/°C. Sensitivity of an instrument system is usually required to be as high as possible because then it becomes easier to take the measurement (read the output).

EXAMPLE 7.4

A spring scale requires a change of 150 N in the applied weight to produce a 2 cm change in the deflection of the spring scale. Determine the static sensitivity.

Solution: $$k = \frac{\text{change of output signal}}{\text{change of input signal}} = \frac{2}{150} = 0.0133 \text{ cm/N}$$

EXAMPLE 7.5

Explain the following statements :

(*i*) A galvanometer has sensitivity specified as 15 mm/mA

(*ii*) An automatic balance has a quoted sensitivity of 1 vernier division/0.1 mg

Solution:

(*i*) This means that for 1 mA input the display (which is the light spot moving across a scale) shows a movement of an index of 15 mm.

(*ii*) This means that the index moves through one division when the mass changes by 0.1 mg.

Threshold and Resolution

The smallest increment of quantity being measured which can be detected with certainty by an instrument represents the threshold and resolution of the instrument.

When the input signal to an instrument is gradually increased from zero, there will be some minimum value input before which the instrument will not detect any output change. This minimum value is called the threshold of the instrument. Thus *threshold* defines the minimum value of input which is necessary to cause a detectable change from zero output. Threshold may be caused by backlash or internal noise.

When the input signal is increased from non-zero value, one observes that the instrument output does not change until a certain input increment is exceeded. This increment is termed *resolution* or *discrimination*. Thus resolution defines the smallest change of input for which there will be a change of output. With analog instruments, the resolution is determined by the ability of the observer to judge the position of a pointer on a scale, *e.g.*, the level of mercury in a glass tube.

Threshold and resolution may be expressed as an actual value or as a fraction or percentage of full scale value.

EXAMPLE 7.6

How resolution is reckoned for the analog and digital read out devices?

A force transducer measures a range of 0-150 N with a resolution of 0.1 percent of full scale. Find the smallest change which can be measured.

Solution: Resolution = 0.1% of full scale value

= 0.1/100 × 150 = 0.15 N

and this represents the smallest measurable change in force.

EXAMPLE 7.7

Distinguish between threshold and resolution (or discrimination).

The pointer scale of a thermometer has 100 uniform divisions, full scale reading is 200°C and 1/10th of a scale division can be estimated with a fair degree of accuracy. Determine the resolution of the instrument.

Solution: 1 scale division = 200/100 = 2°C

Resolution = 1/10th of scale division

= 1/10 × 2 = 0.2°C

Precision, Repeatability and Reproducibility

These terms refer to the closeness of agreement among several measurements of the same true value under the same operating conditions.

Let us differentiate between accuracy and precision as applied to the realms of measurements. Accuracy refers to the closeness or conformity to the true value of the quantity under measurement. Precision refers to the degree of agreement within a group of measurements, *i.e.*, it prescribes the ability of the instrument to reproduce its reading over and over again for a constant input signal. This distinction can be elaborated by considering the following two examples:

(*i*) Consider a micrometer normal in every respect but with its anvil displaced from its true position. The readings taken with this micrometer would be clearly defined and consistent, *i.e.*, a negligible scatter amongst different readings for the same dimension. We would say that the micrometer is as precise as ever. The readings, however, do not conform to truth as the anvil is not placed at its correct position. The readings of the dimension with this micrometer are thus not accurate.

(*ii*) Consider two voltmeters of the same model, make and range. Further, let both have knife-edge pointers, carefully ruled and mirror backed scale to help avoid parallax errors. Both the voltmeters can be read to the same precision. In case the series resistance of one of the voltmeters is defective, its readings would be subjected to an error. The accuracy of the two instruments would then be different.

The difference between accuracy and precision has been illustrated in Fig. 7.5. The arrangement may be thought to correspond to the game of darts where one is asked to strike a target represented by centre circle. The centre circle then represents the true value, and the result achieved by the striker has been indicated by the mark '*X*'.

(a) High precision high accuracy

(b) High precision low accuracy

(c) Low precision low accuracy

Fig. 7.5. Difference between accuracy and precision

Two further terms used to define reproducibility are :

- *Stability* refers to the reproducibility of the mean reading of an instrument, repeated on different occasions separated by intervals of time which are long compared with the time of taking a reading. The conditions of use of the instrument remain unchanged.
- *Constancy* refers to the reproducibility of the mean reading of an instrument when a constant input is presented continuously and the conditions of test are allowed to vary within specified limits. This variation may be due to some change in the external environmental conditions.

The above discussion also points out that it is possible to obtain high precision with poor accuracy, but not high accuracy with low precision. In other words precision is a necessary prerequisite to accuracy but it does not guarantee accuracy.

Linearity

The working range of most of the instruments provides a linear relationship between the output (reading taken from the scale of the instrument) and input (measurand, signal presented to the measuring system). Linearity is defined as the ability to reproduce the input characteristics symmetrically, and this can be expressed by the straight line equation.

$$y = mx + c$$

where y is the output, x the input, m the slope and c the intercept. Apparently the closeness of the calibration curve to a specified straight line is the linearity of the instrument.

Any departure from the straight line relationship is *non-linearity*. The non-linearity may be due to non-linear elements in the measurement device, mechanical hysteresis, viscous flow or creep, and elastic after-effects in the mechanical system.

Some other terms associated with the static performance of an instrument are:

- ***Tolerance*** : Range of inaccuracy which can be tolerated in measurements : it is the maximum permissible error. For example, the tolerance would be ±1% when an inaccuracy of ±1 bar can be tolerated for 100 bar value of pressure.
- ***Readability and least count*** : The term *readability* indicates the closeness with which the scale of the instrument may be read. The term *least count* represents the smallest

difference that can be detected on the instrument scale. Both readability and least count are dependent on length scale, spacing of graduations, size of the pointer and parallax effect.

- *Backlash* : The maximum distance or angle through which any part of a mechanical system may be moved in one direction without applying appreciable force or motion to the next part in a mechanical system.
- *Zero stability* : A measure of the ability of the instrument to restore to zero reading after the measurand has returned to zero, and other variations (temperature, pressure, humidity, vibration etc.) have been removed.
- *Stiction (Static friction)* : Force or torque that is necessary just to initiate motion from rest.

Calibration

The magnitude of the error and consequently the correction to be applied is determined by making a periodic comparison of the instrument with standards which are known to be constant. The entire procedure laid down for making, adjusting or checking a scale so that readings of an instrument or measurement system conform to an accepted standard is called *calibration*. The graphical representation of the calibration record is called *calibration curve* and this curve relates standard values of input or measurand to actual values of ouput throughout the operating range of the instrument.

A comparison of the instrument reading may be made with

(*i*) a primary standard,

(*ii*) a secondary standard of accuracy greater than the instrument to be calibrated,

(*iii*) a known input source.

For example, we may calibrate a flowmeter by comparing it with a standard flow measurement facility at the National Bureau of Standards; by comparing it with another flow meter (a secondary standard) which has already been compared with a primary standard; or by direct comparison with a primary measurement such as weighing a certain amount of water in a tank and recording the time elapsed for this quantity to flow through the meter.

The following points and observations need consideration while calibrating an instrument :

(*i*) Calibration of the instrument is carried out with the instrument in the same position (upright, horizontal, etc.) and subjected to the same temperature and other environmental conditions under which it is to operate while in service.

(*ii*) The instrument is calibrated with values of the measurand impressed both in the increasing and in the decreasing order. The results are then expressed graphically; typically the output is plotted as the ordinate and the input or measurand as the abscissa.

(*iii*) Output readings for a series of impressed values going up the scale may not agree with the output readings for the same input values when going down.

(*iv*) Lines or curves plotted in the graphs may not close to form a loop.

In a typical calibration curve (Fig. 7.6) ABC represents the readings obtained while ascending the scale; DER represents the readings during descent; KLM represents the median and is commonly accepted as the calibration curve. The term 'median' refers to the mean of a series of up and down readings.

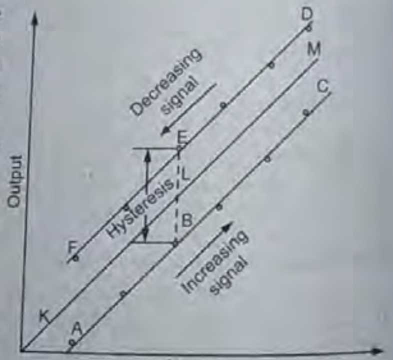


Fig. 7.6. Calibration curve

Quite often, the indicated values are plotted as abscissa and the ordinate represents the variation of the median from the true values. (Fig. 7.7)

A faired curve through the experimental points then represents the correction curve. This type of deviation presentation facilitates a rapid visual assessment of the accuracy of the instrument. The user looks along the abscissa for the value indicated by the instrument and then reads the correction to be applied.

A properly prepared calibration correction curve gives information about the absolute static errors of the measuring device, the extent of the instrument's linearity or conformity, and the hysteresis and repeatability of the instrument.

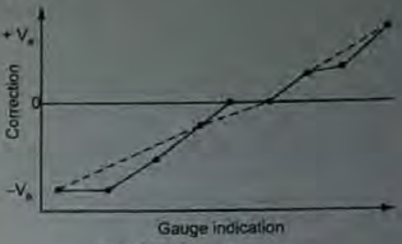


Fig. 7.7. Corrective curve

7.4. MEASUREMENT ERRORS

Despite utmost care and precautions an experimenter may take to eliminate all possible errors, the happy goal is seldom attained and certain errors are bound to creep in. For example, even in an apparently simple measurement of flow velocity with a Pitot tube any misalignment of the probe, leaks in the pressure tubing, changes in the bore and surface conditions of the manometer, any fluctuations in the atmospheric and stream pressure are likely to affect the probe readings and give rise to uncertainties. Errors and uncertainties are inherent in the process of making any measurement and in the instrument with which the measurements are made.

Errors may originate in a variety of ways and the following sources need examination.

Instruments Errors

There are many factors in the design and construction of instruments that limit the accuracy attainable. Instruments and standards possess inherent inaccuracies and certain additional inaccuracies develop with use and time. Example are:

- Improper selection and poor maintenance of the instrument
- Faults of construction resulting from finite width of knife edges ; lost motion due to necessary clearance in gear teeth and bearing; excessive friction at the mating parts etc
- Mechanical friction and wear, backlash, yielding of supports, pen or pointer drag, and hysteresis of elastic members due to aging.
- Unavoidable physical phenomenon due to friction, capillary attraction and imperfect rarefaction.
- Assembly errors resulting from incorrect fitting of the scale zero with respect to the actual zero position of the pointer, non-uniform division of the scale, and bent or distorted pointers.

The assembly errors do not alter with time, and can be easily discovered and corrected. An uncertainty in measurement due to friction at the mating parts, and the pen and pointer drag is frequently reduced by gently tapping of the instruments; a vigorous tapping would however lead to delicate bearing being injured and thus increasing friction all the more.

Environmental Errors

The instrument location and the environment errors are introduced by using an instrument in conditions different for which it has been designed, assembled and calibrated. The different conditions of use may be temperature, pressure, humidity and altitude, etc.; the effect of temperature being more predominant. A change in the temperature may alter the elastic constant of a spring, may change the dimensions of a measuring element or linkage in the system, may alter the resistance values and flux densities of magnetic elements.

Consider a mercury-in-glass thermometer being used for the measurement of air temperature. The instrument will be located wrongly if during measurements the sun happens to be shining on the thermometer bulb. Similarly the bulb would indicate an effect of heat radiation if the thermometer is placed too close to a window. Likewise a high air pressure would tend to compress the walls of the bulb and force the mercury to rise within the capillary and thus give a spurious temperature reading.

Environmental errors alter with time in an unpredictable manner. The following methods have been suggested to eliminate or at least reduce the environmental errors.

- Use the instruments under the conditions for which it was originally assembled and calibrated. This may involve control of temperature, pressure and humidity conditions.
- Measure deviations in the local conditions from the calibrated ones and then apply suitable corrections to the instrument readings.
- Automatic compensation for the departures from the calibrated conditions by using sophisticated devices.
- Make a complete new calibration under the local conditions.

The method chosen would depend on the local assessment of the problem.

Translation and Signal Transmission Errors

The instrument may not sense or translate the measured effect with complete fidelity. The error also includes the non-capability of the instrument to follow rapid changes in the measured quantity due to inertia and hysteresis effects. The transmission errors creep in when the transmitted signal is rendered faulty due to its distortion by resonance, attentuation, loss leakage, or on being absorbed or otherwise consumed within the communication channel. The error may also result from unwanted disturbances such as noise, line pick-up, hum, ripple, etc. The errors are remedied by calibration and by monitoring the signal at one or more points along its transmission path.

Observation Errors

There goes a saying that 'instruments are better than the people who use them'. Even when an instrument has been properly selected, carefully installed and faithfully calibrated, shortcomings in the measurement occur due to certain failings on the part of the observer. The obseration errors may be due to :

- Parallax, *i.e.*, apparent displacement when the line of vision is not normal to the scale.
- Inaccurate estimates of average reading, lack of ability to interpolate properly between graduations.
- Incorrect conversion of units in between consecutive readings, and non-simultaneous observation of interdependent quantities.
- Personal bias, *i.e.*, a tendency to read high or low, or anticipate a signal and read too soon.
- Wrong scale reading, and wrong recording of data.

The poor mistakes resulting from the inexperience and carelessness of observer are obviously remedied with careful training, and by taking independent readings of each item by two or more observers.

Operational Errors

A pre-requisite to precise and meticulous measurements is that the instruments should be properly used. Quite ofen, errors are caused by poor operational techniques. Examples are :

- A differential type of flowmeter will read inaccurately if it is placed immediately after a valve or a bend.

- A thermometer will not read accurately if the sensitive portion is insufficiently immersed or is radiating heat to a colder portion of the installation.
- A pressure gauge will correctly indicate pressure when it is exposed only to the pressure which is to be measured.
- A steam calorimeter will not give the indication of the dryness fraction of steam unless the sample drawn correctly represents the condition of steam.

System Interaction Errors

The act of measurement may affect the condition of the measurements and thus lead to uncertainties in measurements. Examples are :

- Introduction of a thermometer alters the thermal capacity of the system and provides an extra path for heat leakage.
- A ruler pressed against a body results in a differential deformation of the body relative to ruler.
- An obstruction type flowmeter may partially block or disturb the flow conditions. Consequently the flow rate shown by the meter may not be same as before the meter installation.
- Reading shown by a hand tachometer would vary with the pressure with which it is pressed against the shaft.
- A milliammeter would introduce additional resistance in the circuit and thereby alter the flow current by a significant amount.

The job of an instrument designer is to see whether the alteration due to system interference is minimal. Many of the most precise, expensive and elaborate measuring instruments owe their cost and complexity solely to the means adopted to eliminate, or at least reduce interaction between the instrument and the physical state being measured.

The errors discussed above may be grouped into systematic errors and random errors.

Systematic errors are repeated consistently with the repetition of the experiment, and have same magnitude and sign for a given set of conditions. They alter the instrument reading by a fixed magnitude and with same sign from one reading to another. Because of the same algebraic sign, systematic errors tend to accumulate and hence are often called commulative errors. Instrument bias is another term for systematic errors. These errors are caused by such effects as sensitivity shifts, zero offset and known non-linearity. Systematic errors cannot be determined by direct and repetitive observation of the measurand made each time with same technique. The only way to locate these errors is to have repeated measurements under different conditions or with different equipment and where possible by an entirely different method. Some factors leading to systematic errors are:

(*i*) pointer offset
(*ii*) change in ambient temperature
(*iii*) poor design and construction of instrument
(*iv*) buoyant effect of the wind and the weights of a chemical balance
(*v*) inequality of the arms of a beam balance
(*vi*) change in the original state of the system due to interaction between the instrument and the system.

Random errors are accidental, small and independent, and are mainly due to inconsistent factors such as spring hysteresis, stickiness, friction, noise and threshold limitations. Since these errors vary both in magnitude and sign (are positive or negative on the basis of chance alone), they tend to compensate one another and are referred to as chance/accidental/compensating errors. The random errors are detected by lack of consistency in the measured value when the same input is imposed repeatedly on the instrument (measured values are not precise and show a considerable scatter). The magnitude and direction of random errors cannot be predicted from a knowledge of the measurement system; however, these errors are assumed to follow the law of probabilities. Some factors leading to random errors are :

(*i*) stickiness and friction
(*ii*) line voltage fluctuations
(*iii*) vibration of instrument supports
(*iv*) large dimensional tolerances between the mating parts
(*v*) spring hysteresis and elastic deformation
(*vi*) inconsistencies associated with accurate measurement of small quantities.

7.5. PRESSURE MEASUREMENTS

Pressure measurement is undoubtedly one of the most common of all the measurements made on systems. In company with temperature and flow, pressure measurements are extensively used in industry, laboratories and many other fields for a wide variety of reasons. Pressure measurements are concerned not only with determination of force per unit area exerted by a fluid at a point but are also involved in many liquid level, density, flow and temperature measurements. Measurement of pressure is also needed to maintain safe operating conditions, to help control a process and to provide test data.

Pressure measurement by any technique is essentially based on the following well-known propositions :

(*i*) Pressure at any point in a body of liquid at rest is proportional to the depth of the point below the free surface of the liquid, and increases in the downward direction at a rate equivalent to the density of the liquid. Further, within a continuous expanse of the same fluid, pressure is same at any two points which lie in a horizontal plane.

(*ii*) There is a pressure equality throughout a fluid, *i.e.*, a pressure applied to a confined fluid via a movable surface would be transferred undiminished to all the boundary surfaces.

(*iii*) Pressure is unaffected by the shape of the confining boundaries.

Manometers measure pressure by balancing a column of liquid against the pressure to be measured. Height of column so balanced is measured and then converted to the desired pressure units. Manometers may be vertical, inclined, open, differential or compound. Choice of any type depends on its sensitivity of measurement, ease of operation and the magnitude of pressure being measured. Manometers can be used to measure gauge, differential, atmospheric and absolute pressures.

7.5.1. Piezometer

It is a vertical transparent glass tube, the upper end of which is open to atmosphere and the lower end is in communication with the gauge point ; a point in the fluid container at which pressure is to be measured. Rise of fluid in the tube above a certain gauge point is a measure of the pressure at that point.

Fluid pressure at gauge point *A*

= atmospheric pressure p_a at the free surface
+ pressure due to a liquid column of height h_1

$$p_1 = p_a + wh_1$$

where w is the specific weight of the liquid.

Similarly for the gauge point *B*,

$$p_2 = p_a + wh_2$$

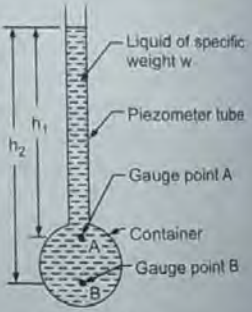


Fig. 7.8. Piezometer

Pressures are generally prescribed with atmospheric pressure taken as the zero of pressure scale. Evidently then, $p_1 = wh_1$ and $p_2 = wh_2$ and the pressures thus evaluated are the *gauge pressures*.

When using a piezometer to measure the pressure of a moving fluid, axis of the tube should be absolutely normal to the direction of flow and its bottom end must flush smoothly with the pipe surface. Any burr or projection would cause obstruction resulting in change in the pressure head. Further, to reduce the surface tension and capillary effects, diameter of the tube must be kept at least 6 mm.

Piezometers cannot be used to measure pressures which are considerably excess of atmospheric pressure. Use of very long glass tube would be unsafe, it being both fragile and unmanageable. Further, gas pressure cannot be measured as gas does not form any free surface with atmosphere. Again measurement of negative pressure is not possible due to flow of atmospheric air into the container through the tube. These difficulties are overcome by modifying the piezometer into a U-tube manometer, also called the double column manometer.

7.5.2. U-Tube Double Column Manometer

This simplest and useful pressure measure device consists of a transparent tube bent in the form of letter U and filled with a manometric liquid whose density is known. The choice of a particular manometric liquid depends upon the pressure range and nature of the fluid whose pressure is sought. For high ranges, mercury (specific gravity 13.6) is the manometric/balancing liquid. For low pressure ranges, liquid like carbon tetrachloride (specific gravity 1.59) or acetylene tetrabromide (specific gravity 2.59) is employed. Quite often, some colors are added to the balancing liquid so as to get clear readings.

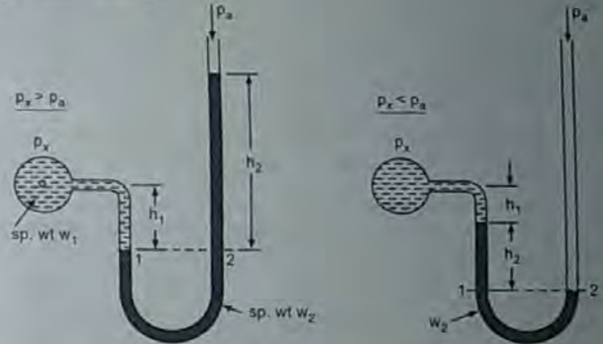


Fig. 7.9. U-tube manometers

When both the limbs are open to atmosphere, manometric liquid stands at even height. Under application of pressure p_x to one limb, manometric liquid is forced downward on the side with a corresponding rise on the other side until the column of liquid between the two levels balances the difference between the unknown pressure p_x and the atmospheric pressure p_a. Figure 7.9 shows the schematics of U-tube being employed for measurement of positive and negative pressures.

Arrangement (*a*) *Measurement of pressure greater than atmospheric pressure*

Due to greater pressure p_x in the container, the manometric liquid is forced downward in the left limb of the U-tube and there is a corresponding rise of manometric liquid in the right limb.

For the right limb, the gauge pressure at point 2 is

p_2 = atmospheric pressure *i.e.*, zero gauge pressure at the free surface + pressure due to head h_2 of manometric liquid of specific weight w_2

$= 0 + w_2 h_2$

For the left limb, the gauge pressure at point 1 is

p_1 = gauge pressure p_x + pressure due to height h_1 of the liquid of specific weight w_1

$= p_x + w_1 h_1$

Points 1 and 2 are at the same horizontal plane ; $p_1 = p_2$ and therefore

$$p_x + w_1 h_1 = w_2 h_2$$

∴ Gauge pressure in the container ,

$$p_x = w_2 h_1 - w_1 h_1$$

or in terms of head of water column,

$$\frac{p_x}{w} = \left(\frac{w_2}{w} h_2 - \frac{w_1}{w} h_1\right) = (s_2 h_2 - s_1 h_1) \qquad ...(7.4)$$

where w is the specific weight of water and symbol s denotes the specific gravity of a liquid.

Arrangement (*b*) *Measurement of pressure less than atmospheric pressure*

Due to negative pressure p_x in the container, the manometric liquid is sucked upwards in the left limb of the U-tube and there is a corresponding fall of manometric liquid in the right limb.

Pressure in the two legs at the same levels 1 and 2 are equal; $p_1 = p_2$ and therefore,

$$p_x + w_1 h_1 + w_2 h_2 = 0$$

∴ Gauge pressure in the container,

$$p_x = -(w_1 h_1 + w_2 h_2)$$

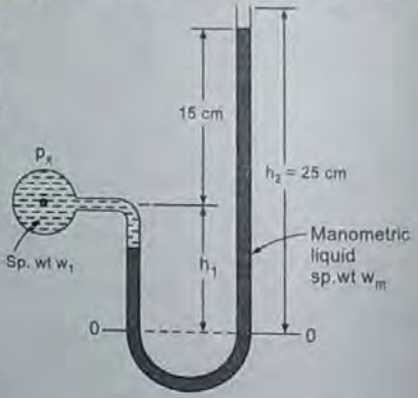
or in terms of head of water column,

$$\frac{p_x}{w} = -(s_1 h_1 + s_2 h_2) \qquad ...(7.5)$$

U-tube manometer necessitates two readings, h_1 and h_2 and that is likely to increase the chance of error. The difficulty is circumvented by adopting a single column manometer.

EXAMPLE 7.8

The right limb of a U-tube manometer containing mercury is open to the atmosphere while the left limb is connected to a pipe through which flows a fluid of specific gravity 0.85. The centre of the pipe lies 15 cm below the level of mercury in the right limb. If the difference of mercury level in the two limbs is 25 cm, determine the pressure of fluid of the pipe.



Solution : Let p_x be the gauge pressure of the fluid in the pipeline.

Consider pressure balance in the horizontal plane 0 – 0; pressures in the left and right limbs at this plane are equal. That is ;

$$p_x + w_1 h_1 = w_m h_2$$

or

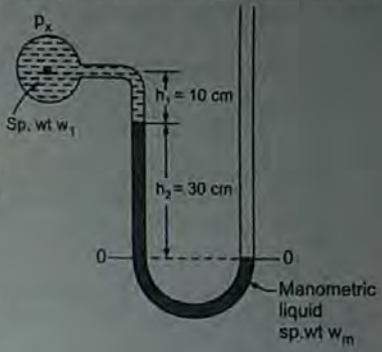
$$p_x = w_m h_2 - w_1 h_1$$

$$= (9810 \times 13.6) \times 0.25 - (9810 \times 0.85) \times 0.1$$

$$= 33354 - 833.85 \approx \mathbf{32520\ N/m^2}$$

EXAMPLE 7.9

The right limb of a simple U-tube manometer containing mercury is open to atmosphere and the left limb is connected to a pipe through which flows a fluid of specific gravity 0.8. Make calculations for the vacuum pressure in the pipe if the difference of mercury level in the two limbs is 30 cm and the level of fluid in the left limb is 10 cm below the centre of pipe.



Solution : Let p_x be the gauge pressure of fluid in the pipeline.

Consider pressure balance in the horizontal plane 0 – 0; the pressures in the left and right limbs at this level are equal. That is :

$$p_x + w_1 h_1 + w_m h_2 = 0$$

$$p_x = -(w_1 h_1 + w_m h_2)$$

$$= -(9810 \times 0.8 \times 0.1 + 9810 \times 13.6 \times 0.3)$$

$$= -(784.8 + 40024.8) = \mathbf{-40809.6\ N/m^2}$$

7.5.3. U-tube Differential Manometer

A differential manometer is a device used to find the difference in pressure between two points in a pipeline or in two different pipes or containers. In general, a differential manometer consists of a U-tube filled with a manometric liquid and with its ends connected to the points between which the pressure difference is to be measured. Figure 7.10 shows the two common arrangements of a differential manometer.

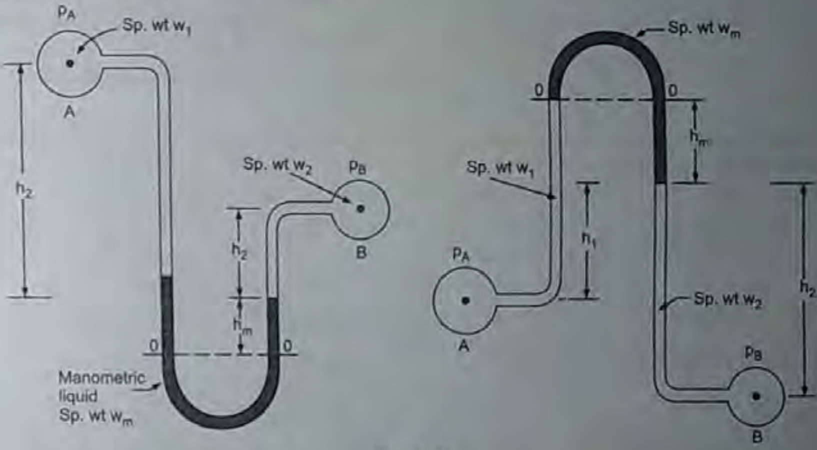


Fig. 7.10.

In the *upright configuration* of U-tube differential manometer, the manometric liquid contained in the U-tube is a heavier liquid, *i.e.*, its specific weight w_m is greater than that of the liquids in the containers.

Consider the pressure balance in the horizontal plane 0 – 0; the pressure in the left and right limbs at this plane are equal. That is :

$$p_A + w_1 (h_1 + h_m) = p_B + w_2 h_2 + w_m h_m$$

or $$p_A - p_B = h_m (w_2 - w_1) + w_2 h_2 - w_1 h_1$$

For the special and frequently encountered case of pipes A and B at the same level ($h_1 = h_2$) and carrying the same fluid ($w_1 = w_2$).

$$p_A - p_B = h_m (w_m - w_1)$$

In terms of head of water column

$$\frac{p_A - p_B}{w} = h_m \left[\frac{w_m}{w} - \frac{w_1}{w}\right] = h_m (s_m - s_1)$$

If water is the fluid in the two pipes and mercury is the manometric liquid, then $s_1 = 1$ and $s_m = 13.6$ and therefore, for the mercury-water differential manometer,

$$\frac{p_A - p_B}{w} = 12.6\, h_m$$

That is the pressure difference measured as a head of water column is 12.6 times the difference in height of mercury column. Sensitivity of such a gauge may be defined as the ratio of the observed difference in levels h_m to the difference of pressure head $\frac{(p_A - p_B)}{w}$ of water being measured.

$$\text{Sensitivity} = \frac{h_m}{\frac{(p_A - p_B)}{w}} = \frac{h_m}{h_m (s_m - 1)} = \frac{1}{s_m - 1}$$

With mercury (relative density 13.6) sensitivity is $\frac{1}{12.6}$ and with paraffin (relative density 0.85) the sensitivity is $-\frac{1}{0.15}$ Negative sensitivity implies that a paraffin-water differential manometer must be used in the inverted position.

In the ***inverted differential manometer***, the manometric liquid is lighter than the fluid whose pressure difference is to be ascertained.

Consider the pressure balance in the horizontal place 0 – 0; the pressures in the left and right limbs of the inverted U-tube at this place are equal. That is :

$$p_A - w_1 h_1 - w_1 h_m = p_B - w_2 h_2 - w_m h_m$$

or $$p_A - p_B = w_1 h_1 - w_2 h_2 + h_m (w_1 - w_m)$$

If the pipes A and B are at the same level ($h_1 = h_2$) and carry the same fluid ($w_1 = w_2$)

$$p_A - p_B = h_m (w_1 - w_m)$$

In terms of head of water column,

$$\frac{p_A - p_B}{w} = h_m \left(\frac{w_1}{w} - \frac{w_m}{w}\right) = = h_m (s_1 - s_m)$$

where s_m and s_1 are the specific gravities of the manometric liquid and the fluid in the pipelines of the flow system.

The following points need to be noted :

(*i*) If the manometric liquid is very light, *i.e.*, $s_m <<< s_1$, then

$$\frac{p_A - p_B}{w} = h_m$$

(*ii*) If the manometric liquid is so chosen that its relative density is very nearly equal to that of fluids in the pipelines ($s_m \approx s_1$) and that the fluids do not intermix, the manometer will become very sensitive. A sensitive manometer gives a large value of h_m for a small pressure difference.

EXAMPLE 7.10

A U-tube differential manometer containing mercury is connected on one side to pipe A containing carbon tetrachloride (sp. gr. 1.6) under a pressure of 120 kPa, and on the other side to pipe B containing oil (sp. gr. 0.8) under a pressure of 200 kPa. The pipe A lies 2.5 m above pipe B and the mercury level in the limb communicating with pipe A lies 4 m below the pipe A. Determine the difference in the levels of mercury in the two limbs of the manometer.

Take specific weight of water = 9.81 kN/m^3.

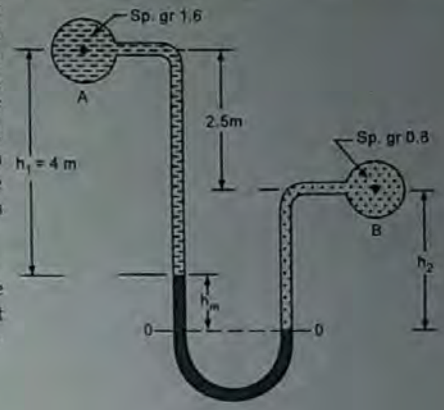


Fig. 7.11.

Solution : Consider pressure balance in the horizontal plane 0 – 0 ; the pressures in the left and right limbs at this plane are equal. That is :

$$p_A + w_c h_1 + w_m h_m = p_B + w_0 h_2$$

$$120 + 9.81 \times 1.6 \times 4 + 9.81 \times 13.6\, h_m$$
$$= 200 + 9.81 \times 0.8\, (1.5 + h_m)$$
$$120 + 62.78 + 133.42\, h_m = 200 + 11.77 + 7.85\, h_m$$
$$h_m = \frac{200 + 11.77 - 120 - 62.78}{133.42 - 7.85}$$
$$= 0.231 \text{ m} = 23.1 \text{ cm}$$

EXAMPLE 7.11

Determine the difference of pressure between pipes A and B when connected to an inverted U-tube differential manometer containing oil of specific gravity 0.8 as the manometric liquid. The pipe A conveys water and a fluid of sp. gr. 0.9 flows through the pipe B. The position of manometric liquid in the manometer limbs is as indicated in Fig. 7.12. If $p_B = 5 \times 10^4$ N/m^2 and the barometer reading is 730 mm of mercury, find the pressure in pipe A in metres of water absolute.

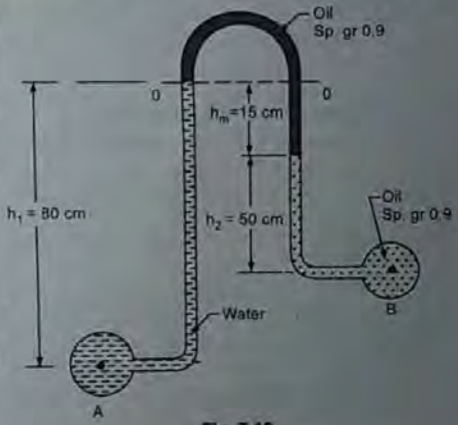


Fig. 7.12.

Solution : Consider pressure balance in the horizontal plane 0 – 0 ; the pressure in the left and right limbs at this plane is equal. That is:

$$p_A - w_1 h_1 = p_B - w_2 h_2 - w_m h_m$$
$$p_A - 9810 \times 0.8 = p_B - 9810 \times 0.9 \times 0.5 - 9810 \times 0.8 \times 0.15$$
$$p_A - p_B = 9810\, (0.8 - 0.9 \times 0.5 - 0.8 \times 0.15)$$
$$= 9810\, (0.8 - 0.45 - 0.12)$$
$$= 2256 \text{ N/m}^2$$

Given : $p_A = 5 \times 10^4$ N/m^2

and $p_{at} = 9810 \times 13.6 \times 0.73 = 9.74 \times 10^4$ N/m^2

Pressure intensity in pipe A

$$p_A = p_B + 2256 = 5 \times 10^4 + 2256 = 52256 \text{ N/m}^2 \text{ (gauge)}$$

Absolute pressure = gauge pressure + atmospheric pressure

$$p_A \text{ (absolute)} = 52256 + 9.74 \times 10^4 = 149656 \text{ N/m}^2$$

$$= \frac{149656}{9810} = 15.25 \text{ m of water absolute}$$

EXAMPLE 7.12

When pressure at a point is so large that the manometric fluid cannot be contained within the height of a single U-tube manometer, use is made of a compound U-tube manometer which essentially consists of a number of simple U-tube manometers arranged in series. For one such unit illustrated in Fig. 7.13, calculate the pressure difference between the points A and B. Take w_w = 10 kN/m^3 for water w_m = 136 kN/m^3 for mercury and w_0 = 8.5 kN/m^3 for oil.

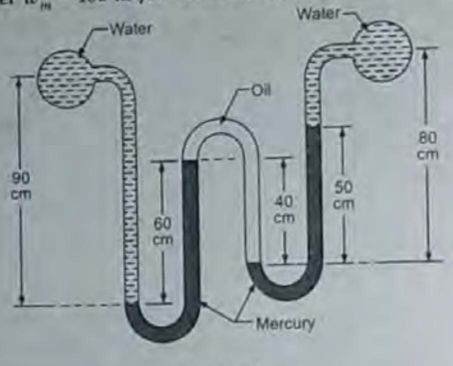


Fig. 7.13.

Solution : Starting from point A, the governing manometric equation is :

$$p_A + 10 \times 0.9 - 136 \times 0.6 + 8.5 \times 0.4 - 136 \times 0.5 - 10\,(0.8 - 0.5) = p_B$$

$$p_A - p_B = -9 + 81.6 - 3.4 + 68 + 3 = 140.2 \text{ kN/m}^2$$

7.5.4. Single Column Manometer

In the industrial well-manometers, one of the legs of U-tube manometer is replaced by a large diameter well; the widened limb is made about 100 times greater than cross-sectional area of the other limb. A change in the level of manometric liquid occurring in the wider limb due to pressure changes would then be so small that it can be neglected. Pressure difference would then be indicated only by the height of liquid column in the narrow limb.

To start with, let both limbs of the manometer be exposed to atmospheric pressure. The liquid level in the wider limb (also called reservoir, well, basin) and narrow limb will correspond to position 0-0. When the wider limb is connected to a vessel containing fluid at pressure p_x (which is greater than the atmospheric pressure p_a), manometric liquid level in the reservoir will fall down by δh and there will be a corresponding level rise h_2 in the narrow limb. By conservation of volume and applying manometric equations, the following expression can be set up for the pressure p_x of the fluid contained in the vessel,

$$p_x = w_2 h_2 \left[1 + \frac{a}{A}\right] \qquad \text{...(7.13)}$$

If the area ratio (a/A) is made so small that it can be neglected, then

$$p_x = w_2 h_2 \qquad \text{...(7.14)}$$

Single column manometers are used as primary standards for calibrating other pressure gauges, and are more sensitive than simple U-tube manometers.

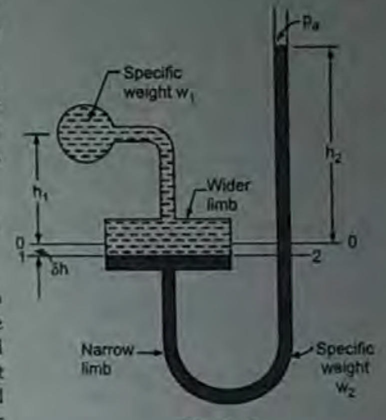


Fig. 7.14.

To expand the scale and thereby increase sensitivity, the narrow limb of the single column manometer is not set vertically but is kept inclined to the horizontal axis by an angle θ as shown in Fig. 7.15. Gauge pressure p_x is then given by :

$$p_x = w_2\, l \left(\sin\theta + \frac{a}{A}\right) \qquad \text{...(7.15)}$$

where l is the rise of liquid in the inclined tube.

Scale of the instrument is obviously expanded due to presence of sin θ. By making θ quite small, l can be increased such that $l \sin\theta$ remains constant. Any desired value of sensitivity (normally up to about 25 times that of U-tube) may be obtained by incorporating a swivel mechanism for the inclined limb. Minimum value of θ = 5°. With inclination angles less than this, exact position of the meniscus is difficult to determine.

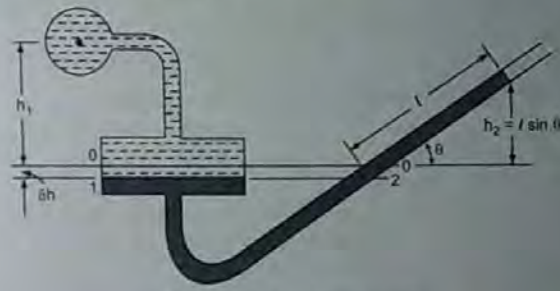


Fig. 7.15. Inclined manometer

This type of manometer is frequently called a ***draft gauge*** because it is so generally used for determining the draft in steam generator setting and for measuring small pressure changes in low velocity gas flows.

7.5.5. Manometric Liquids

Some of the desirable characteristics of a manometric liquid are :

- low viscosity, *i.e.*, capability of quick adjustment with pressure changes,
- low coefficient of thermal expansion, *i.e.*, minimum density changes with temperature,
- low vapour pressure, *i.e.*, little or no evaporation at ambient conditions,
- negligible surface tension and capillary effects,
- non-corrositive, non-poisonous, non-sticky and stable nature.

Mercury is usually used for measuring vacuum and moderate pressure of gas, vapour, or water where moderate sensitivity is required. Mercury does not evaporate readily, has a reasonable stable density, forms a sharp meniscus and is clearly seen. However, it amalgamates or corrodes many metals, is poisonous and expensive.

Water is used for measuring small vacuums and small pressure differences with high sensitivity. Water has a fairly sharp meniscus, is cheap and readily available. However, it has a tendency to evaporate and dissolve some gases in it. Further, its transparent nature renders it difficult to be seen within the manometer tube. A dye added to give it a distinctive colour would be deposited on the tube walls when water evaporates.

For high multiplication in two-liquid manometers, alcohol and kerosene are often used. Kerosene is, however, not satisfactory because of fractional vaporization and consequent changes in density. Alcohol is also apt to change in density by taking up water.

7.5.6. Advantages and Limitations of Manometers

- Relatively inexpensive and easy to fabricate
- Good accuracy and sensitivity
- Requires little maintenance; is not affected by vibrations
- Particularly suitable to low pressure and low differential pressures
- Sensitivity can be altered easily by affecting a change in the quantity of manometric liquid in the manometer
- Generally large and bulky, fragile and gets easily broken
- Measured medium has to be compatible with the manometric fluid used
- Readings are affected by change in gravity, temperature and altitude
- Surface tension of manometric fluid creates a capillary effect
- Meniscus has to be measured by accurate means to ensure improved accuracy.

7.5.7. Mechanical Gauges : Elastic Pressure Transducers

Range of pressures that can be measured with manometer depends upon the manometric fluid used, the minimum displacement which can be sensed and the tube length. Manometers are employed to measure pressure as low as 0.35 N/m^2, and also the pressure difference in the range of 1.4×10^5 to 2.1×10^5 N/m^2. Pressures higher than two or three atmospheres are invariably measured with mechanical gauges of the Bourdon tube or diaphragm type. In these gauges the fluid pressure is applied to a hollow tube, movable diaphragm or bellows. The deflection thus obtained is transmitted through a suitable mechanism to a needle which indicates pressure on a pre-calibrated dial.

Bourdon Gauge: The pressure responsive element of a bourdon gauge consists essentially of metal tube (called bourdon tube or spring), oval in cross-section and bent to form a circular segment of approximately 200 to 300 degrees. The tube is fixed but open at one end and it is through this fixed end that the pressure to be measured is applied. The other end is closed but free to allow displacement under deforming action of the pressure difference across the tube walls. When a pressure (greater than atmosphere) is applied to the inside of the tube, its cross-section tends to become circular. This makes the tube straighten itself out with a consequent increase in its radius of curvature, *i.e.*, the free end would collapse and curve.

The free end of the tube is connected to a spring loaded linkage which amplifies the displacement and transmits it to the angular rotation of a pointer over a calibrated scale to give a mechanical

indication of pressure (Fig. 7.16). The linkage is so designed that the mechanism may be adjusted for optimum linearity and minimum hysteresis as well as to compensate for wear which may develop over a period of time. A hairspring is sometimes used to fasten the spindle to the frame of the instrument to provide necessary tension for proper meshing of the gear teeth and thereby freeing the system from backlash (lost motion). After prolonged use, the tooth gearing of the pinion and sector type linkage wears out and this impairs the accuracy of the gauge.

The reference pressure in the casing containing the bourdon tube is usually atmospheric and so the pointer indicates gauge pressure.

Bourdon tube shapes and configurations : The C-type bourdon tube has a small tip travel and this necessitates amplification by a lever, quadrant, pinion and pointer arrangement. Increased sensitivity can be obtained by using a very long length of tubing in the form of a helix, and a flat spiral as indicated in Fig. 7.17.

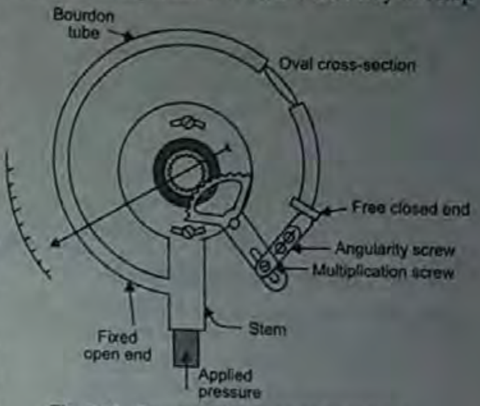


Fig. 7.16. Bourdon tube pressure transducer

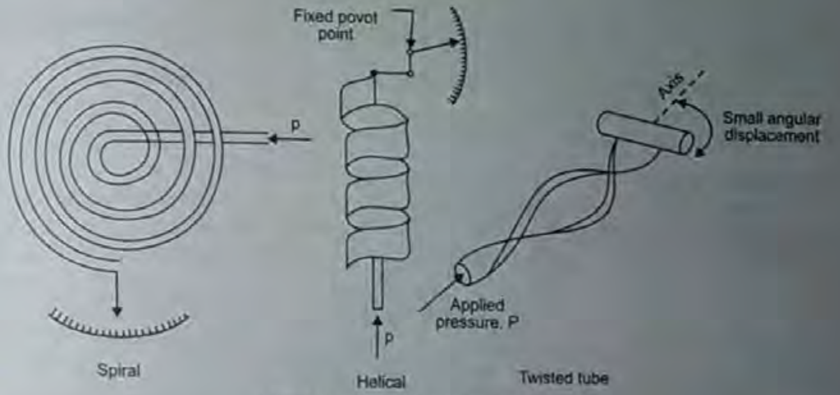


Fig. 7.17. Bourdon tube configuration

The spiral tubing produces the same effect as would be given by a number of C-tubes in series. The tip travel is of amount sufficient enough to indicate directly against a calibrated dial. Likewise, the increased number of turns of a helical bourdon makes it possible to obtain a greater angle of uncoil. Spiral and helical tubes frequently are used where it is desirable to eliminate the multiplication linkages between the pressure element and the indicating or recording arm. The absence of amplification linkage makes the system more robust ; wear friction and the internal effects of the linkage are eliminated.

The twisted tube has a cross wise stability which reduces spurious output motion due to shock and vibration.

taut (in tension) by a streamlined weight. Horizontal positioning (placement of the unit along the flow direction) is ensured by a streamlined tail vane. When the unit is held in a flowing stream, the liquid strikes the buckets and that sets the wheel in rotation. At every revolution, signals are transmitted to the observer or to a revolution counter through electrical contacts. Frequency of rotation is directly related to the velocity of flow by appropriate calibration data.

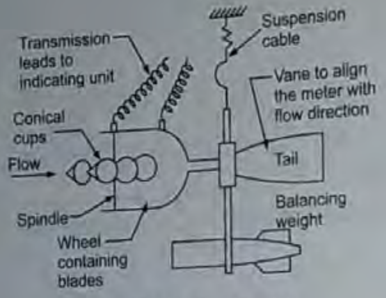


Fig. 7.21. Current meter

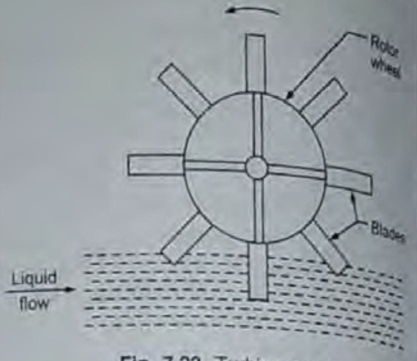


Fig. 7.22. Turbine meter

A turbine meter is similar in operation to a cup anemometer and depends on the application of an eccentric force applied by partial immersion of a bladed rotor in the fluid flow stream.

7.7 FLOW MEASUREMENT

The head meter in the form of venturimeter, orifice and flow nozzle is by far the most common flow meter for closed conduits. When the fluid flows through these obstruction meters, the fluid accelerates and a reduction in pressure occurs. The difference in pressure before and after the obstruction is measured by means of differential pressure sensor and is related to the flow rate.

Venturi flow meter : The venturimeter was invented by Clemens Hershel in 1887 and has been named in the honour of an Italian engineer Venturi. This simple and reliable device finds an extensive use for water flow measurement, particularly in large sized pipes and for large flow rates.

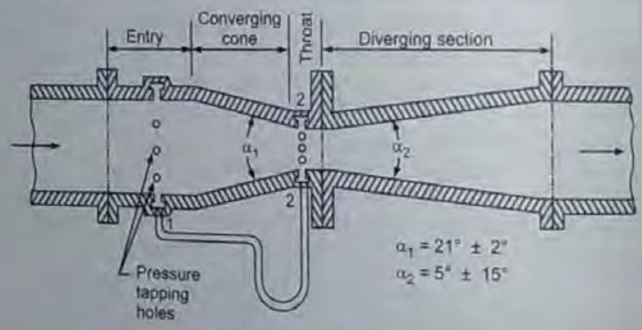


Fig. 7.23. Venturi flow meter

The important constructional features of a venturi meter are shown in Fig. 7.23. The meter consists of :

(i) *Cylindrical entrance section* : This section has the size of pipe to which it is attached. For satisfactory operation, the venturimeter should be preceded by a straight pipe of not less than 5 to 10 pipe diameters and be free from fittings, misalignment and other sources of large scale turbulence. If these conditions cannot be met, straightening vanes should be placed upstream from the meter for reduction of rotational motion in flow.

(ii) *Converging conical section* : The converging takes place at angle of 21° ± 2°. The velocity of fluid increases as it passes through the converging section and correspondingly the static pressure falls.

(iii) *Throat* : This is a cylindrical section of minimum area. At this section the velocity is maximum and the pressure is minimum. The throat diameter is usually between 1/2 to 1/4 of the inlet diameter. Length of the throat equals its diameter.

(iv) *Diverging section* in which there is a change of stream area back to the entrance area. The recovery of kinetic energy by its conversion to pressure is nearly complete and so the overall pressure loss is small. To accomplish a maximum recovery of kinetic energy, the diffuser section is made with an included angle of 5° to 7°. This angle has to be kept less so that the flowing fluid has least tendency to separate out from the boundary of the section. However, with small angles the length and hence the cost of the meter would increase. So where pressure recovery is not of much importance, the angle of the diverging cone may be kept as high as 14°.

The pressure taps are made at the throat and at entrance where the venturimeter has a diameter equal to that of pipe. The pressure taps may be made either from a single hole or at piezometer rings thereby giving average values at the two sections.

The small sized venturimeter, suitable for pipelines less than 5 cm in diameter, are usually made of brass or bronze. The inside surface is smoothly finished to reduce friction. Large venturies are usually made of cast iron ; the throat is however, lined with brass or bronze and machined to smooth finish. Very large venturies upto 6 m pipe diameter have been made of smooth surface concrete ; only the throat being made of machined bronze.

Advantages and Limitations

- High pressure recovery is attainable, *i.e.*, loss of head due to installation in the pipelines is small. Due to low value of losses, the coefficient of discharge is high and it may approach unity under favourable conditions.
- Because of smooth surface, the meter is not much affected by wear and tear. Less likelihood of becoming clogged with sediments.
- Well-established characteristics ; years of application experience.
- Ideally suited for large flow of water, process fluids, wastes, gases and suspended solids.
- Long laying length; space requirements are more. Quite expensive in installation and replacement.

Venturimeters are not standardized yet to an extent that permits discharge coefficient from one meter to be used with another. From dimensional analysis and dynamic similarity conditions, the discharge coefficient for a venturimeter is found to be a function of Reynolds number and meter size. These meters are not generally useful below 7.5 cm pipe diameter.

Flow nozzle: Nozzles are used in engineering practice for the creation of jets and streams for all purposes as well as for fluid metering. When placed in or at the end of a pipeline as metering devices, they are called flow nozzles.

The flow nozzle comprises a smooth, gradual contraction to throat by a free uncontrolled expansion back to the pipe flow area. Because the device contains no provision for an orderly transformation of velocity into static pressure, the nozzle has a pressure loss from 80 to 90% of the differential pressure obtained. The discharge coefficient of a flow nozzle is dependent upon the smoothness of approach to tangency, the length of the cylindrical portion of the nozzle and the location of the pressure taps. Pipe wall taps located at one pipe diameter upstream and half pipe downstream from the inlet face of the nozzle give best results. The flow nozzles are usually made of gun metal, stainless steel or monel metal.

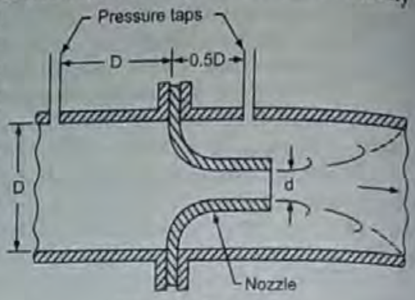


Fig. 7.24. Flow nozzle

Advantages and Limitations

- Cheaper than a standard venturimeter ; can be installed in an existing main without great difficulty.
- Increased coefficient of discharge when compared to orifice, and less physical length compared to venturimeter
- Widely accepted for high pressure/temperature steam flow ; further good for fluids containing solids that settle.
- Pressure recovery is poor and so cannot be used where available pressure head is small or where pressure recovery is a must. The pressure loss is, however, less than that of an orifice plate.
- Compared to orifice meter, it is expensive and difficult to install.
- Limited to moderate pipe size ; not available above 120 cm.

Orifice flow meter : The orifice meter consists of a thin, circular metal plate with a hole in it. The plate is held in the pipeline between two flanges called orifice flanges (Fig. 7.25). The flow characteristics of the orifice differ from those of a nozzle in that minimum section of the stream-tube occurs not within the orifice but downstream from orifice edge. Section of minimum area is called vena contracta and minimum pressure exists at this section. Location of vena contracta depends on Reynolds number, area ratio between orifice and pipe, roughness of pipe and, compressibility of the flowing medium. It is also sensitive to the upstream velocity profiles and sharpness of the upstream edge of the orifice plate. Evidently location of downstream pressure connection at vena contracta is not feasible and as such it is taken at a fixed proportion of the pipe diameter and a correction for vena contracta is made. Ideally it should be placed where disturbing factors are least. For accuracy of results, there should be uniform flow conditions upstream of the orifice and for this a straight pipeline of atleast 10 pipe diameter should precede the orifice. Discharge coefficient varies with the type of orifice, the pipe size, ratio of orifice diameter to pipe diameter, Reynolds number and location of pressure connections.

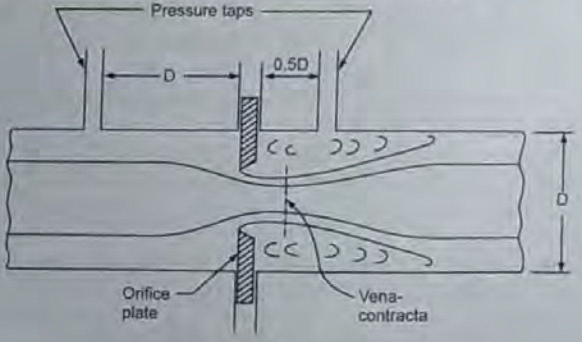


Fig. 7.25. Orifice flow meter

Orifice plates are made from steel, stainless steel, phosphor bronze and other such materials that can withstand the corrosive effect of the flowing medium. Its thickness is only sufficient to withstand the buckling forces caused by the pressure differential. The circular hole is carefully made with 90° square sharp edge. Wear and abrasion of this sharp edge greatly affect the accuracy of the orifice flow measurement. For this reason an orifice should not be used to measure flow containing abrasives or other materials which would damage the edge. In some cases it is advisable to replace the orifice plate frequently to maintain accuracy.

Advantages and Limitations

- Low initial cost, ease of installation and replacement. Requires less space as compared to venturimeter.
- Can be used in wide range of pipe sizes (1.25 cm to 150 cm).
- Pressure recovery is poor ; the overall pressure loss varies from 40 to 90% of the differential pressure.
- Coefficient of discharge has a low value.
- Necessity of providing straightening vanes upstream.
- Susceptible to inaccuracies resulting from erosion, corrosion and scaling. Tends to clog and as such not suitable for slurries or entrained particles.

Theory of variable head meters : The equations convenient for practical use and for providing the basis of operation of variable head meters are derived by following three steps given below:

(*i*) Apply the Bernoulli's equation to the upstream and downstream pressure connections and modify it for the assumed conditions

(*ii*) Solve the modified equation for the downstream velocity

(*iii*) Express the flow rate by the product of area and velocity, *i.e.*, $Q = AV$

Let subscript 1 refer to the pipe and the fluid at the upstream pressure connection and subscript 2 refer to the pipe and fluid at the section of minimum area. Bernoulli's equation gives:

$$\frac{p_1}{w}+\frac{V_1^2}{2g}+y_1=\frac{p_2}{w}+\frac{V_2^2}{2g}+y_2+\text{losses}$$

Neglecting losses and assuming the measuring device to be horizontal, *i.e.*, $y_1 = y_2$, we get

$$\frac{V_2^2-V_1^2}{2g}=\frac{p_1-p_2}{w} \qquad ...(7.11)$$

For incompressible fluids, the continuity relation for the situation is $A_1V_1 = A_2V_2$ and that yields

$$V_1=\frac{A_2}{A_1}V_2 \qquad ...(7.12)$$

Solution of equations 7.11 and 7.12 gives the outflow velocity V_2,

$$V_2 = \frac{A_1}{\sqrt{A_1^2 - A_2^2}} \times \sqrt{2g\frac{p_1 - p_2}{w}} \qquad \text{...(7.13)}$$

The downstream fluid velocity as given by equation 7.13 has been derived without considering any losses and so it is the ideal or theoretical velocity at the minimum section. The actual velocity can be obtained by multiplying the theoretical velocity by a factor C_v called the **coefficient of velocity.** The coefficient of velocity is the ratio of actual mean velocity which would occur without any friction loss

$$C_v = \frac{\text{actual mean velocity}}{\text{ideal mean velocity}}$$

$$\therefore \quad V_2\text{ (actual)} = C_v \frac{A_1}{\sqrt{A_1^2 - A_2^2}} \times \sqrt{2g\frac{p_1 - p_2}{w}}$$

For obtaining the volume flow rate, we apply the continuity equation :

discharge = area × velocity

$$\therefore \quad Q = C_v \frac{A_1 A_2}{\sqrt{A_1^2 - A_2^2}} \times \sqrt{2g\frac{p_1 - p_2}{w}} \qquad \text{...(7.14)}$$

During flow through an orifice meter, the fluid jet on leaving the orifice contracts to a minimum area at the vena contracta. Area of fluid jet at vena contracta is less than the area of the orifice and the two areas are related by the equation:

area of jet at vena contracta = C_c × orifice area

where C_c is the coefficient of contraction. Thus if the orifice area is A_2 then the area at minimum section which controls the flow rate and where the path of particles becomes parallel again would be $C_c A_2$

$$\therefore \quad \text{Actual discharge } Q = C_v \frac{C_c A_1 A_2}{\sqrt{A_1^2 - A_2^2}} \times \sqrt{2g\frac{p_1 - p_2}{w}} \qquad \text{...(7.15)}$$

For venturimeter and flow nozzle, there is almost no formation of vena contracta and the coefficient of contraction can be taken as unity.

Combining C_v and C_c into single factor C_d called the coefficient of discharge, the volumetric flow rate through the meter can be written as:

$$Q = C_d \frac{A_1 A_2}{\sqrt{A_1^2 - A_2^2}} \times \sqrt{2g\frac{p_1 - p_2}{w}} \qquad \text{...(7.16)}$$

Discharge coefficient C_d is not constant ; it depends primarily on the flow Reynolds number and the channel geometry.

The quantity $\frac{A_1 A_2}{\sqrt{A_1^2 - A_2^2}}\sqrt{2g}$ is constant for a given meter; this quantity is generally designed by K and is known as the **meter constant.** Thus

$$Q = C_d K \sqrt{\frac{p_1 - p_2}{w}} \qquad \text{..(7.17)}$$

The pressure differential $\frac{p_1 - p_2}{w}$, called the pressure head or piezometer head, is measured by a differential U-tube manometer. The manometer reading is same for a given discharge irrespective of the inclination of the pipeline.

EXAMPLE 7.16

A venturimeter with 200 mm diameter at inlet and 100 mm throat is laid with axis horizontal, and is used for measuring the flow of oil of specific gravity 0.8. The difference of levels in the U-tube differential manometer reads 180 mm of mercury whilst 11.52 × 10³ kg of oil is collected in 4 minutes. Calculate the discharge coefficient for the meter. Take specific gravity of mercury as 13.6.

Solution : $A_1 = \frac{\pi}{4}(0.2)^2 = 0.0314\text{ m}^2\ ;\ A_2 = \frac{\pi}{4}(0.1)^2 = 0.00785\text{ m}^2$

$$\frac{A_1}{A_2} = \frac{0.0314}{0.00785} = 4$$

Piezometric head $P_h = h\,(s_m - 1)\ 0.18\left(\frac{13.6}{0.8} - 1\right) = 2.88$ m of oil

Mass of oil = 11.52 × 10³ kg in 4 minutes

$$\therefore \text{ Discharge of oil, } Q = \frac{11.52 \times 10^3}{4 \times 60} \times \left(\frac{1}{800}\right) = 0.06\text{ m}^3/\text{s} \qquad (\because m = \rho Q)$$

Substitute the given data in the discharge equation,

$$Q = C_d \frac{A_1 A_2}{\sqrt{A_1^2 - A_2^2}}\sqrt{2g\,P_h} = C_d \frac{A_1}{\sqrt{\left(\frac{A_1}{A_2}\right)^2 - 1}}\sqrt{2gP_h}$$

or

$$0.06 = C_d \frac{0.0314}{\sqrt{4^2 - 1}} \times \sqrt{2 \times 9.81 \times 2.88} = 0.0609\ C_d$$

$$\therefore \text{ Discharge coefficient for the venturimeter, } C_d = \frac{0.06}{0.0609} = 0.985$$

7.7.1. Rotameter

The rotameter consists of a tapered metering glass tube, inside which is located the rotor or active element (float) of the rotor. This tapering tube is provided with suitable inlet and outlet connections. The float or bob material has specific gravity higher than that of the fluid to be metered.

With increase in the flow rate, the float rises in the tube and there occurs an increase in the annular area between the float and the tube. The float adjusts its position in relation to discharge through the passage, *i.e.*, the float rises higher or lower depending on the flow rate. The discharge equation for flow through a rotameter is given by

$$Q = C_d A\left[2gV_f(\rho_f - \rho)/A_f\,\rho\right]^{\frac{1}{2}} \qquad \text{... (7.18)}$$

where Q is the volume flow rate, C_d is the discharge coefficient, V_f is the volume of float, ρ_f is the density of float material, ρ is the density of fluid flowing, A_f is the cross-sectional area of the float and A is the annular area between float and tube.

The glass tube is often made of high strength borosilicate glass and the flow rate scale is engraved on the tube corresponding to a particular float material. However, where greater strength is required, the metallic tubes are used and the position of float is detected magnetically. Further, for remote indication, the position of float can be monitored electrically by using a suitable displacement transducer.

The rotameter is equally suitable for measuring both gas and liquid flows. When metering gas flows, a small sphere is used in a narrow tube and no guidance needs to be provided to its motion. While metering liquid fluids, spherical slots are cut on a part of the float and these slots cause it to rotate slowly about the axis of tube and keep it central. This spinning helps also to prevent accumulation of any sediment on the top and sides of the float. Alternatively, stability of the bob is ensured by employing a guide along which the float would slide.

The float or bob material has a specific gravity higher than that of the fluid to be metered. The density difference $(\rho_f - \rho)$ required for metering a particular liquid or gas can be obtained by selecting different materials for the float. An examination of the discharge equation 7.28 would reveal that when $\rho_f >> \rho$, the volume flow rate becomes independent of the density ρ of the flowing fluid.

Rotameters are widely used for metering purge flows, pump-seal fluids and coolants and lubricants for operating machinery. In these applications, flows are relatively small and accuracy requirements are not rigid.

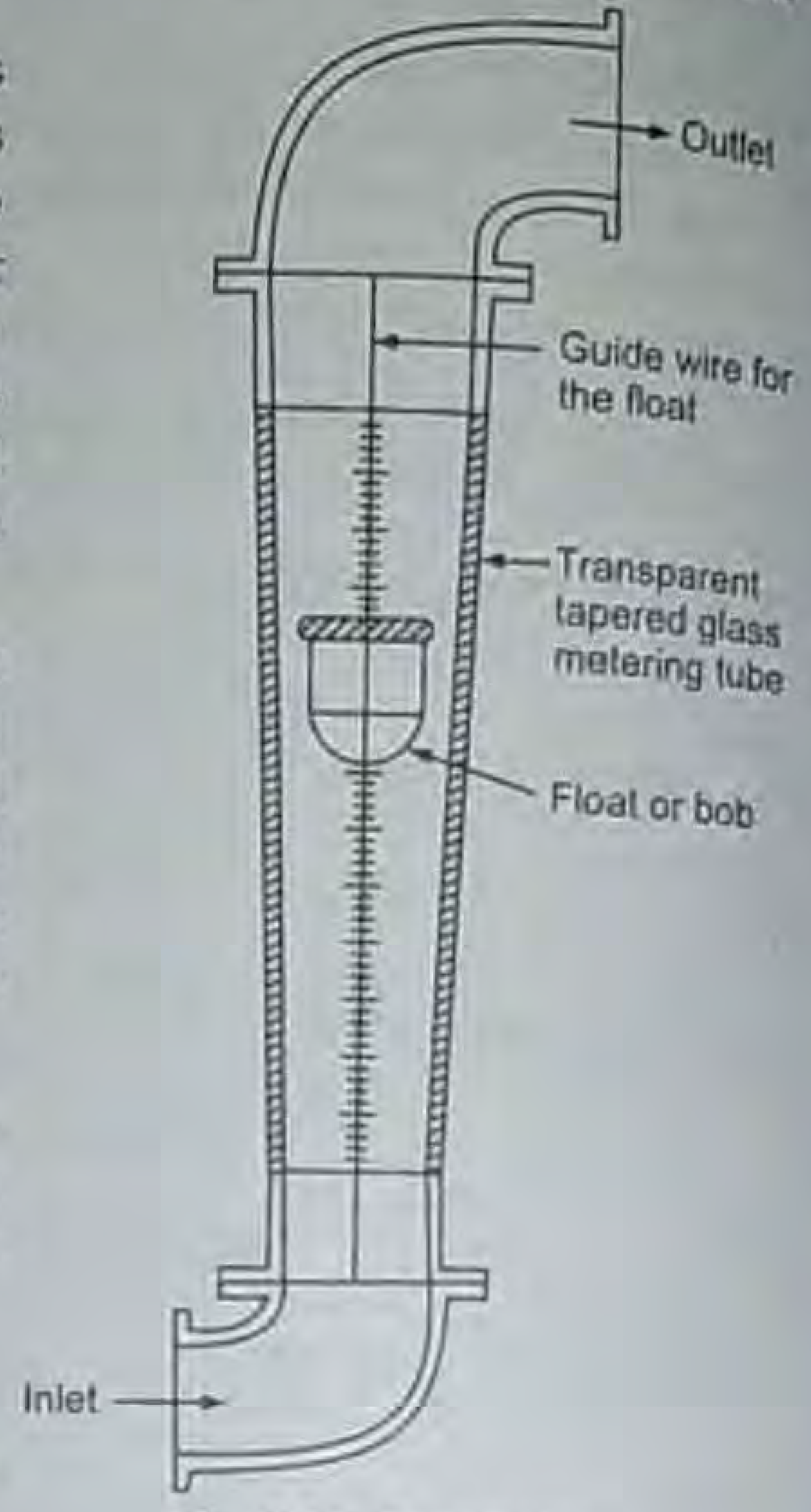


Fig. 7.26. Rotameter

Advantages and Limitations of a Rotameter

- Simplicity of operation, ease of reading and installation
- Relatively low cost
- Handles wide variety of corrosive fluids
- Easily equipped with data transmission, indicating and recording devices
- Possibility of convenient and visible flow comparisons by mounting several rotameters side by side
- Glass tube subject to breakage
- Limited to small pipe sizes and capacities
- Less accurate compared to venturi and orifice meters
- Must be mounted vertically
- Subject to oscillations in pulsating flows

7.8 TEMPERATURE MEASUREMENT

Temperature is probably the most widely measured and frequently controlled variable encountered in industrial processing of all kinds. Measurement of temperature potential is involved in thermodynamics, heat transfer and many chemical operations. Basically all the properties of matter such as size, colour, electrical and magnetic characteristics, and the physical states (*i.e.,* solid, liquid and gas) change with changing temperatures The occurrence of physical and chemical changes is governed by the temperature at which a system is maintained.

Temperature measurement depends upon the establishment of thermodynamic equilibrium between the system and the device used to sense the temperature, *e.g.* a thermometer bulb or thermocouple wires. The sensor has certain physical characteristics which change with temperature and this effect is taken as a measure of the temperature. The physical characteristics which are so used could be:

(*i*) A change in dimension, *i.e,* expansion or contraction of material in the form of solid, liquid or gas.

(*ii*) A change in electrical resistance of metals and semi-conductors.

(*iii*) A thermo-electric emf for two different metals and alloys joined together.

(*iv*) A change in the intensity and colour or radiation emitted by the hot body.

(*v*) Fusion of materials when exposed to the temperature under investigation.

Calibration is then achieved through comparison with established standards. The international temperature scale serves to define temperature in terms of observable characteristic of materials.

7.8.1. Liquid-in-Glass Thermometers

The liquid-in-glass thermometer is one of the most common types of temperature measuring devices. The unit consists of a glass envelope, a responsive liquid and an indicating scale. The envelope comprises a thick walled glass tube with a capillary bore, and a spherical or cylindrical bulb filled with the liquid. The two parts are fused together and the top end of the capillary tube is sealed. The size of the capillary depends on the size of the sensing bulb, responsive liquid and the desired temperature range of the instrument. Changes in the temperature will cause the fluid to expand and rise up the stem. Since the area of the stem is much less than the bulb, the relatively small change of fluid volume will result in significant fluid rise in the stem. The length of the movement of the free surface of the fluid column serves, by a prior calibration to indicate the temperature of the bulb. The laboratory work thermometers have a scale engraved directly on the glass stem, while the industry types have separate scale located adjacent to the stem. Quite often the top of the capillary tube is also bulb shaped to provide safety feature in case the temperature range of the instrument is inadvertently exceeded.

The thermometer bulb is usually filled with mercury. It has the advantages of a broad temperature span between its freezing and boiling points, a nearly linear coefficient of expansion, relative ease of obtaining it in a very pure state and its nonwetting glass characteristics. When measuring temperature above the boiling point of mercury (390°C at atmospheric pressure), mercury may evaporate and condense in the top of the stem. This is prevented by filling the space above mercury with nitrogen or carbon dioxide under high pressure. This raises the boiling point and allows temperatures upto 610° C to be measured.

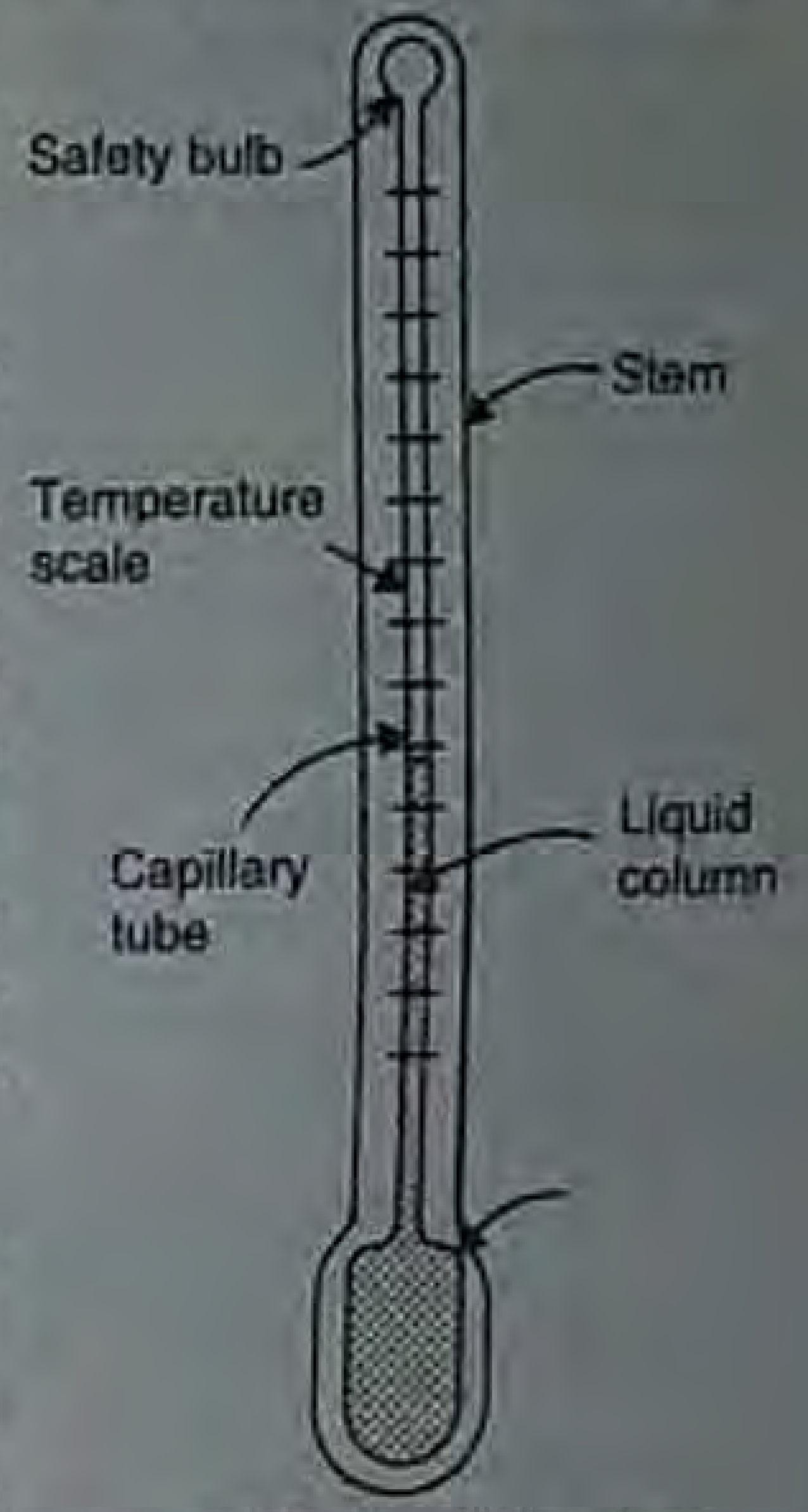


Fig. 7.27. Liquid-in-glass thermometer

However, in many industrial applications the escape of mercury through breakage causes considerable damage to the products. This may necessitate the use of other liquids such as alcohol, pentane and toluene, etc., which do not cause contamination. These liquids are also used for temperature measurements below the freezing point of mercury. These liquids have further advantages of superior readability to mercury when coloured with inert dyes and of low cost. However, they have low boiling points, a greater tendency to separate in the capillary, and wetting glass characteristics.

The choice in the type of glass used is a matter of economics influenced by the range of the thermometer – the higher the range, the higher the cost. For temperature upto 450°C, normal glass is used. At high temperature upto about 520°C, barosilicate glass is used. Above this temperature quartz thermometers have been used but they are not common.

Salient features/characteristics:

- simplicity of use and relatively low cost
- easily portable
- ease of checking for physical damage
- absence of need for auxiliary power
- no need of additional indicating instruments
- fragile construction; range limited to about 600°C
- lack of adaptability to remote reading
- time lag between change of temperature and thermometer response due to relatively high heat capacity of the bulb.

7.8.2. Solid Expansion or Bimetallic Thermometer

A bimetal strip consists of two pieces of different metals firmly bonded together by welding. For a bi-metal in the form of a straight cantilever beam, temperature changes cause the free end to deflect because of the different expansion rates of the components. This deflection can be correlated quantitatively to the temperature change.

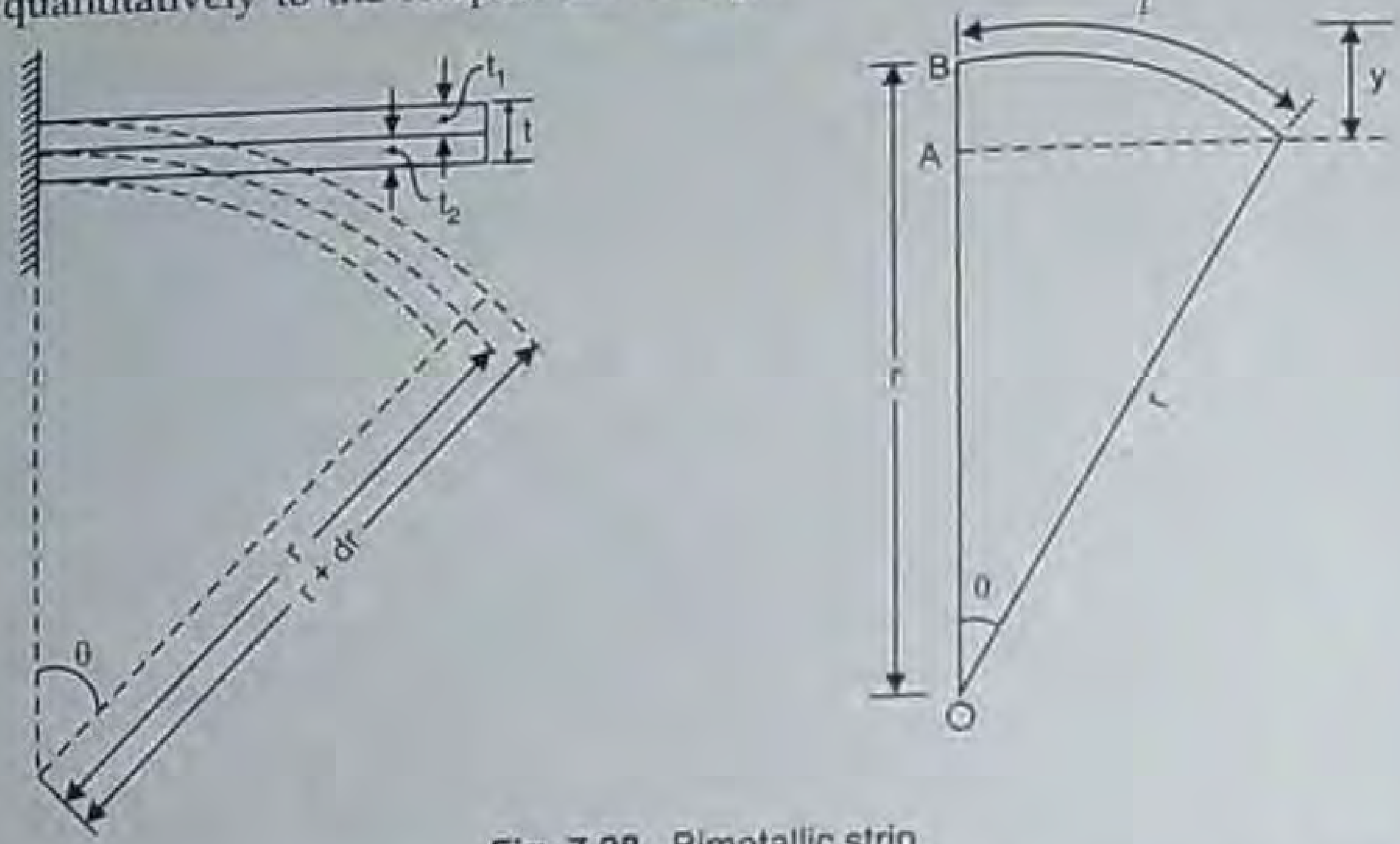


Fig. 7.28. Bimetallic strip

When a bimetal strip in the form of cantilever is assumed to bend through a circular atc, then

$$\frac{r+dr}{r} = \frac{\text{expanded length of strip having higher expansion coefficient}}{\text{expanded length of strip having lower expansion coefficient}}$$

$$= \frac{l[1+\alpha_2(T-T_0)]}{l[1+\alpha_1(T-T_0)]}$$

Simplification gives :

$$r = \frac{dr[1+\alpha_1(T-T_0)]}{(\alpha_2-\alpha_1)(T_1-T_0)}$$

The tip deflection can be increased with choice of materials that give a large value to the difference in their coefficient of expansion. Normally the low expansion material is invar (an iron nickel alloy containing about 36% nickel) and the high expansion metal is brass.

Taking $\alpha_1 = 0$ and $dr = t/2$ (thickness of each metal strip), we get

$$r = \frac{t}{2\alpha_2(T-T_0)}$$

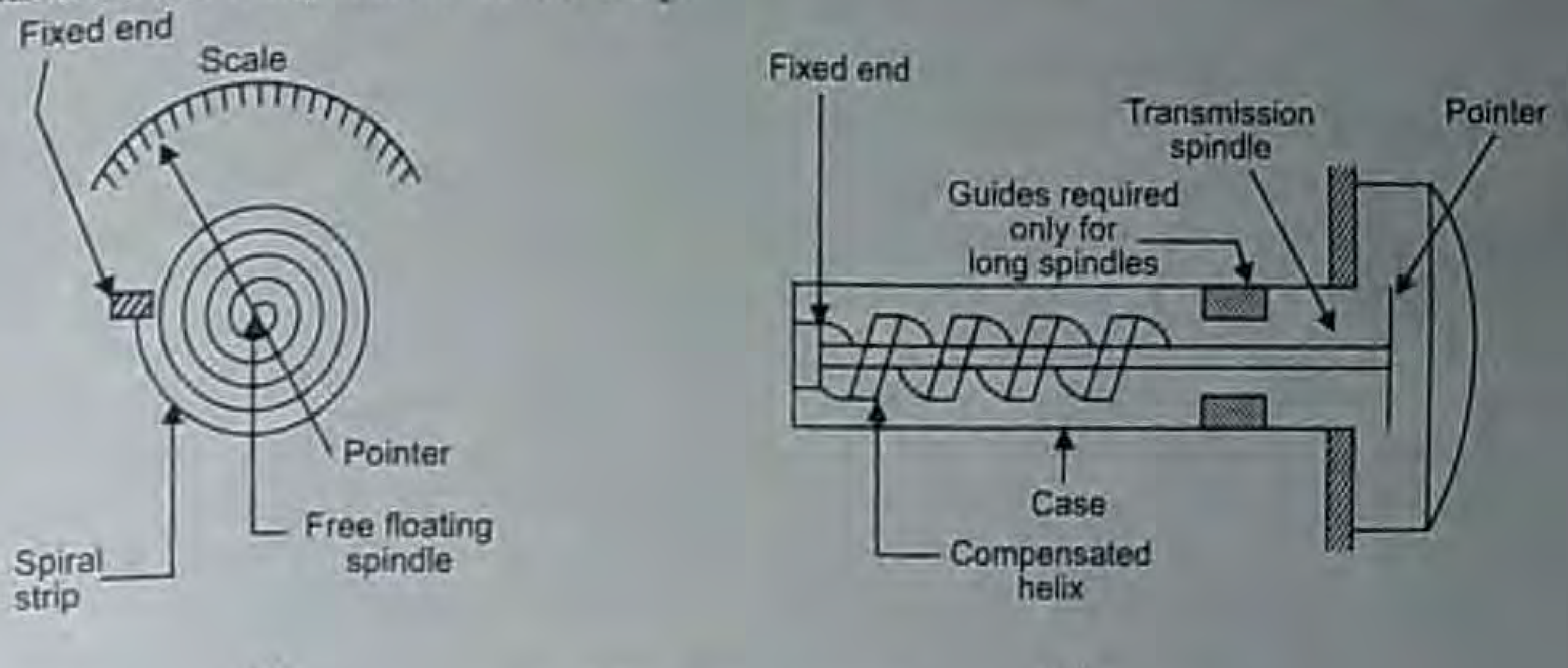
The movement of free end of the cantilever in a perpendicular direction from the initial horizontal line is worked out as follows :

angular displacement $\theta = l/r$

vertical displacement $y = OB - OA = r - r\cos\theta$

$= r(1-\cos\theta)$

Apparently when one end of the bimetallic strip is fixed, the position is free and is a direct indication of the temperature of the strip.



(a) (b)

Fig. 7.29. Bimetal strip thermometer

Bimetalic elements can be arranged in the flat, spiral, the single helix, and the multiple helix configuration. Figure 7.29 illustrates the functional principle of the usual industrial form of a bimetal thermometer. One end of the helix is anchored permanently to the casing and the other end is secured to a pointer which sweeps over a circular dial graduated in degree of temperature. In response to temperature change, the bimetal expands and the helical bimetal rotates at its free end, thus turning the stem and pointer to a new position on the dial. Likewise the curvature of bimetal spiral strip (Fig. 7.29 (*b*)) varies with temperature and causes a pointer to deflect. The continuous strip wound into helical or spiral form has the advantages of compactness while providing a long length of strip required for adequate indicator movement.

Bimetallic elements find wide application in simple thermometers in which the deflection of the elements is made to open or close electrical contacts in the electrical heat supply or to control a gas flow. Important applications include the switching devices used in domestic ovens, electric irons, car winker lamps and the refrigerators.

7.8.3. Thermocouples

When two conductors of dissimilar metals M_1 and M_2 are joined together to form a loop (a thermocouple) and two unequal temperatures T_1 and T_2 are imposed at the two interface connections, an electric current flows through the loop.

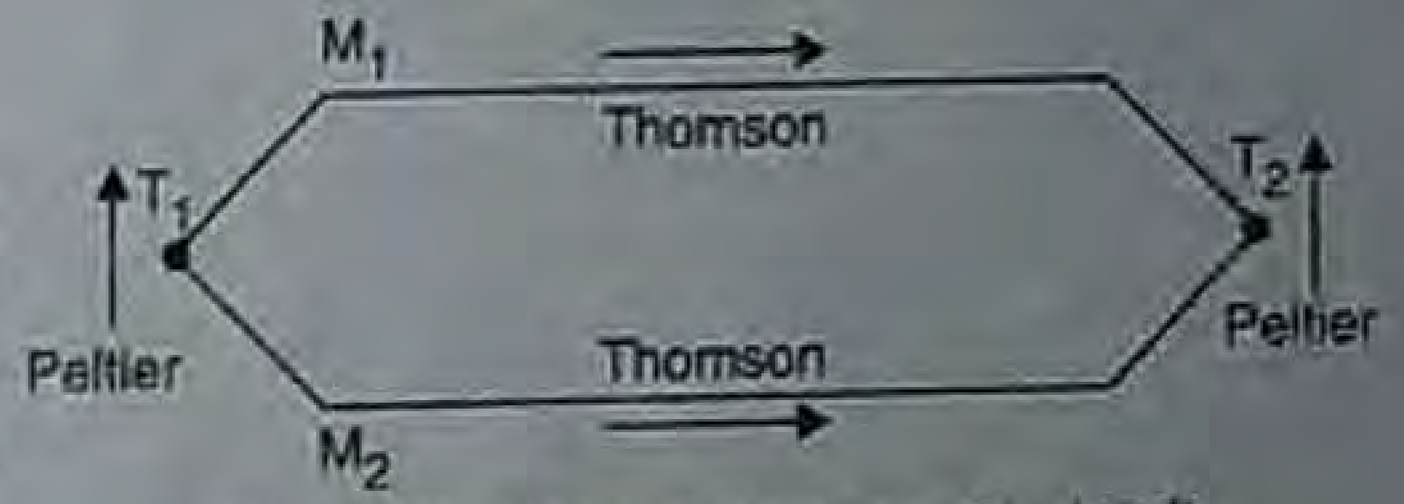


Fig. 7.30. Basic thermocouple circuit

Experimentally it has been found that the magnitude of the current is directly related to the two materials M_1 and M_2 and the temperature difference $(T_1 - T_2)$. In the practical application of the effect, a suitable device is incorporated in the circuit to indicate any electromotive force or flow of current. For convenience of measurement and standardisation, one of the two junctions is usually maintained at some constant known temperature. The output voltage of the circuit then indicates the temperature difference relative to the reference temperature.

Thermo-electric effects arise in two ways:

- a potential difference always exists between two dissimilar metals in contact with each other (*Peltier effect*)
- a potential gradient exists even in a single conductor having a temperature gradient (*Thomson effect*)

In commercial instruments, the thermocouple materials are so chosen that the Peltier and Thomson emf's act in such a manner that the combined value is maximum and that varies directly with temperature.

Elements of a Thermo-electric Pyrometer

The essential elements of a thermo-electrical pyrometer are shown schematically in Fig. 7.31.

- Two dissimilar conductors electrically insulated except at the hot junction, where the conductors may either be soldered or welded together, or may be completely separated from each other.
- A refractory and a metal sheath to protect the thermocouple from injurious furnace gases and to prevent it from mechanical damage.
- Compensating leads which allow the measuring instrument to be placed at a considerable distance from the thermocouple without the necessity of using expensive thermocouple materials as extension leads.
- The cold or the reference junction provided by the instrument used for measuring the emf.

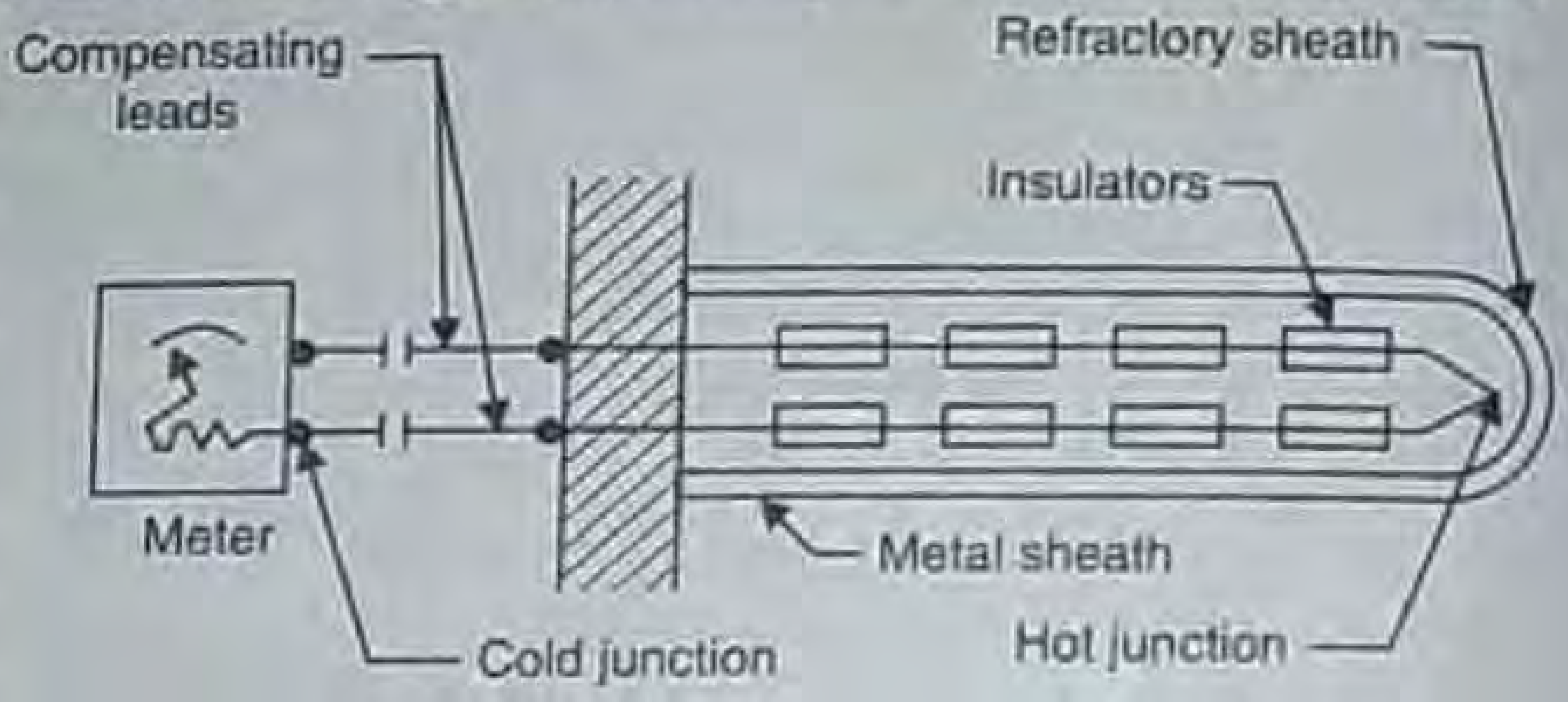


Fig. 7.31. Element of a thermo-electric pyrometer

Thermocouple Materials

The desirable characteristics of thermocouple materials are:

(*i*) The emf produced per degree of temperature change must be sufficient to facilitate detection and measurement.

(*ii*) The temperature-emf relationship should be reasonably linear and reproducible. This will make the scale more easily read and also reduce the problem of reference junction compensation.

(*iii*) The thermocouple should maintain its calibration without drift over a long period of time.

(*iv*) The thermocouple should have a long life so that the cost of temperature measurement is not unnecessarily increased with frequent replacement of the thermocouple. For that, the thermocouple materials should be highly resistant to oxidation, corrosion and contamination.

(*v*) The material should physically be able to withstand high and rapidly fluctuating temperatures. Any phase change or other internal phenomenon will give rise to discontinuity in the temperature-emf relationship.

(*vi*) The material must be such that successive batches can be produced with the same thermo-electric characteristics. This will allow the replacement of thermocouples without the necessity of recalibrating the temperature scale of the indicating instrument.

Depending upon the composition of metals used, the thermocouples are sometimes grouped into the following broad categories :

(*i*) *Base metal thermocouples* use combinations of pure metal and alloys of iron, copper and nickel, and are used in lower ranges of temperature upto 1375°C.

(*ii*) Rare metal *thermocouples* use combinations of pure metals and alloys of
  (*a*) platinum and rhodium for temperatures upto 1725°C, and
  (*b*) tungsten, rhodium and molybdenum for temperatures upto 2625°C.

7.8.4. Resistance Thermometers and Thermistors

The resistance R (ohms) of an electrical conductor of resistivity ρ (ohms Ω), length L (cm) and cross sectional area A (cm²) is given by

$$R = \rho L/A \qquad \text{...(7.19)}$$

As temperature changes, the resistance of the conductor also changes. This is due to two factors : (*i*) dimensional change due to expansion or contraction and (*ii*) change in the current opposing properties of the material itself. For an unconstrained conductor, the latter is much more than 99% of the total change for copper. This change in resistance with temperature is used for measuring temperature.

Resistance Thermometers

Most metals become more resistant to the passage of electric current as they become hotter, *i.e.*, their resistance increases with growth in temperature. An adequate approximation of the resistance-temperature relationship is given by :

$$R_t = R_o\,(1 + \alpha t + \beta t^2) \qquad \text{.....(7.20)}$$

where R_t is resistance at any temperature t° C, R_o is resistance at 0°C, α and β are constants depending on the material. The constants R_o, α and β are determined at the ice, steam and sulphur points respectively.

Over a limited temperature range around 0°C, the following linear relationship is equally valid:

$$R = R_o\,(1+\alpha\,\theta)$$

where α is the temperature coefficient of resistance in °C^{-1} and θ is temperature relative to 0°C. Some typical values for temperature coefficient are:

$\alpha = 0.0039°\text{C}^{-1}$ for platinum, $\alpha = 0.0043°\text{C}^{-1}$ for copper, $\alpha = 0.0068°\text{C}^{-1}$ for nickel

If a change in temperature from θ_1 to θ_2 is considered, then

$$R_1 = R_o\,(1 + \alpha\,\theta_1)\ ;\ R_2 = R_o\,(1 + \alpha\,\theta_2)$$

Rearrangement gives

$$\theta_2 = \theta_1 + \frac{R_2 - R_1}{\alpha R_o}\ ;\ \frac{R_2 - R_1}{\theta_2 - \theta_1} = \alpha\,R_o \qquad \text{...(7.21)}$$

Apparently the linear relationship implies that changes in resistance are directly proportional to changes in temperature.

The thermometer comprises a resistance element or bulb, suitable electrical leads, and an indicating—recording or resistance measuring instrument. The resistance element is usually in the

the concave mirror are adjusted to focus the radiation from the furnace onto the target. Small mirrors help in the focussing process. These mirrors appear as shown at (*i*) when the radiation is not focuseed onto the target and when focusing is achieved they appear as at (*ii*).

The object of directing radiations from the measured surface onto the temperature sensing element can also be achieved by a parabolic reflector [Fig. 7.34(*b*)], or by a lens system [Fig. 7.34(*c*)].

Characteristic of radiation pyrometers

1. High speed of response (0.01 to 0.02 min; fast response is due to small thermal capacitance of the detector. Accuracy ± 2% of scale range.
2. No direct contact is necessary with the object whose temperature is to be measured. This fact allows its use in situations where it is impossible or undesirable to bring the measuring instrument in contact with the object under consideration.
3. Primarily used to measure temperatures in the range 700-2000°C where thermocouple and resistance thermometers cannot be employed.
4. Capable of measures the temperature of an object which may be either stationary or moving, and so adaptable to continuous industrial processing.
5. Suitable for measuring temperatures where the atmospheric or other envirnmental conditions prevent satisfactory operation of other temperature sensing devices.
6. Relatively independent of the distance between the measuring element and the heated body. However, for optimum working the distance from target to receiver should not be greater than 10 or 20 times the maximum useful diameter of the target. Further, with increase in the distance there will be greater opportunity for gases, smoke etc. to intervene and absorb some of the radiant energy. This would tend to reduce the indicated temperature.
7. The effect of dust and dirt on the mirrors or lens is to cause the instrument to read too low.
8. Cooling is required to protect the instrument from overheating where the temperature may be high because of operating conditions.

Optical Pyrometers

A metallic surface is usually dark and dull coloured at room temperature. When the surface is heated, it emits radiations of different wavelengths; these radiations are, however, not visible at low temperatures. As the temperature is progressively increased beyond 540°C, the surface becomes dark red, orange and finally white in colour. A colour variation with temperature growth may thus be taken as an index of the probable temperature.

This principle of temperature measurement by colour or brightness comparison is utilized in optical pyrometers designed to measure temperatures in the range 700-3000°C. These pyrometers compare the energy emitted by a body at a given wavelength with that of a black body calibrated lamp. A sketch of one of the several types of optical pyrometers is shown in Fig. 7.35.

Radiations from the target surface are focused by an objective lens (*L*) upon the plane filament (*F*) of an incandescent electric light bulb. The eye price (*E*) is also adjusted until the filament is in sharp focus and under these conditions the filament is seen supermiposed on the image of the target surface. A red filter (*R*) is placed between the eyepiece and filament, and it allows only a narrowband of wavelength 0.65 μ to pass through it. Matching of brightness of the lamp filament with that of target surface is achieved by adjusting current through the standard lamp by changing the value of circuit resistance. The variable resistance or the magnitude of milliammeter reading (a measure of current through the lamp) may then be calibrated in terms of the target temperature.

When the filament is indistinguishable, in terms of brightness, from the image of the target surface, then it is radiating at the same intensity as the target surface. Three different conditions of the filament as sighted through the eyepiece are also shown in Fig. 7.35. When the filament is colder than the target surface, it appears as a dark wire against a light coloured background. Filament brightness is then increased by causing more current to pass through the filament. A filament hotter than the object would appear brighter than the target surface. The current through the filament is then reduced to provide correct merging of filament and the object.

In an alternative approach, current through the lamp filament is maintained constant. An optical wedge of absorbing material is moved up and down and its variable thickness accentuates the incoming energy to match the filament. The wedge position is then calibrated for temperature. The pyrometer is calibrated by sighting it upon a black body at various known temperatures.

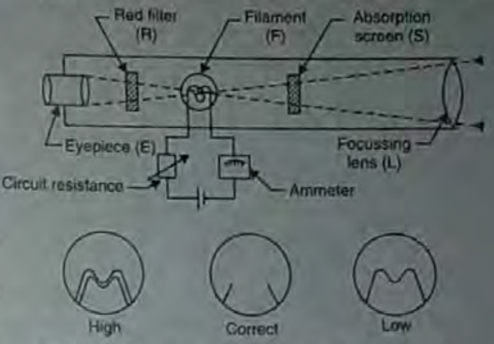


Fig. 7.35. Disappearing—filament optical pyrometer

The noteable characteristics of an optical pyrometer are:

(1) No direct contact is necessary with the object whose temperature is to be measured. This aspect allows their use in situations where the measuring target is remote and inaccessible such as molten metals, furnace interiors. etc.

(2) Excellent accuracy; the temperature in the useful operating range (700 – 1000°C) can be determined within ± 5°C.

(3) Measurement is independent of the distance between the target and the measuring instrument. The image of the target, however, should be sufficiently large to make it possible to secure a definite brightness match with the filament of the test spot.

(4) The skill in operating the thermometer can be acquired readily. However, the skill of the operator has more effect upon the resulting temperature measurements when an optical pyrometer is used than when a radiation pyrometer is used.

(5) Because of its manual null-balance operation, this pyrometer is not suitable for continuous recording or automatic control applications.

(6) The lower measuring temperature is limited to 700°C. Below this termperature, the eye is insentive to wavelength characteristics.

7.9 STRAIN MEASUREMENT

A strain gauge is a device for measuring dimensional change on the surface of a structural member under test. Measurement of strain is indispensable in a variety of applications due to utility of strain measurement as a means of determining maximum stress values or in specialized transducers to measure force, pressure, accelerations, torque, etc.

The operation of an electrical resistance strain gauge is based on the fact that when a conductor is subjeted to mechanical deformation, its length and diameter are altered and a change in its resistance occurs. The resistance change is measured by the wheatstone bridge circuit and correlated to strain or the physical effect causing the strain. For many metals used as strain gauge meterial, the following correlation is applicable.

$$F = 1 + 2\mu$$

where μ = Poisson's ratio $= \dfrac{\text{diametral strain}}{\text{longitudinal strain}} = \dfrac{\delta d/d}{\delta l/l}$

and F = Gauge factor $= \dfrac{\text{fractional change in resistance}}{\text{longitudinal strain}} = \dfrac{\delta R/R}{\delta l/l}$

It is to be noted that

(*i*) For most metals $\mu = 0.3$, and as such the guage factor has the value around 1.6

(*ii*) For any given value of resistance R for the gauge element and strain, the change in resistance varies directly with the gauge factor.

(*iii*) A high gauge factor is desirable because that would give a large change in resistance for a given strain input, thereby needing less sensitive circuit for measuring the change in resistance.

Commercial solid strain gauges using doped crystal structures (semi-conductors) have gauge factors from 100 to 5000. These gauges are becoming very popular in modern instrumentation system.

7.10 FORCE MEASUREMENT

A measure of the unknown force may be accomplished by the methods incroporating the following principles :

(*i*) Balancing the force against a known gravitational force on a standard mass (scales and balances).

(*ii*) Translating the force to a fluid pressure and then measuring the resulting pressure (hydraulic and pneumatic load cells).

(*iii*) Applying the force to some elastic member and then measuring the resulting deflection (proving ring).

(*iv*) Applying the force to a known mass and then measuring the resulting acceleration.

(*v*) Balancing the force against a magnetic force developed by interaction of a magnet and a current carrying coil.

Scales and Balances

Force or weight is indicated by making a comparison between the force due to gravity acting on a standard mass and the force due to gravity acting on the unknown mass.

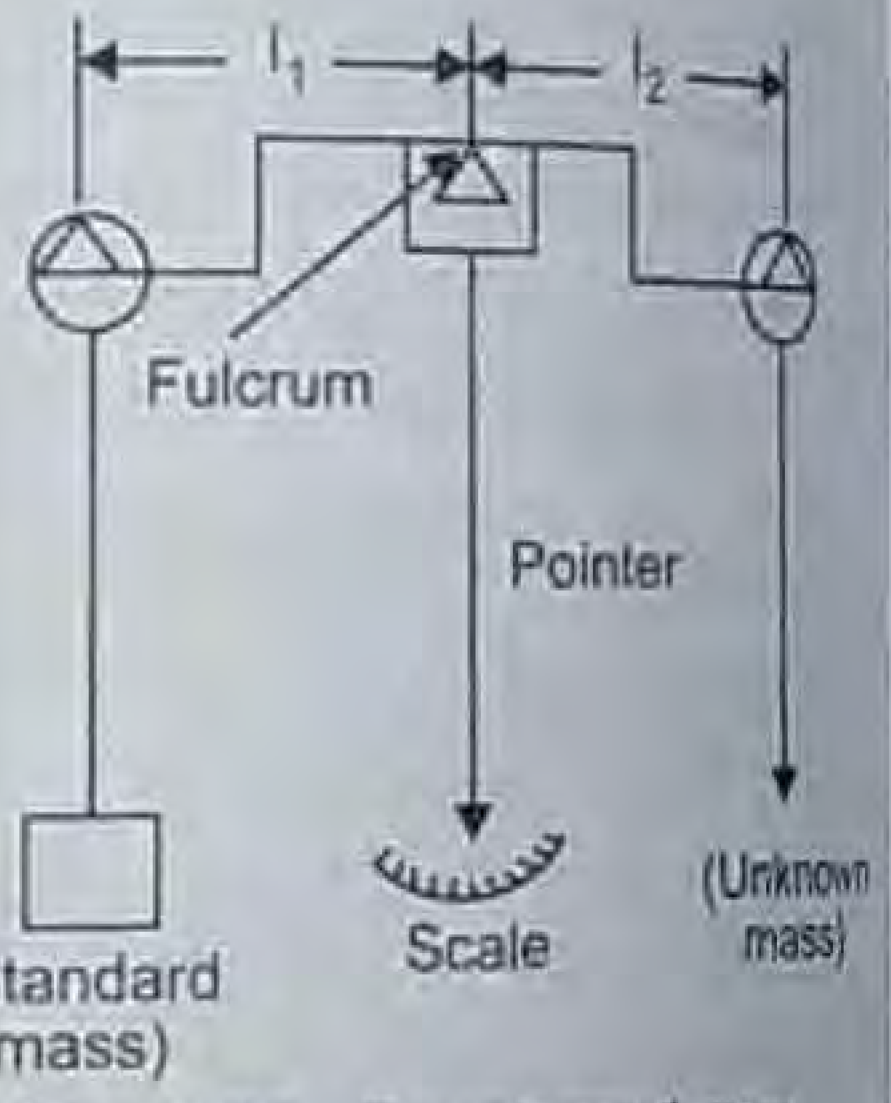


Fig. 7.36. Equal-arm beam balance

An *equal-arm beam balance* (Fig. 7.36) consists of a beam pivoted on a knife-edge fulcrum at the centre. Attached to the centre of the beam is a pointer which points vertically downwards when the beam is in equilibrium. The equilibrium conditions exist when the clockwise rotating moment equals the anti-clockwise rotating moment, *i.e.,* $m_1 l_1 = m_2 l_2$. Since the two arms of the beam are equal; the beam would be in equilibrium again when $m_1 = m_2$. Further for a given location, the earth's attraction acts equally on both the masses and therefore at the equilibrium conditions $W_1 = W_2$, *i.e.,* the unknown force or weights equal the known force or weights.

The *pendulum scale* (Fig. 7.37) is a self-balancing and direct reading force measuring device of multiple lever tape. The weights are however mounted on bent levers, and the movement of the pendulum levers is magnified and transmitted to the indicator pointer.

When the unknown pull P is applied to the load rod, sectors tend to rotate due to unwinding of the loading tapes and consequently the counter weights W swing out. Equilibrium conditions are attained when the counter weight effective moment balances the load moment. The resulting linear movement of the equalizer bar is converted to indicator movement by a rack and pinion arrangement. An electrical signal proportional to the force can also be obtained by incorporating angular displacement transducer that would measure the angular displacement θ.

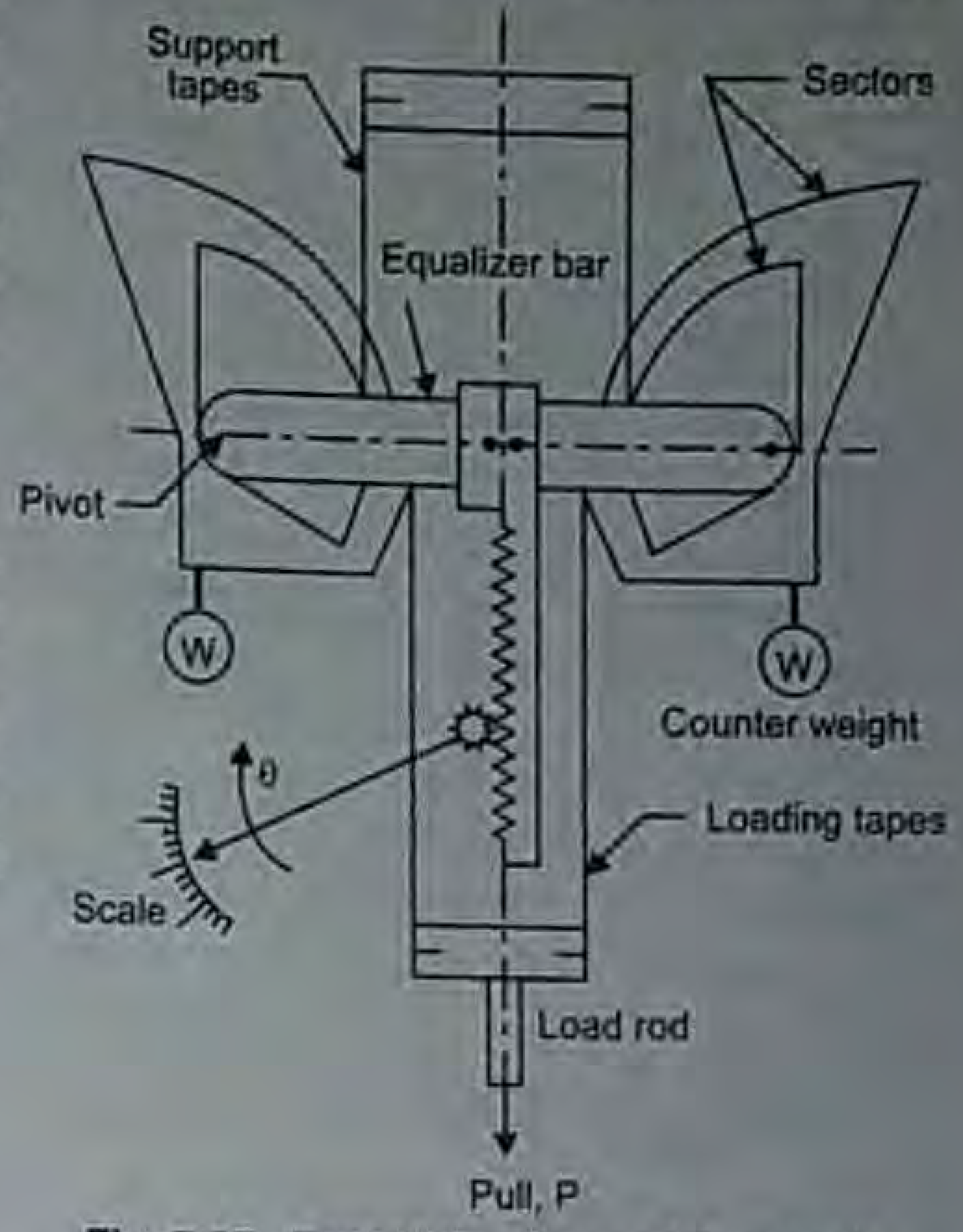


Fig. 7.37. Essentials of a pendulum scale

Elastic Force Meters

These force measuring units measure the force by applying it to an elastic element and then measuring the elastic deformation. Within elastic range of the materials, the deflection of the element is exactly or nearly proportional to the force. Figure 7.38 illustrates the shapes of the more common elastic members used for force estimation.

- *Simple bar* : $x = \dfrac{FL}{AE}$
- *Simply supported beam* : $x = \dfrac{1}{48}\dfrac{FL^3}{EI}$
- *Cantilever* : $x = \dfrac{1}{3}\dfrac{FL^3}{EI}$
- *Spring* : $x = \dfrac{8FD_m^3 N}{E_3 D_w^4}$

where D_m is mean coil diameter, N is number of turns of the coil, D_w is wire diameter E_s is shear modulus.

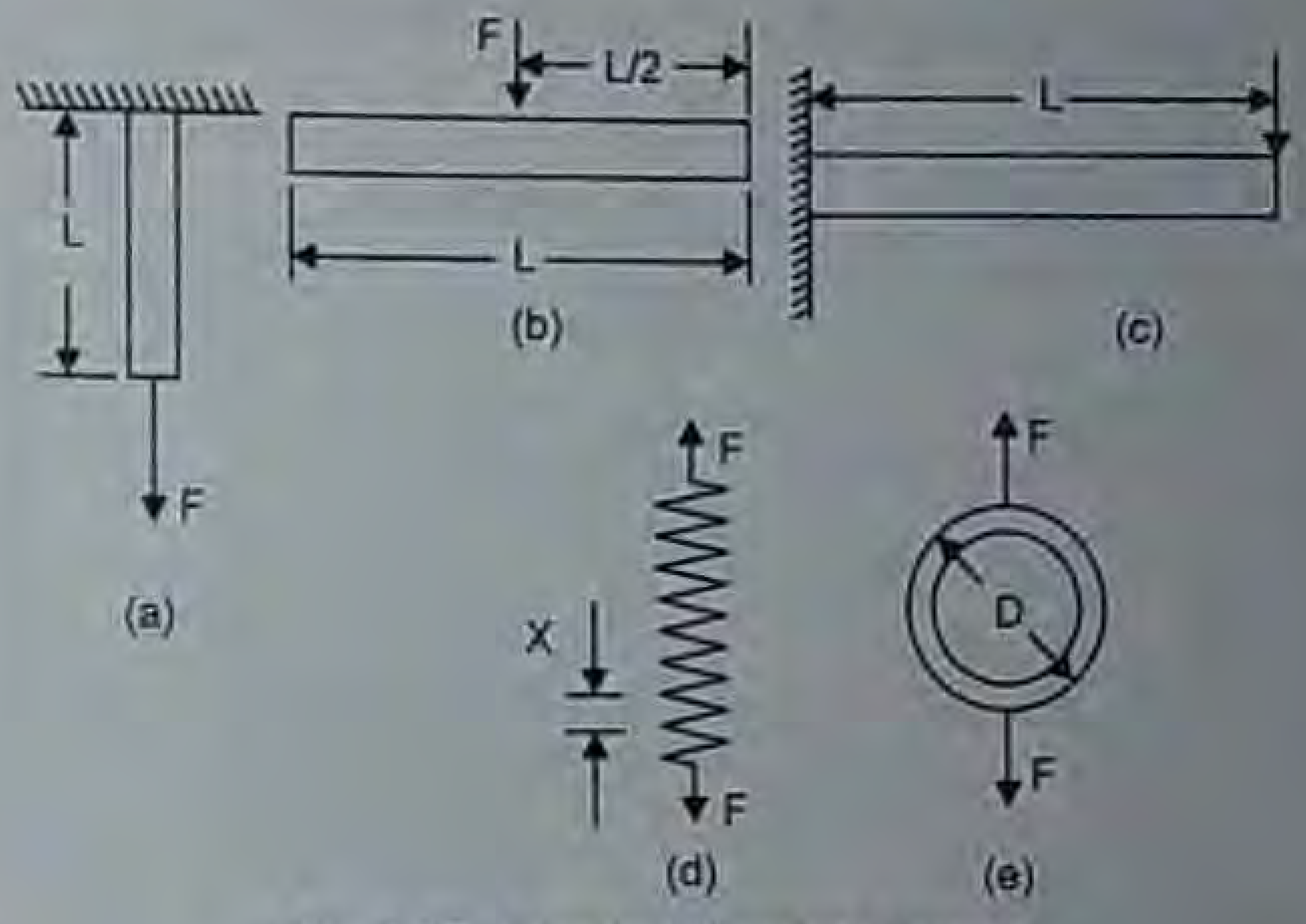


Fig. 7.38. Elastic deflection elements

The desirable properties of the materials used for constructing the elastic-force meters are (*i*) a large and proportional elastic range and (*ii*) freedom from hysteresis.

The *proving* (stress) *ring* is a ring of known physical dimensions and mechanical properties. When an external compressive or tensile load is applied to the lugs or external bosses, the ring changes in its diameter; the change being proportional to the applied force. The amount of ring deflection is measured by means of a micrometer screw and a vibrating reed which are attached to the internal bosses. During use the micrometer tip is advanced and its contact with the reed is indicated by considerable damping of the reed vibration. The difference in the micrometer reading taken before and after the application of load is the measure of the amount of the elongation or compression of the ring. The proving ring deflection can also be picked by LVDT, resulting in a proportional voltage change. The device gives precise results when properly calibrated and corrected for temperature variations.

Instead of deflection, strain in an elastic member may be measured by a strain gauge, and then correlated to the applied force.

Mechanical Load Cells

The term 'load cell' is used to describe a variety of force transducers which may utilize the deflection or strain of elastic member, or the increase in pressure of enclosed fluids. The resulting fluid pressure is transmitted to some form of pressure sensing device such as a manometer or a bourdon tube pressure gauge. The gauge reading is identified and calibrated in units of force.

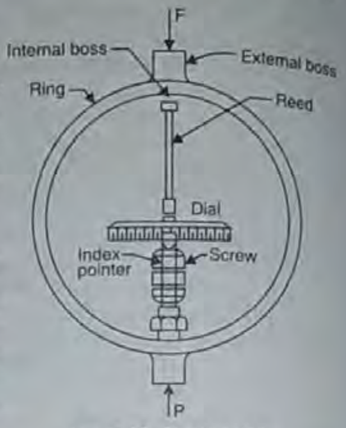


Fig. 7.39. Proving ring

In a ***hydraulic load cell*** (Fig. 7.40) the force variable is impressed upon a diaphragm which deflects and thereby transmits the force to a liquid. The liquid medium, contained in a confined space, has a preload pressure of the order of 2 bar. Application of force increases the liquid pressure; it equals the force magnitude divided by the effective area of the diaphragm. The pressure is transmitted to and read on an accurate pressure gauge calibrated directly in force units. The system has a good dynamic response; the diaphram deflection being less than 0.05 mm under full load. This is because diaphragm has a low modulus and substantially all the force is transmitted to the liquid. These cells have been used to measure loads upto about 25 × 10^5 N with an accuracy of the order of 0.1 percent of full scale; resolution is about 0.02 percent.

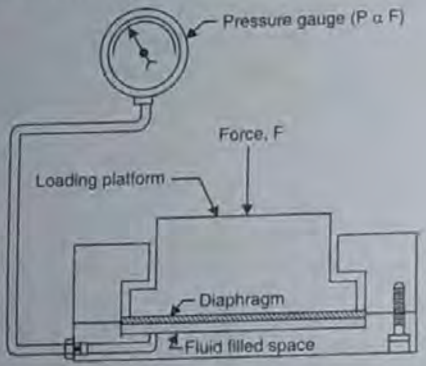


Fig. 7.40. Hydraulic load cell

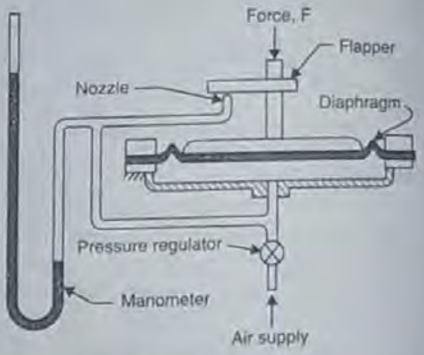


Fig. 7.41. Pneumatic load cell

A ***pneumatic load cell*** (Fig. 7.41), operates on the force-balance principle and employs a nozzle-flapper transducer similar to the conventional relay system. A variable downward force is balanced by an upward force of air pressure against the effective area of a diaphragm. Application of force causes the flapper to come closer to the nozzle, and the diaphragm to deflect downwards. The nozzle opening is nearly shut-off and this results into an increased back pressure in the system. The increased pressure acts on the diaphragm, produces an effective upward force which tends to return the diaphragm to its preload position. For any constant applied force, the system attains equilibrium at a specifie nozzle opening and a corresponding pressure is indicated by the height of mercury column in a manometer. Since the maximum pressure in the system is limited

to the air supply pressure, the range of the unit can be extended only by using a larger diameter diaphragm. The commercially available load cells operating on this principle can measure loads upto 25 × 10^5 N with an accuracy of 0.5 percent of full scale. The air consumption is of the order of 0.17 m^3/hr of free air.

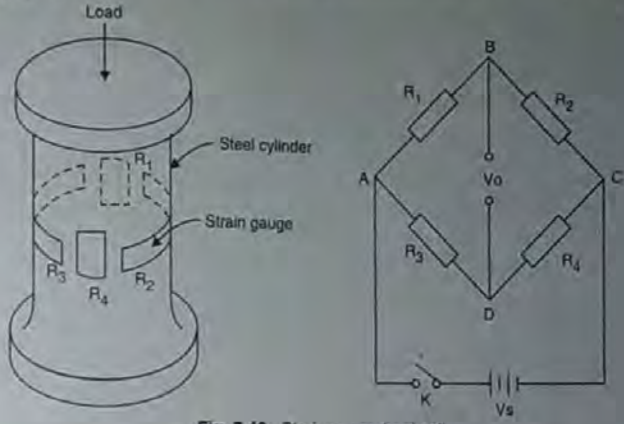


Fig. 7.42. Strain gauge load cell

The ***strain gauge load cells*** convert weight or force into electrical outputs which are provided by the strain gauges; these outputs can be connected to various measuring instruments for indicating, recording and controlling the weight or force.

A simple load cell consists of steel cylinder which has four identical strain gauges mounted upon it; the gauges R_1 and R_4 are along the direction of applied load and the gauges R_2 and R_3 are attached cirmumferentially at right angles to gauges R_1 and R_2. These four gauges are connected electrically to the four limbs of a Wheatstone bridge circuit.

The output voltage or the change in output voltage due to applied load is given by

$$dV_o = 2(1+\mu)\left(\frac{dR}{R} - \frac{V_s}{4}\right)$$

where R is the resistance of each gauge, μ is the Poisson's ratio and V_s is the supply voltage.

Apparently, the output voltage is a measure of applied load.

The strain gauge load cells are excellent force measuring devices, particularly when the force is not steady. They are generally stable, accurate and find extensive use in industrial applications such as drawbar and tool-force dynamometers, crane load monitoring, and road vehicle weighing devices, etc.

7.11. TORQUE MEASUREMENT (TORSION METERS)

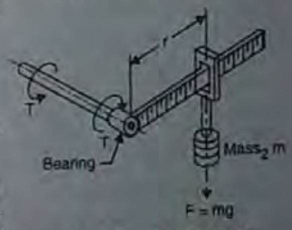


Fig. 7.43. Gravity balance for torque measurement

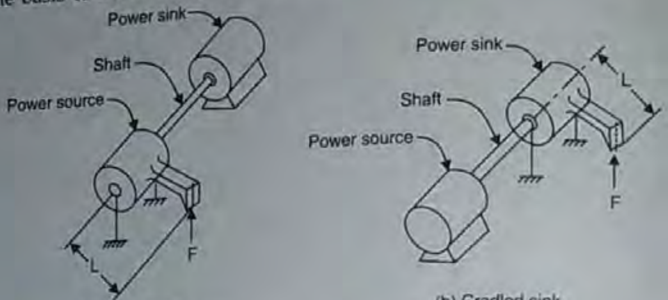
Measurement of torque may be necessitated for its own sake or as a part of power measurement for a rotating shaft.

In a ***gravity balance method*** (Fig. 7.43), the known mass (m) is moved along the arm so that the value of torque ($F \times r$) equals the product (T) which is to be measured. Alternatively magnitude of the mass may be varied, keeping the radius constant. For the two arrangements we have:

$r \alpha T$ (m and g are constant)

$m \alpha T$ (r and g are constant)

Torque transmission through a shaft usually involves a power source, a power transmitter (shaft), and a power sink (also called the power absorber or dissipator). Torque measurement is accomplished by mounting either the source or the sink in bearing and measuring the reaction force F and the arm length L (Fig. 7.44). This concept of bearing mounting is called *cradling* and this forms the basis of most shaft power dynamometers.



(a) Cradled source (b) Cradled sink

Fig. 7.44. Torque measurement of rotating machines

Further, it may be recalled that the following relation holds good for the angular deflection of a shaft subjected to torque within elastic limits :

$$\frac{T}{I_p} = \frac{f_s}{r} = \frac{C\theta}{l}$$

where T is the torque transmitted by the shaft, I_p is the polar moment of inertia of the shaft section, f_s is the maximum induced shear stress at the outside surface, r is the maximum radius at which the maximum shear stress occurs, C is the modulus of rigidity of the shaft material, θ is the angular twist, and l is the length of the shaft over which the twist is measured.

The shaft-twisting relation gives ;

$$T = (I_p/l) \times f_s, \text{ i.e., } T = \text{constant} \times f_s$$

and $$T = (I_p\, C/l) \times \theta, \text{ i.e., } T = \text{constant} \times \theta$$

Thus, torque for any given system can be calculated by measuring either the angle of twist or maximum shear stress.

Figure 7.45 shows the schematics of a mechanical torsion bar wherein angular deflection of a parallel length of shaft is used to measure torque. The angular twist over a fixed length of the bar is observed on a calibrated disk (attached to the rotationg shaft) by using the stroboscopic effect of intermittent viewing and the persistence of vision. The system gives a varying angle of twist between the driving engine and the driven load as the torque changes.

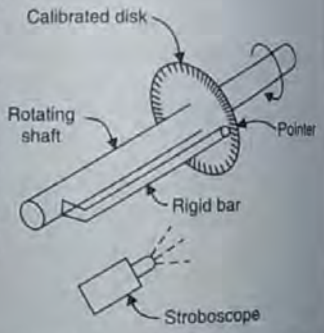


Fig. 7.45. Mechanical torsion meter

Optical Torsion Meter

The meter uses an optical method to detect angular twist of a rotating shaft.

The unit comprises two castings A and B which are fitted to the shaft at a known distance apart. These castings are attached to each other by a tension strip C which transmits torsion but has little resistance to bending. When the shaft is transmitting a torque, there occurs a relative movement between the castings which results in partial inclination between the two mirrors attached to the castings. The mirrors are made to reflect a light beam onto a graduated scale; angular deflection of the light ray is then proportional to the twist of, and hence the torque in the shaft.

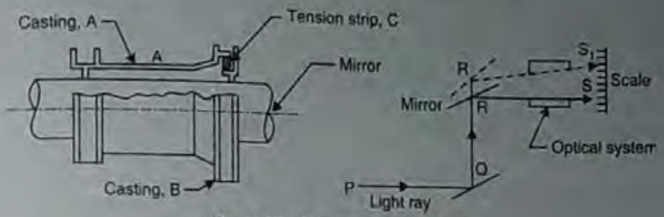


Fig. 7.46. Optical torsion meter

For constant torque measurements from a steam turbine, the two mirrors are arranged back to back and there occurs a reflection from each mirror during every half revolution, A second system of mirrors giving four reflections per revolution is desirable when used with a reciprocating enging whose torque varies during a revolution.

Electrical Torsion Meter

A system using two magnetic or photoelectric transducers, as shown in Fig. 7.47, involves two sets of measurements.

(*i*) A count of the impulse from either slotted wheel. This count gives the frequency or shaft speed.

(*ii*) A measure of the time between pulses from the two wheels. This signal is proportional to the twist θ of, and hence torque T in the shaft.

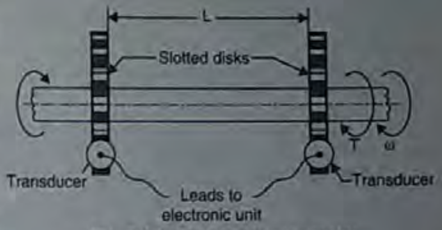


Fig. 7.47. Electrical torsion meter

These two signals, T and ω, can be combined to estimate the power being transmitted by the shaft.

Strain-gauge Torsion Meter

A general configuration of a strain gauge bridge circuit widely employed for torque measurement from a rotating shaft is shown in Fig. 7.48.

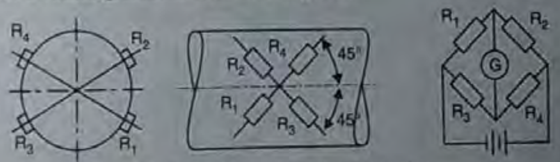
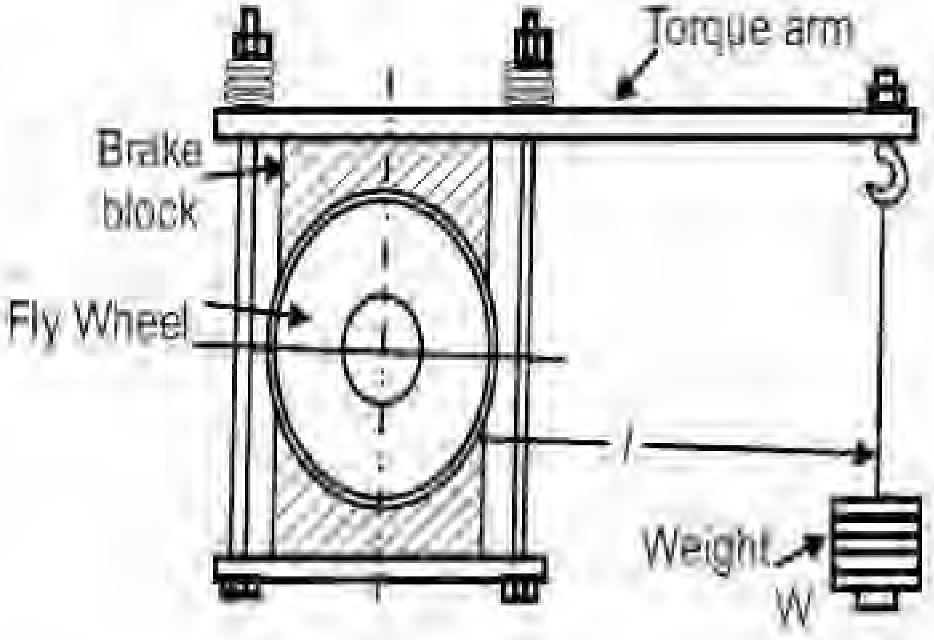


Fig. 7.48. Strain gauge torsion meter

Four bonded-wire strain gauges are mounted on a 45° helix with the axis of the rotation; and are placed in pairs diametrically opposite. If the gauges are accurately placed and have matched

Prony Brake Dynamometer:

Pony Brake is one of the simplest dynamometers for measuring power output (brake power). It is to attempt to stop the engine using a brake on the flywheel and measure the weight which an arm attached to the brake will support, as it tries to rotate with the flywheel.



The Prony brake shown in the above consists of a wooden block, frame, rope, brake shoes and flywheel. It works on the principle of converting power into heat by dry friction. Spring-loaded bolts are provided to increase the friction by tightening the wooden block.

The whole of the power absorbed is converted into heat and hence this type of dynamometer must the cooled.

The brake power is given by the formula

Brake Power (bp) = 2π NT

Where T = Weight applied (W) × distance (l)