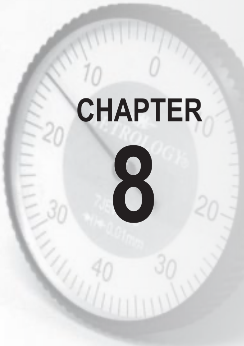

CHAPTER 8

Metrology of Gears and Screw Threads

Some notes for chapters (8) & (9) & (15)
Note : make sure from the sections included in your semester

After studying this chapter, the reader will be able to

- understand the basic principles of measurement of gears and screw threads
- throw light on the geometry of spur gears and screw threads
- elucidate the measurement techniques used for the measurement of runout, pitch, profile, lead, backlash, and tooth thickness of spur gears
- analyse the various gear-measuring instruments such as gear-measuring machine, gear tooth calliper, tooth span micrometer, and Parkinson gear tester.
- explain the measurement principles of major diameter, minor diameter, effective diameter, pitch, angle, and form of screw threads.
- describe thread-measuring instruments such as bench micrometer, floating carriage micrometer, and pitch-measuring machine
- discuss the types and use of thread gauges for screw thread inspection

8.1 INTRODUCTION

Gears are the main elements in a transmission system. It is needless to say that for efficient transfer of speed and power, gears should conform perfectly to the designed profile and dimensions. Misalignments and gear runout will result in vibrations, chatter, noise, and loss of power. Therefore, one cannot understate the importance of precise measurement and inspection techniques for gears. On the other hand, threaded components should meet stringent quality requirements to satisfy the property of *interchangeability*. Geometric aspects of screw threads are quite complex and, therefore, thread gauging is an integral part of a unified thread gauging system.

The most common forms of gear teeth are involute and cycloidal. The major gear types are spur, helical, bevel, spiral, and worm gears. Coverage of the entire range of inspection methods and instrumentation is an arduous task and requires a separate volume altogether. Therefore, this chapter is confined to the major inspection methods suited for spur gears having an involute profile. We are sure that the reader will be benefited with this basic knowledge and be motivated to refer to standard books dealing with inspection of gears and screw threads. While the first part of the chapter deals with measurements of gears, the second part outlines some major techniques used for the measurement of screw threads.

8.2 GEAR TERMINOLOGY

Each gear has a unique form or geometry. The gear form is defined by various elements. An illustration of the gear highlighting the important elements is referred to as 'gear terminology'. This section explains the types of gears and their terminology.

8.2.1 Types of Gears

The common types of gears used in engineering practices are described in this section. The information provided here is very brief, and the reader is advised to read a good book on 'theory of machines' to understand the concepts better.

طرف

Spur gears These gears are the simplest of all gears. The gear teeth are cut on the periphery and are parallel to the axis of the gear. They are used to transmit power and motion between parallel shafts (Fig. 8.1).

Helical gears The gear teeth are cut along the periphery, but at an angle to the axis of the gear. Each tooth has a helical or spiral form. These gears can deliver higher torque since there are more number of teeth in a mesh at any given point of time. They can transmit motion between parallel or non-parallel shafts.

Herringbone gears These gears have two sets of helical teeth, one right-hand and the other left-hand, machined side by side (Fig. 8.2).

Worm and worm gears A worm is similar to a screw having single or multiple start threads, which form the teeth of the worm. The worm drives the worm gear or worm wheel to enable transmission of motion. The axes of worm and worm gear are at right angles to each other (Fig. 8.3). تمكين نقل الحركة.

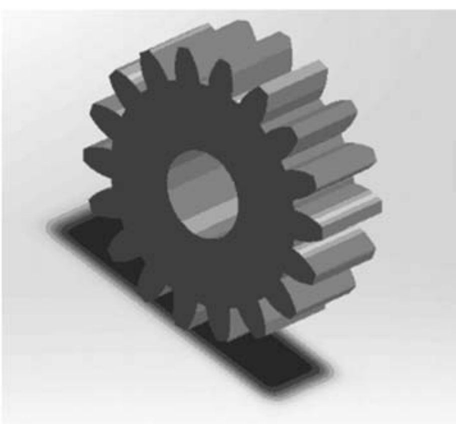

Fig. 8.1 Spur gear

Fig. 8.2 Herringbone gear

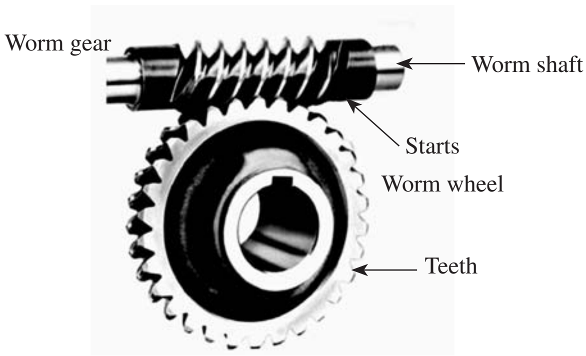

Fig. 8.3 Worm and worm gear

Fig. 8.4 Bevel gears

Bevel gears These gears are used to connect shafts at any desired angle to each other. The shafts may lie in the same plane or in different planes (Fig. 8.4).

Hypoid gears These gears are similar to bevel gears, but the axes of the two connecting shafts do not intersect. They carry curved teeth, are stronger than the common types of bevel gears, and are quiet-running. These gears are mainly used in automobile rear axle drives.

A gear tooth is formed by portions of a pair of opposed involutes. By far, the involute tooth profile is most preferred in gears. A clear understanding of the various terminologies associated with gears is extremely important before an attempt is made to learn about inspection and measurement of gears. The following are some of the key terminologies associated with gears, which have been illustrated in Fig. 8.5:

Base circle It is the circle from which the involute form is generated. Only the base circle of a gear is fixed and unalterable (غير قابل للتغير).

Outside circle It marks the maximum diameter of the gear up to which the involute form is extended. It is also called the addendum circle. In addition, it is the diameter of the blank from which the gear is cut out.

Pitch circle It is the imaginary circle on which lies the centres of the pitch cylinders of two mating gears.

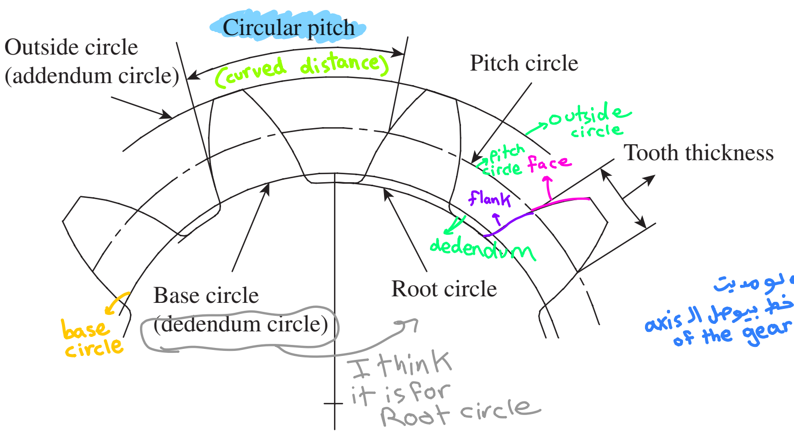

Fig. 8.5 Spur gear terminology

Root circle It is the circle corresponding to the minimum diameter of the gear profile. However, the involute profile is limited only up to the base circle of a spur gear.

Addendum It is the radial distance between the addendum circle and the pitch circle.

علو مدبت
خط بيوصل ال axis of the gear

Dedendum It is the radial distance between the pitch circle and the root circle.

outside

Face The portion of tooth lying between the addendum circle and the pitch circle is called the face.

root ← ...

Flank The portion of tooth lying between the pitch circle and the dedendum circle is called the flank.

Circular pitch It is the distance between corresponding points of adjacent teeth measured along the pitch circle.

Diametrical pitch It is expressed as the number of teeth per unit diameter of the pitch circle.
÷ unit diameter of the pitch circle

$\frac{D_{pitch}}{\text{\# of teeth}}$ **Module** It is simply the metric standard for pitch. It is the linear distance (in millimetres) that each tooth of the gear would occupy if the gear teeth were spaced along the pitch diameter. Accordingly, if the pitch circle diameter of the gear is D and the number of teeth is N, then the module m is given by D/N and is expressed in millimetres.

In order to ensure interchangeability and smooth meshing of gears, standard modules are recommended. These standards are also useful for the design of gear cutting tools. The Indian Standards Institute has recommended the following modules (in mm) in order of preference:

First choice 1, 1.25, 1.5, 2, 2.5, 3, 4, 5, 6, 8, 10, 12, 16, 20

Second choice 1.125, 1.375, 1.75, 2.25, 2.75, 3.5, 4.5, 5.5, 7, 9, 11, 14, 18

Third choice 3.25, 3.75, 6.5

Tooth thickness It is the arc distance measured along the pitch circle from its intercept with one flank to that with the other flank of the same tooth.

Base pitch It is the distance measured around the base circle from the origin of the involute on the tooth to the origin of a similar involute on the next tooth.

Base pitch = Base circumference/Number of teeth

Table 8.1 illustrates the nomenclature of a spur gear.

Table 8.1 Spur gear nomenclature

Nomenclature	Symbol	Formula
Module ($\frac{D_{pitch}}{\text{\# of teeth}}$)	m	D_p/N
Diametrical pitch	DP	$N/D = \pi/p = 1/m$
Pitch	p	$P = \pi m$ $= \frac{\pi \times D}{N}$
Pitch circle diameter	D_p	Nm
Tooth height	h	$2.2m$
Addendum	h'	M
Dedendum	h''	$1.2m$
Outside diameter	D_0	$m(N + 2)$
Root circle diameter	D_r	$D_0 - 4.4m$
Pressure angle	α	20° or 14½°

N = Number of teeth on the gear, D = Outside diameter of the gear.

8.2.2 Line of Action and Pressure Angle

The mating teeth of two gears in the mesh make contact with each other along a common tangent to their base circle, as shown in Fig. 8.6. This line is referred to as the 'line of action'. The load or the so-called pressure between the two gears is transmitted along this line.

The angle between the line of action and the common tangent to the pitch circles is known as the *pressure angle*. Using trigonometry, it can be shown that the pressure angle is also given by the angle made between the normal drawn at the point of contact of line of action to the base circle and the line joining the centres of the gears.

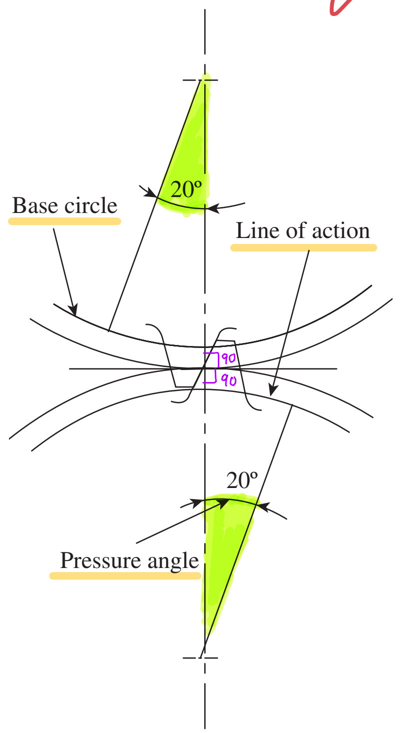

Fig. 8.6 Line of action and pressure angle

Tangent for the first and second base circle

Pitch point و يمر بال

8.3 ERRORS IN SPUR GEARS

A basic understanding of the errors in spur gears during manufacturing is important before we consider the possible ways of measuring the different elements of gears. A spur gear is a rotating member that constantly meshes with its mating gear. It should have the perfect geometry to maximize transmission of power and speed without any loss. From a metrological point of view, the major types of errors are as follows:

1. Gear blank runout errors
2. Gear tooth profile errors
3. Gear tooth errors
4. Pitch errors
5. Runout errors
6. Lead errors
7. Assembly errors

Gear blank runout errors Gear machining is done on the gear blank, which may be a cast or a forged part. The blank would have undergone preliminary machining on its outside diameter (OD) and the two faces. The blank may have radial runout on its OD surface due to errors in the preliminary machining. In addition, it may have excessive face runout. Unless these two runouts are within prescribed limits, it is not possible to meet the tolerance requirements at later stages of gear manufacture.

Gear tooth profile errors These errors are caused by the deviation of the actual tooth profile from the ideal tooth profile. Excessive profile error will result in either friction between the mating teeth or backlash, depending on whether it is on the positive or negative side.

Gear tooth errors This type of error can take the form of either tooth thickness error or tooth alignment error. The tooth thickness measured along the pitch circle may have a large amount of error. On the other hand, the locus of a point on the machined gear teeth may not follow an ideal trace or path. This results in a loss in alignment of the gear.

ما بدنا ال error

Pitch errors Errors in pitch cannot be tolerated, especially when the gear transmission system is expected to provide a high degree of positional accuracy for a machine slide or axis. Pitch error can be either *single pitch error* or *accumulated pitch error*. Single pitch error is the error in actual measured pitch value between adjacent teeth. Accumulated pitch error is the difference between theoretical summation over any number of teeth intervals and summation of actual pitch measurement over the same interval.

Runout errors This type of error refers to the runout of the pitch circle. Runout causes vibrations and noise, and reduces the life of the gears and bearings. This error creeps in due to inaccuracies in the cutting arbour and tooling system.

Lead errors This type of error is caused by the deviation of the actual advance of the gear tooth profile from the ideal value or position. This error results in poor contact between the mating teeth, resulting in loss of power.

Assembly errors Errors in assembly may be due to either the centre distance error or the axes alignment error. An error in centre distance between the two engaging gears results in either backlash error or jamming of gears if the distance is too little. In addition, the axes of the two gears must be parallel to each other, failing which misalignment will be a major problem.

8.4 MEASUREMENT OF GEAR ELEMENTS

A number of standard gear inspection methods are used in the industry. The choice of the inspection procedure and methods not only depends on the magnitude of tolerance and size of the gears, but also on lot sizes, equipment available, and inspection costs. While a number of analytical methods are recommended for inspection of gears, statistical quality control is normally resorted to when large quantities of gears are manufactured. The following elements of gears are important for analytical inspection:

1. Runout
2. Pitch
3. Profile
4. Lead
5. Backlash
6. Tooth thickness

8.4.1 Measurement of Runout

Runout is caused when there is some deviation in the trajectories of the points on a section of a circular surface in relation to the axis of rotation. In case of a gear, runout is the resultant of the radial throw of the axis of a gear due to the out of roundness of the gear profile. *Runout tolerance* is the total allowable runout. In case of gear teeth, runout is measured by a specified probe such as a cylinder, ball, cone, rack, or gear teeth. The measurement is made perpendicular to the surface of revolution. On bevel and hypoid gears, both axial and radial runouts are included in one measurement.

A common method of runout inspection, called a single-probe check and shown in Fig. 8.7(a), uses an indicator with a single probe whose diameter makes contact with the flanks of adjacent teeth in the area of the pitch circle. On the other hand, in a two-probe check illustrated in Fig. 8.7(b), one fixed and one free-moving probe, are positioned on diametrically opposite sides of the gear and make contact with identically located elements of the tooth profile. The range of indications obtained with the two-probe check during a complete revolution of the gear is twice the amount resulting from the single-probe check.

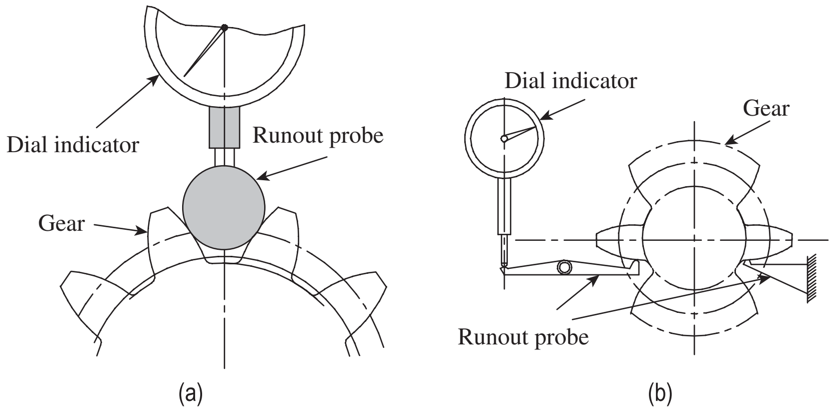

Fig. 8.7 Measurement of radial runout (a) Single-probe check (b) Two-probe check

fixed واحد
movable واحد

8.4.2 Measurement of Pitch

Pitch is the distance between corresponding points on equally spaced and adjacent teeth. Pitch error is the difference in distance between equally spaced adjacent teeth and the measured distance between any two adjacent teeth. The two types of instruments that are usually employed for checking pitch are discussed in this section.

Pitch-measuring Instruments

These instruments enable the measurement of chordal pitch between successive pairs of teeth. The instrument comprises a fixed finger and a movable finger, which can be set to two identical points on adjacent teeth along the pitch circle. The pitch variation is displayed on a dial indicator attached to the instrument, as shown in Fig. 8.8. In some cases, the pitch variation is recorded on a chart recorder, which can be used for further measurements. A major limitation of this method is that readings are influenced by profile variations as well as runout of the gear.

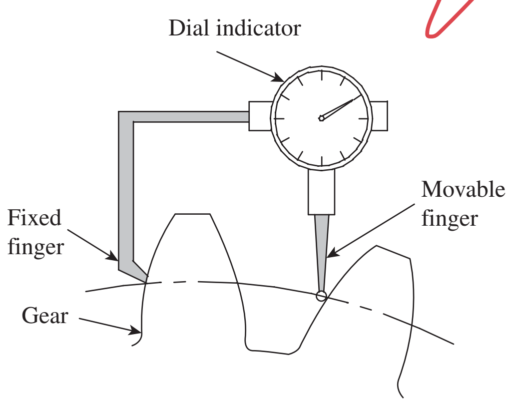

Fig. 8.8 Pitch-measuring instrument

Pitch-checking Instrument

A pitch-checking instrument is essentially a dividing head that can be used to measure pitch variations. The instrument can be used for checking small as well as large gears due to its portability. Figure 8.9 explains the measuring principle for a spur gear. It has two probes—one fixed, called the anvil, and the other movable, called the measuring feeler. The latter is connected to a dial indicator through levers.

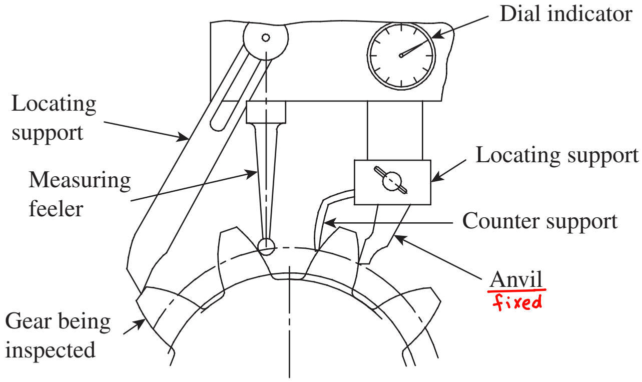

Fig. 8.9 Pitch-checking instrument

The instrument is located by two adjacent supports resting on the crests of the teeth. A tooth flank is butted against the fixed anvil and locating supports. The measuring feeler senses the corresponding next flank. The instrument is used as a comparator from which we can calculate the adjacent pitch error, actual pitch, and accumulated pitch error.

8.4.3 Measurement of Profile

The profile is the portion of the tooth flank between the specified form circle and the outside circle or start of tip chamfer. Profile tolerance is the allowable deviation of the actual tooth form from the theoretical profile in the designated reference plane of rotation. As the most commonly used profile for spur and helical gears is the involute profile, our discussions are limited to the measurement of involute profile and errors in this profile. We will now discuss two of the preferred methods of measuring a tooth profile.

Profile Measurement Using First Principle of Metrology

In this method, a dividing head and a height gauge are used to inspect the involute profile of a gear. With reference to Fig. 8.10, A is the start of the involute profile and AT is the vertical tangent to the base circle. When the involute curve is rotated through the roll angle ϕ_1, the point C_1 of the true involute profile is on the vertical tangent AT.

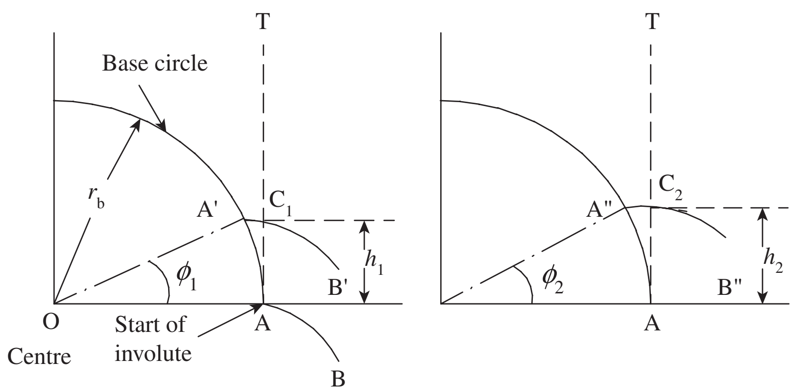

Fig. 8.10 Principle of involute measurement

Therefore, $h_1 = AC_1 = \text{Arc}AA' = r_b \times \phi_1$
Similarly, for any other position we have

$$h_n = r_b \times \phi_n$$

In order to carry out the measurement, the gear is supported between the centres of a dividing head and its tailstock. The height gauge is set at zero at a convenient position on the gear, for example, point C. This is done by rotating the gear against the stylus of the gauge so that the gauge reads zero. Now, the gear is rotated in small increments such as 1° or 1', depending on the degree of precision required by the user. Readings are tabulated as shown in Table 8.2.

Table 8.2 Readings of dividing head

Roll angle	True reading *h*	Actual reading	Error
0	0	0	0
1°	$h_1 = r_b \dfrac{1 \times \pi}{180}$	h_1'	$\in_1 = h_1' - h_1$
2°	$h_2 = r_b \dfrac{2 \times \pi}{180}$	h_2'	$\in_2 = h_2' - h_2$
.	.	.	.
.	.	.	.
.	.	.	.
n°	$h_n = r_b \dfrac{n \times \pi}{180}$	h_n'	$\in_n = h_n' - h_n$

This procedure provides a reasonable and accurate means of measuring the deviation of the actual tooth profile from the true involute profile.

Profile Measurement Using Special Profile-measuring Instruments

The gear to be inspected is mounted on an arbour on the gear-measuring machine, as shown in Fig. 8.11. The probe is brought into contact with the tooth profile. To obtain the most accurate readings, it is essential that the feeler (probe) is sharp, positioned accurately, and centred correctly on the origin of the involute at 0° of the roll. The machine is provided with multiple axes movement to enable measurement of the various types of gears. The measuring head comprising the feeler, electronic unit, and chart recorder can be moved up and down by operating a handwheel.

The arbour assembly holding the gear can be moved in two perpendicular directions in the horizontal plane by the movement of a carriage and a cross-slide. Additionally, the base circle disk on which the gear is mounted can be rotated by 360°, thereby providing the necessary rotary motion for the gear being inspected. The feeler is kept in such a way that it is in a spring-loaded contact with the tooth flank of the gear under inspection. As the feeler is mounted exactly above the straight edge, there is no movement of the feeler if the involute is a true involute. If there is an error, it is sensed due to the deflection of the feeler, and is amplified by the electronic unit and recorded by the chart recorder. The movement of the

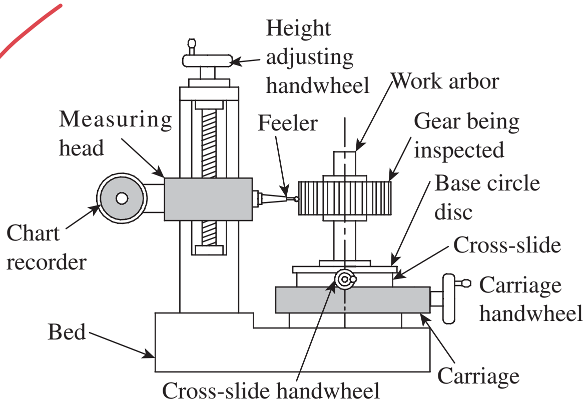

Fig. 8.11 Gear-measuring machine

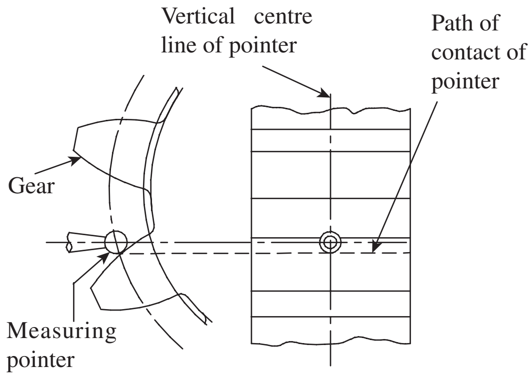

Fig. 8.12 Measurement of lead

feeler can be amplified 250, 500, or 1000 times, the amplification ratio being selected by a selector switch. When there is no error in the involute profile, the trace on the recording chart will be a straight line. Gleason gear inspection machine, a product of Gleason Metrology Systems Corporation, USA, follows the fundamental design aspect of any testing machine with the capability to handle up to 350 mm dia gears. It also integrates certain object-oriented tools to achieve faster cycle times and a better human–machine interaction.

8.4.4 Measurement of Lead

Lead is the axial advance of a helix for one complete rotation about its axis. In case of spur gears, lead tolerance is defined as the allowable deviation across the face width of a tooth surface. Control of lead is necessary in order to ensure adequate contact across the face width when gear and pinion are in mesh. Figure 8.12 illustrates the procedure adopted for checking lead tolerance of a spur gear.

A measuring pointer traces the tooth surface at the pitch circle and parallel to the axis of the gear. The measuring pointer is mounted on a slide, which travels parallel to the centre on which the gear is held. The measuring pointer is connected to a dial gauge or any other suitable comparator, which continuously indicates the deviation. The total deviation shown by the dial indicator over the distance measured indicates the amount of displacement of the gear tooth in the face width traversed.

Measurement of lead is more important in helical and worm gears. Interested readers are advised to refer to a gear handbook to learn more about the same.

8.4.5 Measurement of Backlash

If the two mating gears are produced such that tooth spaces are equal to tooth thicknesses at the reference diameter, then there will not be any clearance in between the teeth that are getting engaged with each other. This is not a practical proposition because the gears will get jammed even from the slightest mounting error or eccentricity of bore to the pitch circle diameter. Therefore, the tooth profile is kept uniformly thinned, as shown in Fig. 8.13. This results in a small play between the mating tooth surfaces, which is called a *backlash*.

We can define backlash as the amount by which a tooth space exceeds the thickness of an engaging tooth. Backlash should be measured at the tightest point of mesh on the pitch circle, in a direction normal to the tooth surface when the gears are mounted at their specified position. Backlash value can be described as the shortest or normal distance between the trailing flanks when the driving flank and the driven flank are in contact. A dial gauge is usually employed to measure the backlash. Holding the driver gear firmly, the driven gear can be rocked back and forth. This movement is registered by a dial indicator having its pointer positioned along the tangent to the pitch circle of the driven gear.

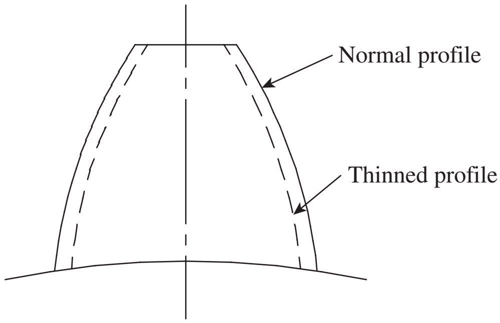

Fig. 8.13 Tooth thinning

8.4.6 Measurement of Tooth Thickness

Various methods are recommended for the measurement of gear tooth thickness. There is a choice of instruments such as the gear tooth calliper, and span gauging or tooth span micrometer. Constant chord measurement and measurement over rolls or balls are additional options. Two such methods, namely measurement with gear tooth calliper and tooth span micrometer are discussed in detail here.

Measurement with Gear Tooth Callipers

This is one of the most commonly used methods and perhaps the most accurate one. Figure 8.14 illustrates the construction details of a gear calliper. It has two vernier scales, one horizontal and the other vertical. The vertical vernier gives the position of a blade, which can slide up and down. When the surface of the blade is flush with the tips of the measuring anvils, the vertical scale will read zero. The blade position can be set to any required value by referring to the vernier scale.

From Fig. 8.15, it is clear that tooth thickness should be measured at the pitch circle (chord thickness C_1C_2 in the figure). Now, the blade position is set to a value equal to the addendum of the gear tooth and locked into position with a locking screw. The calliper is set on the gear in such a manner that the blade surface snugly fits with the top surface of a gear tooth. The two anvils are brought into close contact with the gear, and the chordal thickness is noted down on the horizontal vernier scale.

Let d = Pitch circle diameter

g_c = Chordal thickness of gear tooth along the pitch circle

h_c = Chordal height

z = Number of teeth on the gear

$$\text{Chordal thickness } g_c = \text{Chord } C_1C_2$$
$$= 2(\text{pitch circle radius}) \times \sin ç$$
$$= 2 \times \frac{d}{2} \times \sin ç$$
$$= d \sin ç$$

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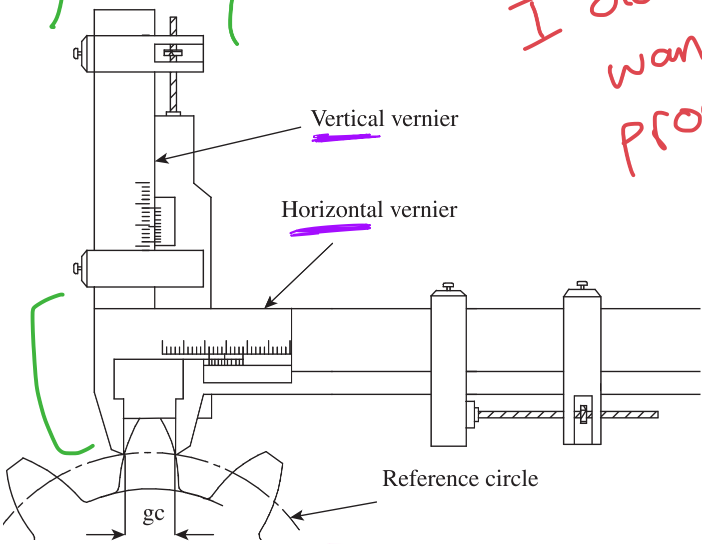

Fig. 8.14 Gear tooth calliper

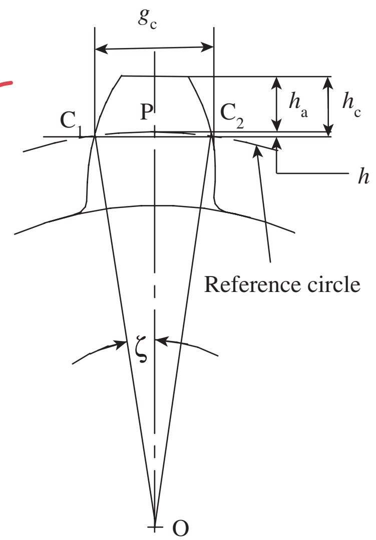

Fig. 8.15 Chordal thickness and chordal height

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Arc $C_1PC_2 = \frac{d}{2} \times 2ç$ (value of ç in radians)

$= d \times ç = \frac{\pi d}{2z}$

Therefore, $ç = \frac{\pi}{2z}$

$g_c = d\sin(\pi/2z)$ (where $\pi/2z$ is in radians)

$g_c = d\sin(90/2z)$ (argument of sin is in degrees)

Chordal height $h_c = h_a + \Delta h = m + \Delta h$

However, $\Delta h(d - \Delta h) = \frac{gc}{2} \times \frac{gc}{2}$

and $4(\Delta h)^2 - 4\Delta h \times d + g_c^2 = 0$

$\Delta h = [d \pm \sqrt{d^2 - g_c^2}]/2$

$= [d - \sqrt{d^2 - g_c^2}]/2$; the other value is neglected because $\Delta h > d$ is not possible.

Neglecting $(\Delta h)^2$, we get $\Delta h \times d = g_c^2/4$

$\Delta h = g_c^2/4d$

Thus, $h_c = h_a + g_c^2/4d = m + g_c^2/4d$

Therefore, $g_c = d \sin (90°/z)$ (8.1)

and $h_c = m + g_c^2/4d$ (8.2)

Measurement with Tooth Span Micrometers

In this case, tooth thickness is measured by measuring the chordal distance over a number of teeth by using a *tooth span micrometer*, also called a *flange micrometer*. The inspection of gear is simple, easy, and fast. The measurement is based on the base tangent method and is illustrated in Fig. 8.16.

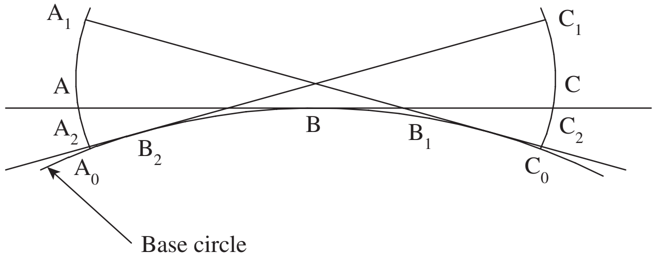


Fig. 8.16 Base tangent method

The reader may recall that an involute is the path traced by a point on a circle that is rolling on a straight line without slipping. We can easily see that if a straight generator ABC is being rolled along a base circle, then its ends trace involute profiles A_2AA_1 and C_2CC_1, as shown in Fig. 8.16. Therefore, any measurement made by gauging the span of a number of teeth will be constant, that is, $AC = A_1C_2 = A_2C_1 = A_0C_0$, where A_0C_0 is the arc length of the base circle between the origins of involutes. Thus, the accuracy of this method is better than that of a gear calliper since it is independent of the position of flanges of the micrometer on teeth flanks.

Suppose, the gear has N number of teeth and the length AC on the pitch circle corresponds to S number of teeth (called the tooth span), then AC = (S − ½) pitches.

Therefore, angle subtended by AC = (S − ½) × 2π/N radians

Figure 8.17 illustrates the measurement across two opposed involutes over a span of several teeth.

Involute function of pressure angle = δ = tan ϕ − ϕ, where ϕ is the pressure angle.

Therefore, angle of arc BD = (S − ½) × 2π/N + 2(tan ϕ − ϕ).

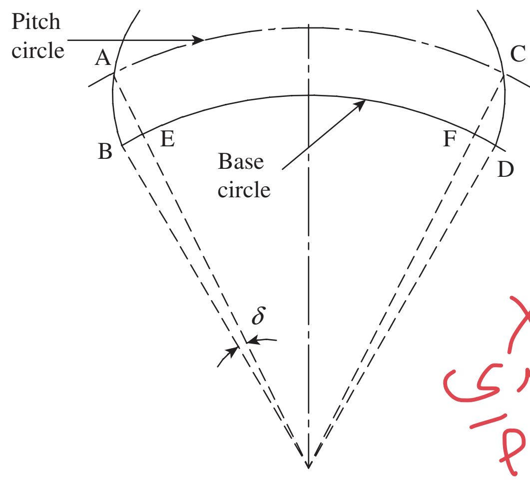


Fig. 8.17 Measurement across two opposed involutes

X to CSN-proof

From Fig. 8.17, it is clear that BD = angle of arc BD × R_b, where R_b is the radius of the base circle.

Thus, $BD = [(S - ½) \times 2\pi/N + 2(\tan\phi - \phi)] \times R_p \cos\phi \quad (R_b = R_p \cos\phi)$

$$= \frac{mN}{2}\cos\phi\,[(S - ½) \times 2\pi/N + 2(\tan\phi - \phi)] \quad (R_b = R_p \cos\phi)$$

Therefore,

$$\text{length of arc BD} = Nm\cos\phi\left[\frac{\pi S}{N} - \frac{\pi}{2N} + \tan\phi - \phi\right] \qquad (8.3)$$

This is the measurement W_s made across opposed involutes using the tooth span micrometer (Fig. 8.18). The following paragraphs illustrate the methodology.

Span gauging length is called the base tangent length and is denoted by W_s, where s is the number of spans. If the measurement is carried over five teeth, then s will be denoted as 5. While carrying out measurements, the micrometer reading is set to the value of W_s as determined from Eq. (8.3). If the span selected is 3, then s is taken as 3 in the equation. The micrometer reading

المعادلات في هاد السكشن المتعلقة بال gears ما بدنا اياهم

micrometer
tooth caliper
* قياس ال Tooth thickness بال gears

is locked using a locking screw. Now, the micrometer is as good as an inspection gauge and can be used to check gears for accuracy of span width. The inspection is carried out with the contact of measuring flanges being made approximately at the mid-working depth of the gear teeth.

Tables that serve as ready reckoners for the span width for given values of module, number of teeth on the gear, and span width are available. Table 8.3 gives a sample of the tabulated values. The advantage of using the table is that the span width can be readily measured without having to calculate the value using relevant equations.

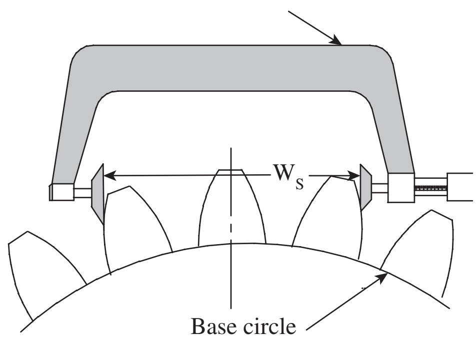


Fig. 8.18 Tooth span micrometer

Table 8.3 Values of span width

Value of base tangent length W_s for uncorrected spur gears in mm					
Pressure angle = 20°			**Module m = 1**		
Number of teeth on the gear (z)	Number of teeth spanned (s)	Base tangent length (W_s; mm)	Number of teeth on the gear (z)	Number of teeth spanned (s)	Base tangent length (W_s; mm)
7	1	1.5741	25	3	7.7305
8	1	1.5881	26	3	7.7445
9	2	4.5542	27	4	10.7106
10	2	4.5683	28	4	10.7246
11	2	4.5823	29	4	10.7386
–	–		–	–	–
–	–		–	–	–

8.5 COMPOSITE METHOD OF GEAR INSPECTION

Composite action refers to the variation in centre distance when a gear is rolled in tight mesh with a standard gear. It is standard practice to specify composite tolerance, which reflects gear runout, tooth-to-tooth spacing, and profile variations. Composite tolerance is defined as the allowable centre distance variation of the given gear, in tight mesh with a standard gear, for one complete revolution. The Parkinson gear testing machine is generally used to carry out composite gear inspection.

8.5.1 Parkinson Gear Tester

It is a popular gear testing machine used in metrology laboratories and tool rooms. The gear being inspected will be made to mesh with a standard gear, and a dial indicator is used to capture radial errors. The features of a Parkinson gear tester are illustrated in Fig. 8.19. The standard gear is mounted on a fixed frame, while the gear being inspected is fixed to a sliding carriage. The two gears are mounted on mandrels, which facilitate accurate mounting of gears in machines, so that a dial indicator will primarily measure irregularities in the gear under inspection. A dial indicator of high resolution is used to measure the composite error, which reflects errors due to runout, tooth-to-tooth spacing, and profile variations.

الهدف منه قياس ال Error باد gear التاني

Termin
Mager → maj of / minor / pitch
effective screw
شرحنا وحدة

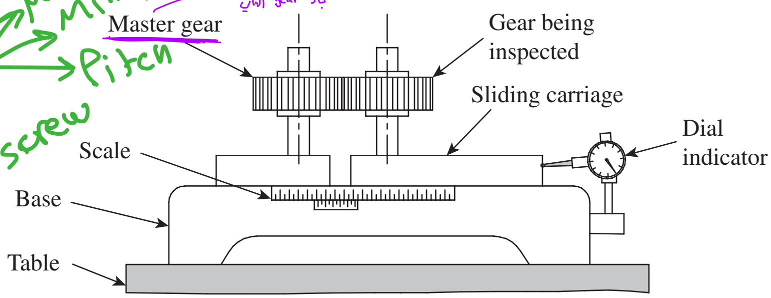


Fig. 8.19 Parkinson gear tester

معادلة ال square gear
ليست حفظ لكن يجب نفهمو

To start with, the two gears are mounted on respective mandrels and the slide comprising the standard gear is fixed at a convenient position. The sliding carriage is moved along the table, the two gears are brought into mesh, and the sliding carriage base is also locked in its position. Positions of the two mandrels are adjusted in such a way that their axial distance is equal to the gear centre distance as per drawings. However, the sliding carriage is free to slide for a small distance on steel rollers under a light spring force. A vernier scale attached to the machine enables measurement of the centre distance up to 25 μm. The dial indicator is set to zero and the gear under inspection is rotated. Radial variations of the gear being inspected are indicated by the dial indicator. This variation is plotted on a chart or graph sheet, which indicates the radial variations in the gear for one complete rotation.

Many improvisations are possible to the basic machine explained in Section 8.5.1. A waxed paper recorder can be fitted to the machine so that a trace of the variations of a needle in contact with the sliding carriage is made simultaneously. The mechanism can be designed to provide a high degree of magnification.

معادلة ال outside diameter وال module اللي انشرحت بال online داخلة وجاي عليها سؤال

8.6 MEASUREMENT OF SCREW THREADS

Screw thread geometry has evolved since the early 19th century, thanks to the importance of threaded fasteners in machine assemblies. The property of *interchangeability* is associated more strongly with screw threads than with any other machine part. Perhaps, the *Whitworth thread system*, proposed as early as the 1840s, was the first documented screw thread profile that came into use. A couple of decades later, the *Sellers* system of screw threads came into use in the United States. Both these systems were in practice for a long time and laid the foundation for a more comprehensive *unified screw thread system*.

Screw thread gauging plays a vital role in industrial metrology. In contrast to measurements of geometric features such as length and diameter, screw thread measurement is more complex. We need to measure inter-related geometric aspects such as pitch diameter, lead, helix, and flank angle, among others. The following sections introduce screw thread terminology and

Right hand thread → مشهور أكثر

discuss the measurements of screw thread elements and thread gauging, which speeds up the inspection process.

8.7 SCREW THREAD TERMINOLOGY

Figure 8.20 illustrates the various terminologies associated with screw threads.

Screw thread The American Society of Tool and Manufacturing Engineers (ASTME) defines a screw thread as follows: screw thread is the helical ridge produced by forming a continuous helical groove of uniform section on the external or internal surface of a cylinder or cone.

Form of thread This is the shape of the contour of one complete thread, as seen in an axial section. Some of the popular thread forms are British Standard Whitworth, American Standard, British Association, Knuckle, Buttress, Unified, Acme, etc.

External thread The screw thread formed on the external surface of a workpiece is called an external thread. Examples of this include bolts and studs.

Internal thread The screw thread formed on the internal surface of a workpiece is called an internal thread. The best example for this is the thread on a nut.

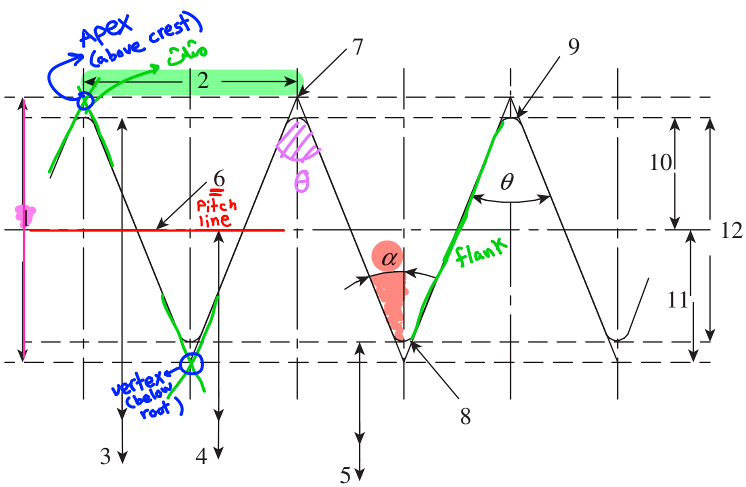
Axis of thread (pitch line) This is the imaginary line running longitudinally through the centre of the screw.

Fundamental triangle It is the imaginary triangle that is formed when the flanks are extended till they meet each other to form an apex or a vertex.

θ **Angle of thread** This is the angle between the flanks of a thread measured in the axial plane. It is also called an included angle.

α **Flank angle** It is the angle formed between a flank of the thread and the perpendicular to the axis of the thread that passes through the vertex of the fundamental triangle.

For External thread

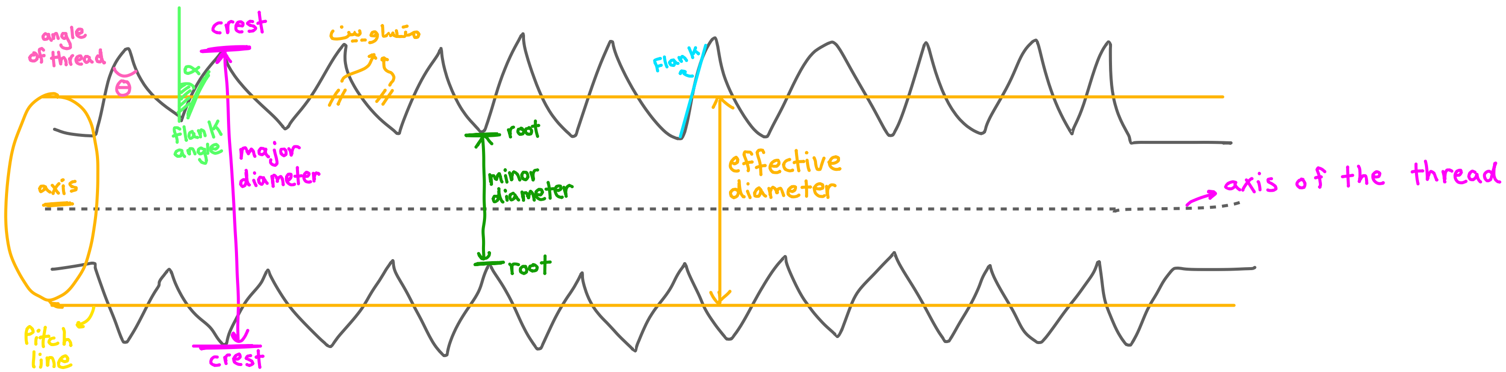


Legend

1: Angular pitch
2: Pitch
3: Major diameter
4: Pitch diameter
5: Minor diameter
6: Pitch line
7: Apex
8: Root
9: Crest
10: Addendum
11: Dedendum
12: Depth of thread
θ : Angle of thread → included angle
α : Flank angle

Fig. 8.20 Screw thread terminology

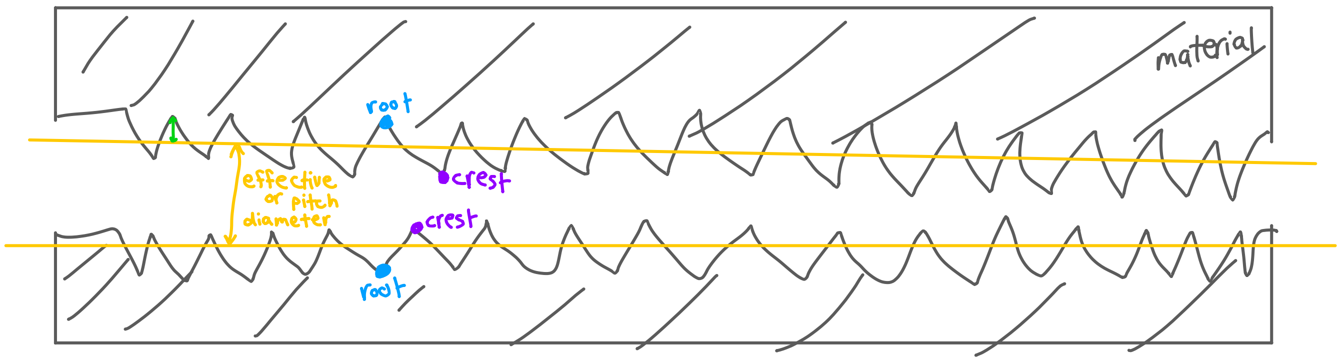
External Thread في حالة ال *



measured by → $\boxed{\text{major diameter}}$

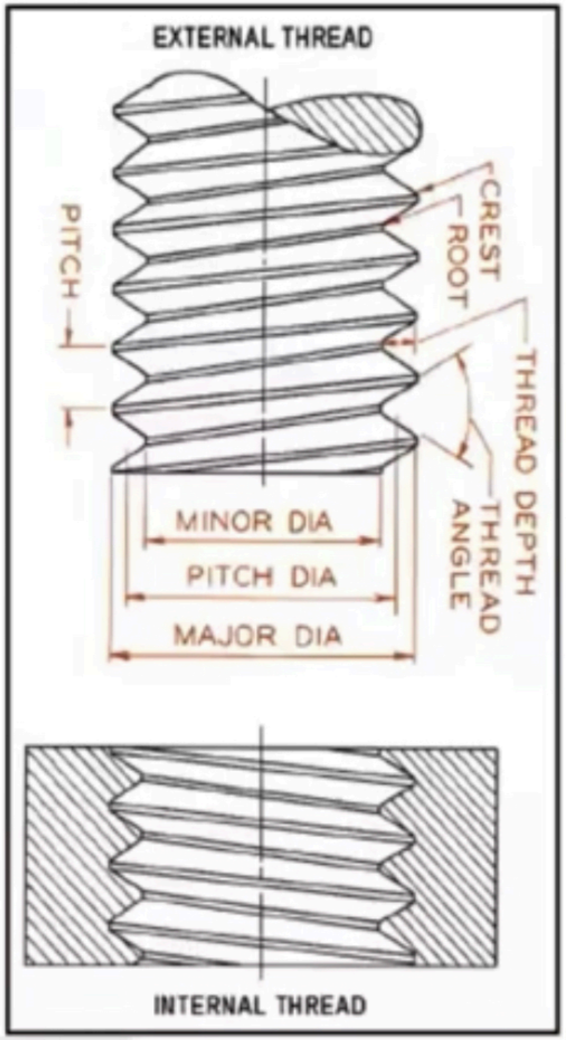
→ bench micrometer
- wide range
- more accurate (.0002mm)

Internal Thread في حالة ال *



Pitch diameter ⟷ effective diameter

- Thread: the helical grooves opened to inner and outer surfaces.
- External thread (screw): A thread on the external surface of a cylinder.
- Internal thread (nut): A thread on the internal surface of a cylinder.
- Major diameter (diş üstü çap): The largest diameter of a screw thread.
- Minor diameter (diş dibi çap): The smallest diameter of a screw thread.
- Pitch diameter (bölüm çapı): The diameter of an imaginary cylinder, the surface of which cuts the thread forms where the width of the thread and groove are equal.
- Crest: The edge or surface that joins the sides of a thread and is farthest from the cylinder or cone from which the thread projects.
- Root: The edge or surface that joins the sides of adjacent thread forms and coincides with the cylinder or cone from which the thread projects.
- Thread Depth: The distance between crest and root.
- Pitch (hatve, adım): The distance between corresponding points on adjacent thread forms measured parallel to the axis.
- Right-hand thread: A thread that when viewed axially winds in a CW and receding direction. Threads are RH unless otherwise specified.
- Left-hand thread: A thread that when viewed axially winds in a CCW and receding direction. The:



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Pitch It is the distance between two corresponding points on adjacent threads, measured parallel to the axis of the thread.

Lead It is the axial distance moved by the screw when the crew is given one complete revolution about its axis.

Lead angle It is the angle made by the helix of the thread at the pitch line with the plane perpendicular to the axis.

Helix angle It is the angle made by the helix of the thread at the pitch line with the axis. This angle is measured in an axial plane.

Major diameter In case of external threads, the major diameter is the diameter of the major cylinder (imaginary), which is coaxial with the screw and touches the crests of an external thread. For internal threads, it is the diameter of the cylinder that touches the root of the threads.

Minor diameter In case of external threads, the minor diameter is the diameter of the minor cylinder (imaginary), which is coaxial with the screw and touches the roots of an external thread. For internal threads, it is the diameter of the cylinder that touches the crests of the threads. It is also called the root diameter.

Addendum It is the radial distance between the major diameter and pitch line for external threads. On the other hand, it is the radial distance between the minor diameter and pitch line for internal threads.

Dedendum It is the radial distance between the minor diameter and pitch line for external threads. On the other hand, it is the radial distance between the major diameter and pitch line for internal threads.

Effective diameter or pitch diameter It is the diameter of the pitch cylinder, which is coaxial with the axis of the screw and intersects the flanks of the threads in such a way as to make the widths of threads and the widths of spaces between them equal. In general, each of the screw threads is specified by an effective diameter as it decides the quality of fit between the screw and a nut.

Single-start thread In case of a single-start thread, the lead is equal to the pitch. Therefore, the axial distance moved by the screw equals the pitch of the thread.

Multiple-start thread In a multiple-start thread, the lead is an integral multiple of the pitch. Accordingly, a double start will move by an amount equal to two pitch lengths for one complete revolution of the screw.

8.8 MEASUREMENT OF SCREW THREAD ELEMENTS

Measurement of screw thread elements is necessary not only for manufactured components, but also for threading tools, taps, threading hobs, etc. The following sections discuss the methods for measuring major diameter, minor diameter, effective diameter, pitch, angle, and form of threads.

8.8.1 Measurement of Major Diameter

The simplest way of measuring a major diameter is to measure it using a screw thread micrometer. While taking readings, only light pressure must be used, as the anvils make contact with the screw solely at points and any excess application of pressure may result in a slight deformation of anvil due to compressive force, resulting in an error in the measurement. However, for a more precise measurement, it is recommended to use a bench micrometer shown in Fig. 8.21.

A major advantage of a bench micrometer is that a fiducial indicator is a part of the measuring system. It is thus possible to apply a pressure already decided upon by referring to the fiducial indicator. However, there is no provision for holding the workpiece between the centres, unlike a floating carriage micrometer. The inspector has to hold the workpiece by hand while the readings are being taken.

The machine is essentially used as a comparator. To start with, the anvil positions are set by inserting a setting cylinder. A setting cylinder serves as a gauge and has a diameter that equals the OD of the screw thread being inspected. Now, the setting cylinder is taken out, the workpiece is inserted between the anvils, and the deviation is noted down on the micrometer head. Since the position of the fixed anvil will remain unaltered due to the setting of the fiducial arrangement, the movable anvil will shift axially depending on the variation in the value of OD of the screw being inspected. In order to sense deviations on either side of the preset value, the movable anvil will always be set to a position, which can detect small movements in either direction. The error, as measured by the micrometer head, is added to or subtracted from, as the case may be, the diameter of the setting cylinder to get the actual value of OD.

Measurement of the OD of internal threads is trickier, as it is cumbersome to take measurements using conventional instruments. An easier option is to employ some indirect measurement techniques. A cast of the thread is made, which results in a male counterpart of the internal thread. Now, the measurement can be carried out using techniques used for external threads. The cast may be made of plaster of Paris or wax.

8.8.2 Measurement of Minor Diameter

The best way of measuring a minor diameter is to measure it using a floating carriage micrometer described in Chapter 4. The carriage has a micrometer with a fixed spindle on one side and a movable spindle with a micrometer on the other side. The carriage moves on a finely ground 'V' guideway or an anti-friction guideway to facilitate movement in a direction parallel to the axis of the plug gauge mounted between centres.

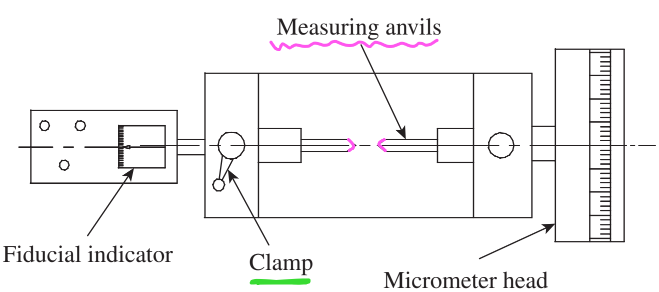
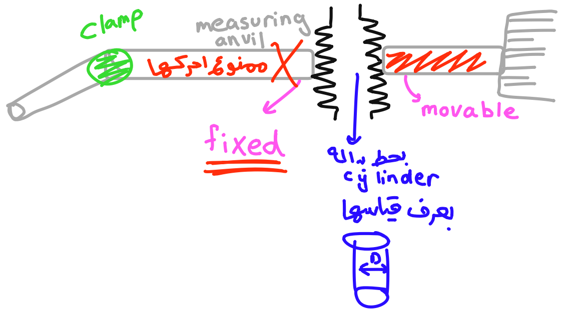


Fig. 8.21 Bench micrometer



* عندما يكون Pitch micrometer $\neq$ قراءة ال actual dimension

* Reading on the thread

→ actual diameter of the cylinder = 10 mm

→ Reading for the cylinder = 12 mm

⟹ Reading on the thread = R_{th}

⟹ Major diameter of the thread = D_{major}

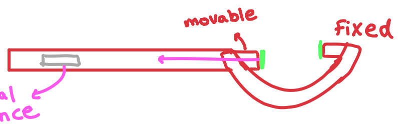
⟹ Reading of the cylinder = D_{cy}

$$\boxed{R_{cy} - \underbrace{D_{cy}}_{\text{Known}} = R_{th} - D_{major}}$$

Known: من السؤال

D_{major}: المجهول الوحيد

for the readings of R_{cy}, R_{th}
شرط استخدام هذه المعادلة انه يكون
نفس الsettings يعني ال clamp
Fixed



عندما يكون (الانفض) منطبق على بعض
تكون قراءة الmicrometer ← (Zero)
و هي تكون الactual dimension بين ال spindle و ال anvil (الاجزاء الاخضر)

1. To find **the major diameter** of the external thread

D_c: diameter of cylinder (known)
R_c: reading of micrometer over the cylinder (measured value)
D_{th}: diameter of the thread (unknown)
R_{th}: reading of micrometer over the thread (measured value)

$(R_{th} - D_{th} = R_c - D_c)$ or $\boxed{(R_{th} - R_c = D_{th} - D_c)}$

After rearrange the formula

$\therefore majorD_{th} = D_c + (R_{th} - R_c)$

الاختلاف هنا ان ال movable anvils
ما بيوصلو ال Root of thread
فثبتت على ال movable anvils → prisims

2. To find the **Minor diameter** of an external thread

$\therefore minorD_{th} = D_c + (R_{th(prism)} - R_{c(prism)})$

3. To find the **effective diameter** E_d of the external thread (using the three wires method)

For the distance T

$T = D_c + (R_{th(wire)} - R_{c(wire)})$

$E_d = T + 2x$

Where $2x = \frac{P}{2}\cot\theta - d(cosec\,\theta - 1)$

$(d: diameter\ of\ the\ wire)$

The proof for $(E_d = T + 2x)$ is

From the Fig-14, $E_d = T + 2x$

In the ΔABC, $AB = BC\cot\theta$

But, $BC = ¼\text{ pitch} = ¼\,P$

Therefore, $AB = ¼\,P\cot\theta$

In the ΔADE, $AE = DE\,\mathrm{cosec}\,\theta = \frac{d}{2}\mathrm{cosec}\,\theta$

Now, $x = AB - AF$ and $AF = AE - EF = AE - d/2$

$$\therefore AF = \frac{d}{2}(\mathrm{cosec}\,\theta - 1)$$

Therefore, $$x = \frac{P}{4}\cot\theta - \frac{d}{2}(\mathrm{cosec}\,\theta - 1)$$

where,

P = Nominal Pitch
D = Wire Diameter
θ = Nominal Flank Angle or semi angle of thread

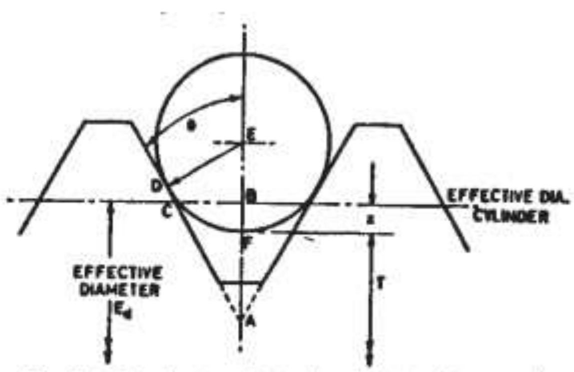
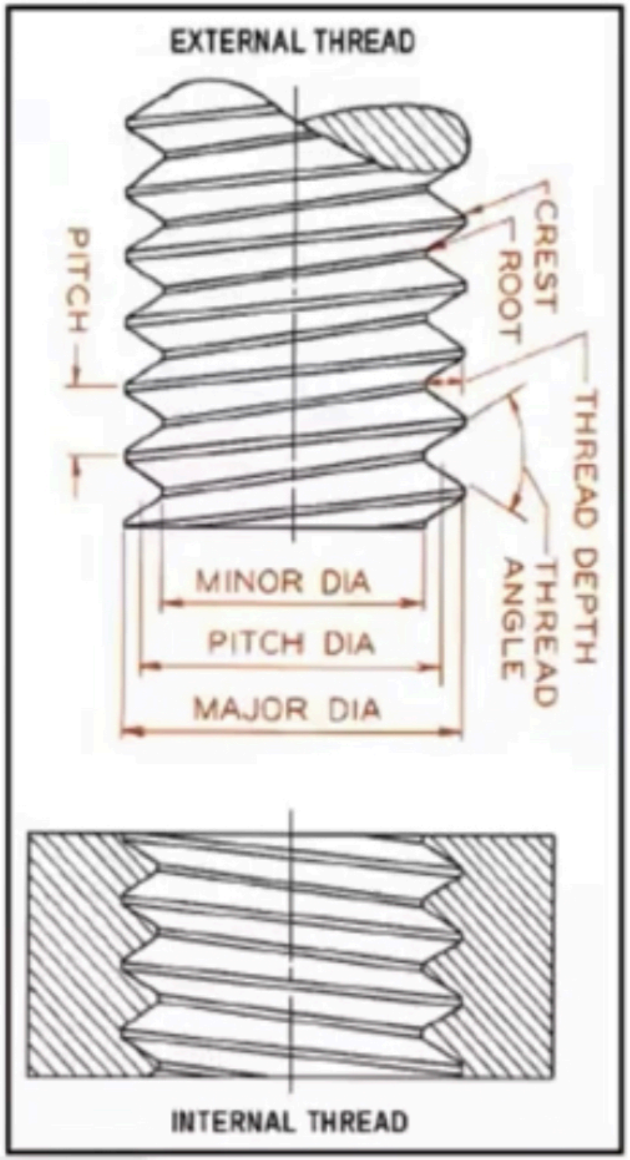


Fig-14 Calculation of simple effective diameter.[4]

الفرق بين (2 wire method) و ال (3 wire method)

← ال wire الثالث ← سطح ال movable anvil يكون Flat

- Thread: the helical grooves opened to inner and outer surfaces.
- External thread (screw): A thread on the external surface of a cylinder.
- Internal thread (nut): A thread on the internal surface of a cylinder.
- Major diameter (diş üstü çap): The largest diameter of a screw thread.
- Minor diameter (diş dibi çap): The smallest diameter of a screw thread.
- Pitch diameter (bölüm çapı): The diameter of an imaginary cylinder, the surface of which cuts the thread forms where the width of the thread and groove are equal.
- Crest: The edge or surface that joins the sides of a thread and is farthest from the cylinder or cone from which the thread projects.
- Root: The edge or surface that joins the sides of adjacent thread forms and coincides with the cylinder or cone from which the thread projects.
- Thread Depth: The distance between crest and root.
- Pitch (hatve, adım): The distance between corresponding points on adjacent thread forms measured parallel to the axis.
- Right-hand thread: A thread that when viewed axially winds in a CW and receding direction. Threads are RH unless otherwise specified.
- Left-hand thread: A thread that when viewed axially winds in a CCW and receding direction. The



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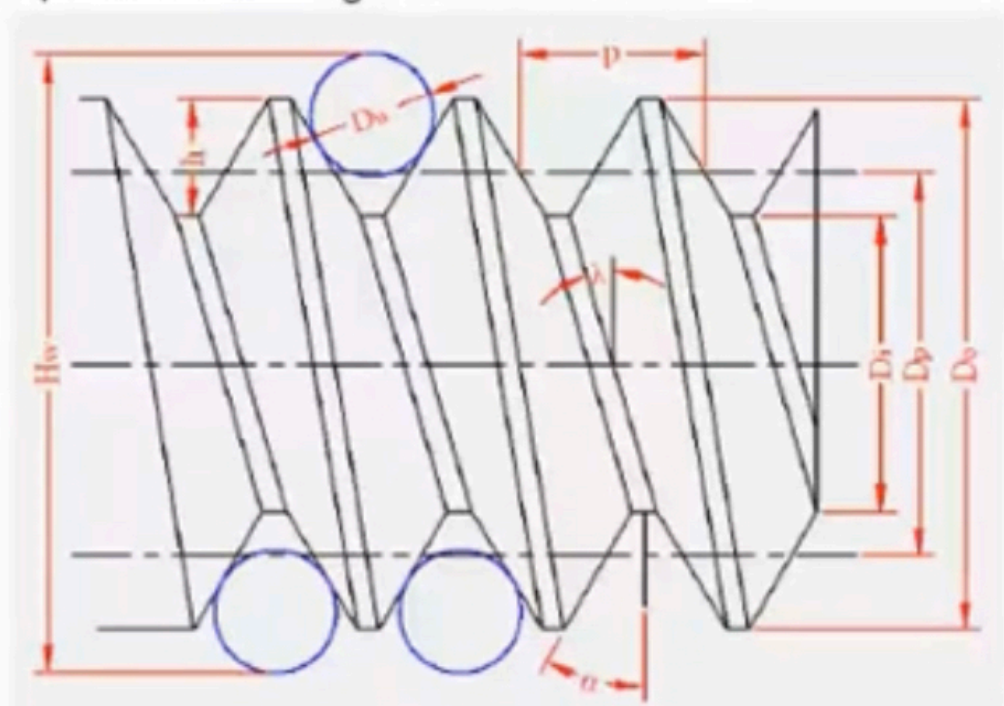
- **Handedness:** The right-hand rule of screw threads. The helix of a thread can twist in two possible directions, which is known as *handedness*. Most threads are oriented so that a bolt or nut, seen from above, is tightened (the item turned moves away from the viewer) by turning it in a clockwise direction, and loosened (the item moves towards the viewer) by turning counterclockwise. This is known as a *right-handed* (*RH*) thread, because it follows the right hand grip rule (often called, more ambiguously, "the right-hand rule"). Threads oriented in the opposite direction are known as *left-handed* (*LH*).

- **Three-wire method** is one of the most accurate and versatile ways of measuring **the pitch diameter** of a thread by using three lapped and polished wires and a micrometer.

- Wires touching the thread at the pitch diameter are known as "**Best Size Wires**". Such wires are used since the measurements of pitch diameter are least affected by errors that may be present in the angle of the thread.



D_i : Minor diameter **h** : Depth of thread **p** : Pitch

D_p : Pitch diameter λ : Lead (helix) angle **D_w** : Wire diameter

D_o : Major diameter α : Flank angle **H_w** : Measurement over wires

The micrometer has a non-rotary spindle with a least count of up to 0.001 or 0.002 mm. The instrument is very useful for thread plug gauge manufacturers; in gauge calibration laboratories, established under NABL accreditation; and in standard rooms where in-house gauge calibration is carried out.

Minor diameter is measured by a comparative process, wherein small V-pieces that make contact at the root of the threads are used. The selection of V-pieces should be such that the included angle of a V-piece is less than the angle of the thread. V-pieces are placed on each side of the screw with their bases against the micrometer faces. As in the previous case, the initial reading is taken by mounting a setting cylinder corresponding to the dimension being measured. Then, the threaded workpiece is mounted between the centres and the reading is taken. The difference in the two readings directly gives the error in the minor diameter.

8.8.3 Measurement of Effective Diameter

In Section 8.7 we defined an effective diameter of a screw thread as the diameter of the pitch cylinder, which is coaxial with the axis of the screw and intersects the flanks of the threads in such a way so as to make the width of threads and widths of spaces between them equal. Since it is a notional value, it cannot be measured directly and we have to find the means of measuring it in an indirect way. Thread measurement by wire method is a simple and popular way of measuring an effective diameter. Small, hardened steel wires (best-size wire) are placed in the thread groove, and the distance over them is measured as part of the measurement process. There are three methods of using wires: one-wire, two-wire, and three-wire methods.

X

One-wire Method

This method is used if a standard gauge of the same dimension as the theoretical value of dimension over wire is available. First of all, the micrometer anvils are set over the standard gauge and the dimension is noted down. Thereafter, the screw to be inspected is held either in hand or in a fixture, and the micrometer anvils are set over the wire as shown in Fig. 8.22.

Micrometer readings are taken at two or three different locations and the average value is calculated. This value is compared with the value obtained with the standard gauge. The resulting difference is a reflection of error in the effective diameter of the screw. An important point to be kept in mind is that the diameter of the wire selected should be such that it makes contact with the screw along the pitch cylinder. The significance of this condition will become obvious in the two-wire method explained in the next section.

X

Two-wire Method

In this method, two steel wires of identical diameter are placed on opposite flanks of a screw, as shown in Fig. 8.23.

The distance over wires (M) is measured using a suitable micrometer. Then, the effective diameter,

$$D_e = T + P \tag{8.4}$$

where T is the dimension under the wires and P is the correction factor.

And,

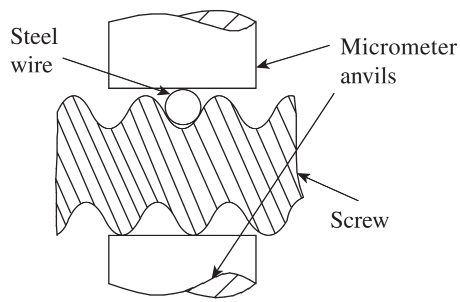


Fig. 8.22 One-wire method

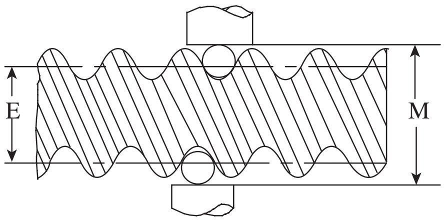


Fig. 8.23 Two-wire method

$$T = M - 2d \tag{8.5}$$

where d is the diameter of the best-size wire.

These relationships can be easily derived by referring to Fig. 8.24.

The two wires of identical diameter are so selected that they make contact with the screw thread on the pitch line. The aforementioned equations are valid only if this condition is met.

Accordingly, from triangle OFD, OF $= \dfrac{d}{2}$ cosec $(x/2)$

$$\text{FA} = \frac{d}{2}\text{ cosec }(x/2) - \frac{d}{2} = \frac{d[\text{cosec}(x/2) - 1}{2}$$

$$\text{FG} = \text{GC cot }(x/2) = \frac{p}{4}\text{ cot }(x/2) \quad \text{(because BC = pitch/2 and GC = pitch/4)}$$

Therefore, $\text{AG} = \text{FG} - \text{FA} = \dfrac{p}{4}\text{ cot }(x/2) - \dfrac{d[\text{cosec}(x/2) - 1}{2}$

Since AG accounts for the correction factor only on one side of the screw, we have to multiply this value by 2 in order to account for that on the opposite flank.

Therefore, total correction factor is as follows:

$$P = 2\text{ AG} = \frac{p}{2}\text{ cot }(x/2) - d[\text{cosec}(x/2) - 1] \tag{8.6}$$

Although it is possible to measure the value of M, the distance over the wires, using a hand-held micrometer, this method is prone to errors. A better alternative is to use a floating carriage micrometer shown in Fig. 4.41 of Chapter 4, which helps in aligning the micrometer square to the thread, enabling more accurate readings.

Diameter of Best-size Wire

The best-size wire, of diameter d, makes contact with the thread flank along the pitch line.

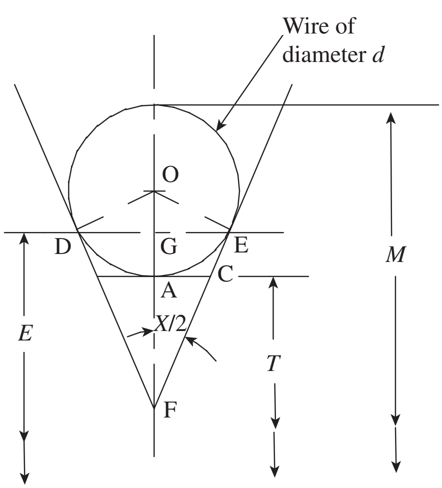


Fig. 8.24 Measurements in two-wire method

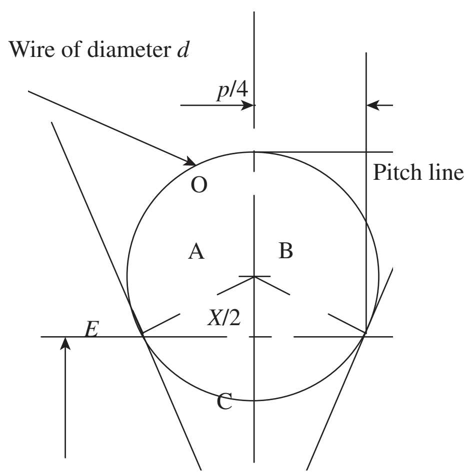


Fig. 8.25 Determination of the best-size wire

Equations (8.4)–(8.6) hold true if this condition is met. Figure 8.25 illustrates the condition achieved by the best-size wire.

In triangle OAB, sin (AOB) = AB/OB

that is, sin $(90 - x/2)$ = AB/OB

$$\text{or, OB} = \frac{\text{AB}}{\sin(90 - x/2)} = \frac{\text{AB}}{\cos(x/2)} = \text{AB} \sec(x/2)$$

Diameter of the best-size wire = 2(OB) = 2(AB) sec $(x/2)$.

However, from Fig. 8.25, AB = $p/4$, where p is the pitch of the thread.

Therefore, diameter of the best-size wire is

$$d = (p/2)\sec(x/2) \qquad (8.7)$$

Three-wire Method

The three-wire method is an extension of the principle of the two-wire method. As illustrated in Fig. 8.26, three wires are used to measure the value of M, one wire on one side and two wires on adjacent thread flanks on the other side of the screw. Measurement can be made either by holding the screw, wires, and micrometer in hand or by using a stand with an attachment to hold the screw in position. Since three wires are used, the micrometer can be positioned more accurately to measure M, the distance over the wires.

x → thread angle

With reference to Fig. 8.27, let M be the distance over the wires, E the effective diameter of the screw, d the diameter of best-size wires, and H the height of threads.

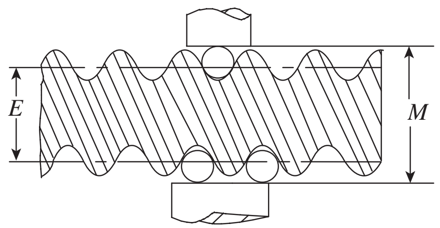


Fig. 8.26 Three-wire method

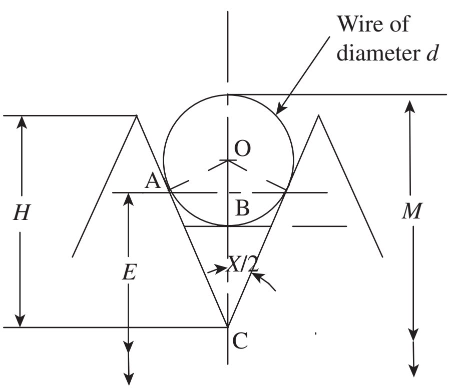


Fig. 8.27 Principle of three-wire method

$$\text{Now, OC} = \text{OA} \operatorname{cosec}(x/2) = \frac{d}{2}\operatorname{cosec}(x/2) \qquad (8.8)$$

$$H = \frac{p}{2}\cot(x/2) \text{ and, therefore, BC} = H/2$$

$$= \frac{p}{4}\cot(x/2) \qquad (8.9)$$

If h is the height of the centre of wire from the pitch line, then h = OC − BC.

$$h = \frac{d}{2}\operatorname{cosec}(x/2) - \frac{p}{4}\cot(x/2) \qquad (8.10)$$

Distance over wires, $M = E + 2h + 2r$, where r is the radius of the wires.

Therefore, effective diameter

$$E = M - d\operatorname{cosec}(x/2) + \frac{p}{2}\cot(x/2) - d$$

$$E = M - d[1 + \operatorname{cosec}(x/2)] + \frac{p}{2}\cot(x/2) \qquad (8.11)$$

Guidelines for Two- and Three-wire methods

The ASTME has prescribed guidelines for measuring the effective diameter of a screw thread using wire methods. The following points summarize this:

1. Care must be exercised to exert minimum force while holding the wires against the screw thread. Since a wire touches a minute area on each thread flank, de

formation of wire and thread will be sufficiently large to warrant some type of correction.

2. The wires should be accurately finished and hardened steel cylinders. The working surface should at least be 25 mm in length. The wires should be provided with a suitable means of suspension.
3. One set of wires should consist of three wires having the same diameter within 0.000025 mm. These wires should be measured between a flat contact and a hardened and accurately finished cylinder having a surface roughness not over 5 µm.
4. If it becomes necessary to measure the effective diameter by means of wires other than the best size, the following size limitations should be followed:
   (a) The minimum size is limited to that which permits the wire to project above the crest of the thread.
   (b) The maximum size is limited to that which permits the wire to rest on the flanks of the thread just below the crest, and not ride on the crest of the thread.
5. The wires should be free to assume their positions in the thread grooves without any restraint (the practice of holding wires in position with elastic bands can introduce errors in the measurement).

8.8.4 Measurement of Pitch

Usually, a screw thread is generated by a single-point cutting tool, with the two basic parameters being angular velocity of the workpiece and linear velocity of the tool. The tool should advance exactly by an amount equal to the pitch for one complete rotation of the workpiece. Pitch errors are bound to crop up if this condition is not satisfied. Pitch errors may be classified into the following types:

Progressive pitch error This error occurs whenever the tool–work velocity ratio is incorrect but constant. Generally, it is caused by the pitch error in the lead screw of the machine. Figure 8.28 illustrates a progressive pitch error, in which the cumulative pitch error increases linearly along the thread numbers. Other factors contributing to the pitch error are an incorrect gear train or an approximate gear train when, for example, metric threads are being generated on basically a system suited for producing British Standard threads.

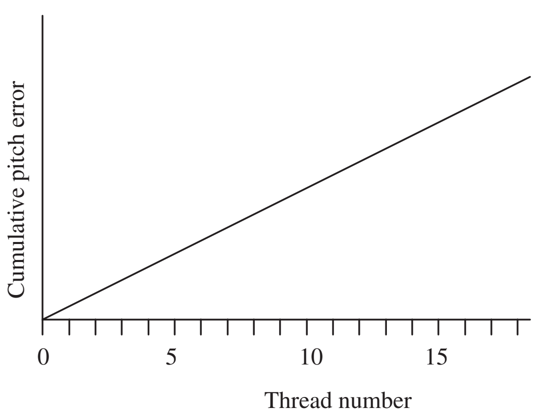


Fig. 8.28 Progressive pitch error

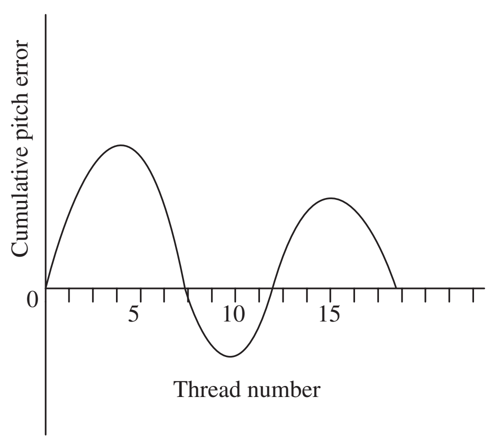


Fig. 8.29 Periodic pitch error

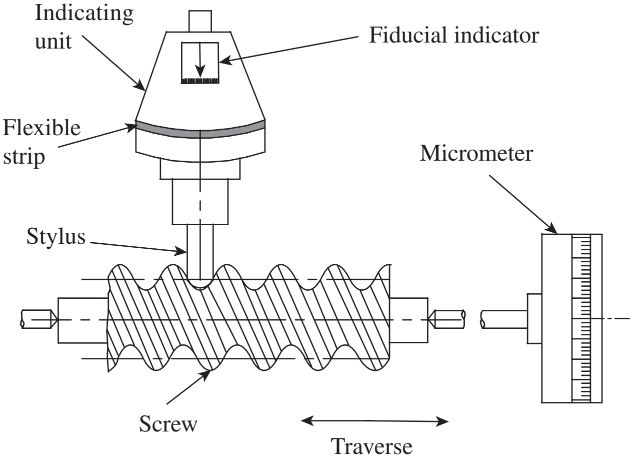


Fig. 8.30 Pitch-measuring machine

Periodic pitch error This error occurs when the tool–work velocity ratio is not constant. This results in a profile shown in Fig. 8.29. The contributing factors are pitch errors in the gear trains and/or axial movement of the lead screw due to worn out thrust bearings. A graph of cumulative pitch error versus thread number shows an approximate sinusoidal form. It can be seen that the pitch increases to a maximum value and reduces to a minimum value, and the pattern repeats throughout the length of the screw.

Drunken threads We can draw an analogy between drunken threads and a drunken (alcoholic) person, because of the fact that the thread helix will develop into a curve instead of a straight line. This results in a periodic error creeping in at intervals of one pitch. The pitch measured parallel to the thread axis will be correct, but the threads are not cut to a true helix. This error does not pose a serious problem for the function of a screw, but may result in a noticeable error for large-diameter screws.

Measurement of Pitch Error

Figure 8.30 illustrates a pitch-measuring machine.

A round-nosed stylus makes contact with the thread at approximately the pitch line. The screw, which is mounted between the centres on a slide, is given a traverse motion in a direction parallel to its axis. This makes the stylus ride over the threads. A micrometer connected to the slide enables measurement of the pitch.

A few improvisations are made in the machine for performing an accurate measurement. Since the stylus is required to make contact approximately along the pitch line, a fiducial indicator is used to ensure that it registers zero reading whenever the stylus is at the precise location. The stylus is mounted on a block supported by a thin flexible strip and a strut. This enables the stylus in moving back and forth over the threads. The micrometer reading is taken each time the fiducial indicator reads zero. These readings show the pitch error of each thread of the screw along its length and can be plotted on a graph sheet. Special graduated disks are used to fit the micrometer to suit all ordinary pitches and/or special pitches as per the requirements of the user.

8.9 THREAD GAUGES

There are two methods for checking screw threads: inspection by variables and inspection by attributes. The former involves the application of measuring instruments to measure the extent of deviation of individual elements of a screw thread. The latter involves the use of limit gauges, called *thread gauges*, to assure that the screw is within the prescribed limits of size. Thread gauges offer simpler and speedier means for checking screw threads. Gauging of screw threads is a process for assessing the extent to which screw threads conform to specified limits of size. A complete set of standards is available for thread gauging, which comprises limits of size, gauging methodology, and measurement. These standards assure interchangeability in assembly, acceptance of satisfactory threads, and rejection of those threads that are outside the prescribed limits of size.

Thread gauges are classified on the basis of the following criteria:

1. Classification of thread gauges based on the type of application
   (a) Working gauges
   (b) Inspection gauges
   (c) Master gauges
2. Classification of thread gauges based on their forms
   (a) Plug screw gauges
   (b) Ring screw gauges

Working gauges are used by production workers when the screws are being manufactured. On the other hand, inspection gauges are used by an inspector after the production process is completed. Working and inspection gauges differ in the accuracy with which they are made. Inspection gauges are manufactured to closer tolerance than working gauges and are therefore more accurate. Obviously, master gauges are even more accurate than inspection gauges. This kind of hierarchy, with respect to accuracy, ensures that the parts that are produced will have a high level of quality.

In practice, plug gauges are used to inspect external thread forms, while ring gauges are used to inspect internal thread forms. Taylor's principle of limit gauging, explained in Section 3.6.4, is also applicable for thread gauging also. It may be remembered that according to Taylor's principle, a GO gauge should check both size and geometric features, and thus be of full form. On the other hand, a NOT GO gauge should check only one dimension at a time. However, if the NOT GO gauge is made of full form, any reduction in the effective diameter due to pitch error may give misleading results. To account for this aspect, the NOT GO gauge is designed to only check for the effective diameter, which is not influenced by errors in pitch or form of the thread. The following paragraphs provide basic information on these two types of gauges.

Plug Screw Gauges

The thread form for a NOT GO gauge is truncated as shown in Fig. 8.31. This is necessary to avoid contact with the crest of the mating thread, which, while being large on the effective diameter, may have a minor diameter on the low limit. The truncation also helps in avoiding contact with the root of the nut. This modification will not have any bearing on the accuracy of measurement, because the NOT GO gauge will primarily check for only the effective diameter.

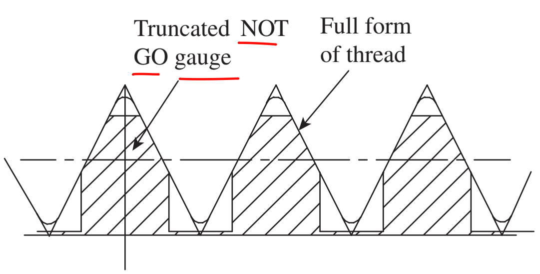


Fig. 8.31 Truncated thread form for a NOT GO gauge

A straight thread plug gauge assures the accuracy of the basic elements of a screw thread, namely major diameter, pitch diameter, root clearance, lead, and flank angle. A taper thread plug gauge checks, in addition to these elements, taper of the screw as well as length from the front end to the gauge notch. The gauges are made of hardened gauge steel. The entering portion of a plug gauge is vulnerable to rapid wear and tear because of frequent contact with metal surfaces. Therefore, the ends are slightly extended with lower diameter, so that contact with the workpiece takes place gradually rather then abruptly (Fig. 8.32).

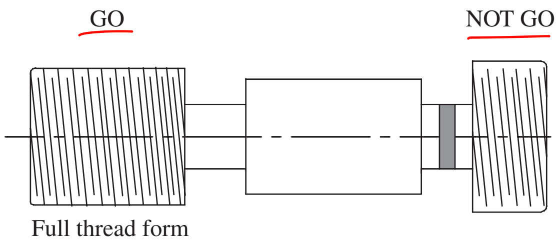


Fig. 8.32 Plug screw gauge

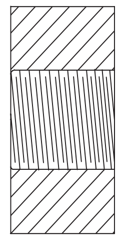


Fig. 8.33 Ring screw gauge

Ring Screw Gauges

Ring gauges are used to check external thread forms like bolts. Similar to plug gauges, a system of limit gauges is provided by the full-form GO gauge and NOT GO gauge to check the effective diameter (Fig. 8.33).

8.10 NUMERICAL EXAMPLES

Example 8.1 The following data is available for the measurement of chordal thickness of a gear having an involute profile: the number of teeth = 32, addendum circle diameter = 136 mm, and pressure angle = 20°. Determine the chordal height to which the gear tooth calliper should be set during measurement.

Solution

Pitch circle diameter, $d = mz$, where m is the module and z is the number of teeth on the gear.

However, m = (addendum circle diameter)/(z + 2)

Therefore, $m = 136/(32 + 2) = 4$

$d = 4(32) = 128$ mm

Theoretical value of chordal thickness $g_c = d \sin(90°/z) = 128 \sin(90/32) = 6.28$ mm

Chordal height $h_c = m + g_c^2/4d = 4 + (6.28)^2/4(128) = 4.077$ mm

Thus, the gear tooth calliper should be set to a chordal height of 4.077 mm

Example 8.2 A tooth span micrometer is being used to measure the span across three teeth. Three trials are conducted and the average value of span width is 31.120 mm. The following data is available for the gear being inspected: the number of teeth = 32, addendum circle diameter = 136 mm, pressure angle = 20°, and span of measurement = 3. Determine the percentage error of measurement.

Solution

Theoretical span width $W_{3T} = Nm \cos\phi \left[\frac{\pi S}{N} - \frac{S}{2N} + \tan\phi - \phi\right]$

Here, N is the number of teeth on the gear, m is the module, s is the span, and ϕ is the pressure angle.

However, m = (addendum circle diameter)/(z + 2)

Therefore, $m = 136/(32 + 2) = 4$

Therefore, $W_{3T} = (32)(4)\cos 20\left[\frac{\pi\, 3}{32} - \frac{\pi}{2(32)} + \tan 20 - \pi/9\right]$

$= 31.314\,\text{mm}$

Error $= 31.314 - 31.120 = 0.194\,\text{mm}$

Percentage error $= 0.194/31.314 = 0.006\%$

Example 8.3 It is required to measure the effective diameter of a screw using the two-wire method. The distance across 10 threads measured using a scale is 12.5 mm. Determine the size of the best wire for metric threads.

Solution

Pitch $p = 12.5/10 = 1.25\,\text{mm}$

$d = (p/2)\sec(x/2)$, where $x = 60°$ for metric threads.

Therefore, diameter of the best-size wire $d = \frac{1.25}{2}\sec(60/2) = 0.722\,\text{mm}$.

Example 8.4 A metric screw thread is being inspected using the two-wire method in order to measure its effective diameter and the following data is generated: Pitch = 1.25 mm, diameter of the best-size wire = 0.722 mm, and distance over the wires = 25.08 mm. Determine the effective diameter of the screw thread.

Solution

Effective diameter, $D_e = T + P$

where T is the dimension under the wires and P is the correction factor.

$T = M - 2d$

$P = \frac{p}{2}\cot(x/2) - d[\operatorname{cosec}(x/2) - 1]$

Therefore, $P = \frac{1.25}{2}\cot(60/2) - 0.722\left[\operatorname{cosec}\left(\frac{60}{2}\right) - 1\right] = 0.3605\,\text{mm}$

$T = 25.08 - 2(0.722) = 23.636\,\text{mm}$

$D_e = 23.636 + 0.3605 = 23.9965\,\text{mm}$

A QUICK OVERVIEW

- Gears are the main elements in a transmission system. It is needless to say that for efficient transfer of speed and power, gears should perfectly conform to the designed profile and dimensions. Misalignments and gear runout will result in vibrations, chatter, noise, and loss of power. On the other hand, threaded components should meet stringent quality requirements to satisfy the property of *interchangeability*.
- The following elements of gears are important for an analytical inspection: runout, pitch, profile, lead, backlash, and tooth thickness.
- A profile-measuring machine is one of the most versatile machines used in metrology. The machine is provided with multiple axes movement to enable measurement of various types of gears. The measuring head comprising the feeler, electronic unit, and chart recorder can be moved up and down by operating a handwheel. The movement of the feeler can be amplified

250, 500, or 1000 times, the amplification ratio being selected by a selector switch.

- A gear calliper has two vernier scales, one horizontal and the other vertical. The vertical vernier gives the position of a blade, which can slide up and down. The blade position is set to a value equal to the addendum of the gear tooth and the two anvils are brought into close contact with the gear; the chordal thickness can be measured on the horizontal vernier scale.
- Gear tooth thickness can be measured by measuring the chordal distance over a number of teeth by using a *tooth span micrometer*, also called a *flange micrometer*. The inspection of gear is simple, easy, and fast. The measurement is based on the base tangent method.
- The Parkinson gear tester is a composite gear testing machine. The gear being inspected will be made to mesh with a standard gear. A dial indicator of high resolution is used to measure the composite error, which reflects errors due to runout, tooth-to-tooth spacing, and profile variations.
- Screw thread gauging plays a vital role in industrial metrology. In contrast to measurements of geometric features such as length and diameter, screw thread measurement is more complex. We need to measure inter-related geometric aspects such as pitch diameter, lead, helix, and flank angle, to name a few.
- A major advantage of a bench micrometer is that a fiducial indicator is a part of the measuring system. It is thus possible to apply pressure that has ben decided upon by referring to the fiducial indicator. This prevents damage of threads and provides longer life to the measuring anvils.
- Thread measurement by wire method is a simple and popular way of measuring effective diameter. Small, hardened steel wires (best-size wire) are placed in the thread groove, and the distance over them is measured as part of the measurement process. There are three methods of using wires: one-wire, two-wire, and three-wire methods.
- The best-size wire of diameter d makes contact with the thread flank along the pitch line.
- We can draw an analogy between drunken threads and a drunken (alcoholic) person, because of the fact that the thread helix will develop into a curve instead of a straight line. This results in periodic error creeping in at intervals of one pitch. The pitch measured parallel to the thread axis will be correct, but the threads are not cut to a true helix.
- In practice, plug gauges are used to inspect external thread forms, while ring gauges are used to inspect internal thread forms. In accordance with Taylor's principle, a GO gauge should check both size and geometric features, and thus be of full form. On the other hand, a NOT GO gauge should check only one dimension at a time. The NOT GO gauge is designed to check for only effective diameter, which is not influenced by errors in pitch or form of the thread.

MULTIPLE-CHOICE QUESTIONS

1. The involute profile of a spur gear is limited to only the
   (a) root circle (c) pitch circle
   (b) base circle (d) addendum circle
2. The angle between the line of action and the common tangent to the pitch circles is known as
   (a) flank angle (c) included angle
   (b) tooth angle (d) pressure angle
3. The path traced by a point on a circle that is rolling on a straight line without slipping is
   (a) involute (c) epicycloid
   (b) cycloid (d) hypocycloid
4. The tooth profile of mating gears is kept uniformly thinned, which results in a small play between mating tooth surfaces. This is called
   (a) backlash (c) lead correction
   (b) pitch correction (d) none of these
5. In order to measure the chordal thickness of a

gear using a gear calliper, the position of the blade is set to
(a) the entire depth of the gear tooth
(b) addendum of the gear tooth
(c) dedendum of the gear tooth
(d) top surface of the gear tooth

6. Which of the following is the tester in which the gear being inspected is made to mesh with a standard gear and a dial indicator is used to capture the radial errors?
(a) Pitch-checking instrument
(b) Johnson gear tester
(c) Parkinson gear tester
(d) McMillan gear tester

7. The angle formed between a flank of the thread and the perpendicular to the axis of the thread, which passes through the vertex of the fundamental triangle, is called
(a) a helix angle (c) a lead angle
(b) a flank angle (d) an included angle

8. The indicator that enables the application of a pressure already decided upon on the screw thread in a bench micrometer is called
(a) a fiducial indicator
(b) a pressure indicator
(c) a span indicator
(d) none of these

9. In wire methods, the diameter of the wire selected should be such that it makes contact with the screw along the
(a) outer diameter (c) root diameter
(b) pitch cylinder (d) axis of the screw

10. In a two-wire method, diameter of the best-size wire is given by
(a) $d = (p/2) \sec (x/2)$
(b) $d = (p/4) \sec (x/2)$
(c) $d = (p/2) \operatorname{cosec} (x/2)$
(d) $d = (p/2) \cot (x/2)$

11. The pitch error that occurs whenever the tool–work velocity ratio is incorrect but constant is referred to as a
(a) cyclic error
(b) velocity error
(c) progressive error
(d) non-progressive error

12. In which of the following cases is the pitch measured parallel to the thread axis correct, but the threads are not cut to a true helix?
(a) Drunken threads (c) Whitworth threads
(b) Sunken threads (d) Metric threads

13. The two methods of inspecting screw threads are
(a) inspection by constants and variables
(b) inspection by variables and attributes
(c) inspection by quality and cost
(d) inspection of attributes and constants

14. Thread gauges that are used to inspect external thread forms are called
(a) plug screw gauges
(b) ring screw gauges
(c) external screw gauges
(d) all of these

15. A NOT GO screw gauge will primarily check for
(a) outer diameter and nothing else
(b) inside diameter and nothing else
(c) effective diameter and nothing else
(d) all of these

REVIEW QUESTIONS

1. Which elements of a spur gear require inspection? Name at least one instrument that is used for measuring each of these elements.
2. What is the radial runout of a gear? How is it measured?
3. With the help of a neat sketch, describe the construction and working of a pitch-measuring instrument.
4. What is the principle of involute measurement?
5. Define profile tolerance. How is the profile of a spur gear traced using a profile-measuring instrument?
6. Is backlash inevitable in a gear pair? Discuss.
7. Explain how a gear calliper enables an accurate measurement of chordal thickness of a spur gear.
8. ‘The accuracy of the base tangent method is better than the system of using a gear calliper, since it is independent of the position of the

flanges of the micrometer on teeth flanks.' Justify this statement.

9. Write a note on the Parkinson gear tester.
10. With the help of a sketch, discuss screw thread terminologies.
11. Define the effective diameter of a screw thread.
12. With the help of a sketch, explain the construction and working of a bench micrometer.
13. Differentiate between two- and three-wire methods.
14. Derive the expression for the best-size wire in a two-wire method.
15. List the guidelines for the proper application of two-wire/three-wire methods.
16. Distinguish between progressive pitch error and periodic pitch error.
17. What is drunken thread?
18. Give a classification of thread gauges.
19. How is Taylor's principle applicable to thread gauging?
20. What is the need for using the truncated thread form in a NOT GO screw gauge?

PROBLEMS

1. The chordal thickness of an involute gear is being measured using a gear calliper. Determine the chordal height to which the gear tooth calliper should be set during measurement, if the number of teeth = 28, addendum circle diameter = 120 mm, pressure angle = 20°, and least count of the calliper is 0.02 mm.
2. Determine the effective diameter of a metric screw using the three-wire method. The following data is available: diameter of the best-size wire = 0.740 mm, distance over the wires = 25.58 mm, and pitch = 1.25 mm.
3. A metric screw thread is being inspected using the two-wire method in order to measure its effective diameter and the following data is generated: pitch = 1.5 mm, diameter of the best-size wire = 0.866 mm, distance over the wires = 26.58 mm, and thread angle = 60°. Determine the effective diameter of the screw thread.

ANSWERS

Multiple-choice Questions

1. (b) 2. (d) 3. (a) 4. (a) 5. (b) 6. (c) 7. (b) 8. (a) 9. (b)
10. (a) 11. (c) 12. (a) 13. (b) 14. (a) 15. (c)

Problems

1. 4.08 mm, 2. 23.442 mm, 3. 25.281 mm

9.2
9.3
9.4
9.5
9.6

CHAPTER 9

Metrology of Surface Finish

After studying this chapter, the reader will be able to

- appreciate the importance of surface texture measurement and its significance
- understand the basic reasons for surface irregularities
- explain the terminology associated with the quantification and measurement of surface irregularities
- describe the surface texture characteristics and their symbolic representations
- elucidate the various methods of measurement of surface roughness
- explain the relationship between wavelength of surface roughness, frequency, and cut-off

9.1 INTRODUCTION

In contrast to the concepts we have studied hitherto, surface metrology is basically concerned with deviations between points on the same surface. On the other hand, in all other topics, the fundamental concern has been the relationship between a feature of a part or assembly and some other feature. Even though surface texture is important in many fields of interest such as aesthetics and cosmetics, among others, the primary concern in this chapter pertains to manufactured items that are subject to stress, move in relation to one another, and have close fits joining them. Surface roughness (a term used in a general way here, since it has specific connotations that will be explained shortly) or surface texture depends, to a large extent, on the type of the manufacturing operation. If rough surface for a part is acceptable, one may choose a casting, forging, or rolling operation. In many cases, the surfaces that need to contact each other for some functional requirement have to be machined, possibly followed by a finishing operation like grinding.

The reasons for pursuing surface metrology as a specialized subject are manifold. We would like to make our products operate better, cost less, and look better. In order to achieve these objectives, we need to examine the surfaces of the parts or components more closely, at the microscopic level. It would be naive to assume that two apparently flat contacting surfaces are in perfect contact throughout the apparent area of contact. Most of the earlier laws of friction were based on this assumption (perhaps until 1950). In reality, surfaces have *asperities*, which refer to the peaks and valleys of surface irregularities. Contact between the mating parts is believed to take place at the peaks. When the parts are forced against each other, they deform either elastically or plastically. In case of elastic behaviour, they return to the full height after deformation by the mating surface. If they behave plastically, some of the deformation is permanent. These aspects have a bearing on the friction characteristics of the parts in contact. As mechanical engineering is primarily concerned with machines and moving parts that are designed to precisely fit with each other, surface metrology has become an important topic in engineering metrology.

9.2 SURFACE METROLOGY CONCEPTS

If one takes a look at the topology of a surface, one can notice that surface irregularities are متراكب superimposed on a widely spaced component of surface texture called waviness. Surface irregularities generally have a pattern and are oriented in a particular direction depending on the factors that cause these irregularities in the first place. Figure 9.1 illustrates some of these features.

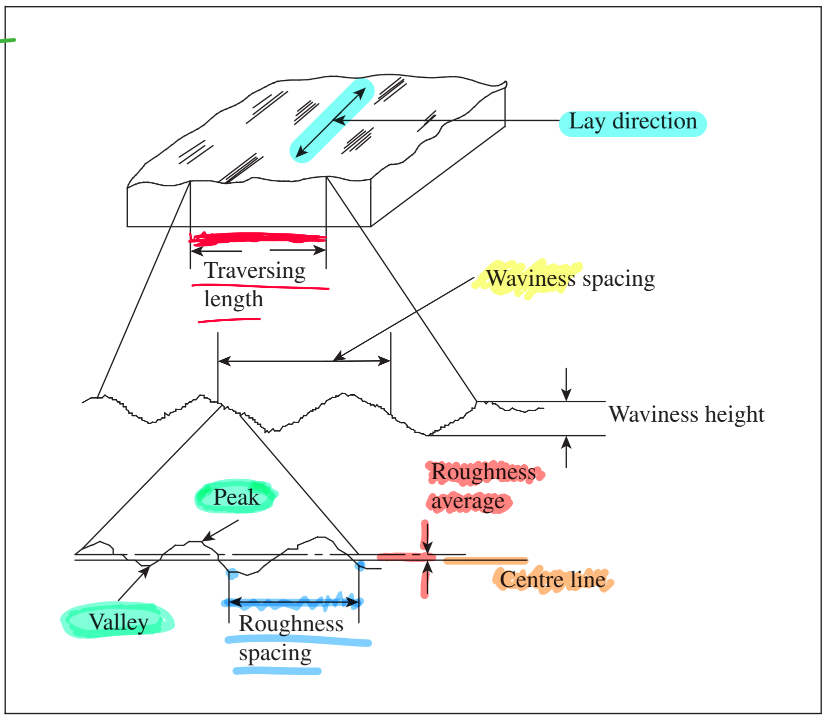


Fig. 9.1 Waviness and roughness

Surface irregularities primarily arise due to the following factors:

1. Feed marks of cutting tools
2. Chatter marks on the workpiece due to vibrations caused during the manufacturing operation
3. Irregularities on the surface due to rupture of workpiece material during the metal cutting operation

4. Surface variations caused by the deformation of workpiece under the action of cutting forces
5. Irregularities in the machine tool itself like lack of straightness of guideways

Thus, it is obvious that it is practically impossible to produce a component that is free from surface irregularities. Imperfections on a surface are in the form of succession of hills and valleys varying in both height and spacing. In order to distinguish one surface from another, we need to quantify surface roughness; for this purpose, parameters such as height and spacing of surface irregularities can be considered. In mechanical engineering applications, we are primarily concerned with the roughness of the surface influenced by a machining process. For example, a surface machined by a single-point cutting tool will have a roughness that is uniformly spaced and directional. In the case of a finish machining, the roughness is irregular and non-directional. In general, if the hills and valleys on a surface are closely packed, the wavelength of the waviness is small and the surface appears rough. On the other hand, if the hills and valleys are relatively far apart, waviness is the predominant parameter of interest and is most likely caused by imperfections in the machine tool. If the hills and valleys are closely packed, the surface is said to have a primary texture, whereas surfaces with pronounced waviness are said to have a secondary texture.

9.3 TERMINOLOGY

Roughness The American Society of Tool and Manufacturing Engineers (ASTME) defines roughness as the finer irregularities in the surface texture, including those irregularities that result from an inherent action of the production process. Roughness spacing is the distance between successive peaks or ridges that constitute the predominant pattern of roughness. Roughness height is the arithmetic average deviation expressed in micrometres and measured perpendicular to the centre line.

Waviness It is the more widely spaced component of surface texture. Roughness may be considered to be superimposed on a wavy surface. Waviness is an error in form due to incorrect geometry of the tool producing the surface. On the other hand, roughness may be caused by problems such as tool chatter or traverse feed marks in a supposedly geometrically perfect machine. The spacing of waviness is the width between successive wave peaks or valleys. Waviness height is the distance from a peak to a valley.

Lay It is the direction of the predominant surface pattern, ordinarily determined by the production process used for manufacturing the component. Symbols are used to represent lays of surface pattern, which will be discussed in Section 9.5.

Flaws These are the irregularities that occur in isolation or infrequently because of specific causes such as scratches, cracks, and blemishes.

Surface texture It is generally understood as the repetitive or random deviations from the nominal surface that form the pattern of the surface. Surface texture encompasses roughness, waviness, lay, and flaws.

Errors of form These are the widely spaced repetitive irregularities occurring over the full length of the work surface. Common types of errors of form include bow, snaking, and lobbing.

9.4 ANALYSIS OF SURFACE TRACES

It is required to assign a numerical value to surface roughness in order to measure its degree. This will enable the analyst to assess whether the surface quality meets the functional requirements of a component. Various methodologies are employed to arrive at a representative parameter of surface roughness. Some of these are 10-point height average (Rz), root mean square (RMS) value, and the centre line average height (Ra), which are explained in the following paragraphs.

9.4.1 Ten-point Height Average Value

It is also referred to as the *peak-to-valley height*. In this case, we basically consider the average height encompassing a number of successive peaks and valleys of the asperities. As can be seen in Fig. 9.2, a line AA parallel to the general lay of the trace is drawn. The heights of five consecutive peaks and valleys from the line AA are noted down.

The average peak-to-valley height Rz is given by the following expression:

في معلومة عن هاي

$$\text{Rz} = \frac{(h_1 + h_3 + h_5 + h_7 + h_9) - (h_2 + h_4 + h_6 + h_8 + h_{10})}{5} \times \frac{1000}{\text{Vertical magnification}}\ \mu\text{m}$$

9.4.2 Root Mean Square Value

Until recently, RMS value was a popular choice for quantifying surface roughness; however, this has been superseded by the centre line average value. The RMS value is defined as the square root of the mean of squares of the ordinates of the surface measured from a mean line. Figure 9.3 illustrates the graphical procedure for arriving at an RMS value.

With reference to this figure, if $h_1, h_2, \ldots, h_n$ are equally spaced ordinates at points 1, 2, ... , n, then

$$h_{\text{RMS}} = \sqrt{\frac{(h_1^2 + h_2^2 + \ldots + h_n^2)}{n}} = \sqrt{\frac{\Sigma h_i^2}{n}}$$

كل ما زاد عدد النقاط بكون more accurate

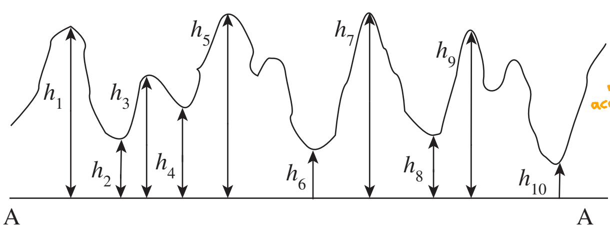


Fig. 9.2 Measurement to calculate the 10-point height average

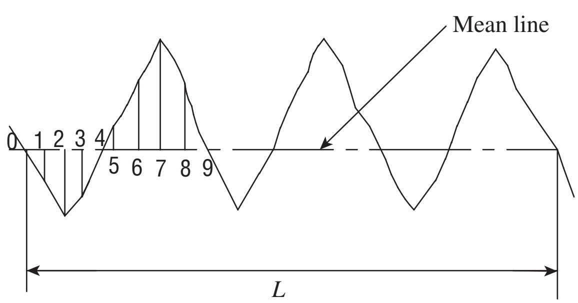


Fig. 9.3 Representation of an RMS value

9.4.3 Centre Line Average Value

The Ra value is the prevalent standard for measuring surface roughness. It is defined as the average height from a mean line of all ordinates of the surface, regardless of sign. With reference to Fig. 9.4, it can be shown that

$$\text{Ra} = \frac{A_1 + A_2 + \ldots + A_N}{L}$$
$$= \Sigma A/L$$

Interestingly, four countries (USA, Canada, Switzerland, and Netherlands) have exclusively adopted Ra value as the standard for measuring surface roughness. All other countries have included other assessment methods in addition to the Ra method. For instance, France has seven additional standards.

It should be mentioned here that the Ra value is an index for surface texture comparison and not a dimension. This value is always much less than the peak-to-valley height. It is generally a popular choice as it is easily understood and applied for the purpose of measurement. The bar chart shown in Fig. 9.5 illustrates the typical Ra values obtained in basic manufacturing operations.

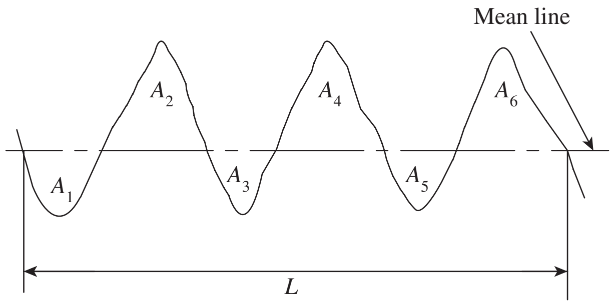


Fig. 9.4 Representation of Ra value

كل ما كانت Ra أقل يكون السطح Smooth

اختصار لـ Surface Roughness value

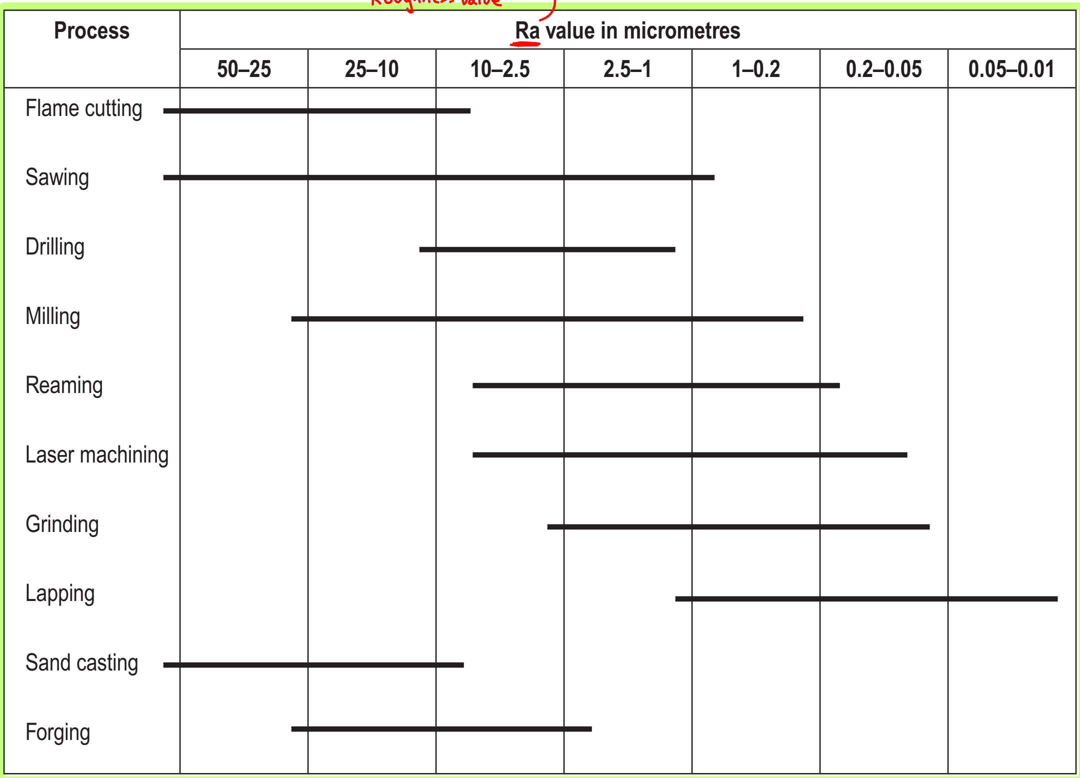


Fig. 9.5 Bar chart indicating the range of Ra values for various manufacturing operations

Note: The bars indicate the entire range. In most cases, the Ra value is restricted to the mid 50% portion of the bars.

9.5 SPECIFICATION OF SURFACE TEXTURE CHARACTERISTICS

Design and production engineers should be familiar with the standards adopted for specification of the characteristics of surface texture. Symbols are used to designate surface irregularities such as the lay of surface pattern and the roughness value. Figure 9.6 illustrates the symbolic

Lay → depends on the manufacturing process
يلي استعملناها بالقطع

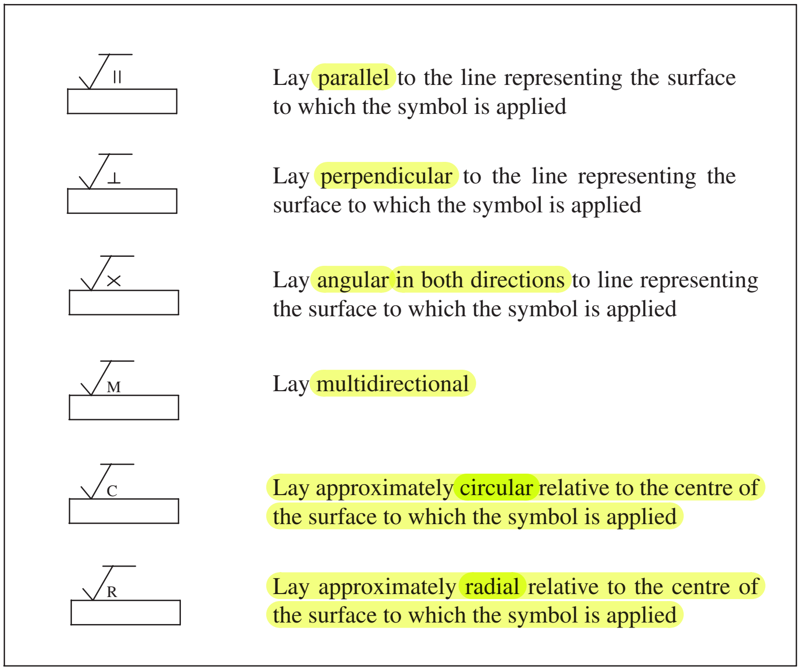


Fig. 9.6 Symbolic representation of the various types of lays of a surface texture

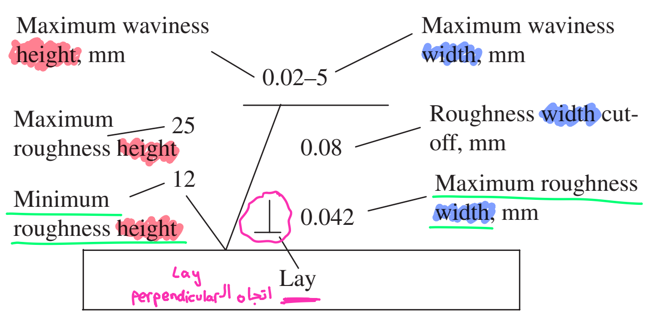


Fig. 9.7 Surface texture symbols

representation of the various types of lays and Fig. 9.7 highlights surface texture symbols with specifications.

9.6 METHODS OF MEASURING SURFACE FINISH

There are basically two approaches for measuring surface finish: comparison and direct measurement. The former is the simpler of the two but is more subjective in nature. The comparative method advocates assessment of surface texture by observation or feel of the surface. Microscopic examination is an obvious improvisation of this method. However, it still has two major drawbacks. First, the view of a surface may be deceptive; two surfaces that appear identical may be quite different. Second, the height of the asperities cannot be readily determined. Touch is perhaps a better method than visual observation. However, this method is also subjective in nature and depends, to a large extent, on the judgement of a person, and therefore not reliable.

These limitations have driven metrology experts to devise ways and means of directly measuring surface texture by employing direct methods. Direct measurement enables a numerical value to be assigned to the surface finish. The following sections explain the popular methods for the determination of surface texture.

9.7 STYLUS SYSTEM OF MEASUREMENT

The stylus system of measurement is the most popular method to measure surface finish. The operation of stylus instruments is quite similar to a phonograph pickup. A stylus drawn across the surface of the workpiece generates electrical signals that are proportional to the dimensions of the asperities. The output can be generated on a hard copy unit or stored on some magnetizable media. This enables extraction of measurable parameters from the data, which can quantify the degree of surface roughness. The following are the features of a stylus system:

1. A skid or shoe drawn over the workpiece surface such that it follows the general contours of the surface as accurately as possible (the skid also provides the datum for the stylus)
2. A stylus that moves over the surface along with the skid such that its motion is vertical relative to the skid, a property that enables the stylus to capture the contours of surface roughness independent of surface waviness
3. An amplifying device for magnifying the stylus movements
4. A recording device to produce a trace or record of the surface profile
5. A means for analysing the profile thus obtained

9.7.1 Stylus and Datum

There are two types of stylus instruments: true datum and surface datum, which are also known as *skidless* and *skid* type, respectively. In the skidless instrument, the stylus is drawn across the surface by a mechanical movement that results in a precise path. The path is the datum from which the assessment is made. In the skid-type instrument, the stylus pickup unit is supported by a member that rests on the surface and slides along with it. This additional member is the skid or the shoe. Figure 9.8 illustrates the relationship between the stylus and the skid.

Skids are rounded at the bottom and fixed to the pickup unit. They may be located in front of or behind the stylus. Some instruments use a shoe as a supporting slide instead of a skid. Shoes are flat pads with swivel mountings in the head. The datum created by a skid or a shoe is the locus of its centre of curvature as it slides along the surface.

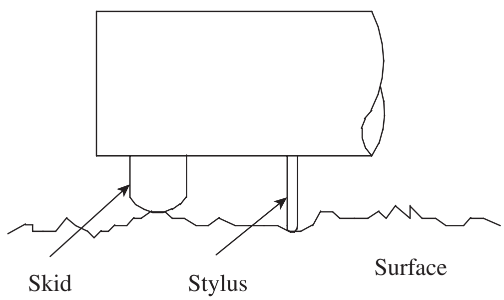


Fig. 9.8 Skid and stylus type

The stylus is typically a diamond having a cone angle of 90° and a spherical tip radius of 1–5 μm or even less. The stylus tip radius should be small enough to follow the details of the surface irregularities, but should also have the strength to resist wear and shocks. Stylus load should also be controlled so that it does not leave additional scratch marks on the component being inspected.

In order to capture the complete picture of surface irregularities, it is necessary to investigate waviness (secondary texture) in addition to roughness (primary texture). Waviness may occur with the same lay as the primary texture. While a pointed stylus is used to measure roughness, a blunt stylus is required to plot the waviness.

9.8 STYLUS PROBE INSTRUMENTS

In most stylus-based instruments, a stylus drawn across the surface of a component being inspected generates electrical signals that are proportional to the changes in the surface asperities. An electrical means of amplifying signals, rather than a purely mechanical one, minimizes the pressure of the stylus on the component. Changes in the height of asperities may be directly read by a meter or a chart. Most instruments provide a graph of the stylus path along the surface. The following paragraphs explain some of the popular stylus probe instruments used for measuring surface roughness.

9.8.1 Tomlinson Surface Meter

This is a mechanical–optical instrument designed by Dr Tomlinson of the National Physical laboratory of the UK. Figure 9.9 illustrates the construction details of the Tomlinson surface meter. The sensing element is the stylus, which moves up and down depending on the irregularities of the workpiece surface. The stylus is constrained to move only in the vertical direction because of a leaf spring and a coil spring. The tension in the coil spring P causes a similar tension in the leaf spring. These two combined forces hold a cross-roller in position between the stylus and a pair of parallel fixed rollers. A shoe is attached to the body of the instrument to provide the required datum for the measurement of surface roughness.

A light spring steel arm is attached to the cross-roller and carries a diamond tip. The translatory motion of the stylus causes rotation of the cross-roller about the point A, which in turn is converted to a magnified motion of the diamond point. The diamond tip traces the profile of the workpiece on a smoked glass sheet. The glass sheet is transferred to an optical projector and magnified further. Typically, a magnification of the order of 50–100 is easily achieved in this instrument.

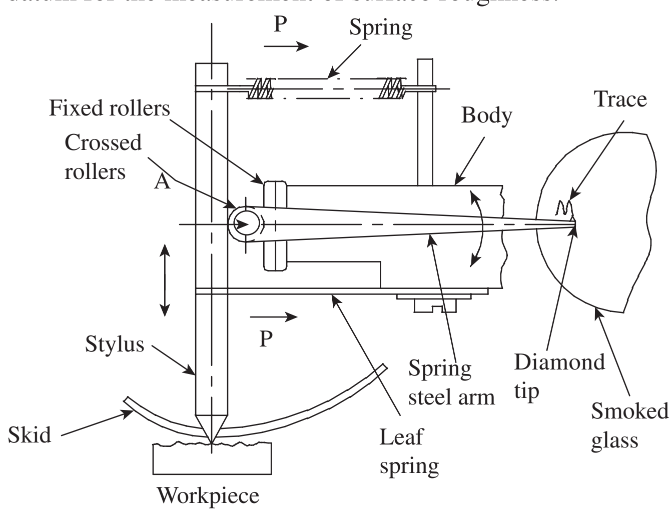


Fig. 9.9 Tomlinson surface meter

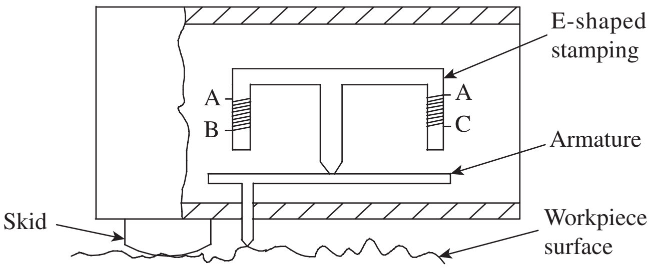


Fig. 9.10 Taylor–Hobson talysurf

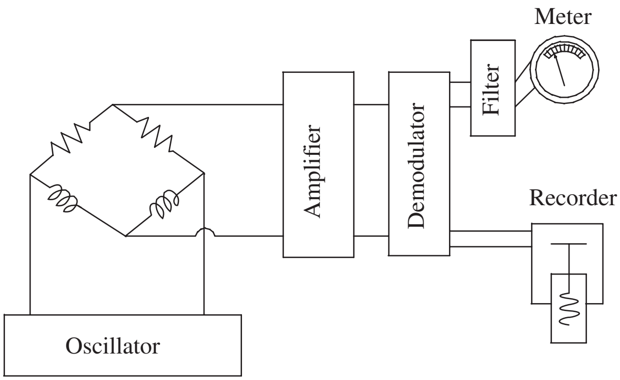


Fig. 9.11 Bridge circuit and electronics

In order to get a trace of the surface irregularities, a relative motion needs to be generated between the stylus and the workpiece surface. Usually, this requirement is met by moving the body of the instrument slowly with a screw driven by an electric motor at a very slow speed. Anti-friction guide-ways are used to provide friction-free movement in a straight path.

9.8.2 Taylor–Hobson Talysurf

The Taylor–Hobson talysurf works on the same principle as that of the Tomlinson surface meter. However, unlike the surface meter, which is purely a mechanical instrument, the talysurf is an electronic instrument. This factor makes the talysurf a more versatile instrument and can be used in any condition, be it a metrology laboratory or the factory shop floor.

Figure 9.10 illustrates the cross section of the measuring head. The stylus is attached to an armature, which pivots about the centre of piece of an E-shaped stamping. The outer legs of the E-shaped stamping are wound with electrical coils. A predetermined value of alternating current (excitation current) is supplied to the coils. The coils form part of a bridge circuit. A skid or shoe provides the datum to plot surface roughness. The measuring head can be traversed in a linear path by an electric motor. The motor, which may be of a variable speed type or provided with a gear box, provides the required speed for the movement of the measuring head.

As the stylus moves up and down due to surface irregularities, the armature is also displaced. This causes variation in the air gap, leading to an imbalance in the bridge circuit. The resulting bridge circuit output consists of only modulation. This is fed to an amplifier and a pen recorder is used to make a permanent record (Fig. 9.11). The instrument has the capability to calculate and display the roughness value according to a standard formula.

9.8.3 Profilometer

A profilometer is a compact device that can be used for the direct measurement of surface texture. A finely pointed stylus will be in contact with the workpiece surface. An electrical pickup attached to the stylus amplifies the signal and feeds it to either an indicating unit or a recording unit. The stylus may be moved either by hand or by a motorized mechanism.

The profilometer is capable of measuring roughness together with waviness and any other surface flaws. It provides a quick-fix means of conducting an initial investigation before attempting a major investigation of surface quality.

9.9 WAVELENGTH, FREQUENCY, AND CUT-OFF

The complete traverse length of the stylus instrument is called the *measuring traverse length*. It is divided into several sampling lengths. The sampling length is chosen based on the surface under test. Generally, results of all the samples in the measuring traverse length are averaged out by the instrument to give the final result.

Skids simplify surface assessment while using stylus instruments. However, there is a distortion because of phase relationship between the stylus and the skid. This aspect is illustrated in Fig. 9.12. In case A, the stylus and the skid are in phase. Therefore, roughness (the primary texture) will be relatively undistorted. In case B, the two are out of phase. In this situation, waviness superimposes on the roughness reading and is misleading. In case C also, the stylus and skid are out of phase, resulting in an unrealistic interpretation of roughness value.

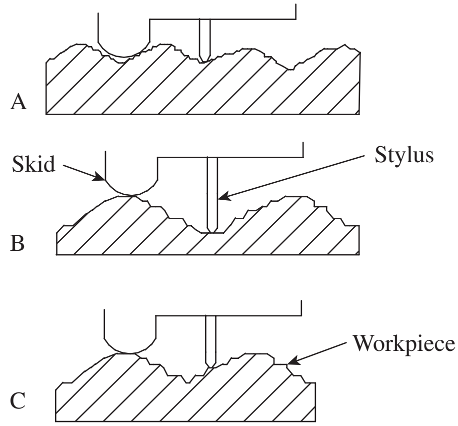


Fig. 9.12 Phase relationship between the skid and stylus

Thus, since the skid, like the stylus, is also rising and falling according to the surface asperities, stylus height measurement may be distorted. Therefore, care must be exercised for the selection of sampling length.

9.9.1 Cut-off Wavelength

The frequency of the stylus movement as it rises up and down the workpiece surface is determined by the traversing speed. Assuming that f is the frequency of the stylus movement, λ is the surface wavelength, and v is the traverse speed, one gets the following equation:

$$f = v/\lambda$$

Therefore, $f \propto 1/\lambda$, if v remains constant.

For surfaces produced by single-point cutting tools, a simple guideline for selecting cut-off wavelength is that it should not exceed one feed spacing. However, for many fine irregular surfaces, a cut-off length of 0.8 mm is recommended. Table 9.1 illustrates the recommended cut-off wavelengths for machining processes.

Table 9.1 Recommended wavelengths for machining processes

Finishing processes	Cut-off length (mm)
Superfinishing, lapping, honing, diamond boring, polishing, and buffing	0.25–0.8
Grinding	0.25–0.8
Turning, reaming, and broaching	0.8–2.5
Boring, milling, and shaping	0.8–8.0
Planning	2.5–25

9.10 OTHER METHODS FOR MEASURING SURFACE ROUGHNESS

In addition to the stylus-based methods of surface roughness measurement explained in Section 9.8, this section presents in brief some of the alternative methods used in the industry.

9.10.1 Pneumatic Method

The *air leakage method* is often used for assessing surface texture. A pneumatic comparator is used for conducting mass inspection of parts. Compressed air is discharged from a self-aligning nozzle held close to the surface being inspected. Depending on height variations in the surface irregularities, the gap between the nozzle tip and the workpiece surface varies. This results in the variation of flow rate of air, which in turn varies the rotation speed of a rotameter. Rotation of the rotameter is an indication of surface irregularities. Alternatively, a float can also be used to measure surface deviations. The comparator is initially set using reference gauges.

9.10.2 Light Interference Microscopes

The light interference technique offers a non-contact method of assessing surface texture. Advantages of this method are that it allows an area of the workpiece surface to be examined, a wide range of magnifications to be used, and the opportunity for making a permanent record of the fringe pattern using a camera. Good magnification capability allows good resolution up to a scratch spacing of 0.5 μm.

A monochromatic light passing through an optical flat and falling on the workpiece surface generates the fringe pattern. The technique of measurement using interference fringes has already been explained in Chapter 7. However, assessment of surface irregularities cannot be directly related to the Ra value. Master specimens are used to generate a reference fringe pattern, which is compared with the fringe pattern of the workpiece in order to arrive at a conclusion regarding surface quality. This method provides a viable alternative for inspecting soft or thin surfaces, which normally cannot be examined using stylus instruments.

9.10.3 Mecrin Instrument

The Mecrin instrument assesses surface irregularities through frictional properties and the average slope of the irregularities. This gauge is suited for surfaces manufactured by processes such as grinding, honing, and lapping, which have low Ra values in the range 3–5 μm. Figure 9.13 illustrates the working principle of this instrument.

A thin metallic blade is pushed against the workpiece surface at a certain angle. The blade may slide or buckle, depending on the surface roughness and the angle of attack. At lower angles of attack, the blade tip will slide over the surface of the workpiece. As the angle of attack is increased, a critical

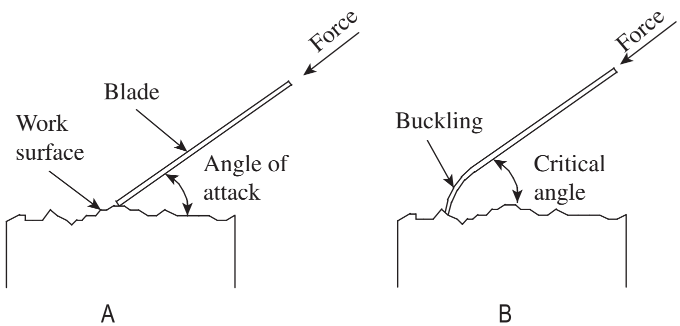


Fig. 9.13 Principle of the Mecrin instrument

value is reached at which the blade starts to buckle. This critical angle is a measure of the degree of roughness of the surface. The instrument is provided with additional features for easier handling. A graduated dial will directly give the reading of roughness value.

A QUICK OVERVIEW

- Workpiece surfaces have *asperities*, which are the peaks and valleys of surface irregularities. Contact between mating parts is believed to take place at the peaks. When the parts are forced against each other, they deform either elastically or plastically. In case of elastic behaviour, they return to the full height after deformation by the mating surface. If they behave plastically, some of the deformation is permanent. As these aspects have a bearing on the friction characteristics of the parts in contact, the study of surface texture has become an important part of metrology.
- To measure the degree of surface roughness, it is required to assign a numerical value to it. This will enable the analyst to assess whether the surface quality meets the functional requirements of a component. Various methodologies are employed to arrive at a representative parameter of surface roughness. Some of these are 10-point height average, RMS value, and the centre line average height.
- There are two approaches for measuring surface finish: comparison and direct measurement. The former is the simpler of the two, but is more subjective in nature. The comparative method advocates assessment of surface texture by observation or feel of the surface. On the other hand, direct measurement is more reliable since it enables a numerical value to be assigned to the surface finish.
- The stylus system of measurement is the most popular method to measure surface finish. Operation of stylus instruments is quite similar to a phonograph pickup. A stylus drawn across the surface of the workpiece generates electrical signals that are proportional to the dimensions of the asperities. The output can be generated on a hard copy unit or stored on some magnetizable media. This enables extraction of measurable parameters from the data, which can quantify the degree of surface roughness.
- Among the stylus-based measurement systems, the Tomlinson surface meter and Taylor–Hobson talysurf are popular.
- The complete traverse length of the stylus instrument is called the measuring traverse length. It is divided into several sampling lengths. The sampling length is chosen based on the surface under test. Generally, the results of all the samples in the measuring traverse length are averaged out by the instrument to give the final result.
- The frequency of the stylus movement as it rises up and down the workpiece surface is determined by the traversing speed. If f is the frequency of the stylus movement, λ is the surface wavelength, and v is the traverse speed, then $f = v/\lambda$.

MULTIPLE-CHOICE QUESTIONS

1. Surface texture depends to a large extent on
   (a) material composition
   (b) type of manufacturing operation
   (c) skill of the operator
   (d) accuracy of measurement
2. Peaks and valleys of surface irregularities are called
   (a) waves
   (b) manifolds
   (c) asperities
   (d) perspectives
3. While roughness is referred to as a primary

Answers to Multiple-choice Questions

1. (b)	2. (c)	3. (a)	4. (a)	5. (d)	6. (b)	7. (b)	8. (a)
9. (d)	10. (d)	11. (c)	12. (a)	13. (b)	14. (d)	15. (c)	

texture, __________ is called a secondary texture.
(a) waviness (c) error of form
(b) lay (d) error of geometry

4. The direction of the predominant surface pattern, ordinarily determined by the production process used for manufacturing the component, is referred to as
(a) lay (c) waviness
(b) flaw (d) none of these

5. Irregularities that occur in isolation or infrequently because of specific causes such as scratches, cracks, and blemishes are called
(a) surface texture (c) waviness
(b) lay (d) flaws

6. The direction of a lay is
(a) the direction that the stylus trace is made
(b) the direction of the asperities
(c) perpendicular to the asperities
(d) any selected straight line taken as reference

7. The average height from a mean line of all ordinates of the surface, regardless of sign, is the
(a) RMS value (c) Rz value
(b) Ra value (d) Rm value

8. The datum created by a skid or shoe is the locus of its __________ as it slides along the workpiece surface.
(a) centre of curvature
(b) centre of its bottom
(c) centre line
(d) all of these

9. A __________ provides a quick-fix means of conducting an initial investigation before attempting a major investigation of surface quality.
(a) Tomlinson surface meter
(b) Taylor–Hobson talysurf
(c) light interference microscope
(d) profilometer

10. Which of the following is the best analogy for the trace of a stylus instrument?
(a) A topographical map
(b) A rolling ball
(c) A pin-ball machine
(d) A phonograph

11. What characteristics of asperities are quantified by the stylus instruments?
(a) Peakedness (c) Heights
(b) Percentages (d) Volumes

12. The frequency of the stylus movement as it rises up and down the workpiece surface is determined by
(a) the traversing speed
(b) the length of stylus
(c) the curvature of skid
(d) all of these

13. The measurement of roughness is relatively undistorted
(a) irrespective of the phase difference between the stylus and the skid
(b) if the stylus and the skid are in phase
(c) if the stylus and the skid have a large phase difference
(d) in none of these cases

14. In graphs, heights of asperities are exaggerated compared to their spacings. This is known as
(a) aspect ratio (c) articulated ratio
(b) asperities ratio (d) distortion ratio

15. The Mecrin instrument assesses the surface irregularities through
(a) fringe pattern
(b) air-leakage method
(c) frictional properties
(d) thermal properties

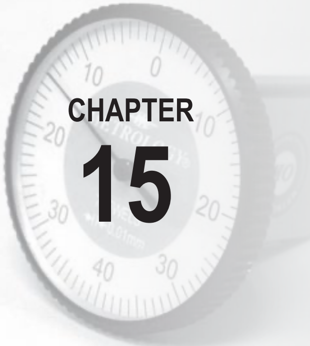
REVIEW QUESTIONS

1. What is the justification for studying surface metrology as a specialized subject?
2. With the help of an illustration, explain the following terms: roughness, waviness, lay, and flaws.
3. What are the primary reasons for surface irregularities?
4. Explain the following methods of quantifying surface roughness: (a) Rz value, (b) RMS value, and (c) Ra value.
5. Identify the prominent types of ‘lay’ by means of symbols only.

6. Distinguish between comparison and direct measurement of surface roughness.
7. List the major features of the stylus system of measurement.
8. Distinguish between skidless and skid-type instruments.
9. With the help of a neat sketch, explain the working principle of the Tomlinson surface meter.
10. With the help of a neat sketch, explain the Taylor–Hobson talysurf.
11. What is a profilometer?
12. Discuss the effect of phase relationship between the stylus and the skid on measurement accuracy.
13. What is a cut-off wavelength? List the recommended cut-off wavelengths for some of the typical manufacturing operations.
14. How is the interferometry technique useful for measurement of surface irregularities?
15. What is the measurement concept in the 'Mecrin' instrument?

Answers to Multiple-choice Questions

1. (b) 2. (c) 3. (a) 4. (a) 5. (d) 6. (b) 7. (b) 8. (a)
9. (d) 10. (d) 11. (c) 12. (a) 13. (b) 14. (d) 15. (c)



CHAPTER 15

Measurement of Temperature

After studying this chapter, the reader will be able to

- understand the basics of temperature measurement
- describe the methods of temperature measurements
- explain thermocouples and the different laws of thermocouples
- elucidate the different resistance temperature detectors
- comprehend calibration of liquids in glass thermometers
- discuss bimetallic strip thermometers
- throw light on pyrometers

15.1 INTRODUCTION

We know that temperature is a physical property of a material that gives a measure of the average kinetic energy of the molecular movement in an object or a system. Temperature can be defined as a condition of a body by virtue of which heat is transferred from one system to another. It is pertinent to mention here that both temperature and heat are different. Temperature is a measure of the internal energy of a system, whereas heat is a measure of the transfer of energy from one system to another. Heat transfer takes place from a body at a higher temperature to one at a lower temperature. The two bodies are said to be in thermal equilibrium when both of them are at the same temperature and no heat transfer takes place between them. The rise in temperature of a body is due to greater absorption of heat, which increases the movement of the molecules within the body.

The first thermometer was developed by Galileo Galilei in the 17th century, which has undergone significant improvement with the advancement of science and technology; present-day thermometers are capable of measuring temperatures more accurately and precisely. In 1724, D.G. Fahrenheit, a German physicist, contributed significantly to the development of thermometry. He proposed his own scale, in which 32° and 212° were considered the freezing point and boiling point of water, respectively. The Swedish physicist Anders Celsius, in 1742, developed the mercury-in-glass thermometer. He identified two points, namely the melting point of ice and the boiling point of water, and assigned 0° and 100°, respectively, to them. He made 100 divisions between these two points. In 1859, William John Macquorn Rankine, a Scottish physicist, proposed an absolute or thermodynamic scale, known as Rankine scale when, after investigating the changes in thermal energy with changes in temperature, he came to a conclusion that the theoretical temperature of each of the substances was the same at zero thermal energy level. According to him, this temperature was approximately equal to –460 °F.

William Thomson, first Baron Kelvin, popularly known as Lord Kelvin, a British physicist, introduced a new concept, known as the Kelvin scale, in the mid-1800s. He suggested 0 K as the absolute temperature of gas and 273 K as the freezing point of water. A comparison between Kelvin, Celsius, and Fahrenheit scales with respect to absolute zero, and boiling and freezing points of water is shown in Table 15.1. Although human beings generally perceive temperature as hot, warm (neutral), or cold, from an engineering perspective, a precise and accurate measurement of temperature is essential.

Table 15.1 Comparison of temperature scales

Scales	Water boils	Water freezes	Absolute zero
Kelvin	373.16 K	273.16 K	0 K
Celsius	100 °C	0 °C	−273.16°C
Fahrenheit	212 °F	32 °F	−459.7 °F

100 divisions عدد ال

180 divisions عدد ال

The scales used to measure temperature can be divided into relative scales [Fahrenheit (°F) and Celsius (°C)] and absolute scales [Rankine (°R) and Kelvin (K)]. The various temperature scales are related as follows:

$$F = 1.8C + 32$$
$$C = (F - 32)/1.8$$
$$R = F + 460$$
$$K = C + 273$$

Linear Relationship

$$\frac{F-32}{180} = \frac{C-0}{180}$$
$$\rightarrow F = 1.8\,C + 32$$

15.2 METHODS OF MEASURING TEMPERATURE

Measurement of temperature cannot be accomplished by direct comparison with basic standards such as length and mass. A standardized calibrated device or system is necessary to determine temperature. In order to measure temperature, various primary effects that cause changes in temperature can be used. The temperature may change due to changes in physical or chemical states, electrical property, radiation ability, or physical dimensions. The response of the temperature-sensing device is influenced by any of the following factors:

1. Thermal conductivity and heat capacity of an element
2. Surface area per unit mass of the element
3. Film coefficient of heat transfer
4. Mass velocity of a fluid surrounding the element
5. Thermal conductivity and heat capacity of the fluid surrounding the element

* Temperature can be sensed using many devices, which can broadly be classified into two categories: contact- and non-contact-type sensors. In case of contact-type sensors, the object whose temperature is to be measured remains in contact with the sensor. Inference is then drawn on the assessment of temperature either by knowing or by assuming that the object and

the sensor are in thermal equilibrium. Contact-type sensors are classified as follows:

1. Thermocouples
2. Resistance temperature detectors (RTDs)
3. Thermistors
4. Liquid-in-glass thermometers
5. Pressure thermometers
6. Bimetallic strip thermometers

In case of non-contact-type sensors, the radiant power of the infrared or optical radiation received by the object or system is measured. Temperature is determined using instruments such as radiation or optical pyrometers. Non-contact-type sensors are categorized as follows:

1. Radiation pyrometers
2. Optical pyrometers
3. Fibre-optic thermometers

15.3 THERMOCOUPLES

(15.3)
all exept
15.3.4

Thermocouples are active sensors employed for the measurement of temperature. The thermoelectric effect is the direct conversion of temperature differences to an electric voltage. In 1821, Thomas Johan Seebeck discovered that when two dissimilar metals are joined together to form two junctions such that one junction (known as the hot junction or the measured junction) is at a higher temperature than the other junction (known as the cold junction or the reference junction), a net emf is generated. This emf, which also establishes the flow of current, can be measured using an instrument connected as shown in Fig. 15.1. The magnitude of emf generated is a function of the junction temperature. It is also dependent on the materials used to form the two junctions. The thermoelectric emf is a result of the combination of two different effects—the Peltier effect and the Thomson effect.

The French physicist Jean Charles Athanase Peltier discovered that if two dissimilar metals are connected to an external circuit in a way such that a current is drawn, the emf may be slightly altered owing to a phenomenon called Peltier effect. A potential difference always exists between two dissimilar metals in contact with each other. This is known as the Peltier effect.

Thomson found out that the emf at a junction undergoes an additional change due to the existence of a temperature gradient along either or both the metals. The Thomson effect states that even in a single metal a potential gradient exists, provided there is a temperature gradient.

Both these effects form the basis of a thermocouple, which finds application in temperature measurement. The flow of current through the circuit is spontaneous when two dissimilar metals are joined together to form a closed circuit, that is, a thermocouple, provided one junction is maintained at a temperature different from the other. This effect is termed the Seebeck effect.

In Fig. 15.1, if temperatures at the hot junction (T_1) and the cold junction (T_2) are equal and at the same time opposite, then there will not be any flow of current. However, if they are unequal, then the emfs will not balance and hence current will flow. It is to be mentioned here that the voltage signal is a function of the junction temperature at the measured end and the voltage increases as the temperature rises. Variations in emf are calibrated in terms of temperatures; the devices employed to record these observations are termed thermocouple pyrometers.

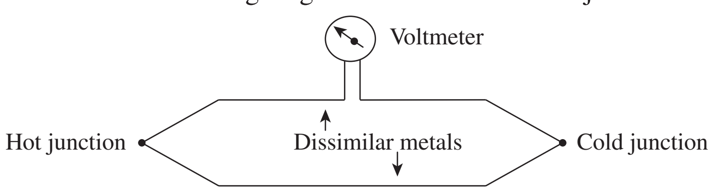


Fig. 15.1 Basic thermocouple circuit

*assume the temperature in the cold junction is (0°C)

بالتالي الـVoltage على الـHot junction الذي هو نفسه الـdifference in Voltage between the Hot and cold

سوف تساوي الـVoltage على الـHot junction و هو قراءة الـVoltmeter

15.3.1 Laws of Thermocouples

Apart from the Peltier and Thomson effects, which form the basis of thermoelectric emf generation, three laws of thermocouples that govern this phenomenon are required to be studied in order to understand their theory and applicability. They also provide some useful information on the measurement of temperature.

Law of Homogeneous Circuit

This law states that a thermoelectric current cannot be sustained in a circuit of a single homogenous material, regardless of the variation in its cross section and by the application of heat alone. This law suggests that two dissimilar materials are required for the formation of any thermocouple circuit.

Law of Intermediate Metals

If an intermediate metal is inserted into a thermocouple circuit at any point, the net emf will not be affected provided the two junctions introduced by the third metal are at identical temperatures. This law allows the measurement of the thermoelectric emf by introducing a device into the circuit at any point without affecting the net emf, provided that additional junctions introduced are all at the same temperature.

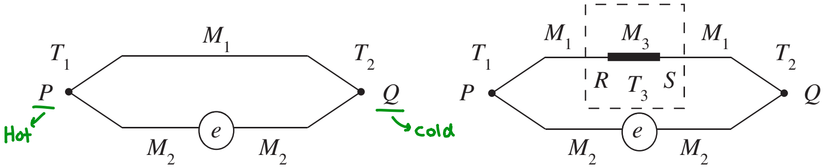


Fig. 15.2 Law of intermediate metals

It is clear from Fig. 15.2 that when a third metal, M_3, is introduced into the system, two more junctions, R and S, are formed. If these two additional junctions are maintained at the same temperature, say T_3, the net emf of the thermocouple circuit remains unaltered.

Law of Intermediate Temperatures

If a thermocouple circuit generates an emf e_1 when its two junctions are at temperatures T_1 and T_2, and e_2 when the two junctions are at temperatures T_2 and T_3, then the thermocouple will generate an emf of $e_1 + e_2$ when its junction temperatures are maintained at T_1 and T_3 (Fig. 15.3).

This law pertains to the calibration of the thermocouple and is important for providing reference junction compensation. This law allows us to make corrections to the thermocouple readings when the reference junction temperature is different from the temperature at which the thermocouple was calibrated. Usually while preparing the calibration chart of a thermocouple, the reference or cold junction temperature is taken to be equal to 0 °C. However, in practice, the reference junction is seldom maintained at 0 °C; it is usually maintained at ambient conditions. Thus, with the help of the third law, the actual temperature can be determined by means of the calibration chart.

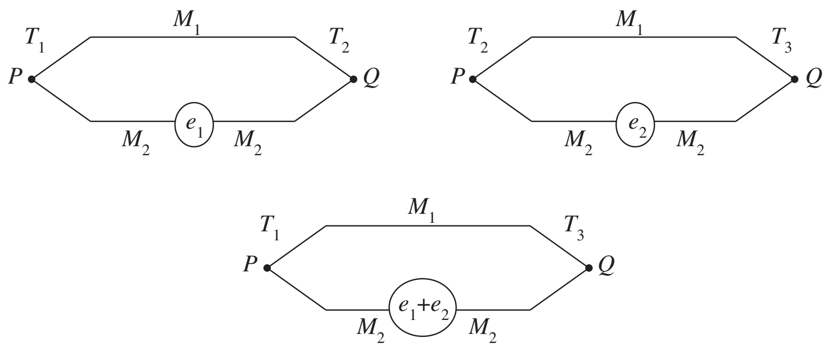


Fig. 15.3 Law of intermediate temperatures

15.3.2 Thermocouple Materials

is an electrical device

كل ما زادت درجة الحرارة على ال Hot junction for the thermocouple ال difference بين ال Hot وال Cold سوف يزداد

Theoretically, any two different materials can be used to form a thermocouple. However, only a few are suitable for temperature measurement applications. Combinations of different thermocouple materials and their temperature range are given in Table 15.2. Base metal-type thermocouples like copper–constantan pose high resistance to condensed moisture corrosion. The iron–constantan type is essentially an inexpensive thermocouple capable of enduring oxidizing and reducing atmospheres. The chromel–alumel thermocouple can resist an oxidizing atmosphere.

The relationship between the (Temperature) and (Voltage) is not Linear → So we have tables

Table 15.2 Temperature range of various thermocouple materials

Type	Thermocouple materials	Temperature range (ºC)
Base metal type		
T	Positive part negative part Copper (40%)–constantan (60%)	−200 to 350
J	P N Iron–constantan	−150 to 750
E	P N Chromel–constantan (57% Cu, 43% Ni)	−200 to 1000
K	Chromel (90% Ni, 10% Cr)–Alumel (94% Ni, 2% Al, 3% Mn, 1% Si)	−200 to 1300
Rare metal type		
S	Platinum (90%)–rhodium–platinum (10%)	0–1500
R	Platinum–rhodium (87% Pt, 13% Rh)–platinum	0–1500

Thermocouple materials are divided into base metal type and rare, noble, or precious metal type. Platinum (platinum–rhodium) thermocouples are called noble thermocouples, and all other thermocouples belong to the base metal type. In a reducing atmosphere, these thermocouples more sensitive ترتيب ال

1. Thermistor → اكثر اشي sensitive
2. RTD
3. Thermocouple → اقل اشي sensitive

are used with protection. Material combinations such as tungsten–tungsten–rhenium, iridium–tungsten, and iridium–iridium–rhodium are called special types of thermocouples and are used for a high temperature range of 1500–2300 °C. For high-temperature measurements, the thermocouple wire should be thicker. However, an increase in the thickness of the wire lowers the time of response of the thermocouple to temperature variations. Depending on the range of temperature that thermocouples can measure, they are designated by a single letter and grouped accordingly. Base metals, which can measure up to 1000 °C, are designated as Type K, Type E, Type T, and Type J. Noble metals, which can measure up to a temperature of 2000 °C, is classified as Type R, Type S, or Type B. Refractory metals are designated as Type C, Type D, or Type G.

The choice of the thermocouple materials is influenced by several factors. Different combinations of thermocouple materials should possess the following characteristics in order to be used for temperature measurement:

1. Capable of producing a reasonable linear temperature–emf relationship
2. Able to generate sufficient thermo-emf per degree temperature change to facilitate detection and measurement
3. Capable of withstanding persistent high temperatures, rapid temperature variations, and the effects of corrosive environments
4. Good sensitivity to record even small temperature variations
5. Very good reproducibility, which enables easy replacement of the thermocouple by a similar one without any need for recalibration
6. Good calibration stability
7. Economical

15.3.3 Advantages and Disadvantages of Thermocouple Materials

الفهم مهم

The following are some distinct advantages that merit the use of thermocouples:

1. Temperature can be measured over a wide range.
2. Thermocouples are self-powered and do not require any auxiliary power source.
3. A quick and good response can be obtained.
4. The readings obtained are consistent and hence are consistently repeatable.
5. Thermocouples are rugged, and can be employed in harsh and corrosive conditions
6. They are inexpensive.
7. They can be installed easily.

However, thermocouples also have certain disadvantages, which are listed as follows:

1. They have low sensitivity when compared to other temperature-measuring devices such as thermistors and RTDs.
2. Calibration is required because of the presence of some non-linearity.
3. Temperature measurement may be inaccurate due to changes in the reference junction temperature; hence thermocouples cannot be employed for precise measurements.
4. For enhancing the life of thermocouples, they should be protected against contamination and have to be chemically inert.

Not required

15.3.4 Thermopiles

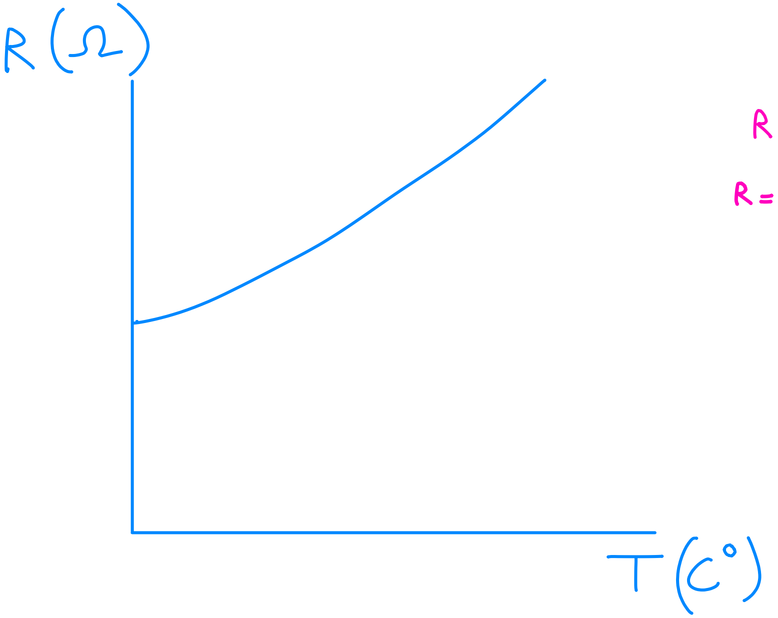
An extension of thermocouples is known as a thermopile. A thermopile comprises a number

	Advantages	Disadvantages
Thermo-couples	1. Temperature can be measured over a wide range. 2. Thermocouples are self-powered and do not require any auxiliary power source. 3. A quick and good response can be obtained. 4. The readings obtained are consistent and hence are consistently repeatable. 5. Thermocouples are rugged, and can be employed in harsh and corrosive conditions 6. They are inexpensive. 7. They can be installed easily.	1. They have low sensitivity when compared to other temperature-measuring devices such as thermistors and RTDs. 2. Calibration is required because of the presence of some non-linearity. 3. Temperature measurement may be inaccurate due to changes in the reference junction tem-perature; hence thermocouples cannot be employed for precise measurements. 4. For enhancing the life of thermocouples, they should be protected against contamination and have to be chemically inert.
RTD	1. The resistance versus temperature linearity characteristics of RTDs are higher. 2. They possess greater accuracy (as high as ±0.1 °C). Standard platinum resistance thermom- eters have ultra-high accuracy of around ±0.0001 °C. 3. They have excellent stability over time. 4. Resistance elements can be used for the measurement of differential tem- perature. 5. Temperature-sensitive resistance ele- ments can be replaced easily. 6. RTDs show high flexibility with re- spect to the choice of measuring equipment, interchangeability of ele- ments, and assembly of components. 7. Multiple resistance elements can be used in an instrument. 8. RTDs have a wide working range without any loss of accuracy and, at the same time, can be employed for small ranges also. 9. They are best suited for remote indi- cation applications. 10. It is possible to operate indicators, re- corders, or controllers.	1. The use of platinum in RTDs makes them more expensive than other tem- perature sensors. 2. The nominal resistance is low for a given size, and the change in resis- tance is much smaller than other tem- perature sensors. 3. Although its temperature sensitivity is high, it is less than that of thermistors.
	1. Thermistors possess very high sensitivity, which is much higher than that of RTDs and ther- R=RReβ(T T) R 1– 1 mocouples, and hence have the capability to detect very small changes in temperature. Their response is very fast, and hence, they are employed for precise control of temperature. They are inexpensive.	They have highly non-linear resistance temperature characteristics. The temperature range is narrow. Low fragility is often a problem. High-temperature performance of thermistors is not good and they exhibit instability with time. They are prone to self-heating errors.

RTD file

$$R = R_o\left(1 + \alpha_1(T - T_o) + \alpha_2(T - T_o)^2 + \alpha_3(T - T_o)^4\right)$$

Relationship is not linear
but for small amounts of temprature we can take it linear



$$R = R_o(1 + \alpha_1(T))$$

$$R = R_o + \alpha_1 R_o T \Longrightarrow \text{Slope} = \alpha_1 R_o$$

$$\alpha_1 = \frac{\text{slope}}{R_o} = \frac{1}{R_o} \times \frac{\Delta R}{\Delta T}$$

Nominal Resistance when (T_o = zero)

RTD
Thermistor
File

+مهم المثال في هذا الفايل

اهم اشي المعادلات

of thermocouples connected in series, wherein the hot junctions are arranged side by side or in a star formation. In such cases, the total output is given by the sum of individual emfs. The advantage of combining thermocouples to form a thermopile is that a much more sensitive element is obtained. For example, a sensitivity of 0.002 °C at 1 mV/°C can be achieved with a chromel–constantan thermopile consisting of 14 thermocouples. If n identical thermocouples are combined to form a thermopile, then the total emf will be n times the output of the single thermocouple.

For special-purpose applications such as measurement of temperature of sheet glass, thermopiles are constructed using a series of semiconductors. For average temperature measurement, thermocouples can be connected in parallel. During the formation of a thermopile, one has to ensure that the hot junctions of the individual thermocouples are properly insulated from one another.

Figures 15.4(a) and 15.4(b) illustrate, respectively, a thermopile having a series connection and one having a star connection.

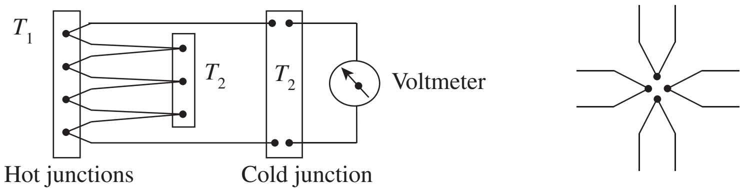


Fig. 15.4 Thermopiles (a) Series connection (b) Star connection

15.4 RESISTANCE TEMPERATURE DETECTORS

Thomas Johan Seebeck, in 1821, discovered thermoelectric emf. In the same year, Sir Humphrey Davy showed that the resistivity of metals is highly dependent on temperature. In 1871, Sir William Siemens proposed the use of platinum as the primary element in resistance thermometers. Platinum is extensively used in high-accuracy resistance thermometers because it is capable of withstanding high temperatures and, at the same time, can sustain excellent stability and exhibit good linearity. The first classical RTD was constructed by C.H. Meyers in 1932, using platinum. A helical coil of platinum was wound on a crossed mica web, and the entire assembly was mounted inside a glass tube. The advantage of this type of construction is that the strain on the wire can be minimized and its resistance can be maximized. Slow thermal response time and fragility of the structure limited its application due to poor thermal contact between platinum and the measured point. Technological advancement led to the development of more rugged RTDs later. The International Practical Temperature Scale was developed in 1968, and pure platinum RTDs have been used as the standard instruments for interpolating between fixed points of the scale. The triple point of water (0.01 °C), boiling point of water (100 °C), triple point of hydrogen (13.81 K), and freezing point of zinc (419.505 °C) are some of the fixed points.

RTDs are also known as resistance thermometers. The American Society for Testing and

Materials has defined the term resistance thermometer as follows: RTD is 'a temperature-measuring device composed of a resistance thermometer element, internal connecting wires, a protective shell with or without means for mounting a connection head, or connecting wire or other fittings, or both'.

We know that the electrical conductivity of a metal is dependent on the movement of electrons through its crystal lattice. An RTD is a temperature sensor that works on the principle that the resistance of electrically conductive materials is proportional to the temperature to which they are exposed. Resistance of a metal increases with an increase in temperature. Hence, metals can be classified as per their positive temperature coefficient (PTC).

When temperature measurement is performed by a resistance thermometer using metallic conductors, it is called a resistance temperature detector (RTD); on the other hand, semiconductors used for temperature measurement are called thermistors.

We know that an RTD measures temperature using the principle that the resistance of a metal changes with temperature. In practice, the RTD element or resistor that is located in proximity to the area where the temperature is to be measured transmits an electrical current. Then, using an instrument, the value of the resistance of the RTD element is measured. Further, on the basis of known resistance characteristics of the RTD element, the value of the resistance is correlated to temperature. RTDs are more rugged and have more or less linear characteristics over a wide temperature range. The range of RTDs is between 200 and 650 °C.

Many materials are commonly used for making resistance thermometers, such as platinum, nickel, and copper, which are contained in a bulb. However, platinum is the most popular and internationally preferred material. When platinum is employed in RTD elements, they are sometimes termed platinum resistance thermometers. The popularity of platinum is due to the following factors:

1. Chemical inertness
2. Almost linear relationship between temperature and resistance
3. Large temperature coefficient of resistance, resulting in readily measurable values of resistance changes due to variations in temperature
4. Greater stability because the temperature resistance remains constant over a long period of time

Selection of a suitable material for RTD elements depends on the following criteria:

1. The material should be ductile so that it can be formed into small wires.
2. It should have a linear temperature-versus-resistance graph.
3. It must resist corrosion.
4. It should be inexpensive.
5. It should possess greater stability and sensitivity.
6. It must have good reproducibility.

RTDs essentially have the following three configurations:

1. A partially supported wound element: A small coil of wire inserted into a hole in a ceramic insulator and attached along one side of that hole
2. Wire-wound RTD: Prepared by winding a platinum or metal wire on a glass or ceramic bobbin and sealed with a coating on molten glass known as wire-wound RTD elements (Fig. 15.5)
3. Thin film RTD: Prepared by depositing or screening a platinum or metal glass slurry film onto a small flat ceramic substrate called thin film RTD elements

Sensitivity
accuracy
linearity or not
اشيا
مهمة

The general construction of a resistance thermometer is shown in Fig. 15.6. It comprises a number of turns of resistance wire wrapped around a solid silver core. Transmission of heat takes place quickly from the end flange through the core to the winding.

The thin film element used for temperature sensing is manufactured by depositing a very thin (around 10–100 Å) layer of platinum on a ceramic substrate. The platinum layer is coated with epoxy or glass, which protects the deposited platinum film and also acts as a strain reliever for external lead wires. During the early stages of development, thin film sensors were unreliable due to their instability and susceptibility to mechanical failure resulting in the breakage of lead wires. Thin film RTD is the most rugged of the three RTD elements and is preferred for its increased accuracy over time and improved reliability. A thin film responds faster due to its low thermal mass and ease of assembly into smaller packages. Figure 15.7 shows a thin film RTD.

Compared to other types of temperature sensors, RTDs have the following advantages:

1. The resistance versus temperature linearity characteristics of RTDs are higher.
2. They possess greater accuracy (as high as ±0.1 °C). Standard platinum resistance thermometers have ultra-high accuracy of around ±0.0001 °C.
3. They have excellent stability over time.
4. Resistance elements can be used for the measurement of differential temperature.
5. Temperature-sensitive resistance elements can be replaced easily.
6. RTDs show high flexibility with respect to the choice of measuring equipment, interchangeability of elements, and assembly of components.
7. Multiple resistance elements can be used in an instrument.
8. RTDs have a wide working range without any loss of accuracy and, at the same time, can be employed for small ranges also.
9. They are best suited for remote indication applications.
10. It is possible to operate indicators, recorders, or controllers.

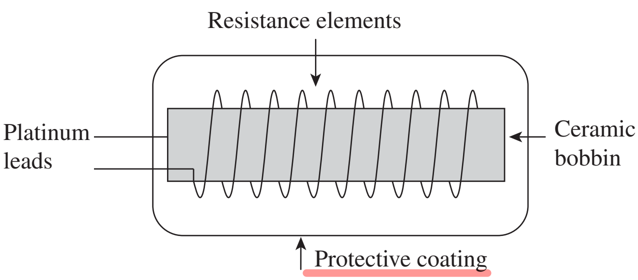


Fig. 15.5 Wire-wound RTD

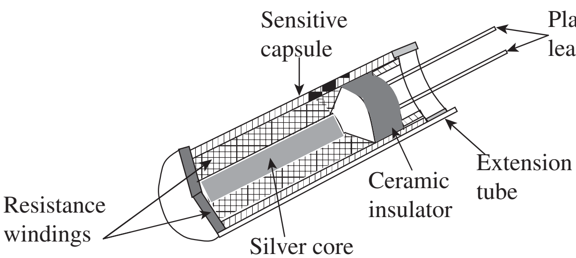


Fig. 15.6 General construction of an RTD

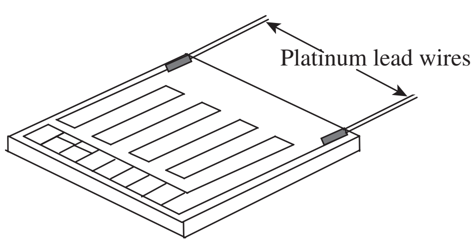


Fig. 15.7 Thin film RTD

RTDs are also associated with some disadvantages. They are as follows:

1. The use of platinum in RTDs makes them more expensive than other temperature sensors.
2. The nominal resistance is low for a given size, and the change in resistance is much smaller than other temperature sensors.

RTD → PTC

مع زيادة الحرارة يزداد الcoefficient

Positive temprature coefficient

Thermistor → +ve PTC Positive

-ve NTC negative ← هذا أكثر انتشاراً بال Thermistor

داخل كامل

3. Although its temperature sensitivity is high, it is less than that of thermistors.

15.5 THERMISTORS

→ Electrical Resistance تتغير قيمة المقاومة لها بتغير درجة الحرارة

more sensetive than the RTD

NTC negative temperature coefficient ← يعني مع زيادة درجة حرارة الdevice قيمة الResistance تقل

Semiconductors that are used to measure temperature are called thermistors. When a thermistor is employed for temperature measurement, its resistance decreases with increase in temperature. The valence electrons, which are mutually shared by the metal atoms, move continuously and freely through the metal during their movement from atom to atom. The vibration in the crystal lattice of atoms increases with the increase in temperature. The free movement of electrons becomes restricted due to an increase in the volume of space occupied by the atoms. In case of thermistors, the valence electrons are attached more firmly to the atoms; some of the electrons are detached and flow due to the increase in temperature, which decreases electrical resistance facilitating the easy flow of electrons. Materials used in thermistors for temperature measurements have very high temperature coefficients (8–10 times higher than platinum and copper) and high resistivity (higher than any pure metal). Thus, they are very sensitive to small variations in temperature and respond very quickly. The relationship between temperature and resistance is given by the following equation:

$R_{ij} = R_j e^{\beta\left(\frac{1}{T_i} - \frac{1}{T_j}\right)}$ → Note T_i, T_j in Kelvins

Relation Not Linear

$$R = R_R e^{\beta\left(\frac{1}{T} - \frac{1}{T_R}\right)}$$

Here, R is the resistance at temperature T, R_R is the resistance at the reference temperature T_R, e is the base of the Napierian logarithm, and β is a constant, which lies in the range of 3000–4600 K depending on the composition.

The temperature coefficient of resistance is given by the following equation:

$$\frac{dR/dT}{R} = \frac{\beta}{T^2}$$

The temperature coefficient of platinum at 25 °C is +0.0036/K and, for thermistors, it is generally around –0.045/K, which is more than 10 times sensitive when compared to platinum. A variety of ceramic semiconductor materials qualify as thermistor materials. Among them, germanium containing precise proportions of arsenic, gallium, or antimony is most preferred. The temperature measurement range of thermistors is –250 to 650 °C.

Thermistors are also produced using oxides of manganese, nickel cobalt, nickel copper, iron, zinc, titanium, and tin. In order to attain better reproducibility and stability of the thermistor characteristics, some chemically stabilizing oxides are added. The oxides are milled into powder form and mixed with a plastic binder, which are then compressed into desired forms such as disks or wafers. Disks are formed by compressing the mixtures using pelleting machines, and the wafers are compression moulded. They are then sintered at high temperatures to produce thermistor bodies. Depending on their intended application, leads are then added to these thermistors and coated if necessary. To achieve the required stability, the thermistors so formed are subjected to a special ageing process. Figure 15.8 illustrates the different forms in which thermistors can be made.

The variation of temperature with voltage and resistance is shown in Fig. 15.9. The use of thermistors as temperature sensors has several advantages:

1. Thermistors possess very high sensitivity, which is much higher than that of RTDs and thermocouples, and hence have the capability to detect very small changes in temperature.

Introduction ✓

15.3 ✓

15.3.2 ✓

Table مو حفظ

Not required ← Thermopilies

RTD File

Advantage and disadvantage ✓

Thermistor ✓ كلو

Advantage disadvantages ✓

Thermocouple section بعد

مدري ؟

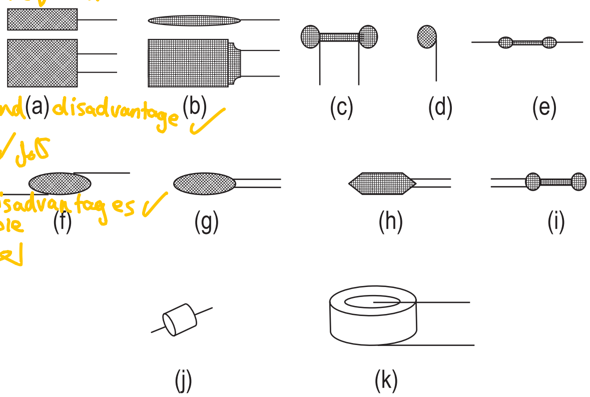


Fig. 15.8 Different forms of thermistors (a, b) Wafers (c–e) Rods (f–i) Beads (j, k) Disks

three devices

مهم المقارنة بين ال

→ Thermistor

→ RTD

→ Thermocouple

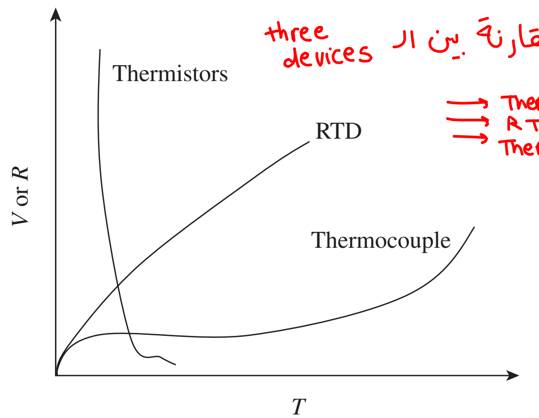


Fig. 15.9 Comparison of temperature characteristics

2. Their response is very fast, and hence, they are employed for precise control of temperature.
3. They are inexpensive.

Thermistors also have certain disadvantages:

1. They have highly non-linear resistance temperature characteristics.
2. The temperature range is narrow.
3. Low fragility is often a problem.
4. High-temperature performance of thermistors is not good and they exhibit instability with time.
5. They are prone to self-heating errors.

I think till here

15.6 LIQUID-IN-GLASS THERMOMETERS

The liquid-in-glass thermometer is the most popular and is widely used for temperature measurement. It comprises a bulb that contains a temperature-sensing liquid, preferably mercury. Alcohol and pentane, which have lower freezing points than mercury and do not contaminate if the bulb is broken, are also used. Since alcohol has a better expansion coefficient than mercury, it is also used. A graduated capillary tube is connected to the bulb. At the top of the capillary, a safety or expansion bulb is provided. Figure 15.10 shows a liquid-in-glass thermometer. A range cavity is provided just above the bulb to accommodate the range variation. The walls of the bulb should be thin in order to facilitate quick transfer of heat. Further, for the response to be quick, the volume of liquid should be small. However, the larger the volume of the liquid, the higher the sensitivity. Since speed of response depends on the volume of the liquid, a compromise needs to be made between sensitivity and response.

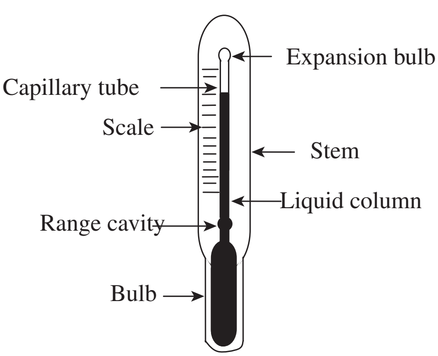


Fig. 15.10 Liquid-in-glass thermometer

The entire assembly is enclosed in a casing to provide protection from breakage. An extra-long stem may be provided to facilitate easy dipping into hot liquids. Calibration of thermometers has to be carried out for better

Picture from the recorded lecture

RTDs are commonly categorized by their nominal resistance at 0 °C. Typical nominal resistance values for platinum thin-film RTDs include 100 and 1000 Ω. In TMT a **PT100 RTD** is used.

In order to measure temperature with the RTD, you only need to measure the resistance of the RTD, and then substitute the resistance value in the following equation

$$T = \frac{R_o - R}{-0.5\left(R_o A + \sqrt{R_o^2 A^2 - 4R_o B(R_o - R)}\right)}$$

Where :

T : *Calculated temperature in (^{o}C).*
R_o : *RTD nominal resistance at 0 °C, R_o=100 Ω.*
R : *Measured resistance (Ω).*
$A = 3.90802 \times 10^{-3}$
$B = -5.80195 \times 10^{-7}$

The above equation will give you the temperature in °C. The value of R_o, A & B differs from one type of RTD to another.

RTD File

Resistance Temperature detector

5.15. RESISTANCE THERMOMETERS

The resistance of a conductor changes when its temperature is changed. This property is utilized for measurement of temperature.

The variation of resistance R with temperature T (°K) can be represented by the following relationship for most of the metals as :

$$R = R_0 (1 + \alpha_1 T + \alpha_2 T^2 + ... + \alpha_n T^n + ...) \quad ...(5.55)$$

where R_0 = resistance at temperature $T = 0$ and $\alpha_1, \alpha_2, \alpha_3 ... \alpha_n$ are constants.

The resistance thermometer uses the change in electrical resistance of conductor to determine the temperature.

The resistivity of metals showed a marked dependence on temperature was discovered by Sir Humphry Davy. A few years later Sir William Siemens proferred the use of platinum as an element in the resistance thermometer. His choice proved most propitious, as platinum is used to this day as the primary element in all high accuracy resistance thermometers. In fact, the platinum resistance temperature detector (PRTD) is used today as an interpolation standard from oxygen point (– 182.96°C) to antimony point (630.74°C)

Platinum is especially suited for this purpose, as it can withstand high temperatures while maintaining excellent stability. As a noble metal, it shows limited susceptibility to contamination. All metals produce a positive change in resistance with temperature. This, of course, is the main function of an RTD. The system error is minimized when the nominal value of RTD is large. This implies a metal with a high value of resistivity should be used for RTDs. The lower is the resistivity of the metal, the more material we will have to use.

The requirements of a conductor material to be used in RTDs are :

(*i*) The change in resistance of material per unit change in temperature should be as large as possible.

(*ii*) The material should have a high value of resistivity so that minimum volume of material is used for the construction of RTD.

(*iii*) The resistance of materials should have a continuous and stable relationship with temperature.

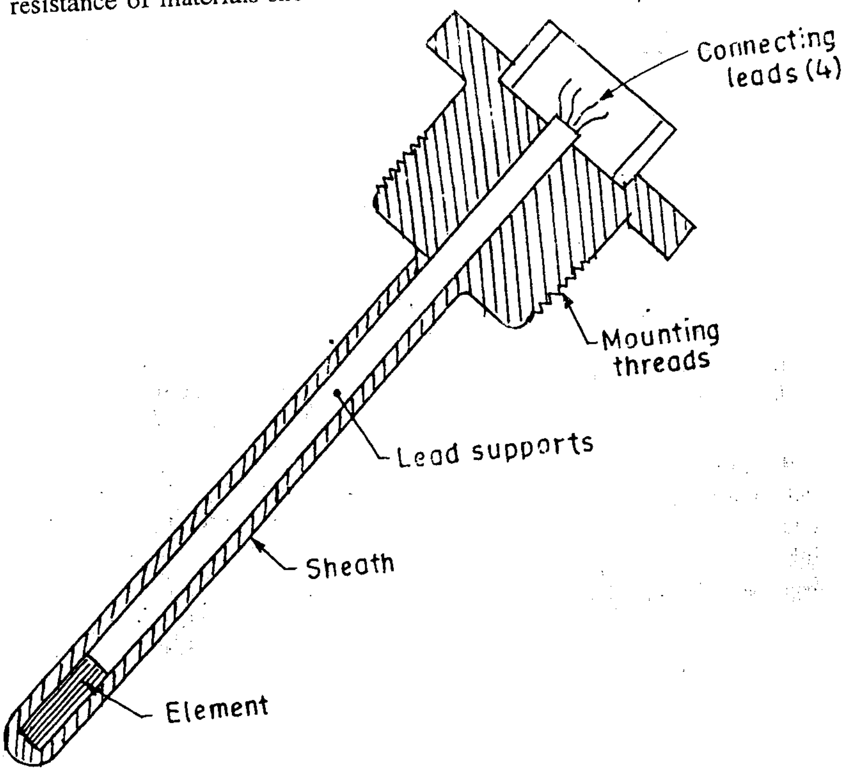


Fig. 5.40. Industrial platinum resistance thermometer.

Gold and **Silver** are rarely used for construction of RTDs on account of their low resistivities. **Tungsten** has relatively a high resistivity, but is reserved for high temperature applications as it is extremely brittle and difficult to work. **Copper** is used occasionally as an RTD element. Its low resistivity forces the element to be longer than the platinum element, but its low linearity and low cost make it an economical alternative. Its upper limit of temperature is about 120°C.

The most common RTDs are made of either platinum, nickel or nickel alloys. The economical **nickel wires** are used over a limited temperature range. They are quite non-linear and tend to drift with time. For measurement integrity, **platinum** is the obvious choice.

The common values of resistance for a platinum RTD range from 10 Ω for the bird cage model to several thousands ohm for the film RTD. The single most common value is 100 Ω at 0°C with a resistance temperature co-efficient of 0.00385/°C. The more chemically pure platinum wire has a resistance temperature co-efficient of 0.00392/°C.

The construction of an industrial type of platinum RTD is shown in Fig. 5.40.

The characteristics of various materials used for resistance thermometers are plotted in Fig. 5.41.

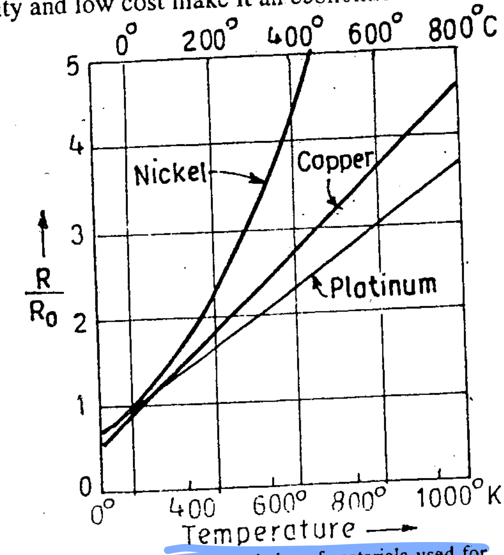


Fig. 5.41. Characteristics of materials used for resistance thermometers.

Metals commonly used for resistance thermometers are listed in Table 5.5 along with their salient properties.

Table 5.5. Metals Used for Resistance Thermometers

Metal	*Resistance temperature Co-efficient /°C*	*Temperature range °C*		*Melting point °C*
		Min	*Max*	
Platinum	0.39	– 260	110	1773
Copper	0.39	0	180	1083
Nickel	0.62	– 220	300	1435
Tungsten	0.45	– 200	1000	3370

An examination of the resistance versus temperature curves of Fig. 5.41, shows that the curves are nearly linear. If fact, when only short temperature spans are considered, the linearity is more evident. This fact is employed to develop approximate analytical equations for resistance versus temperature for a particular metal.

5.15.1. Linear Approximation. A linear approximation means that we may develop an equation for a straight line which approximates the resistance versus temperature curve over a specified span. Fig. 5.42 shows a curve of variation of resistance R with temperature θ°C.

Here a straight line has been drawn between the points of the curve which represent θ_1°C and θ_2°C with θ_0°C representing the mid point temperature. The equation of this straight line is the *linear approximation* of the curve from θ_1°C to θ_2°C. The equation of the straight line is written as :

$$R_\theta = R_{\theta 0}\,(1 + \alpha_{\theta_0}\,\Delta\theta) \text{ with } \theta_1 < \theta_0 < \theta_2 \qquad ...(5.56)$$

where R_θ = approximate resistance at θ°C ; Ω,

R_{θ_0} = approximate resistance at θ_0°C ; Ω,

$\Delta\theta = \theta - \theta_0$ = change in temperature ; °C, using values of resistance and temperature at three different points. Two equations are formed and values of α_1 and α_2 are calculated from these.

Example 5.17. Use the following values of resistance versus temperature for an RTD to find the linear and quadratic approximations of resistance between 100°C and 130°C about a mean temperature of 115°C.

Temperature, C°	90	95	100	105	110	115	120	125	130
Resistance Ω	562.66	568.03	573.40	578.77	584.13	589.48	594.84	600.18	605.52

Solution.

1. Linear Expansion : Given :

$$\theta_1 = 100°C,\ \theta_2 = 130°C,\ \theta_0 = 115°C$$

$$R_{\theta_1} = 573.40\ \Omega,\ R_{\theta_2} = 605.52\ \Omega,\ R_{\theta_0} = 589.48\ \Omega$$

From Eqn. 5.57,

$$\alpha_{\theta_1} = \alpha_1 = \frac{1}{R_{\theta_0}} \times \frac{R_{\theta_2} - R_{\theta_1}}{\theta_2 - \theta_1}$$

$$= \frac{1}{589.48} \times \frac{605.52 - 573.40}{130 - 100} = 0.00182\ /°C$$

∴ The linear approximation is :

$$R_\theta = 589.48\ [1 + 0.00182\ (\theta - 115)]\ \Omega.$$

2. Quadratic Expansion : The resistance R_θ at any temperature θ°C is given by :

$$R_\theta = R_{\theta_0}\ [1 + \alpha_1\ \Delta\theta + \alpha_2\ (\Delta\theta)^2]$$

We can find the quadratic terms, by forming two equations using two points about the mean temperature $\theta_0 = 115°C$.

We have, $R_{\theta_0} = 589.48\ \Omega$ at $\theta_0 = 115°C$.

Now using 100°C and 130°C as the two points, we have :

$$573.40 = 589.48\ [1 + \alpha_1\ (100 - 115) + \alpha_2\ (100 - 115)^2]$$

$$605.52 = 589.48\ [1 + \alpha_1\ (130 - 115) + \alpha_2\ (130 - 115)^2]$$

From above have,

$$\alpha_1 = 1.823 \times 10^{-3}/°C \text{ and } \alpha_2 = -0.22 \times 10^{-6}/(°C)^2$$

Hence,

$$R_\theta = 589.48\ [1 + 1.823 \times 10^{-3}\ (\theta - 115) - 0.22 \times 10^{-6}\ (\theta - 115)^2]\ \Omega.$$

Example 5.18. A platinum thermometer has a resistance of 100 Ω at 25°C. (*a*) Find its resistance at 65°C if the platinum has a resistance temperature co-efficient of 0.00392/°C. (*b*) If the thermometer has a resistance of 150 Ω, calculate the temperature.

Solution. (*a*) Using the linear approximation, the resistance at any temperature θ°C, is

$$R_\theta = R_{\theta_0}\ [1 + \alpha_{\theta_0}\Delta\theta]$$

∴ Resistance at 65°C is,

$$R_{65} = 100\ [1 + 0.00392\ (65 - 25)]$$
$$= 115.68\ \Omega.$$

(*b*) Suppose θ is the unknown temperature,

$$150 = 100\ [1 + 0.00392\ (\theta - 25)]$$
$$\theta = 152.55°C.$$

or

Example 5.19. A copper resistor at 20°C is to used to indicate the temperature of bearings of a machine. What resistance should not be exceeded if the maximum bearing temperature is not to exceed 150°C ? The resistance temperature co-efficient of copper is 0.00393/°C at 20°C.

Solution. The value of resistance in case the temperature is not to exceed 150°C can be calculated as under.

$$R_{150} = 10\ [1 + 0.00393\ (150 - 20)]$$
$$= 15.11\ \Omega.$$

Example 5.20. A temperature alarm unit with a time constant of 120s is subjected to a sudden rise of temperature of 50°C because of fire. If an increase of 30°C is required to actuate the alarm, what will be the delay in sudden temperature increase ?

Solution. Assume the thermometer be a first order system, the variation of indicated temperature θ, to a step input temperature θ_0 is

$$\theta = \theta_0\ [1 - \exp\ (-\ t/\tau)]$$
$$30 = 50\ [1 - \exp\ (-\ t/120)]$$

or
$$t = 110\ \text{s}.$$

The alarm would be delayed by 110 s.

5.16. THERMISTORS

Thermistor is a contraction of a term **"thermal resistors"**. Thermistors are generally composed of semi-conductor materials. Although positive temperature co-efficient of units (which exhibit an increase in the value of resistance with increase in temperature) are available, most thermistors have a negative coefficient of temperature resistance *i.e.* their resistance decreases with increase of temperature. The negative temperature coefficient of resistance can be as large as several percent per degree celcius. This allows the thermistor circuits to detect very small changes in temperature which could not be observed with an RTD or a thermocouple. In some cases the resistance of thermistor at room temperature may decrease as much as 5 percent for each 1°C rise in temperature. This high sensitivity to temperature changes makes thermistors extremely useful for precision temperature measurements control and compensation.

Thermistors are widely used in applications which involve measurements in the range of − 60°C to 15°C. The resistance of thermistors ranges from 0.5 Ω to 0.75 MΩ. Thermistor is a highly sensitive device. The price to be paid off for the high sensitivity is in terms of linearity. The thermistor exhibits a highly non-linear characteristic of resistance versus temperature.

5.16.1. Construction of Thermistors. Thermistors are composed of sintered mixture of metallic oxides such as manganese, nickel, cobalt, copper, iron and uranium. They are available in variety of sizes and shapes. The thermistors may be in the form of beads, rods and discs. Some of the commercial forms are shown in Fig. 5.43.

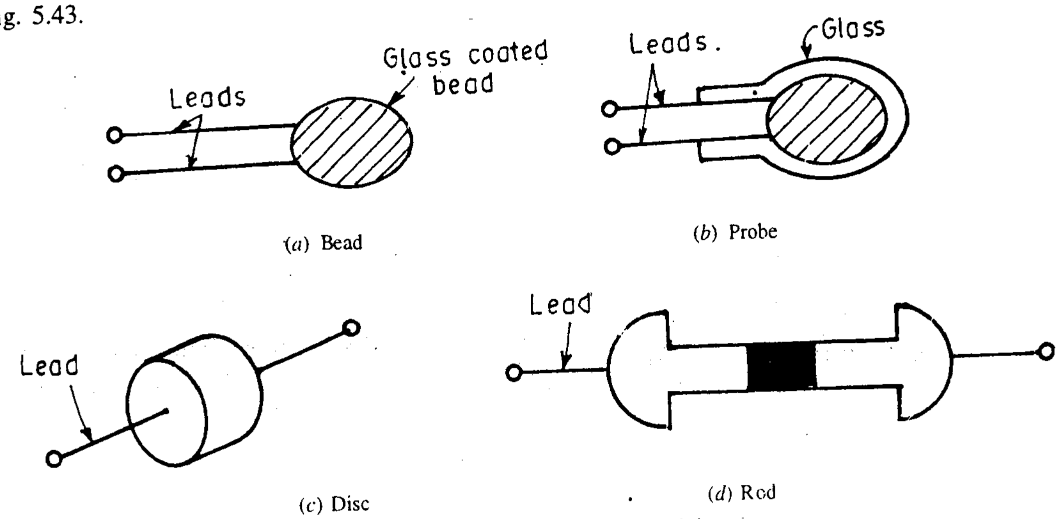


Fig. 5.43. Different forms of construction of thermistors.

A thermistor in the form of a bead is smallest in size and the bead may have a diameter of 0.015 mm to 1.25 mm. Beads may be sealed in the tips of solid glass rods to form probes which may be easier to mount than the beads. Glass probes have a diameter of about 2.5 mm and a length which varies from 6 mm to 50 mm. Discs are made by pressing material under high pressure into cylindrical flat shapes with diameters ranging from 2.5 mm to 25 mm.

5.16.2. Resistance-Temperature Characteristics of Thermistors. The mathematical expression for the relationship between the resistance of a thermistor and absolute temperature of thermistor is :

$$R_{T1} = R_{T2} \exp\left[\beta\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \quad \text{...(5.59)}$$

T_1, T_2 in kelvin

where R_{T1} = resistance of the thermistor at absolute temperature T_1 ; K,

R_{T2} = resistance of the thermistor at absolute temperature T_2 ; K

and β = a constant depending upon the material of thermistor, typically 3500 to 4500 K

The resistance temperature characteristics of a typical thermistor are given in Fig. 5.44. The resistance temperature characteristics of Fig. 5.44 show that a thermistor has a very high negative temperature co-efficient of resistance, making it an ideal **temperature transducer.**

Fig. 5.44 also shows the resistance-temperature characteristics of platinum which is a commonly used material for resistance thermometers. Let us compare the characteristics of the two materials. Between —100°C and 400°C, the thermistor changes its resistivity from 10^5 to 10^{-2} Ωm, a factor of 10^7, while platinum changes its resistivity by a factor of about 10 within the same temperature range. This explains the high sensitivity of thermistors for measurement of temperature.

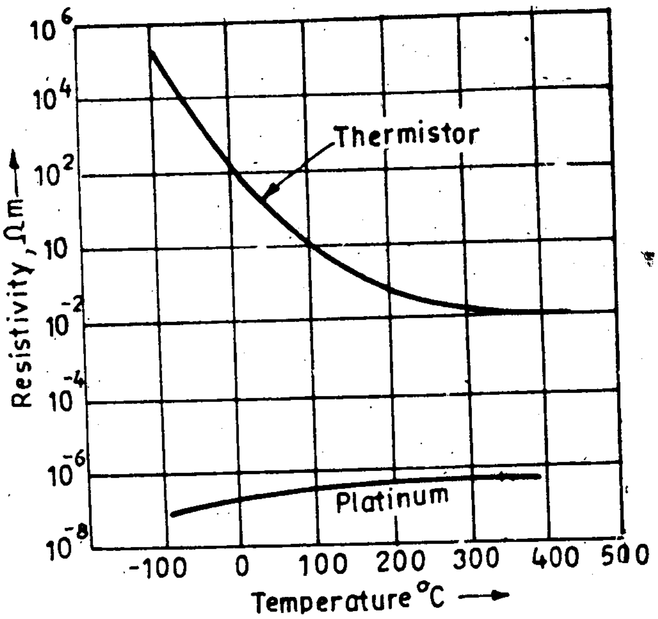


Fig. 5.44. Resistance-temperature characteristics of a typical thermistor and platinum.

The characteristics of thermistors are no doubt non-linear but a linear approximation of the resistance-temperature curve can be obtained over a small range of temperatures. Thus, for a limited range of temperature, the resistance of a thermistor varies as given by Eqn. 5.60.

$$R_\theta = R_{\theta_0}\,[1 + \alpha_{\theta_0}\,\Delta\theta] \quad \text{...(5.60)}$$

A thermistor exhibits a negative resistance temperature co-efficient which is typically about 0.05/°C. An individual thermistor curve can be closely approximated through the **Steinhart-Hart equation** :

$$\frac{1}{T} = A + B \log_e R + C (\log_e R)^3 \quad \text{...(5.61)}$$

where T = temperature ; K,

R = resistance of thermistor ; Ω,

A, B, C = curve fitting constants.

A, *B* and *C* are found by selecting three data points on the published data curve and solving the three simultaneous equations. When the data points are chosen to span no more than 100°C within the nominal centre of thermistors temperature range, this equation approaches a remarkable ± 0.2°C curve fit.

A simpler equation is :

$$T = \frac{B}{\log_e R - A} - C \qquad ...(5.62)$$

where *A*, *B* and *C* are found by selecting three (*R*, *T*) data points and solving three resultant simultaneous equations. Eqn. 5.62 must be applied over a narrower temperature range in order to approach the accuracy achieved by Steinhart-Hart Equation. Another, relationship that can be conveniently used for resistance-temperature curve of thermistors is :

$$R_T = aR_o \exp\,(b/T) \qquad ...(5.63)$$

where, R_T, R_o = resistance of thermistor at temperature T°K and ice point respectively.

5.16.3. Voltage-Current and Current-Time Characteristics of Thermistors. Three important characteristics of thermistor make them extremely useful in measurement and control applications. These are :

(*i*) the *resistance–temperature* characteristics,

(*ii*) the *voltage current* characteristics.

(*iii*) the *current–time* characteristics.

1. Resistance Temperature Characteristics. The resistance-temperature characteristics have already been described in Art. 5.16.2. The other two characteristics are described below.

2. Voltage – Current Characteristics. These characteristics are shown in Fig. 5.45. This diagram shows that the voltage drop across a thermistor increases with increasing current until is reaches a peak value beyond which the voltage drop decreases as the current increases. In this portion of the curve, the thermistor exhibits a *negative resistance* characteristic. If a very small voltage is applied to the thermistor, the resulting small current does not produce sufficient heat to raise the temperature of the thermistor above ambient. Under this condition, Ohm's law is followed and the current is proportional to the applied voltage. Larger currents, at larger applied voltages, produce enough heat to raise the thermistor temperature above the ambient temperature and its resistance then decreases. As a result, more current is then drawn and the resistance decreases further. The current continues to increase until the heat dissipation of the thermistor equals the power supplied to it. Therefore, under any fixed ambient conditions, the resistance of a thermistor is largely a function of the power being dissipated within itself, provided that there is enough power available to raise its temperature above ambient. Under such operating conditions, the temperature of the thermistor may rise 100°C or 200°C and its resistance may drop to one-thousandth of its value at low current.

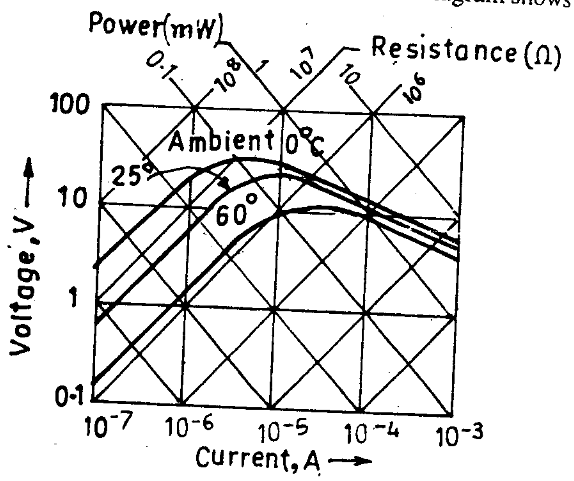


Fig. 5.45. Voltage-currents characteristics of thermistors.

This characteristic of *self-heat* provides an entirely new field of uses for the thermistor. In the self-heat state, the thermistor is sensitive to anything that changes the *rate* at which heat is conduced away from it. It can so be used to measure *flow, pressure, liquid level, composition of gases,* etc. If, on the other hand, the rate of heat removal is fixed, then the thermistor is sensitive to power input and can be used for *voltage* or *power-level* control.

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5 Primary Sensing Elements and Transducers

5.1. INTRODUCTION

The measurand in an instrumentation system makes its first contact with a *Primary Detection Element* or an *Input Device*. There is a multiplicity and variety of measurands to be measured. These include process variables like temperature, pressure and flow rate which are widely employed in process and production plants. The measurands also include electrical quantities like current, voltage, resistance, inductance, capacitance, frequency, phase angle, power and magnetic quantities like flux, flux density, reluctance etc.

All these quantities require a primary detection element and/or a transducer to be converted into another analogous format which is acceptable by the later stages of the measurement system. The measurand or the input signal is called an *information* for the measurement system. The information may be in the form of a physical phenomenon or it may be an electrical signal. The process of detection and conversion of the information into an acceptable form requires energy. This energy may be extracted from the measurand, but in that case it will not be represented in its faithful form as it would be subjected to loading errors. In order that a measurand is represented in its faithful form undistorted, no energy should be extracted from it during the process of conversion *i.e.* it should not be subjected to any kind of loading effects. In fact, efforts should be made to supply energy required for conversion from outside sources so that the measurand is not distorted during the process of conversion in order that it be faithfully reproduced in its analogous form. The ideal conversion is where absolutely no energy is extracted from the measurand during the process of conversion and all the energy that is required for conversion is supplied from outside, so that the measurand is not distorted and the analogous output of the detector is a faithful representation of the measurand.

5.2. MECHANICAL DEVICES AS PRIMARY DETECTORS

In order to extract information from mechanical systems, only mechanical displacement or velocity can be used as detectable variables, and therefore the importance of mechanical sensing elements is obvious. Some of the commonly used mechanical sensing elements are springs – which convert a force or a torque into a displacement ; a diaphragm, a capsule, bellows or Bourdon tube – which convert pressure into a displacement, a bimetallic strip converts temperature into a displacement ; a mass damper system is used for measurement of acceleration, velocity and displacement. Some input devices may involve more than one mechanical conversion, for example, fluid flow measurements may involve conversion of fluid rate into pressure differential using an orifice, venturi tube or pitot tube and then in turn this pressure is converted into displacement for purposes of measurement.

There are a number of mechanical quantities which are to be measured. Some of these quantities are listed in table 5.1 along with their modes of operation for the purposes of measurement.

Table 5.1

Mechanical Quantities and their Modes of Operation

Type	*Operation*
A. Contacting spindle, pin or finger	Displacement to displacement
B. Elastic Member	
1. Proving ring	Force to displacement.
2. Bourdon tube	Pressure to displacement.
3. Bellows	Pressure to displacement.
4. Diaphragm	Pressure to displacement.
5. Spring	Force to displacement.
C. Mass	
1. Seismic mass	Forcing function to displacement.
2. Pendulum scale	Force to displacement.
3. Manometer	Pressure to displacement.
D Thermal	
1. Thermocouple	Temperature to electric current.
2. Bimaterial	Temperature to displacement.
3. Temp-stick	Temperature to phase.
E Hydropneumatic	
1. Static	
(*a*) Float	Fluid level to displacement.
(*b*) Hydrometer	Specific gravity to displacement.
2. Dynamic	
(*a*) Orifice	Velocity to pressure.
(*b*) Venturi	Velocity to pressure.
(*c*) Pitot tube	Velocity to pressure.
(*d*) Vanes	Velocity to force.
(*e*) Turbines	Linear to angular velocity.

These mechanical quantities include force, pressure, displacement, flow rate, temperature and the list is perhaps unending.

The initial concept of converting an applied force into a displacement is basic to many types of primary sensing elements. The mechanical elements which are used to convert the applied force into displacement are usually elastic members. There are many types of these elastic members. They can be classified into three categories, although some elastic members may fall into a combination of these categories. The three categories are :

(*i*) Direct tension or compression type (*ii*) Bending type, (*iii*) Torsion type.

5.3. MECHANICAL SPRING DEVICES

Most mechanical-input measuring systems employ mechanical springs of one form or another. The displacements are usually small and engineering approximations for small displacements or deflections are valid. Various common types of springs are shown in Fig. 5.1. These range from cantilever, helical and spiral springs to torsion bars, proving (proof) rings and spring flexure pivots.

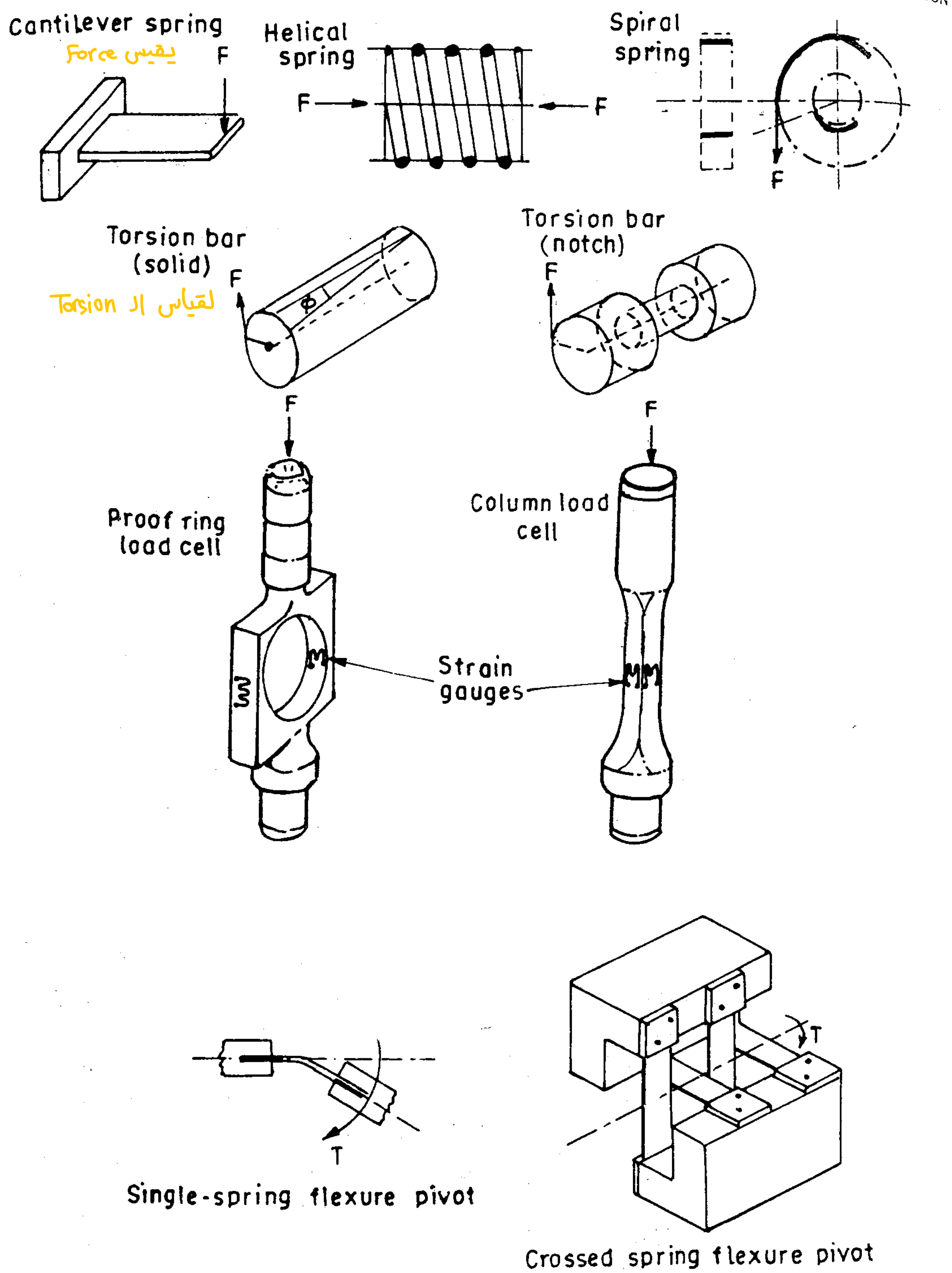


Fig. 5.1. Spring elements used for sensing force (F) or torque (T).

5.3.1. Cantilever. A cantilever is shown in Fig. 5.2 which is subjected to a force at its free end.

كلما كان ال load أكبر
ال displacement أكبر

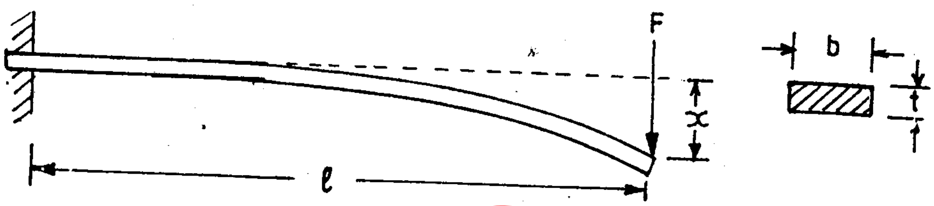


Fig. 5.2. Cantilever.

Deflection at the free end $x = Fl^3/3\,EI$ ...(5.1)

where F = applied force ; N, l = length of cantilever ; m,

E = modulus of elasticity ; N/m²,

I = moment of inertia = $\left(\frac{1}{12}\right) bt^3$; m⁴,

b = width of cantilever ; m,

t = thickness of cantilever ; m.

مهم نكون احنا عارفين شو همة ال variables

Stiffness of cantilever $K = F/x = 3\,EI/l^3$ N/m ...(5.2)

5.3.2. Helical Spring.

Fig. 5.3 shows a close coiled helical spring subjected to a compressive force F.

given المعادلات

Displacement of spring :

اعلى Force
اعلى displacement

$$x = \frac{8\,FD^3n}{Gd^4} \qquad ...(5.3)$$

where F = applied force ; N,

D = mean diameter of coiled spring ; m,

d = diameter of spring wire ; m,

n = number of wires,

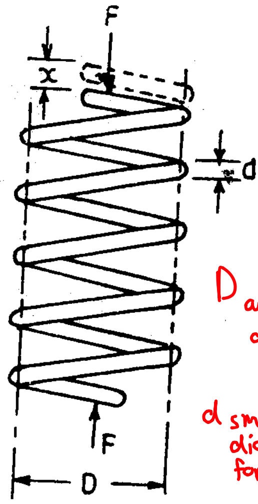
G = shear modulus ; N/m².

Stiffness of spring $K = F/x$

$= Gd^4/8\,D^3n$ N/m. ...(5.4)

Maximum shear stress,

$\tau = 8\,FD/(\pi d^3)$ N/m². ...(5.5)



D average diameter

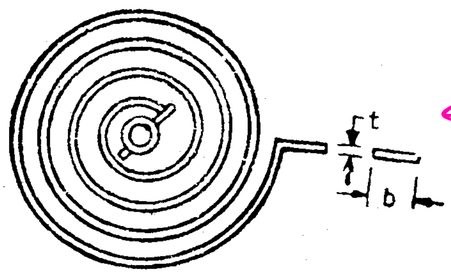
d small diameter for wire

Fig. 5.3. Closed coiled helical spring.

5.3.3. Spiral Spring.

Fig. 5.4 shows a flat spiral spring subjected to a torque T.

The deflection of the spring is :



two parameters

Fig. 5.4. Flat spiral spring.

لقياس ال Torque

$$\theta = E\,bt^3T/12\,l, \text{ rad.} \quad ...(5.6)$$

where E = modulus of elasticity ; N/m^2,

b = width of spring ; m,

t = thickness of spring ; m,

l = length of spring ; m,

T = torque ; Nm.

$\therefore$ Stiffness of spring $K = T/\theta = Ebt^3/12\,l$ Nm/rad. ...(5.7)

The springs should be stressed well below their elastic limit at maximum deflection in order that there is no permanent set or that no change in deflection (or zero shift) will occur from inelastic field

The maximum fibre stress is,

$$s_{max} = 6\,T/bt^2 \text{ N/m}^2 \quad ...(5.8)$$

Combining Eqns. 5.6 and 5.8, we have,

$$l/t = (E/2\,s_{max})\,\theta \quad ...(5.9)$$

Spiral springs are used for production of controlling torque in analog instruments.

5.3.4. Torsion Bars or Shafts. These are primary sensing elements for torque. They are made use of in torque meters. The deflection or twist of the bar is proportional to the applied torque and the deformation is used as a measure of the torque.

Some torque meters are designed so that the angular displacement due to twisting of the bar is measured with the help of displacement transducer. In others, the strain in the surface of the bar, which is proportional to the torque, is measured with the help of strain gauges. The shear strain is a measure of the torque.

Angle of twist $\theta = 16\,T/\pi G d^3$ rad, ...(5.10)

where T = applied torque ; Nm,

G = shear modulus ; N/m^2,

d = diameter of bar ; m.

Sometimes, *notched bars* are used. The notched bar has the advantage that it has a greater sensitivity on account of its reduced diameter (of the notched portion)

5.3.5. Proving (Proof) Rings. They are used for measurement of force, weight or load. The applied force causes a deflection which is measured with the help of electrical transducers.

Proving rings are made up of steel and are used as force standards. They are particularly useful for calibration of material testing machines in situations where dead weight standards are impracticable to use on account of their bulk. A *proving ring* is a circular ring of rectangular cross-section as shown in Fig. 5.5 which may be subjected to either tensile or compressive forces across its diameter.

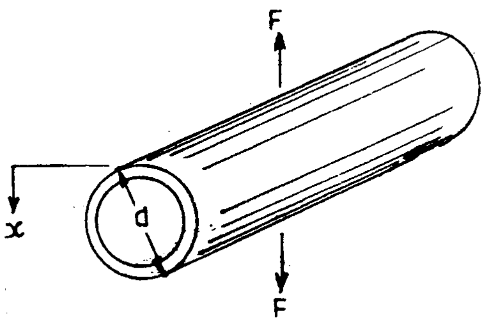


Fig. 5.5. Proving ring.

The deflection is given by :

$$x = \frac{(\pi/2 - 4/\pi)\,d^3}{16\,EI}\,F \quad ...(5.11)$$

where d = outside ring diameter ; m.

The other terms have been explained earlier.

The common practice for measurement of displacement is to attach a displacement transducer between the top and bottom of the proving ring. When the force is applied, the relative displacement can be measured. An LVDT is normally used for measurement of deflection which is of the order of 1 mm or so. Another method is to use strain gauges for measurement of strain caused by the applied force. The strain, then, can be used to compute the applied force.

5.3.6. Load Cells. Load cells utilize an elastic member as the primary transducer and strain gauges as secondary transducers as shown in Fig. 5.6.

5.3.7. Spring Flexure Pivots. Fig. 5.1 shows two different types of arrangements for flexure pivots, one for the single spring flexure pivot and the second for crossed spring flexure pivot. The crossed-spring flexure pivot is widely used in measurement work for the following reasons :

(*i*) it is practically frictionless

(*ii*) the pivot sensitivity *i.e.* the angular deflection per unit applied torque is virtually constant for angular relations less than 15°.

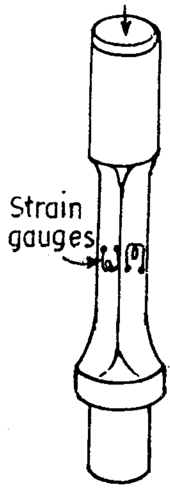


Fig. 5.6. Load cells.

5.4. PRESSURE SENSITIVE PRIMARY DEVICES

Most pressure measuring devices use elastic members for sensing pressure at the primary stage. These elastic members are of many types and convert the pressure into mechanical displacement which is later converted into an electrical form using a secondary transducer. These devices are many a time known as **force summing devices.** Fig. 5.7 shows some of the commonly *pressure sensitive primary devices*

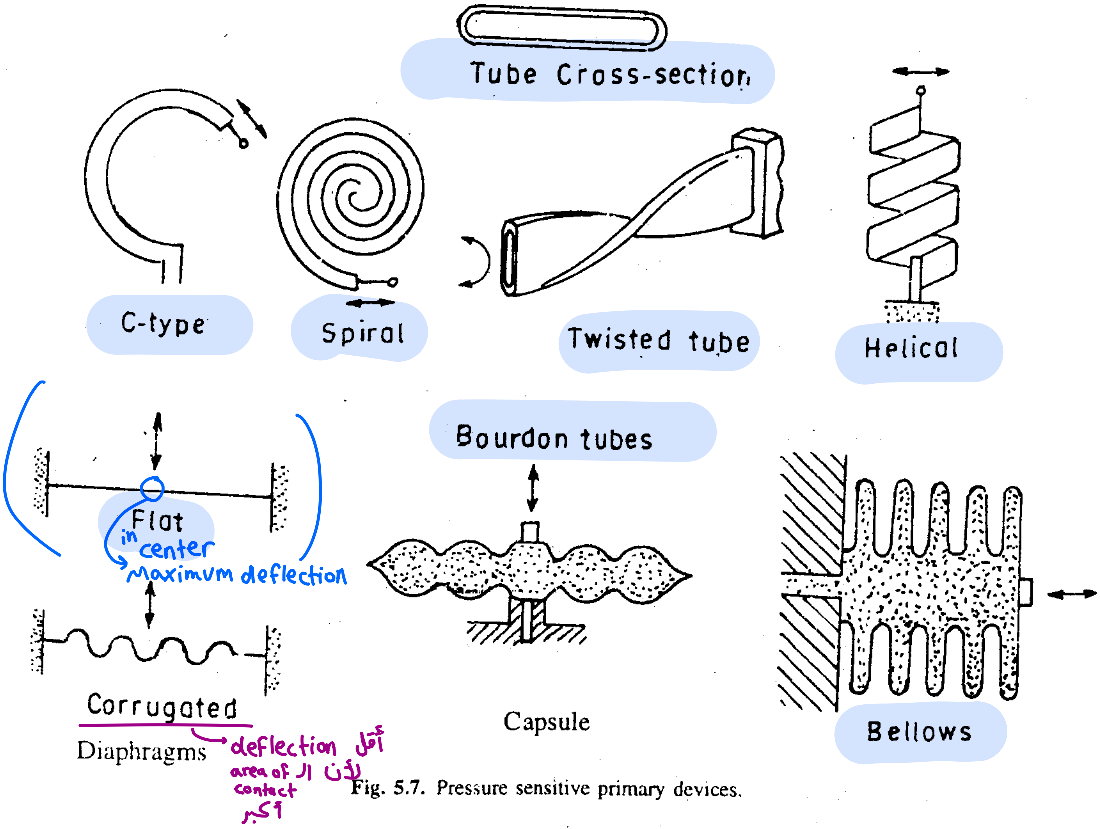


Fig. 5.7. Pressure sensitive primary devices.

The principle of working of these devices is explained as : the fluid whose pressure is to be measured is made to press the pressure sensitive element and since the element is an elastic member, it deflects causing a mechanical displacement. The displacement is proportional to the pressure applied. The displacement is then measured with the help of electrical transducers. The output of the electrical transducers is proportional to the displacement and hence to the applied input pressure.

Some of the commonly used force summing devices are, (*i*) Bourdon tubes, (*ii*) Diaphragms and (*iii*) Bellows. They are described below :

5.4.1. Bourdon Tubes. These are designed in various forms like :

(*i*) C type (*ii*) spiral (*iii*) twisted tube and (*iv*) helical.

The Bourdon tubes are made out of an elliptically sectioned flattened tube bent in such a way as to produce the above mentioned shapes. One end of the tubes is sealed or closed and physically held. The other end is open for the fluid to enter. When the fluid whose pressure is to be measured enters the tube, the tube tends to straighten out on account of the pressure. This causes the movement of the free end and the displacement of this end is amplified through mechanical linkages. The amplified displacement of the free end may be used to move a pointer over a scale calibrated in units of pressure. Bourdon tubes normally measure gauge pressure. The materials used for Bourdon tubes are brass, phosphor bronze, beryllium copper, and steel.

5.4.2. Diaphragms. The movement of a diaphragm is a convenient way of sensing low pressures. A diaphragm is a circular disc of thin, springy metal firmly fixed at its rim. The unknown pressure is applied to one side of the diaphragm and since the rim of the diaphragm is rigidly fixed there is a deflection of the diaphragm. The displacement of the centre of the diaphragm is directly proportional to the pressure and therefore can be used as a measure of pressure.

The displacement of the diaphragm may be transmitted by an arm fastened to its centre to a mechanical linkage, which magnifies the displacement before applying it to a pointer of the indicating device.

The diaphragms are of two types :

(*i*) Flat, and (*ii*) Corrugated.

Corrugated diaphragms have an advantage over flat diaphragms because of the increased effective area and consequent greater sensitivity.

The diaphragms may be thin membranes. However, it is usual to employ thin circular plates which may either be clamped around the circumference between solid rings or are machined to form a solid piece of metal.

In many applications two or more diaphragms are joined to form a *capsule*, as shown in Fig. 5.7. Increasing the pressure in the capsule causes it to expand while decreasing the pressure causes it to contract. As all the diaphragms in the capsule act in unison. the displacement of the arm connected to centre of the capsule, is greater than that of a single diaphragm for the same pressure and hence the sensitivity is greater.

A flat diaphragm is shown in Fig. 5.8.

Maximum deflection

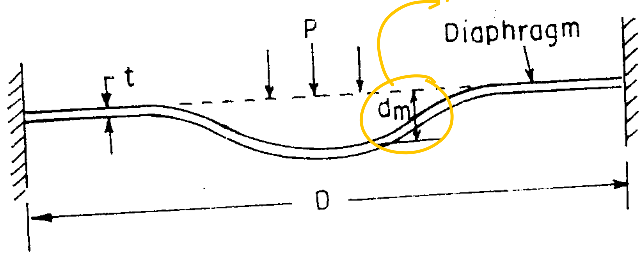


Fig. 5.8. Flat diaphragm.

The pressure is given by :

$$p = \boxed{\frac{256\,Et^3\,d_m}{3(1-\nu^2)D^4}\ \text{N/m}^2} \qquad ...(5.12)$$

RTD
Thermistor
File

where E = Young's modulus, N/m^2 ;

D, t = diameter and thickness of diaphragm respectively, m.

ν = Poisson's ratio,

and d_m = deflection at the centre of the diaphragm ; m.

The above relationship between pressure, P, and the deflection at the centre d_m, is linear. But linearity holds good as long as $d_m < 0.5t$ and not otherwise.

The maximum stress at the circumference of diaphragm is,

$$s_m = \frac{3D^2P}{16t^2} \text{ N/m}^2 \qquad \text{...(5.13)}$$

The lowest natural frequency for air or gas as medium is,

$$\omega_n = \frac{20t}{D^2}\sqrt{\left[\frac{E}{3\rho(1-\nu^2)}\right]} \text{ rad/s.} \qquad \text{...(5.14)}$$

where ρ = density of diaphragm material ; kg/m^3.

5.4.3. Bellows. The bellows element consists of a cylindrical metal box with corrugated walls of thin, springy material like brass, phosphor bronze, or stainless steel. The thickness of walls is typically 0.1 mm. Bellows are used in applications where the pressures involved are low.

The pressure inside the bellows tends to extend its length. This tendency is opposed by the springness of the metals, which tends to restore the bellows to its original size. Pressure on the outside of the bellows tends to reduce its length and this tendency also, is opposed by the springiness of metal. When the pressures are small the springiness of the metal suffices. However, when the pressures are high, the springiness of the walls may not be sufficient to restore the bellows to its original size. For such applications springs are located inside the bellows to provide additional springiness to restore the bellows to its original size.

The action of the bellows is as under :

The pressure to be measured is applied from the left end as shown in Fig. 5.7. The pressure inside the bellows extends its length. Since the left hand end is fixed, there is a displacement of the right hand end to which a rod is connected. The displacement of this rod is directly proportional to the pressure inside the bellows. The displacement of the rod is small and may be amplified by using mechanical linkage and then transferred to a pointer moving over a calibrated scale.

We have seen above that the action of the Bourdon tube, the diaphragm and the Bellows are all based upon the elastic deformations brought out by the force resulting from pressure summation. The deformations or mechanical displacements are normally very small to be detectable with good accuracy by mechanical means and hence secondary transducers which are electrical in nature have to be used invariably and probably compulsorily in order that the output is of intelligible and interpretable form.

Example 5.1. A flat circular diaphragm of mild steel has a diameter of 15 mm. For mild steel, Young's modulus $E = 200 \text{ GN/m}^2$, and Poisson's ratio $\nu = 0.28$

Find the thickness of the diaphragm if the maximum stress is not to exceed 200 MN/m^2 when the pressure is 300 kN/m^2. Find the deflection at the centre for a pressure of 150 kN/m^2.

Sol. From Eqn. 5.13, we have,

maximum stress $s_m = 3\, D^2\, P/16t^2$

$$\therefore \quad \text{Thickness} \qquad t = \sqrt{\frac{3D^2\,P}{16\,s_m}} = \sqrt{\frac{3 \times (15 \times 10^{-3})^2 \times 300 \times 10^3}{16 \times 200 \times 10^6}}$$

$$= 0.205 \times 10^{-3} \text{ m} = 0.205 \text{ mm.}$$ = 0.25 mm

The deflection at the centre for a pressure of 150 kN/m^2 as given by Eqn. 5.12 is,

$$d_m = \frac{3(1-\nu^2)\,D^4P}{256\,Et^3} = \frac{3(1-0.28^2)(15 \times 10^{-3})^4 \times 150 \times 10^3}{256 \times 200 \times 10^9 \times (0.205 \times 10^{-3})^3}$$

~~1.67 × 10^-12~~ m.

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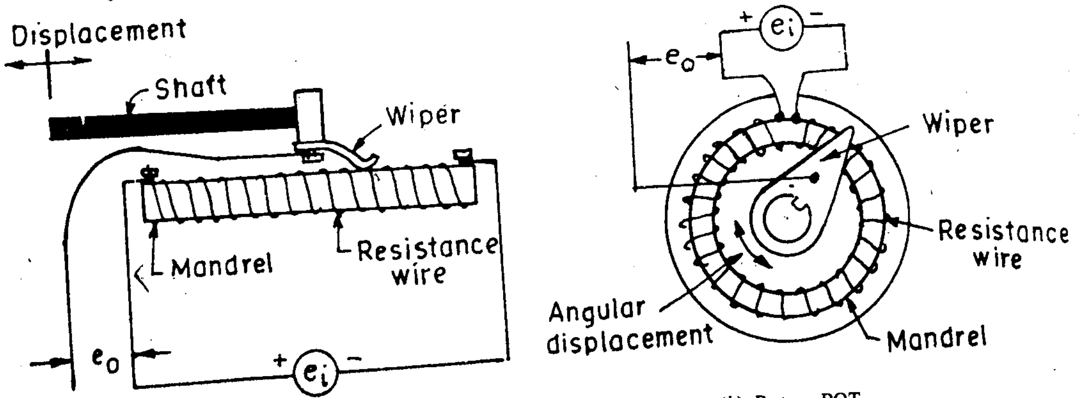
This property may be used for measurement of **temperature.** Thus electrical resistance transducers have a wide field of application.

5.11. POTENTIOMETERS

Basically a resistance potentiometer, or simply a **POT**, (a resistive potentiometer used for the purposes of voltage division is called a **POT**) consists of a resistive element provided with a sliding contact. This sliding contact is called a **wiper**. The motion of the sliding contact may be translatory or rotational. A linear pot and a rotary pot are shown in Fig. 5.24 (*a*) and (*b*) respectively.



(*a*) Linear (translational) POT (*b*) Rotary POT

Fig. 5.24. Resistive potentiometers (POTs)

Some **POTs** use the combination of the two motions, *i.e.* translational as well as rotational. These POTs have their resistive element in the form of a helix and, therefore, they are called **helipots.**

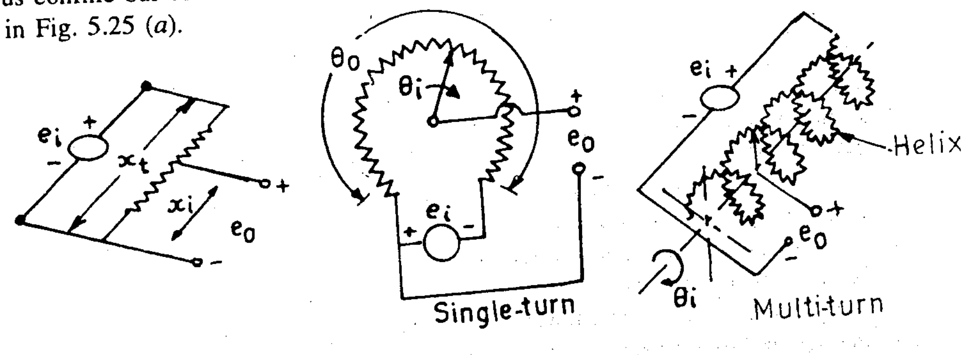
The translational resistive elements are straight devices and have a stroke of 2 mm to 0.5 m. The rotational devices are circular in shape and are used for measurement of angular displacement. They may have a full scale angular displacement as small as 10°. A full single turn potentiometer may provide accurate measurements upto 357°. Multiturn potentiometers may measure upto 3500° of rotation through use of **helipots.**

The helical resistive elements are multiturn rotational devices which can be used for measurement of either translational or rotary motion. The resistive element of the POT may be excited by either d.c. or a.c. voltage. The POT is a **passive transducer** since it requires an external power source for its operation.

The resistive body of potentiometer may be wire wound. A very thin, 0.01 mm diameter of platinum or nickel alloy is carefully wound on an insulated former. The resistance elements are also made up from cermet, hot moulded carbon, carbon film and thin metal.

Fig. 5.25 shows the diagrams for translational, single turn rotational, and multiturn helix potentiometers.

Let us confine our discussion of d.c. excited potentiometers. Consider a translational potentiometer as shown in Fig. 5.25 (*a*).



(*a*) Translational (*b*) Rotational (*c*) Helipot

Fig. 5.25. Diagrams for translational, rotational and helipots.

Let, e_i and e_o = input and output voltages respectively ; V,

x_t = total length of translational pot ; m,

x_i = displacement of wiper from its zero position ; m,

R_p = total resistance of the potentiometer ; Ω.

If the distribution of the resistance with respect to translational movement is linear, the resistance per unit length is R_p/x_t.

The output voltage under ideal conditions is :

$$e_0 = \left(\frac{\text{resistance at the output terminals}}{\text{resistance at the input terminals}}\right) \times \text{input voltage}$$

$$= \left[\frac{R_p(x_i/x_t)}{R_p}\right] e_i = \frac{x_i}{x_t} \times e_i \qquad \text{...(5.28)}$$

Under the ideal circumstances, the output voltage varies linearly with displacement as shown in Fig. 5.26 (*a*).

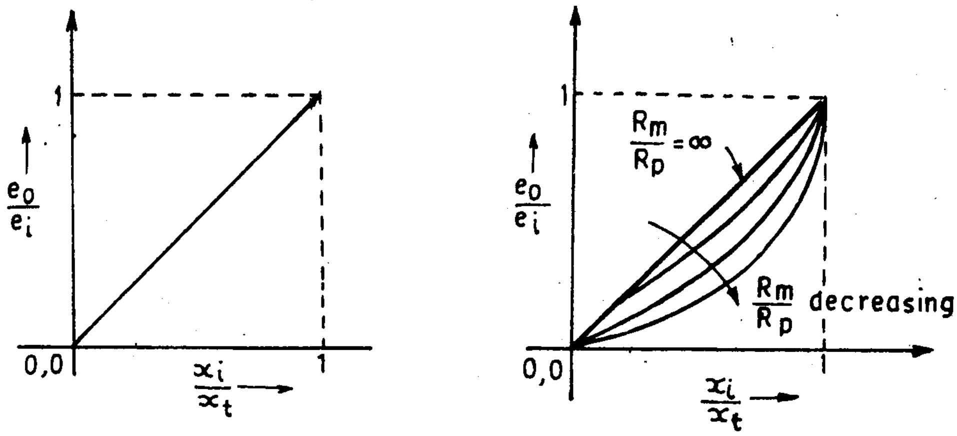


Fig. 5.26. Characteristics of potentiometers.

Sensitivity $\qquad S = \dfrac{\text{output}}{\text{input}} = \dfrac{e_o}{x_i} = \dfrac{e_i}{x_t} \qquad \text{...(5.29)}$

Thus under ideal conditions the sensitivity is constant and the output is faithfully reproduced and has a linear relationship with input. The same is true of rotational motion.

Let θ_i = input angular displacement in degrees, and θ_t = total travel of the wiper in degrees.

∴ Output voltage $e_0 = e_i \,.\, (\theta_i/\theta_t)$ ...(5.30)

This is true of single turn potentiometers only.

The circuits shown in Fig. 5.25 are called **potentiometer dividers** since they produce an output voltage which is a fraction of the input voltage. Thus the input voltage is "divided". The potential divider is a device for dividing the potential in a ratio determined by the position of the sliding contact.

Eqns. 5.29 and 5.30 are based upon the assumption that the distribution of resistance with respect to linear or angular displacement is uniform and the resistance of the voltage measuring device (*i.e.* output device) is infinite. However, in practice, the

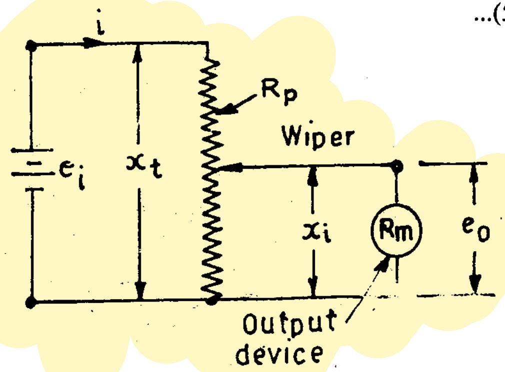


Fig. 5.27. Loaded potentiometer.

...(5.30)

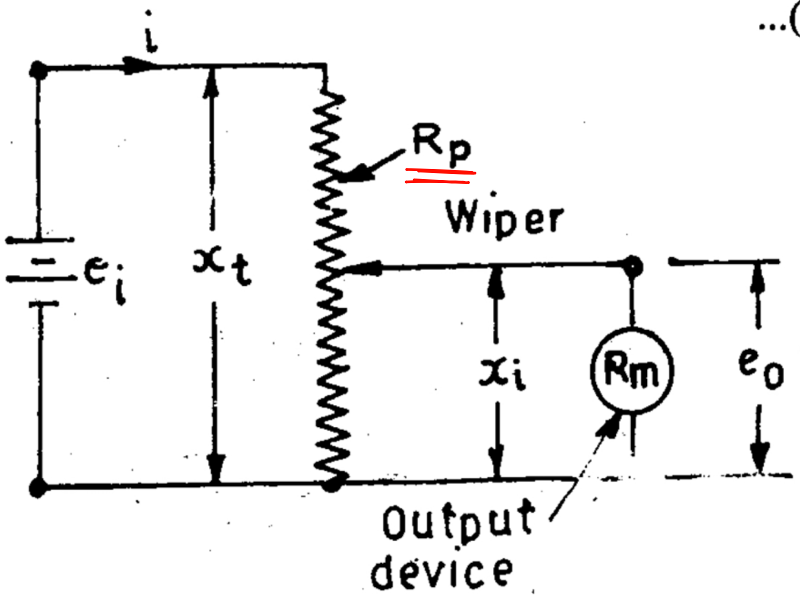
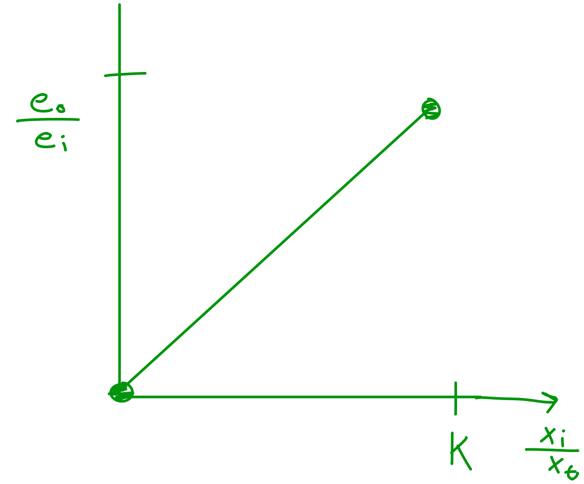
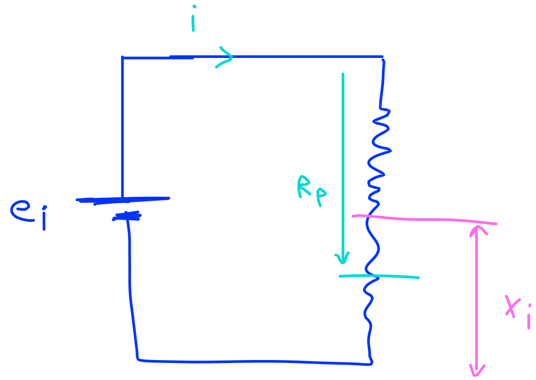


Fig. 5.27. Loaded potentiometer.

No loading effect





$e_o = e_i \times \frac{x_i}{x_t} \rightarrow K$

$\frac{e_o}{e_i} =$

$$R = (1-K)R_p + \frac{R_m(KR_p)}{R_m+KR_p}$$

$$R = \frac{(1-K)R_p\left[R_m+KR_p\right]+(R_m)(K)(R_p)}{R_m+KR_p}$$

$$R = \frac{KR_p^2(1-K)+R_pR_m}{KR_p+R_m}$$

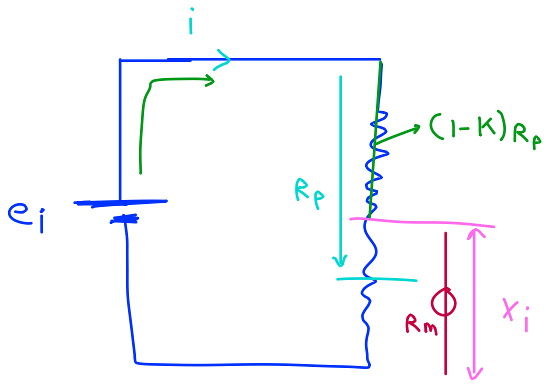
$$i = \frac{e_i * \left[KR_p+R_m\right]}{KR_p^2(1-K)+R_p(R_m)}$$

$$e_o = \underline{i} * \left[\frac{KR_p * R_m}{KR_p+R_m}\right]$$

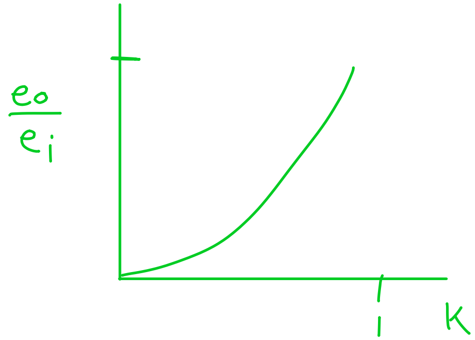
$$e_o = \left[\frac{e_i\cancel{(KR_p+R_m)}}{KR_p^2(1-K)+R_pR_m}\right] * \left[\frac{KR_p * R_m}{\cancel{KR_p+R_m}}\right]$$

$$\frac{e_o}{e_i} = \frac{KR_p * \frac{R_m}{R_pR_m}}{KR_p^2(1-K)+R_pR_m}$$

$$e_o = \frac{K}{K*\frac{R_p}{R_m}*(1-K)+1}$$



$$\boxed{\frac{R_m \times (KR_p)}{R_m+KR_p}}$$



$$\%\ \text{error} = e_{o\,\text{loading}} - e_{o\,\text{no loading}}$$

$$\left[\frac{K*e_i}{K\frac{R_p}{R_m}(1-K)+1} - Ke_i\right] * 100\ \%$$

output terminals of the **pot** are connected to a device whose impedance is finite. Thus, when an electrical instrument, which forms a load for the **pot** and is connected across the output terminals, the indicated voltage is less than that given by Eqn. 5.29. The error, which is referred to as a **loading error** is caused by the input resistance of the output device.

Let us consider the case of a translational potentiometer as shown in Fig. 5.27. Let the resistance of a meter or a recorder monitoring the output be R_m.

As explained earlier if the resistance across the output terminals is infinite, we get a linear relationship between the output and the input voltage.

$$e_0 = (x_i/x_t)\, e_i = Ke_i \qquad \text{...(5.31)}$$

where $K = x_i/x_t$

However, under actual conditions the resistance, R_m, is not infinite. This causes a non-linear relationship between the output and input voltages.

5.11.1. Loading Effect. The resistance of the parallel combination of load resistance and the portion of the resistance of the potentiometer is :

$$\frac{(x_i/x_t)\, R_pR_m}{(x_i/x_t)\, R_p + R_m} = \frac{K\, R_pR_m}{K\, R_p + R_m} \qquad \text{...(5.32)}$$

The total resistance seen by the source is :

$$R = R_p\,(1-K) + \frac{K\, R_pR_m}{K\, R_p + R_m} = \frac{KR_p^2\,(1-K) + R_pR_m}{K\, R_p + R_m} \qquad \text{...(5.33)}$$

$\therefore$ Current

$$i = \frac{e_i}{R} = \frac{e_i\,(K\, R_p + R_m)}{K\, R_p^2\,(1-K) + R_pR_m}$$

The output voltage under load conditions is :

$$e_o = i\,\frac{K\, R_pR_m}{K\, R_p + R_m} = \frac{e_i\,(K\, R_p + R_m)}{K\, R_p^2\,(1-K) + R_pR_m} \cdot \frac{KR_pR_m}{(K\, R_p + R_m)}$$

$$= \frac{e_iK}{K\,(1-K)\,(R_p/R_m) + 1} \qquad \text{...(5.34)}$$

The ratio of output voltage to input voltage under load conditions is :

$$\frac{e_0}{e_i} = \frac{K}{K\,(1-K)\,(R_p/R_m) + 1} \qquad \text{...(5.35)}$$

The Eqn. 5.35 shows that there exists a non-linear relationship between output voltage e_0 and input displacement x_i since $K = x_i/x_t$. In case $R_m = \infty$, $e_o/e_i = K$.

It is evident from Eqn, 5.35 that as the ratio of R_m/R_p decreases, the non-linearity goes on increasing. This is shown in Fig. 5.26 (*b*). Thus, in order to keep linearity, the value of R_m/R_p should be as large as possible. However, when we have to measure the output voltage with a given meter, the resistance of the potentiometer, R_p, should be as small as possible.

$\therefore$ Error = output voltage under load – output voltage under no load

$$= \frac{e_i\, K}{[K\,(1-K)\,(R_p/R_m)+1]} - e_i\, K = -\, e_i \left[\frac{K^2\,(1-K)}{K(1-K) + R_m/R_p}\right] \qquad \text{...(5.36)}$$

يمكن خطأ طباعي نسيوها!!

Based upon full-scale output, this relationship may be written as :

$$\%\ \varepsilon = -\left[\frac{e_i \times K^2\,(1-K)}{K\,(1-K) + (R_m/R_p)}\right] \times 100 \qquad \text{...(5.37)}$$

Except for the two end points where $K = 0$ *i.e.* $x_i = 0$ and $K = 1$ where $x_i = x_t$ the error is always negative. Fig. 5.28 shows a plot of the variation in error with the slider position for different ratios of the load (output device or meter) resistance to the potentiometer resistance.

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The error as indicated in Fig. 5.28 is actually **negative**. Examine Fig. 5.28, the maximum error is about 12 per cent of full scale if $R_m/R_p = 1$. This eror drops down to about 1.5 per cent when $R_m/R_p = 10$. For values of $R_m/R_p > 10$, the position of maximum error occurs in the vicinity of $x_i/x_t = 0.67$.

Maximum percentage error

$$\varepsilon_{max} = 15 \times (R_p/R_m) \quad ...(5.39)$$

It should be understood that the error in POTs is on account of the *non-linearity effect* produced by the output device used for measurement whose input resistance, R_m, is finite. If its meter resistance were infinite there would be no linearity effects and the output voltage will be a linear function of input displacement x_i as shown in Fig. 5.26 and consequently, there would be no error because of the absence of non-linearity.

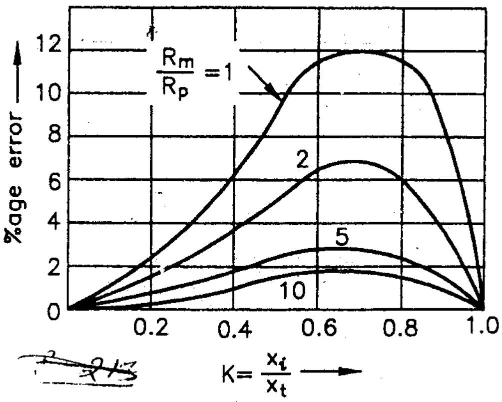


Fig. 5.28. Variation of error due to loading effect of a potentiometer.

5.11.2. Power Rating of Potentiometers. The potentiometers are designed with a definite power rating which is related directly to their heat dissipating capacity. The manufacturer normally designs a series of potentiometers of single turn with a diameter of 50 mm with a wide range of ohmic values ranging from 100 Ω to 10 kΩ in steps of 100 Ω. These potentiometers are essentially of the same size and of the same mechanical configuration. They have the same heat transfer capabilities. Their rating is typically 5 W at an ambient temperature of 21°C. This limits their input excitation voltage. Since power $P = e_i^2/R_p$, the maximum input excitation voltage that can be used is :

$$(e_i)_{max} = \sqrt{PR_p} \text{ volt} \quad ...(5.40)$$

5.11.3. Linearity and Sensitivity. It has been explained earlier that in order to achieve a good linearity, the resistance of potentiometer R_p, should be as low as possible when using a meter for reading the output voltage which has a fixed value of input resistance R_m.

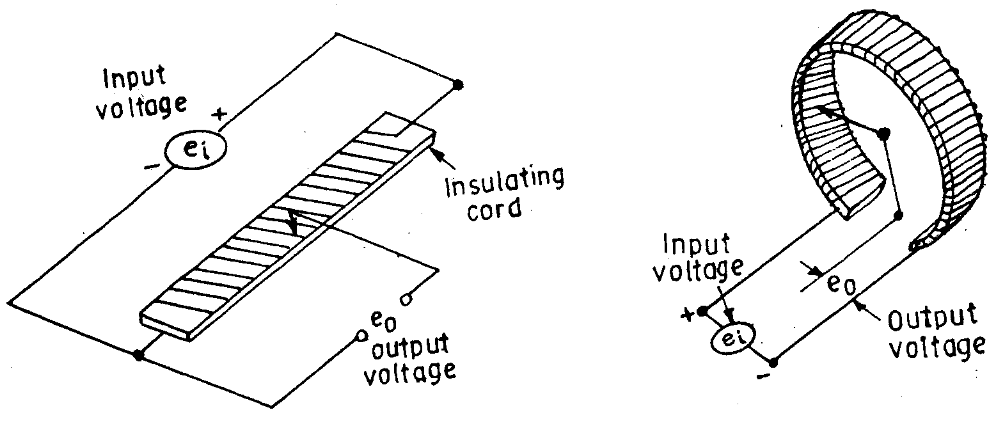
In order to get a high **sensitivity** the output voltage e_0 should be high which in turn requires a high input voltage, e_i. Due to limitations of power dissipation as is clear from Eqn. 5.40, the input voltage is limited by the resistance of the potentiometer. In order to keep the power dissipation at a low level, the input voltage should be small and resistance of the potentiometer should be high. Thus for a high **sensitivity**, the input voltage should be large and this calls for a high value of resistance R_p. On the other if we consider the **linearity**, the resistance of potentiometer R_p, should be as low as possible. The resistance of the potentiometer, R_p; cannot be made low because if we do so the power dissipation goes up with the result that we have to make the input voltage small to keep the power dissipation to the acceptable level. This results in lower **sensitivity**.

Thus **linearity** and **sensitivity** are therefore two conflicting requirements. If R_p is made small, the **linearity** improves, but a low value of R_p requires a lower input voltage e_i in order to keep down the power dissipation and a low value of e_i results in a lower value of output voltage e_0 resulting in lower **sensitivity.** Thus the choice of potentiometer resistance, R_p, has to be made considering both the **linearity** and **sensitivity** and a compromise between the two conflicting requirements has to be struck.

The maximum available sensitivity of potentiometer varies considerably from type to type and also with size in a given type. The sensitivity can be calculated from the data supplied by the manufacturers which includes maximum allowable voltage, current or power and the maximum stroke. The shorter stroke devices have generally a higher sensitivity. Extreme values are of the order of 15 V/degree for short stroke sector type rotational potentiometers and 12 V/mm for short stroke (6.25 mm) translational potentiometers.

These, in fact, are maximum achieveable values and usual values of sensitivity are 10 to 100 times smaller.

5.11.4. Construction of Potentiometers. The resolution of the potentiometers influences the construction of their resistance elements. Normally, the resistive element is a single wire of conducing material which gives a continuous stepless variation of resistance as the wiper travels over it. Such potentiometers



(*a*) Linear potentiometer. (*b*) Circular (Rotational) potentiometer.

Fig. 5.29. Wire wound potentiometers.

are available but their length (in the case of translational potentiometers) and diameter (in the case of rotational potentiometers) restrict their use on account of space considerations.

The resolution of the potentiometers is dependent upon the construction of the resistive element and in order to get high values of resistance in small space **wire wound** potentiometers are used extensively. The resistance wire is wound on a mandrel or a card for translational displacement as shown in Fig. 5.29 (*a*). For the measurement of rotational motion these mandrels or cards are formed into a circle or a helix. This is shown in Fig. 5.29 (*b*). If wire wound type of construction is adopted, the variation of resistance is not a linear continuous change but is in small steps as the sliding contact (wiper) moves from one turn to another. This is shown in Fig. 5.30.

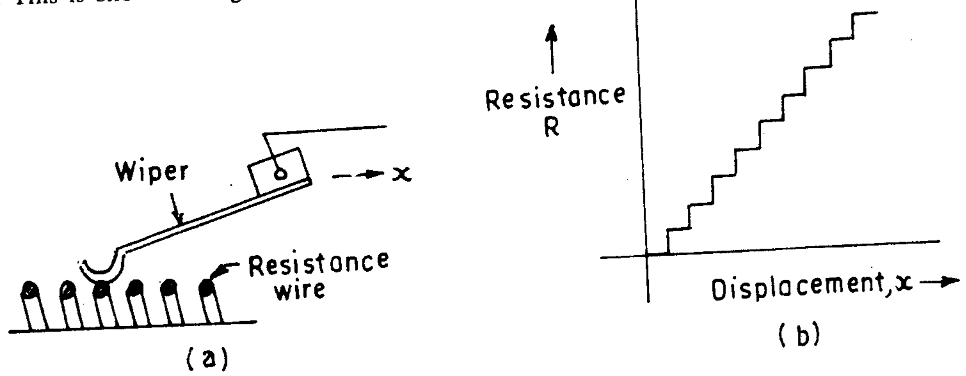


Fig. 5.30. Translational potentiometer and its characteristics.

Since the variation in resistance is in steps the resolution is limited. For instance, a translational potentiometer has about 500 turns of a resistance wire on a card of 25 mm in length and for this device the resolution is limited to 25/500 = 0.05 mm = 50 μm.

The actual practical limit is 20 and 40 turns per mm. Thus for translational devices the resolution is limited to 25—50 μm.

For rotational devices, the best angular resolution $= \frac{3 \text{ to } 6}{D}$ degrees ...(5.41)

where D = diameter of the potentiometer ; mm.

In order to get higher resolution, thin wires which have a high resistance have to be put close to each other and they can be closely wound on account of their small diameter. Thus the resolution and total resistance are interdependent.

In case a fine resolution and high resistance are required a carbon film or a conductive-plastic resistance element are used. Carbon film resistive elements have a resolution of 12.5 nm.

5.11.5. Helipots. The resolution can be increased by using multi-turn potentiometers. These are called **helipots**. The resistance element is in the form of a helix and the wiper travels along a "lead screw". The number of turns is still limited to 20 to 40 turns per mm but an increase in resolution can be obtained by using a gearing arrangement between the shaft whose motion is to be measured and the potentiometer shaft. As an example, one rotation of the measured shaft can cause 10 rotations of the potentiometer shaft. This increases the resolution of the measured shaft motion by 10 times. Multiturn potentiometers are available to about 60 turns.

Similarly, magnifying or amplifying techniques can be used for translational motion as well.

5.12. MATERIALS USED FOR POTENTIOMETERS

The materials used for POTs may be classified as wirewound and non-wire wound.

1. Wire Wound Potentiometers. These are platinum, nickel chromium, nickel copper, or some other precious resistance elements. Wire wound potentiometers carry relatively large currents at high temperatures. Their resistance temperature co-efficient is usually small, is of the order of $20 \times 10^{-6}/C°$ or less. Their resolution is about 0.025 – 0.05 mm and is limited by the number of turns that can be accommodated on the card.

It should be noted that the interwinding capacitance between turns, and between windings and shaft, housing etc. limits the use of wire wound potentiometers to low frequencies. The response is limited to about 5 Hz.

2. Non-Wire Potentiometers. *These are also called continuous potentiometers.* The non-wire wound potentiometers provide improved resolution and life. This is because the resolution is no longer limited by the number of turns that can be wrapped onto a body. The wiper moves across a smooth surface (not bouncing from turn to turn), wear, bounce and the resulting failtures are decreased. The maximum speed that a wirewound potentiometer is turned is about 300 rpm. About that, the noise created as the wiper bounces from turn to turn becomes significant. A continuous potentiometer may be turned at a speed of 2000 rpm. However, they are more sensitive to temperature changes, have a higher wiper contact resistance, which is variable and can carry only moderate currents.

The materials used for non-wire wound (or continuous) potentiometers are :

(*i*) **Cermet.** Cermet uses precious metal particles fused into ceramic base. These fused metal particles act as resistance elements. The advantages of using Cermet are large power ratings at high temperatures, low cost and moderate temperature coefficients of the order 100×10^{-6} to 200×10^{-6} /°C. Cermet is very useful for a.c. applications.

(*ii*) **Hot Moulded Carbon.** The resistance element is fabricated by moulding together a mixture of carbon and a thermosetting plastic binder. Hot moulded carbon units are useful for a.c. applications.

(*iii*) **Carbon Film.** A thin film of carbon deposited on a non-conductive base forms the resistance element. The advantage of carbon film potentiometers is their low cost. Temperature coefficients are upto 1000×10^{-6}/°C.

(*iv*) **Thin Metal Film.** A very thin, vapour deposited layer of metal on glass or ceramic base is used as a resistance element. The advantages of this potentiometer are its excellent resistance to changes in environments and use on a.c. The cost is also moderate.

Advantages and Disadvantages of Resistance Potentiometers.

Resistance potentiometers have the following major advantages :

(*i*) They are inexpensive.

(*ii*) They are simple to operate and very useful for applications where the requirements are not particularly severe.

(*iii*) They are very useful for measurement of large amplitudes of displacement.

(*iv*) Their electrical efficiency is very high and they provide sufficient output to permit control operations without further amplification.

(*v*) It should be understood that while the frequency response of wire wound potentiometers is limited, the other types of potentiometers are free from this problems.

(*vi*) In wire wound potentiometers the resolution is limited while in Cermet and metal film potentiometers, the resolution is infinite.

The disadvantages are :

(*i*) The chief disadvantage of using a linear potentiometer is that they require a large force to move their sliding contacts (wipers).

(*ii*) The other problems with sliding contacts are that they can be contaminated, can wear out, become misaligned and generate noise. So the life of the transducer is limited. However, recent developments have produced a roller contact wiper which, it is claimed, increases the life of the transducer by 40 times.

Example 5.4. A linear resistance potentiometer is 50 mm long and is uniformly wound with a wire having a resistance of 10,000 Ω. Under normal conditions, the slider is at the centre of the potentiometer. Find the linear displacement when the resistances of the potentiometer as measured by a Wheatstone bridge for two cases are :

(*i*) 3850 Ω, (*ii*) 7560 Ω.

Are the two displacements in the same direction ?

If it is possible to measure a minimum value of 10 Ω resistance with the above arrangement, find the resolution of the potentiometer in mm.

Solution. The resistance of the potentiometer at its normal position = 1000/2 = 5000 Ω.

Resistance of potentiometer per unit length = 1000/50 = 200 Ω/mm.

(*i*) Change of resistance from its normal position = 5000 – 3850 = 1150 Ω

∴ Displacement of wiper from its normal position = 1150/200 = 5.75 mm.

(*ii*) Change of resistance from its normal position = 7569 – 5000 = 2560 Ω.

∴ Displacement of wiper from its normal position 2560/200 = 12.80 mm.

Since, one of the displacements represent a decrease and other represents an increase in resistance of potentiometer from its value at the normal position, the two displacements are in the opposite direction.

Resolution = minimum measurable resistance × mm/Ω

= 10 × 1/200 = 0.05 mm.

*

Example 5.5. A variable potential divider has a total resistance of 2 kΩ and is fed from a 10 V d.c. supply. The output is connected to a load resistance of 5 kΩ. Determine the loading errors for the wiper positions corresponding to $K = x_i/x_t$ = 0, 0.25, 0.5, 0.75, and 1.0. Use the results to plot a rough graph of error versus x_i/x_t.

Error هو المطلوب

$R_p = 2000\,\Omega$

$e_i = 10\,V$

$R_m = 5000\,\Omega$

$K = \frac{x_i}{x_t}$	$\%E = \frac{e_i \times K^2(1-K)}{K(1-K) + \frac{R_m}{R_p}}$
0	0
0.25	0.174
0.5	0.454
0.75	0.524
1	0

Solution. We have $R_p = 2$ kΩ and $R_m = 5$ kΩ

From Eqn. 5.36, error is,

$$- e_i \left[\frac{K^2 (1 - K)}{K (1 - K) + R_m/R_p} \right]$$

Substituting the values, the results are tabulated below :

K	0	0.25	0.5	0.75	1
Error, V	0	– 0.174	– 0.454	– 0.524	0

The graph between error versus $K = x_i/x_t$ is plotted in Fig. 5.31. (The errors are no doubt – ve but they are shown as + ve in Fig. 5.31)

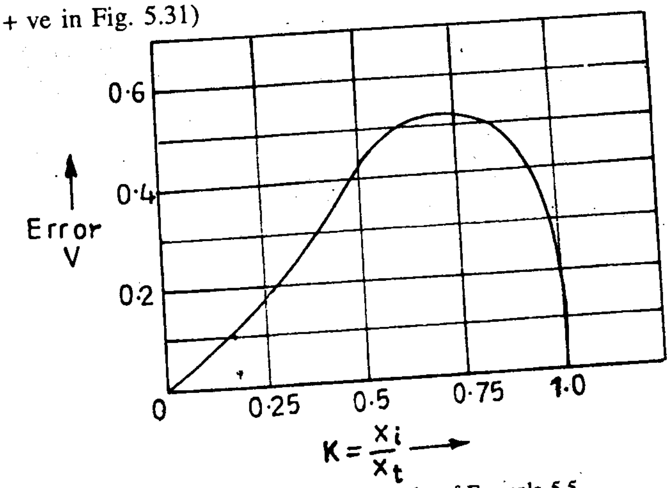


Fig. 5.31. Graph of results of Example 5.5.

Example 5.6. A resistive potential divider R_1 R_2 with a resistance of 5000 Ω and a shaft stroke of 125 mm is used in the arrangement shown in Fig. 5.32. Potentiometer R_3R_4 has a resistance of 5000 Ω and $e_i = 5.0$ V. The initial position to be used as reference point is such that $R_1 = R_2$ *i.e.* the wiper is at midstroke. At the start of the test potentiometer R_3R_4 is adjusted so that the bridge is balanced and $e_o = 0$. Assuming that the displacement being measured will move a maximum distance of 12.5 mm towards A, calculate the value of e_0.

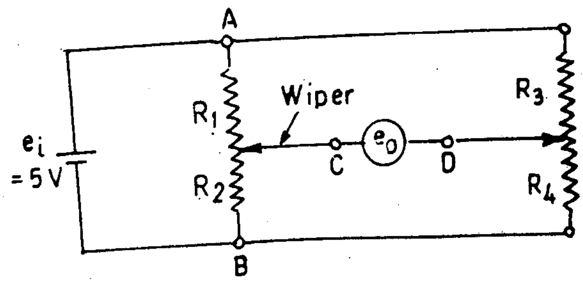


Fig. 5.32. Diagram of Exmaple 5.6.

Solution. Total length of AB = 125 mm Midpoint of AB = 62.5 mm from either A or B. If the wiper moves 12.5 inward towards A from midstroke, its distance from B becomes 62.5 + 12.5 = 75 mm.

$\therefore \qquad R_2 = (75/125) \times 5000 = 3000\ \Omega$

Hence, output voltage
$$e_o = \left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) e_i$$
$$= \left[\frac{3000}{5000} - \frac{2500}{5000} \right] \times 5 = 0.5 \text{ V}.$$

Example 5.7. The output of a potentiometer is to be read by a recorder of 10 kΩ input resistance. The non-linearity must be held to 1 percent. A family of potentiometers having a thermal rating of 5 W and resistances ranging from 100 Ω to 10 kΩ in steps of 100 Ω are available. Choose from the family of potentiometers, a potentiometer that has the greatest possible sensitivity and which meets the non-linearity requirements. Find the maximum excitation voltage permissible with this potentiometer. What is the sensitivity if the potentiometer is a single turn (360° unit) ?

Solution. From Eqn. 5.39, maximum possible percentage linearity = 15 R_p/R_m. This to be limited to 1 percent 15 R_p/R_m = 1. Therefore, the maximum value of resistance of potentiometer is,
$$R_p = R_m/15 = 10{,}000/15 = 666.7\ \Omega$$

Thus we are left with choice of potentiometers having resistances of 100 Ω, 200 Ω, 300 Ω, 400 Ω, 500 Ω and 600 Ω.

The potentiometer with the highest value of resistance has the highest sensitivity. Therefore, a potentiometer with R_p = 600 Ω is selected. With a power dissipation of 5 W, the maximum value of excitation voltage is,
$$e_{i(max)} = \sqrt{PR_p} = \sqrt{5 \times 600} = 54.8 \text{ V}.$$

The sensitivity of potentiometer when it is a single turn unit S = 54.8/360 = 0.152 V/degree.

Example 5.8. A helipot is provided with 400 turns/mm. The gearing arrangement is such that the motion of the main shaft causes 5 revolutions of potentiometer shaft. Calculate the resolution of the potentiometer.

Solution. The resolution of potentiometer without the gearing arrangement = 1/400 mm = 25 μm. With the gearing arrangement which causes 5 revolutions of the potentiometer shaft with one revolution of main shaft = 25/5 = 5 μm.

Example 5.9. It is necessary to measure the position of object. It moves 0.8 m. Its position must be known within 1 mm. Part of the mechanism which moves the object is a shift in a shaft that rotates 250° when the object is moved from one extreme to the other. A control potentiometer has been found which is rated at 300° full scale movement. It has one thousand turns of wire. Is the potentiometer suitable for the application ?

Solution. The shaft provides a $\frac{250°}{0.8}$ = 312.5°/m or 0-3125°/mm conversion

A resolution of 1 mm at the object translates into 1 mm × 0.3125° = 0.3125°. required resolution for the potentiometer.

The potentiometer actually has a resolution $\frac{300}{1000}$ = 0.300°.

∴ The resolution of the potentiometer is higher than that required for the application and hence the potentiometer is very much suited for the application.

Example 5.10. A control potentiometer is rated as :

resistance = 150 Ω, power rating = 1 W, de-rate the potentiometer by 10 mW/°C above 65°C, thermal resistance = 30°C/W.

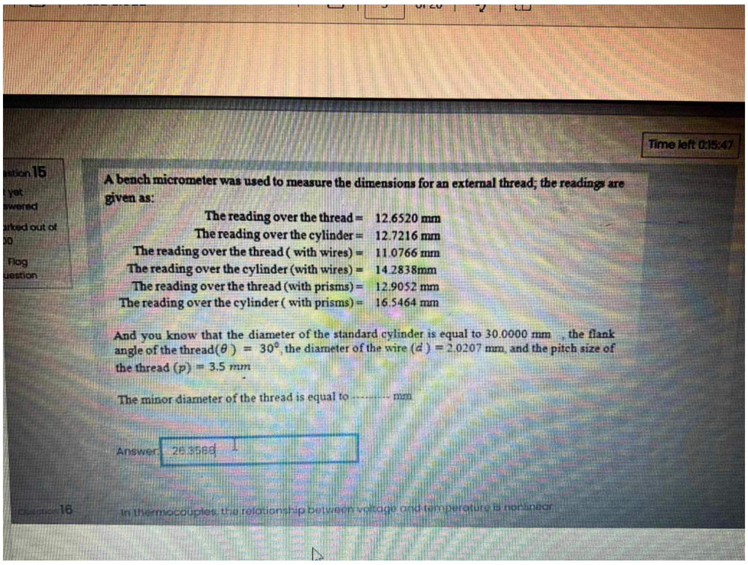
#Final exam questions

* Final Exam (1st semester 2023/2024)

اجي 5 أسئلة حل

و سؤال واحد ب ١٢ علاقة اشياء الحفظ

① اجي ← زي هيك سؤال



Time left 0:15:47

A bench micrometer was used to measure the dimensions for an external thread; the readings are given as:

The reading over the thread = 12.6520 mm
The reading over the cylinder = 12.7216 mm
The reading over the thread (with wires) = 11.0766 mm
The reading over the cylinder (with wires) = 14.2838mm
The reading over the thread (with prisms) = 12.9052 mm
The reading over the cylinder (with prisms) = 16.5464 mm

And you know that the diameter of the standard cylinder is equal to 30.0000 mm , the flank angle of the thread(θ) = 30^0, the diameter of the wire (d) = 2.0207 mm, and the pitch size of the thread (p) = 3.5 mm

The minor diameter of the thread is equal to --------- mm

Answer: 26.3588

In thermocouples, the relationship between voltage and temperature is nonlinear

② سؤال ال نحسب ال Error و معطيتنا قيم (K) 0, .2, .4, .6, .8, 1

زي السؤال يلي بال File

Since, one of the displacements represent a ... of potentiometer from its value at the normal position, the two displacements are in the opp...

Resolution = minimum measurable resistance × mm/Ω
= 10 × 1/200 = 0.05 mm.

ال Error هو المطلوب

* **Example 5.5.** A variable potential divider has a total resistance of 2 kΩ and is fed from a 10 V d.c. supply. The output is connected to a load resistance of 5 kΩ. Determine the loading errors for the wiper positions corresponding to $K = x_i/x_t$ = 0, 0.25, 0.5, 0.75, and 1.0. Use the results to plot a rough graph of error versus x_i/x_t.

$R_p = 2000\,\Omega$
$e_i = 10\,V$
$R_m = 5000\,\Omega$

$K = \frac{x_i}{x_t}$	$\%E = \frac{e_i \times K^2(1-K)}{K(1-K) + \frac{R_m}{R_p}}$
0	0
0.25	0.174
0.5	0.454
0.75	0.524
1	0

زي هار

(معادلة ال Error حفظ)

Solution. We have R_p = 2 kΩ and R_m = 5 kΩ

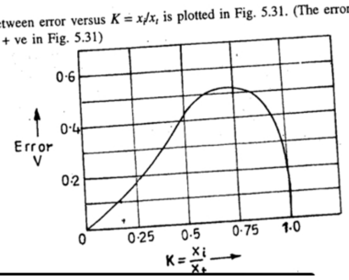
From Eqn. 5.36, error is,

$$-e_i\left[\frac{K^2(1-K)}{K(1-K)+R_m/R_p}\right]$$

Substituting the values, the results are tabulated below :

K	0	0.25	0.5	0.75	1
Error, V	0	− 0.174	− 0.454	− 0.524	0

The graph between error versus $K = x_i/x_t$ is plotted in Fig. 5.31. (The errors are no doubt − ve but they are shown as + ve in Fig. 5.31)



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* سؤال على هاي المعادلة

diameters ranging from 2.5 mm to 25 mm.

5.16.2. Resistance-Temperature Characteristics of Thermistors. The mathematical expression for the relationship between the resistance of a thermistor and absolute temperature of thermistor is :

$$R_{T1} = R_{T2} \exp\left[\beta\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \quad ...(5.59)$$

where R_{T1} = resistance of the thermistor at absolute temperature T_1 ; K,

R_{T2} = resistance of the thermistor at absolute temperature T_2 ; K

T_1, T_2 in kelvin

(المعادلة هنا موحفظ الدكتورة جابتها)

٤

سؤال design GO-NOGO gauge for a shaft (a)

⋮

٥

هيك جدول ← ونحسب Linear expansion and Quadratic Expantion

Example 5.17. Use the following values of resistance versus temperature for an RTD to find the linear and quadratic approximations of resistance between 100°C and 130°C about a mean temperature of 115°C.

Temperature, C°	90	95	100	105	110	115	120	125	130
Resistance Ω	562.66	568.03	573.40	578.77	584.13	589.48	594.84	600.18	605.52

Solution.

1. Linear Expansion : Given :

$\theta_1 = 100°C,\ \theta_2 = 130°C,\ \theta_0 = 115°C$

$R_{\theta_1} = 573.40\ \Omega,\ R_{\theta_2} = 605.52\ \Omega,\ R_{\theta_0} = 589.48\ \Omega$

From Eqn. 5.57,

$$\alpha_{\theta_1} = \alpha_1 = \frac{1}{R_{\theta_0}} \times \frac{R_{\theta_2} - R_{\theta_1}}{\theta_2 - \theta_1} = \frac{1}{589.48} \times \frac{605.52 - 573.40}{130 - 100} = 0.00182\ /°C$$

∴ The linear approximation is :

$$R_\theta = 589.48\ [1 + 0.00182\ (\theta - 115)]\ \Omega.$$

2. Quadratic Expansion : The resistance R_θ at any temperature θ°C is given by :

$$R_\theta = R_{\theta_0}\ [1 + \alpha_1\ \Delta\theta + \alpha_2\ (\Delta\theta)^2]$$

We can find the quadratic terms, by forming two equations using two points about the mean temperature $\theta_0 = 115°C$.

We have, $R_{\theta_0} = 589.48\ \Omega$ at $\theta_0 = 115°C$.

Now using 100°C and 130°C as the two points, we have :

$$573.40 = 589.48\ [1 + \alpha_1\ (100 - 115) + \alpha_2\ (100 - 115)^2]$$
$$605.52 = 589.48\ [1 + \alpha_1\ (130 - 115) + \alpha_2\ (130 - 115)^2]$$

From above have,

$$\alpha_1 = 1.823 \times 10^{-3}/°C \text{ and } \alpha_2 = -0.22 \times 10^{-6}/(°C)^2$$

Hence,

$$R_\theta = 589.48\ [1 + 1.823 \times 10^{-3}\ (\theta - 115) - 0.22 \times 10^{-6}\ (\theta - 115)^2]\ \Omega.$$

(والقوانين هنا حفظ)

وكمان سؤال حل يمكن أو يمكن لا !!

* جزء الحفظ سؤال ١٥ علامة ← ٦ أفرع

1. Describe how to generate involute curve in spur gears

اعطتنا اياه سؤال واجب واجى

2. Describe Taylor principle for GO-NOGO

3. Describe how the earkinson gear testser work

4. Describe the Law of intermediate metals

5. // // // // intermediate temperature

6. سؤال على ال sine bar

given $h = \bigcirc$, $L = \bigcirc$

نحسب ال θ angle

يمكن هاد السؤال الوحيد عى مادة المِيد

$$\sin\theta = \frac{h}{L}$$

Table Files

EMF j

EMF t

EMF k

emf (J) File

J°C

TABLE 7 ***Type J Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

°C	0	1	2	3	4	5	6	7	8	9	10	°C
					Thermoelectric Voltage in Millivolts							
-210	-8.095											-210
-200	-7.890	-7.912	-7.934	-7.955	-7.976	-7.996	-8.017	-8.037	-8.057	-8.076	-8.095	-200
-190	-7.659	-7.683	-7.707	-7.731	-7.755	-7.778	-7.801	-7.824	-7.846	-7.868	-7.890	-190
-180	-7.403	-7.429	-7.456	-7.482	-7.508	-7.534	-7.559	-7.585	-7.610	-7.634	-7.659	-180
-170	-7.123	-7.152	-7.181	-7.209	-7.237	-7.265	-7.293	-7.321	-7.348	-7.376	-7.403	-170
-160	-6.821	-6.853	-6.883	-6.914	-6.944	-6.975	-7.005	-7.035	-7.064	-7.094	-7.123	-160
-150	-6.500	-6.533	-6.566	-6.598	-6.631	-6.663	-6.695	-6.727	-6.759	-6.790	-6.821	-150
-140	-6.159	-6.194	-6.229	-6.263	-6.298	-6.332	-6.366	-6.400	-6.433	-6.467	-6.500	-140
-130	-5.801	-5.838	-5.874	-5.910	-5.946	-5.982	-6.018	-6.054	-6.089	-6.124	-6.159	-130
-120	-5.426	-5.465	-5.503	-5.541	-5.578	-5.616	-5.653	-5.690	-5.727	-5.764	-5.801	-120
-110	-5.037	-5.076	-5.116	-5.155	-5.194	-5.233	-5.272	-5.311	-5.350	-5.388	-5.426	-110
-100	-4.633	-4.674	-4.714	-4.755	-4.796	-4.836	-4.877	-4.917	-4.957	-4.997	-5.037	-100
-90	-4.215	-4.257	-4.300	-4.342	-4.384	-4.425	-4.467	-4.509	-4.550	-4.591	-4.633	-90
-80	-3.786	-3.829	-3.872	-3.916	-3.959	-4.002	-4.045	-4.088	-4.130	-4.173	-4.215	-80
-70	-3.344	-3.389	-3.434	-3.478	-3.522	-3.566	-3.610	-3.654	-3.698	-3.742	-3.786	-70
-60	-2.893	-2.938	-2.984	-3.029	-3.075	-3.120	-3.165	-3.210	-3.255	-3.300	-3.344	-60
-50	-2.431	-2.478	-2.524	-2.571	-2.617	-2.663	-2.709	-2.755	-2.801	-2.847	-2.893	-50
-40	-1.961	-2.008	-2.055	-2.103	-2.150	-2.197	-2.244	-2.291	-2.338	-2.385	-2.431	-40
-30	-1.482	-1.530	-1.578	-1.626	-1.674	-1.722	-1.770	-1.818	-1.865	-1.913	-1.961	-30
-20	-0.995	-1.044	-1.093	-1.142	-1.190	-1.239	-1.288	-1.336	-1.385	-1.433	-1.482	-20
-10	-0.501	-0.550	-0.600	-0.650	-0.699	-0.749	-0.798	-0.847	-0.896	-0.946	-0.995	-10
0	0.000	-0.050	-0.101	-0.151	-0.201	-0.251	-0.301	-0.351	-0.401	-0.451	-0.501	0
0	0.000	0.050	0.101	0.151	0.202	0.253	0.303	0.354	0.405	0.456	0.507	0
10	0.507	0.558	0.609	0.660	0.711	0.762	0.814	0.865	0.916	0.968	1.019	10
20	1.019	1.071	1.122	1.174	1.226	1.277	1.329	1.381	1.433	1.485	1.537	20
30	1.537	1.589	1.641	1.693	1.745	1.797	1.849	1.902	1.954	2.006	2.059	30
40	2.059	2.111	2.164	2.216	2.269	2.322	2.374	2.427	2.480	2.532	2.585	40
50	2.585	2.638	2.691	2.744	2.797	2.850	2.903	2.956	3.009	3.062	3.116	50
60	3.116	3.169	3.222	3.275	3.329	3.382	3.436	3.489	3.543	3.596	3.650	60
70	3.650	3.703	3.757	3.810	3.864	3.918	3.971	4.025	4.079	4.133	4.187	70
80	4.187	4.240	4.294	4.348	4.402	4.456	4.510	4.564	4.618	4.672	4.726	80
90	4.726	4.781	4.835	4.889	4.943	4.997	5.052	5.106	5.160	5.215	5.269	90
100	5.269	5.323	5.378	5.432	5.487	5.541	5.595	5.650	5.705	5.759	5.814	100
110	5.814	5.868	5.923	5.977	6.032	6.087	6.141	6.196	6.251	6.306	6.360	110
120	6.360	6.415	6.470	6.525	6.579	6.634	6.689	6.744	6.799	6.854	6.909	120
130	6.909	6.964	7.019	7.074	7.129	7.184	7.239	7.294	7.349	7.404	7.459	130
140	7.459	7.514	7.569	7.624	7.679	7.734	7.789	7.844	7.900	7.955	8.010	140
150	8.010	8.065	8.120	8.175	8.231	8.286	8.341	8.396	8.452	8.507	8.562	150
160	8.562	8.618	8.673	8.728	8.783	8.839	8.894	8.949	9.005	9.060	9.115	160
170	9.115	9.171	9.226	9.282	9.337	9.392	9.448	9.503	9.559	9.614	9.669	170
180	9.669	9.725	9.780	9.836	9.891	9.947	10.002	10.057	10.113	10.168	10.224	180
190	10.224	10.279	10.335	10.390	10.446	10.501	10.557	10.612	10.668	10.723	10.779	190
200	10.779	10.834	10.890	10.945	11.001	11.056	11.112	11.167	11.223	11.278	11.334	200
210	11.334	11.389	11.445	11.501	11.556	11.612	11.667	11.723	11.778	11.834	11.889	210
220	11.889	11.945	12.000	12.056	12.111	12.167	12.222	12.278	12.334	12.389	12.445	220
230	12.445	12.500	12.556	12.611	12.667	12.722	12.778	12.833	12.889	12.944	13.000	230
240	13.000	13.056	13.111	13.167	13.222	13.278	13.333	13.389	13.444	13.500	13.555	240

$Volt_{hot} = Volt_{cold} + Reading$

Table 7

°C 0 1 2 3 4 5 6 7 8 9 10 °C

TABLE 7 ***Type J Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

Thermoelectric Voltage in Millivolts

°C	0	1	2	3	4	5	6	7	8	9	10	°C
250	13.555	13.611	13.666	13.722	13.777	13.833	13.888	13.944	13.999	14.055	14.110	250
260	14.110	14.166	14.221	14.277	14.332	14.388	14.443	14.499	14.554	14.609	14.665	260
270	14.665	14.720	14.776	14.831	14.887	14.942	14.998	15.053	15.109	15.164	15.219	270
280	15.219	15.275	15.330	15.386	15.441	15.496	15.552	15.607	15.663	15.718	15.773	280
290	15.773	15.829	15.884	15.940	15.995	16.050	16.106	16.161	16.216	16.272	16.327	290
300	16.327	16.383	16.438	16.493	16.549	16.604	16.659	16.715	16.770	16.825	16.881	300
310	16.881	16.936	16.991	17.046	17.102	17.157	17.212	17.268	17.323	17.378	17.434	310
320	17.434	17.489	17.544	17.599	17.655	17.710	17.765	17.820	17.876	17.931	17.986	320
330	17.986	18.041	18.097	18.152	18.207	18.262	18.318	18.373	18.428	18.483	18.538	330
340	18.538	18.594	18.649	18.704	18.759	18.814	18.870	18.925	18.980	19.035	19.090	340
350	19.090	19.146	19.201	19.256	19.311	19.366	19.422	19.477	19.532	19.587	19.642	350
360	19.642	19.697	19.753	19.808	19.863	19.918	19.973	20.028	20.083	20.139	20.194	360
370	20.194	20.249	20.304	20.359	20.414	20.469	20.525	20.580	20.635	20.690	20.745	370
380	20.745	20.800	20.855	20.911	20.966	21.021	21.076	21.131	21.186	21.241	21.297	380
390	21.297	21.352	21.407	21.462	21.517	21.572	21.627	21.683	21.738	21.793	21.848	390
400	21.848	21.903	21.958	22.014	22.069	22.124	22.179	22.234	22.289	22.345	22.400	400
410	22.400	22.455	22.510	22.565	22.620	22.676	22.731	22.786	22.841	22.896	22.952	410
420	22.952	23.007	23.062	23.117	23.172	23.228	23.283	23.338	23.393	23.449	23.504	420
430	23.504	23.559	23.614	23.670	23.725	23.780	23.835	23.891	23.946	24.001	24.057	430
440	24.057	24.112	24.167	24.223	24.278	24.333	24.389	24.444	24.499	24.555	24.610	440
450	24.610	24.665	24.721	24.776	24.832	24.887	24.943	24.998	25.053	25.109	25.164	450
460	25.164	25.220	25.275	25.331	25.386	25.442	25.497	25.553	25.608	25.664	25.720	460
470	25.720	25.775	25.831	25.886	25.942	25.998	26.053	26.109	26.165	26.220	26.276	470
480	26.276	26.332	26.387	26.443	26.499	26.555	26.610	26.666	26.722	26.778	26.834	480
490	26.834	26.889	26.945	27.001	27.057	27.113	27.169	27.225	27.281	27.337	27.393	490
500	27.393	27.449	27.505	27.561	27.617	27.673	27.729	27.785	27.841	27.897	27.953	500
510	27.953	28.010	28.066	28.122	28.178	28.234	28.291	28.347	28.403	28.460	28.516	510
520	28.516	28.572	28.629	28.685	28.741	28.798	28.854	28.911	28.967	29.024	29.080	520
530	29.080	29.137	29.194	29.250	29.307	29.363	29.420	29.477	29.534	29.590	29.647	530
540	29.647	29.704	29.761	29.818	29.874	29.931	29.988	30.045	30.102	30.159	30.216	540
550	30.216	30.273	30.330	30.387	30.444	30.502	30.559	30.616	30.673	30.730	30.788	550
560	30.788	30.845	30.902	30.960	31.017	31.074	31.132	31.189	31.247	31.304	31.362	560
570	31.362	31.419	31.477	31.535	31.592	31.650	31.708	31.766	31.823	31.881	31.939	570
580	31.939	31.997	32.055	32.113	32.171	32.229	32.287	32.345	32.403	32.461	32.519	580
590	32.519	32.577	32.636	32.694	32.752	32.810	32.869	32.927	32.985	33.044	33.102	590
600	33.102	33.161	33.219	33.278	33.337	33.395	33.454	33.513	33.571	33.630	33.689	600
610	33.689	33.748	33.807	33.866	33.925	33.984	34.043	34.102	34.161	34.220	34.279	610
620	34.279	34.338	34.397	34.457	34.516	34.575	34.635	34.694	34.754	34.813	34.873	620
630	34.873	34.932	34.992	35.051	35.111	35.171	35.230	35.290	35.350	35.410	35.470	630
640	35.470	35.530	35.590	35.650	35.710	35.770	35.830	35.890	35.950	36.010	36.071	640
650	36.071	36.131	36.191	36.252	36.312	36.373	36.433	36.494	36.554	36.615	36.675	650
660	36.675	36.736	36.797	36.858	36.918	36.979	37.040	37.101	37.162	37.223	37.284	660
670	37.284	37.345	37.406	37.467	37.528	37.590	37.651	37.712	37.773	37.835	37.896	670
680	37.896	37.958	38.019	38.081	38.142	38.204	38.265	38.327	38.389	38.450	38.512	680
690	38.512	38.574	38.636	38.698	38.760	38.822	38.884	38.946	39.008	39.070	39.132	690
700	39.132	39.194	39.256	39.318	39.381	39.443	39.505	39.568	39.630	39.693	39.755	700
710	39.755	39.818	39.880	39.943	40.005	40.068	40.131	40.193	40.256	40.319	40.382	710
720	40.382	40.445	40.508	40.570	40.633	40.696	40.759	40.822	40.886	40.949	41.012	720
730	41.012	41.075	41.138	41.201	41.265	41.328	41.391	41.455	41.518	41.581	41.645	730
740	41.645	41.708	41.772	41.835	41.899	41.962	42.026	42.090	42.153	42.217	42.281	740
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 7 ***Type J Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

J°C

Thermoelectric Voltage in Millivolts

°C	0	1	2	3	4	5	6	7	8	9	10	°C
750	42.281	42.344	42.408	42.472	42.536	42.599	42.663	42.727	42.791	42.855	42.919	750
760	42.919	42.983	43.047	43.111	43.175	43.239	43.303	43.367	43.431	43.495	43.559	760
770	43.559	43.624	43.688	43.752	43.817	43.881	43.945	44.010	44.074	44.139	44.203	770
780	44.203	44.267	44.332	44.396	44.461	44.525	44.590	44.655	44.719	44.784	44.848	780
790	44.848	44.913	44.977	45.042	45.107	45.171	45.236	45.301	45.365	45.430	45.494	790
800	45.494	45.559	45.624	45.688	45.753	45.818	45.882	45.947	46.011	46.076	46.141	800
810	46.141	46.205	46.270	46.334	46.399	46.464	46.528	46.593	46.657	46.722	46.786	810
820	46.786	46.851	46.915	46.980	47.044	47.109	47.173	47.238	47.302	47.367	47.431	820
830	47.431	47.495	47.560	47.624	47.688	47.753	47.817	47.881	47.946	48.010	48.074	830
840	48.074	48.138	48.202	48.267	48.331	48.395	48.459	48.523	48.587	48.651	48.715	840
850	48.715	48.779	48.843	48.907	48.971	49.034	49.098	49.162	49.226	49.290	49.353	850
860	49.353	49.417	49.481	49.544	49.608	49.672	49.735	49.799	49.862	49.926	49.989	860
870	49.989	50.052	50.116	50.179	50.243	50.306	50.369	50.432	50.495	50.559	50.622	870
880	50.622	50.685	50.748	50.811	50.874	50.937	51.000	51.063	51.126	51.188	51.251	880
890	51.251	51.314	51.377	51.439	51.502	51.565	51.627	51.690	51.752	51.815	51.877	890
900	51.877	51.940	52.002	52.064	52.127	52.189	52.251	52.314	52.376	52.438	52.500	900
910	52.500	52.562	52.624	52.686	52.748	52.810	52.872	52.934	52.996	53.057	53.119	910
920	53.119	53.181	53.243	53.304	53.366	53.427	53.489	53.550	53.612	53.673	53.735	920
930	53.735	53.796	53.857	53.919	53.980	54.041	54.102	54.164	54.225	54.286	54.347	930
940	54.347	54.408	54.469	54.530	54.591	54.652	54.713	54.773	54.834	54.895	54.956	940
950	54.956	55.016	55.077	55.138	55.198	55.259	55.319	55.380	55.440	55.501	55.561	950
960	55.561	55.622	55.682	55.742	55.803	55.863	55.923	55.983	56.043	56.104	56.164	960
970	56.164	56.224	56.284	56.344	56.404	56.464	56.524	56.584	56.643	56.703	56.763	970
980	56.763	56.823	56.883	56.942	57.002	57.062	57.121	57.181	57.240	57.300	57.360	980
990	57.360	57.419	57.479	57.538	57.597	57.657	57.716	57.776	57.835	57.894	57.953	990
1000	57.953	58.013	58.072	58.131	58.190	58.249	58.309	58.368	58.427	58.486	58.545	1000
1010	58.545	58.604	58.663	58.722	58.781	58.840	58.899	58.957	59.016	59.075	59.134	1010
1020	59.134	59.193	59.252	59.310	59.369	59.428	59.487	59.545	59.604	59.663	59.721	1020
1030	59.721	59.780	59.838	59.897	59.956	60.014	60.073	60.131	60.190	60.248	60.307	1030
1040	60.307	60.365	60.423	60.482	60.540	60.599	60.657	60.715	60.774	60.832	60.890	1040
1050	60.890	60.949	61.007	61.065	61.123	61.182	61.240	61.298	61.356	61.415	61.473	1050
1060	61.473	61.531	61.589	61.647	61.705	61.763	61.822	61.880	61.938	61.996	62.054	1060
1070	62.054	62.112	62.170	62.228	62.286	62.344	62.402	62.460	62.518	62.576	62.634	1070
1080	62.634	62.692	62.750	62.808	62.866	62.924	62.982	63.040	63.098	63.156	63.214	1080
1090	63.214	63.271	63.329	63.387	63.445	63.503	63.561	63.619	63.677	63.734	63.792	1090
1100	63.792	63.850	63.908	63.966	64.024	64.081	64.139	64.197	64.255	64.313	64.370	1100
1110	64.370	64.428	64.486	64.544	64.602	64.659	64.717	64.775	64.833	64.890	64.948	1110
1120	64.948	65.006	65.064	65.121	65.179	65.237	65.295	65.352	65.410	65.468	65.525	1120
1130	65.525	65.583	65.641	65.699	65.756	65.814	65.872	65.929	65.987	66.045	66.102	1130
1140	66.102	66.160	66.218	66.275	66.333	66.391	66.448	66.506	66.564	66.621	66.679	1140
1150	66.679	66.737	66.794	66.852	66.910	66.967	67.025	67.082	67.140	67.198	67.255	1150
1160	67.255	67.313	67.370	67.428	67.486	67.543	67.601	67.658	67.716	67.773	67.831	1160
1170	67.831	67.888	67.946	68.003	68.061	68.119	68.176	68.234	68.291	68.348	68.406	1170
1180	68.406	68.463	68.521	68.578	68.636	68.693	68.751	68.808	68.865	68.923	68.980	1180
1190	68.980	69.037	69.095	69.152	69.209	69.267	69.324	69.381	69.439	69.496	69.553	1190
1200	69.553											1200
°C	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**°C**

TABLE 9 ***Type K Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

Thermoelectric Voltage in Millivolts

°C	0	1	2	3	4	5	6	7	8	9	10	°C
-270	-6.458											-270
-260	-6.411	-6.444	-6.446	-6.448	-6.450	-6.452	-6.453	-6.455	-6.456	-6.457	-6.458	-260
-250	-6.404	-6.408	-6.413	-6.417	-6.421	-6.425	-6.429	-6.432	-6.435	-6.438	-6.441	-250
-240	-6.344	-6.351	-6.358	-6.364	-6.370	-6.377	-6.382	-6.388	-6.393	-6.399	-6.404	-240
-230	-6.262	-6.271	-6.280	-6.289	-6.297	-6.306	-6.314	-6.322	-6.329	-6.337	-6.344	-230
-220	-6.158	-6.170	-6.181	-6.192	-6.202	-6.213	-6.223	-6.233	-6.243	-6.252	-6.262	-220
-210	-6.035	-6.048	-6.061	-6.074	-6.087	-6.099	-6.111	-6.123	-6.135	-6.147	-6.158	-210
-200	-5.891	-5.907	-5.922	-5.936	-5.951	-5.965	-5.980	-5.994	-6.007	-6.021	-6.035	-200
-190	-5.730	-5.747	-5.763	-5.780	-5.797	-5.813	-5.829	-5.845	-5.861	-5.876	-5.891	-190
-180	-5.550	-5.569	-5.588	-5.606	-5.624	-5.642	-5.660	-5.678	-5.695	-5.713	-5.730	-180
-170	-5.354	-5.374	-5.395	-5.415	-5.435	-5.454	-5.474	-5.493	-5.512	-5.531	-5.550	-170
-160	-5.141	-5.163	-5.185	-5.207	-5.228	-5.250	-5.271	-5.292	-5.313	-5.333	-5.354	-160
-150	-4.913	-4.936	-4.960	-4.983	-5.006	-5.029	-5.052	-5.074	-5.097	-5.119	-5.141	-150
-140	-4.669	-4.694	-4.719	-4.744	-4.768	-4.793	-4.817	-4.841	-4.865	-4.889	-4.913	-140
-130	-4.411	-4.437	-4.463	-4.490	-4.516	-4.542	-4.567	-4.593	-4.618	-4.644	-4.669	-130
-120	-4.138	-4.166	-4.194	-4.221	-4.249	-4.276	-4.303	-4.330	-4.357	-4.384	-4.411	-120
-110	-3.852	-3.882	-3.911	-3.939	-3.968	-3.997	-4.025	-4.054	-4.082	-4.110	-4.138	-110
-100	-3.554	-3.584	-3.614	-3.645	-3.675	-3.705	-3.734	-3.764	-3.794	-3.823	-3.852	-100
-90	-3.243	-3.274	-3.306	-3.337	-3.368	-3.400	-3.431	-3.462	-3.492	-3.523	-3.554	-90
-80	-2.920	-2.953	-2.986	-3.018	-3.050	-3.083	-3.115	-3.147	-3.179	-3.211	-3.243	-80
-70	-2.587	-2.620	-2.654	-2.688	-2.721	-2.755	-2.788	-2.821	-2.854	-2.887	-2.920	-70
-60	-2.243	-2.278	-2.312	-2.347	-2.382	-2.416	-2.450	-2.485	-2.519	-2.553	-2.587	-60
-50	-1.889	-1.925	-1.961	-1.996	-2.032	-2.067	-2.103	-2.138	-2.173	-2.208	-2.243	-50
-40	-1.527	-1.564	-1.600	-1.637	-1.673	-1.709	-1.745	-1.782	-1.818	-1.854	-1.889	-40
-30	-1.156	-1.194	-1.231	-1.268	-1.305	-1.343	-1.380	-1.417	-1.453	-1.490	-1.527	-30
-20	-0.778	-0.816	-0.854	-0.892	-0.930	-0.968	-1.006	-1.043	-1.081	-1.119	-1.156	-20
-10	-0.392	-0.431	-0.470	-0.508	-0.547	-0.586	-0.624	-0.663	-0.701	-0.739	-0.778	-10
0	0.000	-0.039	-0.079	-0.118	-0.157	-0.197	-0.236	-0.275	-0.314	-0.353	-0.392	0
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397	0
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798	10
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203	20
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612	30
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023	40
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436	50
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851	60
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267	70
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682	80
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096	90
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509	100
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920	110
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328	120
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735	130
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138	140
150	6.138	6.179	6.219	6.259	6.299	6.339	6.380	6.420	6.460	6.500	6.540	150
160	6.540	6.580	6.620	6.660	6.701	6.741	6.781	6.821	6.861	6.901	6.941	160
170	6.941	6.981	7.021	7.060	7.100	7.140	7.180	7.220	7.260	7.300	7.340	170
180	7.340	7.380	7.420	7.460	7.500	7.540	7.579	7.619	7.659	7.699	7.739	180
190	7.739	7.779	7.819	7.859	7.899	7.939	7.979	8.019	8.059	8.099	8.138	190
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 9 ***Type K Thermocouple*** *— thermoelectric voltage as a function of temperature (℃); reference junctions at 0 ℃*

K°C

Thermoelectric Voltage in Millivolts

°C	0	1	2	3	4	5	6	7	8	9	10	°C
200	8.138	8.178	8.218	8.258	8.298	8.338	8.378	8.418	8.458	8.499	8.539	200
210	8.539	8.579	8.619	8.659	8.699	8.739	8.779	8.819	8.860	8.900	8.940	210
220	8.940	8.980	9.020	9.061	9.101	9.141	9.181	9.222	9.262	9.302	9.343	220
230	9.343	9.383	9.423	9.464	9.504	9.545	9.585	9.626	9.666	9.707	9.747	230
240	9.747	9.788	9.828	9.869	9.909	9.950	9.991	10.031	10.072	10.113	10.153	240
250	10.153	10.194	10.235	10.276	10.316	10.357	10.398	10.439	10.480	10.520	10.561	250
260	10.561	10.602	10.643	10.684	10.725	10.766	10.807	10.848	10.889	10.930	10.971	260
270	10.971	11.012	11.053	11.094	11.135	11.176	11.217	11.259	11.300	11.341	11.382	270
280	11.382	11.423	11.465	11.506	11.547	11.588	11.630	11.671	11.712	11.753	11.795	280
290	11.795	11.836	11.877	11.919	11.960	12.001	12.043	12.084	12.126	12.167	12.209	290
300	12.209	12.250	12.291	12.333	12.374	12.416	12.457	12.499	12.540	12.582	12.624	300
310	12.624	12.665	12.707	12.748	12.790	12.831	12.873	12.915	12.956	12.998	13.040	310
320	13.040	13.081	13.123	13.165	13.206	13.248	13.290	13.331	13.373	13.415	13.457	320
330	13.457	13.498	13.540	13.582	13.624	13.665	13.707	13.749	13.791	13.833	13.874	330
340	13.874	13.916	13.958	14.000	14.042	14.084	14.126	14.167	14.209	14.251	14.293	340
350	14.293	14.335	14.377	14.419	14.461	14.503	14.545	14.587	14.629	14.671	14.713	350
360	14.713	14.755	14.797	14.839	14.881	14.923	14.965	15.007	15.049	15.091	15.133	360
370	15.133	15.175	15.217	15.259	15.301	15.343	15.385	15.427	15.469	15.511	15.554	370
380	15.554	15.596	15.638	15.680	15.722	15.764	15.806	15.849	15.891	15.933	15.975	380
390	15.975	16.017	16.059	16.102	16.144	16.186	16.228	16.270	16.313	16.355	16.397	390
400	16.397	16.439	16.482	16.524	16.566	16.608	16.651	16.693	16.735	16.778	16.820	400
410	16.820	16.862	16.904	16.947	16.989	17.031	17.074	17.116	17.158	17.201	17.243	410
420	17.243	17.285	17.328	17.370	17.413	17.455	17.497	17.540	17.582	17.624	17.667	420
430	17.667	17.709	17.752	17.794	17.837	17.879	17.921	17.964	18.006	18.049	18.091	430
440	18.091	18.134	18.176	18.218	18.261	18.303	18.346	18.388	18.431	18.473	18.516	440
450	18.516	18.558	18.601	18.643	18.686	18.728	18.771	18.813	18.856	18.898	18.941	450
460	18.941	18.983	19.026	19.068	19.111	19.154	19.196	19.239	19.281	19.324	19.366	460
470	19.366	19.409	19.451	19.494	19.537	19.579	19.622	19.664	19.707	19.750	19.792	470
480	19.792	19.835	19.877	19.920	19.962	20.005	20.048	20.090	20.133	20.175	20.218	480
490	20.218	20.261	20.303	20.346	20.389	20.431	20.474	20.516	20.559	20.602	20.644	490
500	20.644	20.687	20.730	20.772	20.815	20.857	20.900	20.943	20.985	21.028	21.071	500
510	21.071	21.113	21.156	21.199	21.241	21.284	21.326	21.369	21.412	21.454	21.497	510
520	21.497	21.540	21.582	21.625	21.668	21.710	21.753	21.796	21.838	21.881	21.924	520
530	21.924	21.966	22.009	22.052	22.094	22.137	22.179	22.222	22.265	22.307	22.350	530
540	22.350	22.393	22.435	22.478	22.521	22.563	22.606	22.649	22.691	22.734	22.776	540
550	22.776	22.819	22.862	22.904	22.947	22.990	23.032	23.075	23.117	23.160	23.203	550
560	23.203	23.245	23.288	23.331	23.373	23.416	23.458	23.501	23.544	23.586	23.629	560
570	23.629	23.671	23.714	23.757	23.799	23.842	23.884	23.927	23.970	24.012	24.055	570
580	24.055	24.097	24.140	24.182	24.225	24.267	24.310	24.353	24.395	24.438	24.480	580
590	24.480	24.523	24.565	24.608	24.650	24.693	24.735	24.778	24.820	24.863	24.905	590
600	24.905	24.948	24.990	25.033	25.075	25.118	25.160	25.203	25.245	25.288	25.330	600
610	25.330	25.373	25.415	25.458	25.500	25.543	25.585	25.627	25.670	25.712	25.755	610
620	25.755	25.797	25.840	25.882	25.924	25.967	26.009	26.052	26.094	26.136	26.179	620
630	26.179	26.221	26.263	26.306	26.348	26.390	26.433	26.475	26.517	26.560	26.602	630
640	26.602	26.644	26.687	26.729	26.771	26.814	26.856	26.898	26.940	26.983	27.025	640
650	27.025	27.067	27.109	27.152	27.194	27.236	27.278	27.320	27.363	27.405	27.447	650
660	27.447	27.489	27.531	27.574	27.616	27.658	27.700	27.742	27.784	27.826	27.869	660
670	27.869	27.911	27.953	27.995	28.037	28.079	28.121	28.163	28.205	28.247	28.289	670
680	28.289	28.332	28.374	28.416	28.458	28.500	28.542	28.584	28.626	28.668	28.710	680
690	28.710	28.752	28.794	28.835	28.877	28.919	28.961	29.003	29.045	29.087	29.129	690
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 9 **_Type K Thermocouple_** — *thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

Thermoelectric Voltage in Millivolts

°C	0	1	2	3	4	5	6	7	8	9	10	°C
700	29.129	29.171	29.213	29.255	29.297	29.338	29.380	29.422	29.464	29.506	29.548	700
710	29.548	29.589	29.631	29.673	29.715	29.757	29.798	29.840	29.882	29.924	29.965	710
720	29.965	30.007	30.049	30.090	30.132	30.174	30.216	30.257	30.299	30.341	30.382	720
730	30.382	30.424	30.466	30.507	30.549	30.590	30.632	30.674	30.715	30.757	30.798	730
740	30.798	30.840	30.881	30.923	30.964	31.006	31.047	31.089	31.130	31.172	31.213	740
750	31.213	31.255	31.296	31.338	31.379	31.421	31.462	31.504	31.545	31.586	31.628	750
760	31.628	31.669	31.710	31.752	31.793	31.834	31.876	31.917	31.958	32.000	32.041	760
770	32.041	32.082	32.124	32.165	32.206	32.247	32.289	32.330	32.371	32.412	32.453	770
780	32.453	32.495	32.536	32.577	32.618	32.659	32.700	32.742	32.783	32.824	32.865	780
790	32.865	32.906	32.947	32.988	33.029	33.070	33.111	33.152	33.193	33.234	33.275	790
800	33.275	33.316	33.357	33.398	33.439	33.480	33.521	33.562	33.603	33.644	33.685	800
810	33.685	33.726	33.767	33.808	33.848	33.889	33.930	33.971	34.012	34.053	34.093	810
820	34.093	34.134	34.175	34.216	34.257	34.297	34.338	34.379	34.420	34.460	34.501	820
830	34.501	34.542	34.582	34.623	34.664	34.704	34.745	34.786	34.826	34.867	34.908	830
840	34.908	34.948	34.989	35.029	35.070	35.110	35.151	35.192	35.232	35.273	35.313	840
850	35.313	35.354	35.394	35.435	35.475	35.516	35.556	35.596	35.637	35.677	35.718	850
860	35.718	35.758	35.798	35.839	35.879	35.920	35.960	36.000	36.041	36.081	36.121	860
870	36.121	36.162	36.202	36.242	36.282	36.323	36.363	36.403	36.443	36.484	36.524	870
880	36.524	36.564	36.604	36.644	36.685	36.725	36.765	36.805	36.845	36.885	36.925	880
890	36.925	36.965	37.006	37.046	37.086	37.126	37.166	37.206	37.246	37.286	37.326	890
900	37.326	37.366	37.406	37.446	37.486	37.526	37.566	37.606	37.646	37.686	37.725	900
910	37.725	37.765	37.805	37.845	37.885	37.925	37.965	38.005	38.044	38.084	38.124	910
920	38.124	38.164	38.204	38.243	38.283	38.323	38.363	38.402	38.442	38.482	38.522	920
930	38.522	38.561	38.601	38.641	38.680	38.720	38.760	38.799	38.839	38.878	38.918	930
940	38.918	38.958	38.997	39.037	39.076	39.116	39.155	39.195	39.235	39.274	39.314	940
950	39.314	39.353	39.393	39.432	39.471	39.511	39.550	39.590	39.629	39.669	39.708	950
960	39.708	39.747	39.787	39.826	39.866	39.905	39.944	39.984	40.023	40.062	40.101	960
970	40.101	40.141	40.180	40.219	40.259	40.298	40.337	40.376	40.415	40.455	40.494	970
980	40.494	40.533	40.572	40.611	40.651	40.690	40.729	40.768	40.807	40.846	40.885	980
990	40.885	40.924	40.963	41.002	41.042	41.081	41.120	41.159	41.198	41.237	41.276	990
1000	41.276	41.315	41.354	41.393	41.431	41.470	41.509	41.548	41.587	41.626	41.665	1000
1010	41.665	41.704	41.743	41.781	41.820	41.859	41.898	41.937	41.976	42.014	42.053	1010
1020	42.053	42.092	42.131	42.169	42.208	42.247	42.286	42.324	42.363	42.402	42.440	1020
1030	42.440	42.479	42.518	42.556	42.595	42.633	42.672	42.711	42.749	42.788	42.826	1030
1040	42.826	42.865	42.903	42.942	42.980	43.019	43.057	43.096	43.134	43.173	43.211	1040
1050	43.211	43.250	43.288	43.327	43.365	43.403	43.442	43.480	43.518	43.557	43.595	1050
1060	43.595	43.633	43.672	43.710	43.748	43.787	43.825	43.863	43.901	43.940	43.978	1060
1070	43.978	44.016	44.054	44.092	44.130	44.169	44.207	44.245	44.283	44.321	44.359	1070
1080	44.359	44.397	44.435	44.473	44.512	44.550	44.588	44.626	44.664	44.702	44.740	1080
1090	44.740	44.778	44.816	44.853	44.891	44.929	44.967	45.005	45.043	45.081	45.119	1090
1100	45.119	45.157	45.194	45.232	45.270	45.308	45.346	45.383	45.421	45.459	45.497	1100
1110	45.497	45.534	45.572	45.610	45.647	45.685	45.723	45.760	45.798	45.836	45.873	1110
1120	45.873	45.911	45.948	45.986	46.024	46.061	46.099	46.136	46.174	46.211	46.249	1120
1130	46.249	46.286	46.324	46.361	46.398	46.436	46.473	46.511	46.548	46.585	46.623	1130
1140	46.623	46.660	46.697	46.735	46.772	46.809	46.847	46.884	46.921	46.958	46.995	1140
1150	46.995	47.033	47.070	47.107	47.144	47.181	47.218	47.256	47.293	47.330	47.367	1150
1160	47.367	47.404	47.441	47.478	47.515	47.552	47.589	47.626	47.663	47.700	47.737	1160
1170	47.737	47.774	47.811	47.848	47.884	47.921	47.958	47.995	48.032	48.069	48.105	1170
1180	48.105	48.142	48.179	48.216	48.252	48.289	48.326	48.363	48.399	48.436	48.473	1180
1190	48.473	48.509	48.546	48.582	48.619	48.656	48.692	48.729	48.765	48.802	48.838	1190
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 9 ***Type K Thermocouple*** — *thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

K°C

°C	0	1	2	3	4	5	6	7	8	9	10	°C
						Thermoelectric Voltage in Millivolts						
1200	48.838	48.875	48.911	48.948	48.984	49.021	49.057	49.093	49.130	49.166	49.202	1200
1210	49.202	49.239	49.275	49.311	49.348	49.384	49.420	49.456	49.493	49.529	49.565	1210
1220	49.565	49.601	49.637	49.674	49.710	49.746	49.782	49.818	49.854	49.890	49.926	1220
1230	49.926	49.962	49.998	50.034	50.070	50.106	50.142	50.178	50.214	50.250	50.286	1230
1240	50.286	50.322	50.358	50.393	50.429	50.465	50.501	50.537	50.572	50.608	50.644	1240
1250	50.644	50.680	50.715	50.751	50.787	50.822	50.858	50.894	50.929	50.965	51.000	1250
1260	51.000	51.036	51.071	51.107	51.142	51.178	51.213	51.249	51.284	51.320	51.355	1260
1270	51.355	51.391	51.426	51.461	51.497	51.532	51.567	51.603	51.638	51.673	51.708	1270
1280	51.708	51.744	51.779	51.814	51.849	51.885	51.920	51.955	51.990	52.025	52.060	1280
1290	52.060	52.095	52.130	52.165	52.200	52.235	52.270	52.305	52.340	52.375	52.410	1290
1300	52.410	52.445	52.480	52.515	52.550	52.585	52.620	52.654	52.689	52.724	52.759	1300
1310	52.759	52.794	52.828	52.863	52.898	52.932	52.967	53.002	53.037	53.071	53.106	1310
1320	53.106	53.140	53.175	53.210	53.244	53.279	53.313	53.348	53.382	53.417	53.451	1320
1330	53.451	53.486	53.520	53.555	53.589	53.623	53.658	53.692	53.727	53.761	53.795	1330
1340	53.795	53.830	53.864	53.898	53.932	53.967	54.001	54.035	54.069	54.104	54.138	1340
1350	54.138	54.172	54.206	54.240	54.274	54.308	54.343	54.377	54.411	54.445	54.479	1350
1360	54.479	54.513	54.547	54.581	54.615	54.649	54.683	54.717	54.751	54.785	54.819	1360
1370	54.819	54.852	54.886									1370
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 17 ***Type T Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

Thermoelectric Voltage in Millivolts

°C	0	1	2	3	4	5	6	7	8	9	10	°C
-270	-6.258											-270
-260	-6.232	-6.236	-6.239	-6.242	-6.245	-6.248	-6.251	-6.253	-6.255	-6.256	-6.258	-260
-250	-6.180	-6.187	-6.193	-6.198	-6.204	-6.209	-6.214	-6.219	-6.223	-6.228	-6.232	-250
-240	-6.105	-6.114	-6.122	-6.130	-6.138	-6.146	-6.153	-6.160	-6.167	-6.174	-6.180	-240
-230	-6.007	-6.017	-6.028	-6.038	-6.049	-6.059	-6.068	-6.078	-6.087	-6.096	-6.105	-230
-220	-5.888	-5.901	-5.914	-5.926	-5.938	-5.950	-5.962	-5.973	-5.985	-5.996	-6.007	-220
-210	-5.753	-5.767	-5.782	-5.795	-5.809	-5.823	-5.836	-5.850	-5.863	-5.876	-5.888	-210
-200	-5.603	-5.619	-5.634	-5.650	-5.665	-5.680	-5.695	-5.710	-5.724	-5.739	-5.753	-200
-190	-5.439	-5.456	-5.473	-5.489	-5.506	-5.523	-5.539	-5.555	-5.571	-5.587	-5.603	-190
-180	-5.261	-5.279	-5.297	-5.316	-5.334	-5.351	-5.369	-5.387	-5.404	-5.421	-5.439	-180
-170	-5.070	-5.089	-5.109	-5.128	-5.148	-5.167	-5.186	-5.205	-5.224	-5.242	-5.261	-170
-160	-4.865	-4.886	-4.907	-4.928	-4.949	-4.969	-4.989	-5.010	-5.030	-5.050	-5.070	-160
-150	-4.648	-4.671	-4.693	-4.715	-4.737	-4.759	-4.780	-4.802	-4.823	-4.844	-4.865	-150
-140	-4.419	-4.443	-4.466	-4.489	-4.512	-4.535	-4.558	-4.581	-4.604	-4.626	-4.648	-140
-130	-4.177	-4.202	-4.226	-4.251	-4.275	-4.300	-4.324	-4.348	-4.372	-4.395	-4.419	-130
-120	-3.923	-3.949	-3.975	-4.000	-4.026	-4.052	-4.077	-4.102	-4.127	-4.152	-4.177	-120
-110	-3.657	-3.684	-3.711	-3.738	-3.765	-3.791	-3.818	-3.844	-3.871	-3.897	-3.923	-110
-100	-3.379	-3.407	-3.435	-3.463	-3.491	-3.519	-3.547	-3.574	-3.602	-3.629	-3.657	-100
-90	-3.089	-3.118	-3.148	-3.177	-3.206	-3.235	-3.264	-3.293	-3.322	-3.350	-3.379	-90
-80	-2.788	-2.818	-2.849	-2.879	-2.910	-2.940	-2.970	-3.000	-3.030	-3.059	-3.089	-80
-70	-2.476	-2.507	-2.539	-2.571	-2.602	-2.633	-2.664	-2.695	-2.726	-2.757	-2.788	-70
-60	-2.153	-2.186	-2.218	-2.251	-2.283	-2.316	-2.348	-2.380	-2.412	-2.444	-2.476	-60
-50	-1.819	-1.853	-1.887	-1.920	-1.954	-1.987	-2.021	-2.054	-2.087	-2.120	-2.153	-50
-40	-1.475	-1.510	-1.545	-1.579	-1.614	-1.648	-1.683	-1.717	-1.751	-1.785	-1.819	-40
-30	-1.121	-1.157	-1.192	-1.228	-1.264	-1.299	-1.335	-1.370	-1.405	-1.440	-1.475	-30
-20	-0.757	-0.794	-0.830	-0.867	-0.904	-0.940	-0.976	-1.013	-1.049	-1.085	-1.121	-20
-10	-0.383	-0.421	-0.459	-0.496	-0.534	-0.571	-0.608	-0.646	-0.683	-0.720	-0.757	-10
0	0.000	-0.039	-0.077	-0.116	-0.154	-0.193	-0.231	-0.269	-0.307	-0.345	-0.383	0
0	0.000	0.039	0.078	0.117	0.156	0.195	0.234	0.273	0.312	0.352	0.391	0
10	0.391	0.431	0.470	0.510	0.549	0.589	0.629	0.669	0.709	0.749	0.790	10
20	0.790	0.830	0.870	0.911	0.951	0.992	1.033	1.074	1.114	1.155	1.196	20
30	1.196	1.238	1.279	1.320	1.362	1.403	1.445	1.486	1.528	1.570	1.612	30
40	1.612	1.654	1.696	1.738	1.780	1.823	1.865	1.908	1.950	1.993	2.036	40
50	2.036	2.079	2.122	2.165	2.208	2.251	2.294	2.338	2.381	2.425	2.468	50
60	2.468	2.512	2.556	2.600	2.643	2.687	2.732	2.776	2.820	2.864	2.909	60
70	2.909	2.953	2.998	3.043	3.087	3.132	3.177	3.222	3.267	3.312	3.358	70
80	3.358	3.403	3.448	3.494	3.539	3.585	3.631	3.677	3.722	3.768	3.814	80
90	3.814	3.860	3.907	3.953	3.999	4.046	4.092	4.138	4.185	4.232	4.279	90
100	4.279	4.325	4.372	4.419	4.466	4.513	4.561	4.608	4.655	4.702	4.750	100
110	4.750	4.798	4.845	4.893	4.941	4.988	5.036	5.084	5.132	5.180	5.228	110
120	5.228	5.277	5.325	5.373	5.422	5.470	5.519	5.567	5.616	5.665	5.714	120
130	5.714	5.763	5.812	5.861	5.910	5.959	6.008	6.057	6.107	6.156	6.206	130
140	6.206	6.255	6.305	6.355	6.404	6.454	6.504	6.554	6.604	6.654	6.704	140
150	6.704	6.754	6.805	6.855	6.905	6.956	7.006	7.057	7.107	7.158	7.209	150
160	7.209	7.260	7.310	7.361	7.412	7.463	7.515	7.566	7.617	7.668	7.720	160
170	7.720	7.771	7.823	7.874	7.926	7.977	8.029	8.081	8.133	8.185	8.237	170
180	8.237	8.289	8.341	8.393	8.445	8.497	8.550	8.602	8.654	8.707	8.759	180
190	8.759	8.812	8.865	8.917	8.970	9.023	9.076	9.129	9.182	9.235	9.288	190
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 17 ***Type T Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

°C	0	1	2	3	4	5	6	7	8	9	10	°C
						Thermoelectric Voltage in Millivolts						
200	9.288	9.341	9.395	9.448	9.501	9.555	9.608	9.662	9.715	9.769	9.822	200
210	9.822	9.876	9.930	9.984	10.038	10.092	10.146	10.200	10.254	10.308	10.362	210
220	10.362	10.417	10.471	10.525	10.580	10.634	10.689	10.743	10.798	10.853	10.907	220
230	10.907	10.962	11.017	11.072	11.127	11.182	11.237	11.292	11.347	11.403	11.458	230
240	11.458	11.513	11.569	11.624	11.680	11.735	11.791	11.846	11.902	11.958	12.013	240
250	12.013	12.069	12.125	12.181	12.237	12.293	12.349	12.405	12.461	12.518	12.574	250
260	12.574	12.630	12.687	12.743	12.799	12.856	12.912	12.969	13.026	13.082	13.139	260
270	13.139	13.196	13.253	13.310	13.366	13.423	13.480	13.537	13.595	13.652	13.709	270
280	13.709	13.766	13.823	13.881	13.938	13.995	14.053	14.110	14.168	14.226	14.283	280
290	14.283	14.341	14.399	14.456	14.514	14.572	14.630	14.688	14.746	14.804	14.862	290
300	14.862	14.920	14.978	15.036	15.095	15.153	15.211	15.270	15.328	15.386	15.445	300
310	15.445	15.503	15.562	15.621	15.679	15.738	15.797	15.856	15.914	15.973	16.032	310
320	16.032	16.091	16.150	16.209	16.268	16.327	16.387	16.446	16.505	16.564	16.624	320
330	16.624	16.683	16.742	16.802	16.861	16.921	16.980	17.040	17.100	17.159	17.219	330
340	17.219	17.279	17.339	17.399	17.458	17.518	17.578	17.638	17.698	17.759	17.819	340
350	17.819	17.879	17.939	17.999	18.060	18.120	18.180	18.241	18.301	18.362	18.422	350
360	18.422	18.483	18.543	18.604	18.665	18.725	18.786	18.847	18.908	18.969	19.030	360
370	19.030	19.091	19.152	19.213	19.274	19.335	19.396	19.457	19.518	19.579	19.641	370
380	19.641	19.702	19.763	19.825	19.886	19.947	20.009	20.070	20.132	20.193	20.255	380
390	20.255	20.317	20.378	20.440	20.502	20.563	20.625	20.687	20.748	20.810	20.872	390
400	20.872											400
°C	0	1	2	3	4	5	6	7	8	9	10	°C

From the recorded lecture

قراءة ال voltmeter = Voltage on Hot junction − Voltage on cold Junction

Problem B

ال cold junction بطلع zero

A voltage of 3.444 mV is measured with a type J thermocouple with a 25 degree C reference temperature. Find the temperature of the sensing junction.

From the table

At 25 C = the voltage of the cold junction 1.277 mv

Voltage (hot) = Voltage (cold) + Voltage(voltmeter)

Voltage (hot)= 1.277 +3.444 = 4.721 mV

4.672	89
4.721	T =??
4.726	90

T= 89.907 c

	0	1	2	3	4	5	6					
-120	-5.426	-5.465	-5.503	-5.541	-5.578	-5.616	-5.653	-5.690	-5.727	-5.764	-5.801	-120
-110	-5.037	-5.076	-5.116	-5.155	-5.194	-5.233	-5.272	-5.311	-5.350	-5.388	-5.426	-110
-100	-4.633	-4.674	-4.714	-4.755	-4.796	-4.836	-4.877	-4.917	-4.957	-4.997	-5.037	-100
-90	-4.215	-4.257	-4.300	-4.342	-4.384	-4.425	-4.467	-4.509	-4.550	-4.591	-4.633	-90
-80	-3.786	-3.829	-3.872	-3.916	-3.959	-4.002	-4.045	-4.088	-4.130	-4.173	-4.215	-80
-70	-3.344	-3.389	-3.434	-3.478	-3.522	-3.566	-3.610	-3.654	-3.698	-3.742	-3.786	-70
-60	-2.893	-2.938	-2.984	-3.029	-3.075	-3.120	-3.165	-3.210	-3.255	-3.300	-3.344	-60
-50	-2.431	-2.478	-2.524	-2.571	-2.617	-2.663	-2.709	-2.755	-2.801	-2.847	-2.893	-50
-40	-1.961	-2.008	-2.055	-2.103	-2.150	-2.197	-2.244	-2.291	-2.338	-2.385	-2.431	-40
-30	-1.482	-1.530	-1.578	-1.626	-1.674	-1.722	-1.770	-1.818	-1.865	-1.913	-1.961	-30
-20	-0.995	-1.044	-1.093	-1.142	-1.190	-1.239	-1.288	-1.336	-1.385	-1.433	-1.482	-20
-10	-0.501	-0.550	-0.600	-0.650	-0.699	-0.749	-0.798	-0.847	-0.896	-0.946	-0.995	-10
0	0.000	-0.050	-0.101	-0.151	-0.201	-0.251	-0.301	-0.351	-0.401	-0.451	-0.501	0
0	0.000	0.050	0.101	0.151	0.202	0.253	0.303	0.354	0.405	0.456	0.507	0
10	0.507	0.558	0.609	0.660	0.711	0.762	0.814	0.865	0.916	0.968	1.019	10
20	1.019	1.071	1.122	1.174	1.226	1.277	1.329	1.381	1.433	1.485	1.537	20
30	1.537	1.589	1.641	1.693	1.745	1.797	1.849	1.902	1.954	2.006	2.059	30
40	2.059	2.111	2.164	2.216	2.269	2.322	2.374	2.427	2.480	2.532	2.585	40
50	2.585	2.638	2.691	2.744	2.797	2.850	2.903	2.956	3.009	3.062	3.116	50
60	3.116	3.169	3.222	3.275	3.329	3.382	3.436	3.489	3.543	3.596	3.650	60
70	3.650	3.703	3.757	3.810	3.864	3.918	3.971	4.025	4.079	4.133	4.187	70
80	4.187	4.240	4.294	4.348	4.402	4.456	4.510	4.564	4.618	4.672	4.726	80
90	4.726	4.781	4.835	4.889	4.943	4.997	5.052	5.106	5.160	5.215	5.269	90
100	5.269	5.323	5.378	5.432	5.487	5.541	5.595	5.650	5.705	5.759	5.814	100

results. Liquid-in-glass thermometers are simple, portable, and inexpensive. However, they are fragile and not suitable for remote applications and sensing surface temperature. Under optimal conditions, the accuracy of this type of thermometers is around 0.1 °C.

15.7 PRESSURE THERMOMETERS

The change in temperature can be measured using pressure thermometers. These thermometers work on the principle of thermal expansion of the matter wherein the change in temperature is to be measured. Temperature change can be determined using these thermometers, which rely on pressure measurement. Depending on the filling medium, pressure thermometers can be classified as liquid, gas, or a combination of liquid and its vapour.

Pressure thermometers comprise the following components: a bulb filled with a liquid, vapour, or gas; a flexible capillary tube; and a bourdon tube. Due to variation in temperature, the pressure and volume of the system change and the fluid either expands or contracts. This causes the bourdon tube to move or uncoil, which actuates the needle on the scale, thus providing a measure of the temperature. A typical pressure thermometer is shown in Fig. 15.11.

Pressure thermometers are extensively preferred because of the following advantages:

1. Direct reading or recording is possible since pressure thermometers give adequate force output.
2. Pressure thermometers are less expensive than other systems.

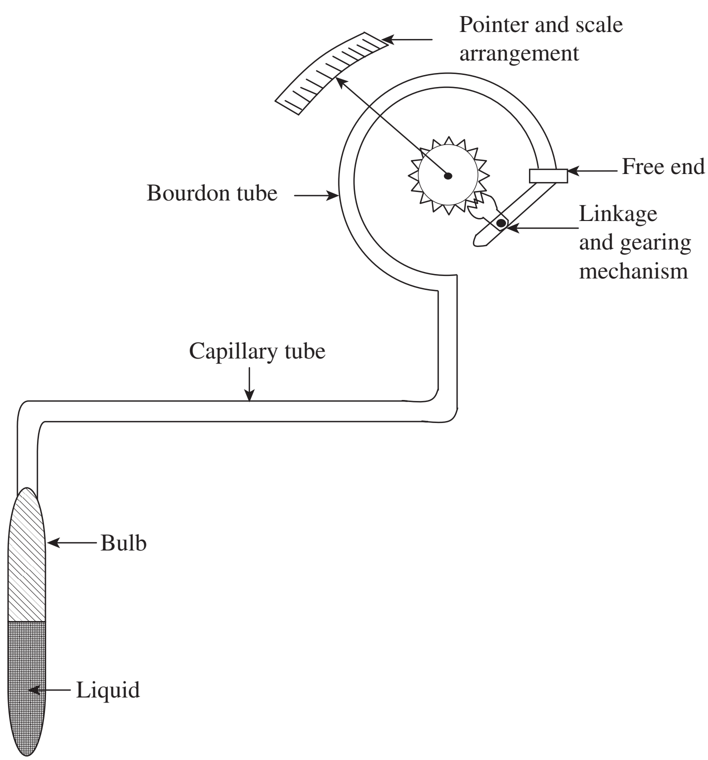

Fig. 15.11 Pressure thermometer

3. They show a superior dynamic response when compared to liquid-in-metal thermometers.
4. They deliver a high-speed response.
5. Their maintenance is easy.

However, they suffer from limited linearity and are prone to output errors. In case of liquid- or gas-filled thermometers, the tube and the filling are temperature sensitive, and if calibration conditions differ along the tube, an error is induced. This error can be minimized by increasing the ratio of volumes of the bulb and the tube. Increasing the bulb size reduces the time response of the system but does not degrade the response. The presence of a pressure gradient resulting from the elevation difference between the bulb and the bourdon tube also contributes to errors.

15.8 BIMETALLIC STRIP THERMOMETERS

John Harrison, who invented bimetallic thermometers, made the first bimetallic strip in 1759 to compensate for changes in the balance spring induced by temperature. A bimetallic strip thermometer works on the well-known principle that different metals expand and contract to different degrees, depending on the coefficient of expansion of the individual metals. For example, if two strips of two different metals (steel and copper) are firmly welded, riveted, or brazed together and subjected to temperature changes, either cooling or heating, the degree of contraction or expansion of the metals differ depending on their coefficient of expansion. The metal strips tend to bend owing to their different coefficients of expansion; the contraction or expansion of one strip will be greater than that of the other. The difference in the expansion of two metals, which makes the strip bend, is a measure of temperature, and since two different metal strips are employed it is called a bimetallic strip thermometer. Figure 15.12 shows the principle of a bimetallic strip.

Bimetallic strips are manufactured in different shapes: cantilever type, flat form, U form, and helical and spiral shapes. In bimetallic strips, the lateral displacement in both the metals is much larger than the small longitudinal expansion. This effect is made use of in mechanical and electrical devices. For industrial use, the strips are wrapped around a spindle into a helical coil. Due to its coil form, the length of the bimetallic strip increases, which in turn increases its sensitivity. Bimetallic strip thermometers are preferred for their ruggedness and availability in

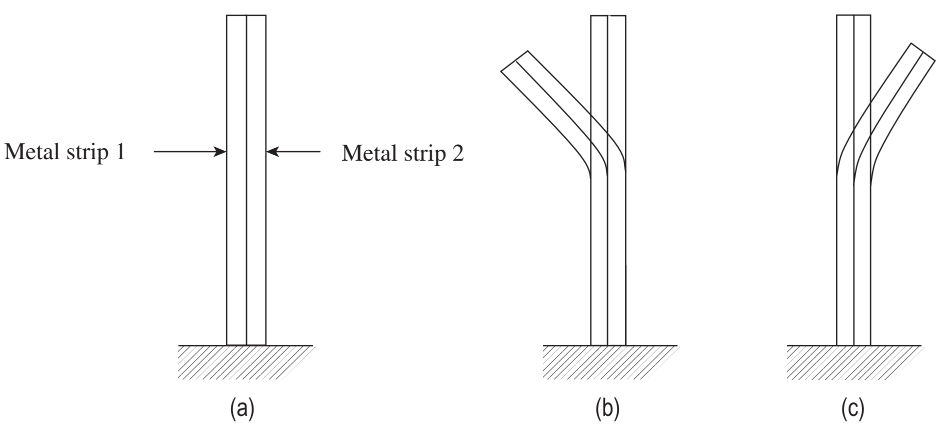

Fig. 15.12 Deflection of a bimetallic strip (a) Normal condition (b) Cold condition (c) Hot condition

suitable forms. These thermometers are used for sensing temperature of hot water pipes, steam chambers, etc. They are also used in temperature compensation clocks and circuit breakers.

15.9 PYROMETRY

In the preceding sections, contact-type temperature measurement devices have been discussed. If the temperature of a very hot body has to be measured, contact-type temperature-measuring devices will not be suitable, because they are liable to be damaged when they come in contact with the hot body. Hence, the use of non-contact-type temperature-measuring devices becomes imperative. When such devices are employed for high-temperature measurement, the distance between the source of the temperature and the instrument has no effect on the measurement. These non-contact-type devices are called pyrometers. The term pyrometer is of Greek origin, wherein pyro stands for 'fire' and metron means 'to measure'. Pyrometer was first invented by the great English potter Josiah Wedgwood in the early 1780s, for which he received the Fellowship of the Royal Society in 1783. Measurements of temperature are carried out either by measuring energy radiated by a hot body or by colour comparison. Pyrometers are classified into two distinct categories: total radiation pyrometers and optical pyrometers.

It is very well known that conduction, convection, and radiation are the three modes of heat transfer. It is also a fact that all bodies above absolute zero radiate energy, and radiation does not require any medium. When heat is radiated by a body at a given intensity, radiation is emitted across a spectrum of wavelengths. Radiation intensity is directly proportional to temperature. When radiation intensity falls, there is a corresponding increase in the wavelength of radiation. On the other hand, the wavelength decreases when there is an increase in the intensity of radiation.

A body that is capable of absorbing all the radiations that fall on it and does not reflect or transmit any radiation is called a black body. A black body is an ideal thermal radiator. The capacity of radiation absorption of a body depends on its surface condition. Under similar conditions, a black body absorbs and loses heat more quickly than a non-black body. The radiation absorption of a body is much superior when its colour is black and when it has a matt or rough surface finish. The heat radiated by a black body is a function of temperature.

When a body radiates less heat than a black body, the ratio of this radiation to the black body radiation is known as the total emissivity of the surface. If the emissivity of a black body radiation is 1, then other bodies that transmit some of the incoming radiation is said to have an emissivity of less than 1.

If E is the radiation impinging on a body (W/m^2), α is the fraction of radiation power absorbed by the body, and e is the total emissivity, then

$$e = \frac{\alpha E}{E} = \frac{\text{Radiation emitted from a body}}{\text{Radiation falling upon the body}}$$

The Stefan–Boltzmann law states that the total energy radiated by a black body is a function of its absolute temperature only and is proportional to the fourth power of that temperature.

If E is the total energy radiated per unit area per unit time, then

$$E \propto T_a^4 \text{ or } E = \sigma T_a^4$$

Here, σ is the Stefan's constant, which is equal to 50×10^{-8} W K^4/m^2 and T_a is the absolute temperature in K.

According to the Stefan–Boltzmann law, if two ideal radiators are considered, the pyrometer not only receives heat from the source, but also radiates heat to the source. Therefore, the net rate of exchange of energy between them is given by

$$E = \sigma\,(T_p^{\,4} - T_s^{\,4})$$

where T_p and T_s are the temperatures of the pyrometer and the radiating source, respectively.

Further, $T_p^{\,4}$ is small when compared to T_s and can be neglected.

If e is the emissivity of the body at a given temperature, then

$$E = e\sigma T_a^{\,4}$$

If the emissivity of the surface is known, then the temperature of the body can be determined provided it is kept in the open. If T_t is the true temperature and T is the apparent temperature taken with a radiation pyrometer positioned in such a way that the body is in full view, then

$$E = \sigma T^4$$

The pyrometer receives energy that is equivalent to the energy emitted by a perfect black body radiating at a temperature T. This temperature is lower than the temperature of the body under consideration. We know that the energy emitted by a non-black body is given by the equation $E = e\sigma T_a^{\,4}$.

Hence, $eT_a^{\,4} = T^4$

With the help of this equation, the value of T_a can be determined.

15.9.1 TOTAL RADIATION PYROMETER

A total radiation pyrometer gives a measure of temperature by evaluating the heat radiation emitted by a body. All the radiations emitted by a hot body or furnace are measured and calibrated for black-body conditions. A total radiation pyrometer (shown in Fig. 15.13) basically comprises an optical system that includes a lens, a mirror, and an adjustable eyepiece. The heat energy emitted from the hot body is focused by an optical system onto the detector. The heat energy sensed by the detector, which may be a thermocouple or a thermopile, is converted to its analogous electrical signal and can be read on a temperature display device.

The pyrometer has to be aligned properly such that it is in line with the furnace or hot body and is placed as close to it as possible. This is essential to minimize the absorption of radiation by the atmosphere. Radiation pyrometers find applications in the measurement of temperature in corrosive environments and in situations where physical contact is impossible. In addition, radiations of moving targets and invisible rays can also be measured. It is also used for temperature measurement when sources under consideration have near-black body conditions.

The following are the advantages of radiation pyrometers:

1. It is a non-contact-type device.
2. It gives a very quick response.
3. High-temperature measurement can be accomplished.

Radiation pyrometers also have certain disadvantages. They are as follows:

1. Errors in temperature measurement are possible due to emission of radiations to the atmosphere.
2. Emissivity errors affect measurements.

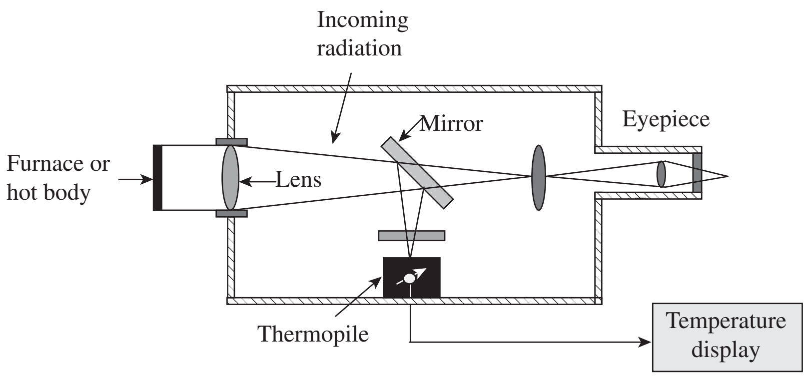

Fig. 15.13 Total radiation pyrometer

15.9.2 Optical Pyrometer

Optical pyrometers work on the disappearing filament principle. In order to measure temperature, the brightness generated by the radiation of the unknown source or hot body whose temperature is to be determined is compared with that of the reference lamp. The brightness of the reference lamp can be adjusted so that its intensity is equal to the brightness of the hot body under consideration. The light intensity of the object depends on its temperature, irrespective of its wavelength. A battery supplies the current required for heating the filament. The current flowing through the filament is adjusted by means of a rheostat and an ammeter is used to measure it. The current passing through the circuit is proportional to the temperature of the unknown source. An optical pyrometer is schematically represented in Fig. 15.14.

An optical pyrometer essentially consists of an eyepiece, by means of which the filament and the source are focused so that they appear superimposed, enabling a clear view for the observer. Between the eyepiece and the reference lamp, a red filter is positioned, which helps narrow

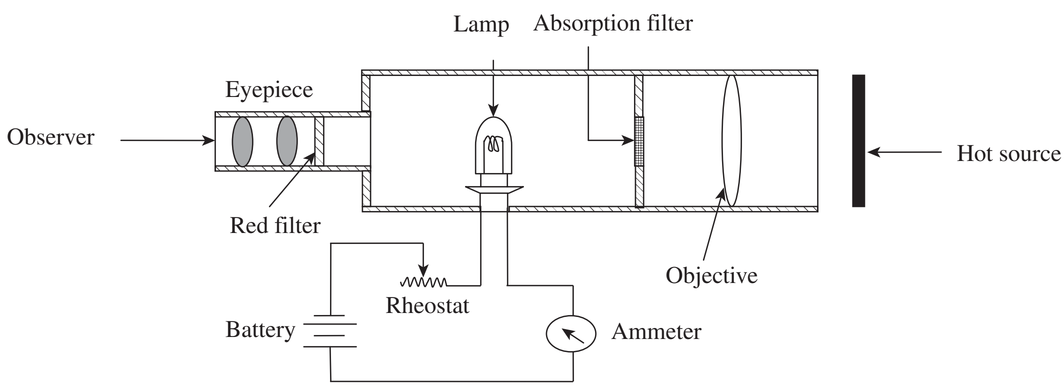

Fig. 15.14 Optical pyrometer

down the wavelength band and attain monochromatic conditions. An absorption filter helps operate the lamp at reduced intensity, thereby enhancing the life of the lamp. The current in the reference lamp can be varied by operating the rheostat and can be measured using the ammeter. Thus, the intensity of the lamp can be altered. The following three situations (represented in Fig. 15.15) arise depending on the current passing through the filament or lamp:

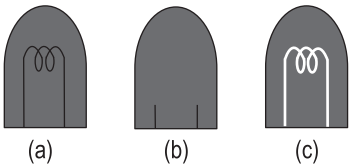

Fig. 15.15 Disappearing filament principle (a) Current passing though the filament is low (b) Current passing though the filament is exact (c) Current passing though the filament is high

1. When the current passing through the filament is very low, the radiation emitted by the filament is of a lesser intensity than that of the source, and the filament appears dark against a bright backdrop, as shown in Fig. 15.15(a).
2. When the current passing through the filament is exact, the intensity of the radiation emitted by the filament is equal to that of the source and hence the filament disappears into the background, as shown in Fig. 15.15(b).
3. When the current passing through the filament is very high, the radiation emitted by the filament is of higher intensity than that of the source and the filament appears brighter than the background, as shown in Fig. 15.15(c).

When the filament disappears, the current that flows in the circuit is measured. The value at which the filament disappears is a measure of the temperature of the radiated light in the temperature source, when calibrated.

In another form of optical pyrometer, the red wavelength from the hot body is compared with the radiation of a similar wavelength emitted by an electric lamp after calibration. The advantages associated with optical pyrometers are as follows:

1. They are simple in construction and portable.
2. Optical pyrometers are flexible and easy to operate.
3. They provide very high accuracy of up to ±5 °C.
4. Since they are non-contact-type sensors, they are used for a variety of applications.
5. They can be used for remote-sensing applications, since the distance between the source and the pyrometer does not affect the temperature measurement.
6. Optical pyrometers can be employed for both temperature measurement and for viewing and measuring wavelengths that are less than 0.65 μm.

The following are the disadvantages of optical pyrometers:

1. Optical pyrometers can be employed for measurement only if the minimum temperature is around 700 °C, since it is based on intensity of light.
2. Temperature measurement at short intervals is not possible.
3. Emissivity errors may affect measurement.
4. Optical pyrometers are used for the measurement of clean gases only.

Optical pyrometers can be employed to measure temperatures of liquid metals and materials that are heated to a high temperature. This method is useful in situations where physical contact is impossible, for example, for determining the temperature of molten metals and materials that are heated to a high temperature. Temperature of furnaces can be measured easily.

15.9.3 Fibre-optic Pyrometers

At the tip of the fibre optics' free end, a temperature-sensing component is placed. The desired radiation is collected by connecting a measuring system to the other end. The information collected is then processed into a temperature value. The fibre-optic pyrometer essentially comprises a fibre-optic cable and an array of components such as probes, sensors or receivers, terminals, lenses, couplers, and connectors. A fibre-optic cable is used to transmit radiation from the black box cavity to a spectrometric device that computes the temperature. The operating temperature of the fibre optics can be raised as they do not possess any electronic components and hence do not require any cooling effort. Fibre optics can be used up to a temperature of 300 °C and are available for wavelengths of 1 and 1.6 μm. With the advent of technology, replacement of fibre-optic cables and optic systems can be carried out without any recalibration. These find applications in procedures such as induction heating and welding. Fibre-optic pyrometers are basically employed in applications where strong electrical and magnetic interference fields act.

The following are the advantages of fibre optics:

1. These can be employed when the path of sight to the target is unclear.
2. When accuracy is a critical parameter, these can be used for measurement.
3. These can be used when the target whose temperature is to be determined is subjected to a physical or chemical change.
4. Temperature as low as 100 °C can be measured.
5. Fibre-optic pyrometers do not carry any electrical current and can hence be safely employed in explosive and hazardous locations.

15.9.4 Infrared Thermometers

It is a well-known fact that every material or matter whose temperature is above absolute zero emits infrared radiations depending on the temperature. Infrared radiations are invisible to the human eye and can be sensed as heat. An infrared thermometer is a non-contact-type sensor that can detect infrared radiation from a heated body. We know that the radiation emitted by an object or a heated body has different wavelengths. Radiations that have longer wavelengths than visible light are known as infrared radiations; these radiations possess less energy and are less harmful. A part of the infrared energy radiated by an object is detected by an infrared sensor. It essentially measures the amount of radiation emitted by an object. Infrared thermometers are ideally suited for high-temperature measurement. The surface of the object begins to radiate when it attains a temperature of around 500–600 °C. The infrared energy increases with increase in temperature. The practical wavelength range of infrared radiations is between 0.7 and 20 μm, but normally radiations in the wavelength range 0.7–14 μm are employed for measurement.

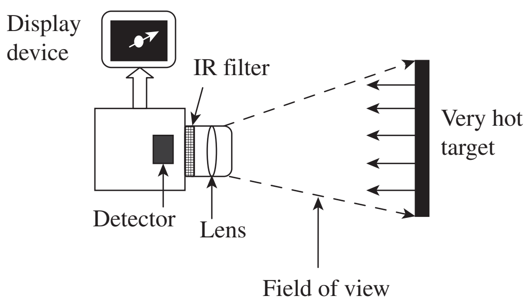

Fig. 15.16 Principle of infrared measurement

An infrared thermometer comprises a lens through which the infrared wave is focused on the detector.

The infrared energy is absorbed and converted into an electrical signal by the detector. The amount of radiation striking the detector determines the electrical output signal. The amplified electrical output signal is then displayed on the screen in terms of temperature units. Variation due to ambient temperature is adequately compensated before display. The principle of infrared measurement is schematically represented in Fig. 15.16.

In order to assess the temperature of the target accurately, care needs to be taken to place the heated body or target in such a way that it is in the complete field of view of the instrument. The field of view can be defined as the angle of vision at which the instrument functions. The infrared instrument determines the average temperature of all the surfaces exposed within the field of vision. Temperature measurement may not be accurate if the temperature of the background surfaces is different from that of the surfaces of the target under consideration. The infrared thermometer provides better accuracy if emissivity of the material is known. Higher the emissivity of the material, higher the accuracy of measurement. Reflection from other surfaces also contributes to measurement errors.

An infrared thermometer facilitates the measurement of temperatures of moving objects. In situations where objects are placed in vacuum or in a controlled atmosphere, or the distance between the source of the temperature and the instrument of measurement is large, an infrared device is most useful. It is particularly helpful when the objects are in inaccessible areas/hazardous conditions, wherein non-contact measurement is the only option available for determining temperature. Ambient conditions such as temperature variations and percentage of CO_2 (since it absorbs infrared radiations) in the atmosphere also affect accuracy. However, infrared thermometers have limited accuracy.

A QUICK OVERVIEW

- Temperature can be defined as a condition of a body by virtue of which heat is transferred from one system to another. Temperature is a measure of the internal energy of a system, whereas heat is a measure of the transfer of energy from one system to another.
- Temperature can be sensed using many devices, which can broadly be classified into two categories: contact- and non-contact-type sensors.
- Thomas Johan Seebeck discovered that when two dissimilar metals are joined together to form two junctions such that one junction (called the hot junction or the measured junction) is at a higher temperature than the other junction (known as the cold junction or the reference junction), a net emf is generated.
- Jean Charles Athanase Peltier discovered that if two dissimilar metals are connected to an external circuit in a way such that a current is drawn, the emf may be slightly altered owing to a phenomenon called Peltier effect. A potential difference always exists between two dissimilar metals in contact with each other. This is known as the Peltier effect.
- Thomson found out that the emf at a junction undergoes an additional change due to the existence of temperature gradient along either or both the metals. The Thomson effect states that even in a single metal, a potential gradient exists, provided there is a temperature gradient.
- Law of homogeneous circuit states that a thermoelectric current cannot be sustained in a circuit of a single homogenous material, regardless of the variation in its cross-section and by the application of heat alone. This law suggests that two dissimilar materials are

required for the formation of any thermocouple circuit.

- Law of intermediate metals states that if an intermediate metal is inserted into a thermocouple circuit at any point, there will not be any effect on the net emf, provided the new two junctions formed by the insertion of the third metal are at identical temperatures. This law allows the measurement of the thermoelectric emf by introducing a device into the circuit at any point without affecting the net emf, provided that additional junctions introduced are all at the same temperature.
- Law of intermediate temperatures states that if a thermocouple circuit generates an emf e_1 when its two junctions are at temperatures T_1 and T_2, and e_2 when the two junctions are at temperatures T_2 and T_3, then the thermocouple will generate an emf $e_1 + e_2$ when its junction temperatures are maintained at T_1 and T_3.
- An extension of thermocouples is known as a thermopile. A thermopile comprises a number of thermocouples connected in series, wherein the hot junctions are arranged side by side or in star formation.
- The American Society for Testing and Materials has defined the term resistance thermometer as follows: RTD is 'a temperature-measuring device composed of a resistance thermometer element, internal connecting wires, a protective shell with or without the means for mounting a connection head, or connecting wire or other fittings, or both'.
- Semiconductors that are used to measure temperature are called thermistors. When a thermistor is employed for temperature measurement, its resistance decreases with increase in temperature.
- The change in temperature can be measured using pressure thermometers. These thermometers work on the principle of thermal expansion of matter wherein change in temperature is to be measured. Temperature change can be determined using these thermometers, which rely on pressure measurement.
- A bimetallic strip thermometer works on the well-known principle that different metals expand and contract to different degrees, depending on the coefficient of expansion of individual metals.
- Radiation thermometers (pyrometers) measure temperature from the amount of thermal electromagnetic radiation received from a spot on the object of measurement.
- Optical pyrometers measure temperature using the human eye to match the brightness of a hot object to the brightness of a calibrated lamp filament inside the instrument.
- A body that is capable of absorbing all the radiations that fall on it and does not reflect or transmit any radiation is called a black body. A black body is an ideal thermal radiator.
- If E is the radiation impinging on a body (W/m^2), α is the fraction of radiation power absorbed by the body, and e is the total emissivity, then

$$e = \frac{\alpha E}{E} = \frac{\text{Radiation emitted from a body}}{\text{Radiation falling upon the body}}$$

- The Stefan–Boltzmann law states that the total energy radiated by a black body is a function of its absolute temperature only and is proportional to the fourth power of that temperature.
- If E is the total energy radiated per unit area per unit time, then

$$E \,\alpha\, T_a^{\,4} \text{ or } E = \sigma T_a^{\,4}$$

where σ is the Stefan's constant, which is equal to 50×10^{-8} W K^4/m^2 and T_a is the absolute temperature in K.

- At the tip of the fibre optics' free end, a temperature-sensing component is placed. The desired radiation is collected by connecting a measuring system to the other end. The information collected is then processed into a temperature value.
- Every material or matter whose temperature is above absolute zero emits infrared radiations depending on the temperature. Infrared radiations are invisible to the human eye and can be sensed as heat. An infrared thermometer is a non-contact-type sensor that detects the infrared radiation of a heated body.

MULTIPLE-CHOICE QUESTIONS

1. Temperature gives a measure of
   (a) internal energy of the system
   (b) external energy of the system
   (c) total energy of the system
   (d) no relationship with energy
2. The first thermometer was developed by
   (a) Rankine (c) Kelvin
   (b) Celsius (d) Galileo Galilei
3. If two bodies that are at different temperatures are so positioned that they are in contact with one another, then
   (a) heat will flow from the colder to the hotter body until they are at the same temperature
   (b) heat will flow from the hotter to the colder body until they are at the same temperature
   (c) heat will not flow
   (d) heat will continue to flow from the hotter to the colder body until you move them apart
4. The measurable property that varies with temperature in a thermocouple is
   (a) expansion (c) voltage
   (b) thermal radiation (d) electrical resistance
5. Which of the following temperatures is correct?
   (a) $F = 1.6C + 32$ (c) $F = 1.8C + 273$
   (b) $F = 1.8C + 32$ (d) $F = 1.8C + 212$
6. When there is no heat exchange between two bodies that are at the same temperature, they are said to be in
   (a) thermal equilibrium
   (b) energy equilibrium
   (c) heat equilibrium
   (d) electrical equilibrium
7. Iron–constantan is a
   (a) K-type thermocouple
   (b) J-type thermocouple
   (c) S-type thermocouple
   (d) R-type thermocouple
8. Peltier effect states that when two dissimilar metals are in contact with each other, there exists a
   (a) current difference
   (b) energy difference
   (c) potential difference
   (d) temperature difference
9. Semiconductors used for temperature measurement are called
   (a) thermistors
   (b) thermopiles
   (c) resistance temperature detectors
   (d) pyrometers
10. The metal extensively used in high-accuracy resistance thermometers is
    (a) rhodium (c) iridium
    (b) nickel (d) platinum
11. When a thermistor is employed for temperature measurement, its
    (a) resistance increases with the increase in temperature
    (b) resistance decreases with the increase in temperature
    (c) resistance increases with the decrease in temperature
    (d) resistance decreases with the decrease in temperature
12. The Stefan–Boltzmann law states that the total energy radiated by a black body is given by
    (a) $E = \sigma T_a^5$ (c) $E = \sigma T_a^4$
    (b) $E = \sigma T_a^3$ (d) $E^2 = \sigma T_a^2$
13. Which of the following statements is true?
    (a) When radiation intensity falls, the wavelength increases.
    (b) When radiation intensity falls, the wavelength decreases.
    (c) When radiation intensity falls, the wavelength remains the same.
    (d) No relationship exists between the wavelength and radiation intensity.
14. Current flows through a circuit spontaneously when two dissimilar metals are joined to form a thermocouple, provided the two junctions formed are maintained at different temperatures. This effect is termed as
    (a) Thomson effect (c) Rankine effect
    (b) Seebeck effect (d) Stefan effect
15. To reduce the band width of a wavelength, an optical pyrometer is provided with a
    (a) radiation filter (c) absorption filter
    (b) blue filter (d) red filter

REVIEW QUESTIONS

1. Define temperature. How is it different from heat?
2. Compare the different temperature scales.
3. List the factors that influence the response of a temperature-sensing device.
4. Explain Seebeck, Thomson, and Peltier effects.
5. State and explain the different laws of thermocouples.
6. Explain the different thermocouple materials and their designation.
7. Explain thermistors with a neat sketch.
8. With sketches, describe the different forms of thermistors.
9. Write a short note on thermopiles.
10. With the help of a neat diagram, explain the construction and working of an RTD.
11. With a neat sketch, explain a liquid-in-glass thermometer.
12. With a schematic diagram, explain the working of a pressure thermometer.
13. Explain the working principle of a bimetallic strip with neat sketches.
14. What is pyrometry? Briefly explain the theory of pyrometry.
15. With a neat sketch, explain a total radiation pyrometer.
16. Explain the construction and working of an optical pyrometer with the help of a schematic diagram.
17. Mention the advantages and disadvantages of an optical pyrometer.
18. List the different applications of a total radiation pyrometer.
19. Write a note on the measurement of temperature using a fibre-optic pyrometer.
20. With a neat sketch, explain the working of an infrared thermometer. In addition, state its application areas.
21. List the factors that contribute to inaccuracy in temperature measurement using infrared systems.

Answers to Multiple-choice Questions

1. (a)	2. (d)	3. (d)	4. (c)	5. (b)	6. (a)	7. (b)	8. (c)
9. (a)	10. (d)	11. (b)	12. (c)	13. (a)	14. (b)	15. (d)	