TWELVE

Introduction To Measurement

The primary purpose of making a measurement is to determine the unknown value of the process parameter. The process of measuring is a comparision of a given unknown quantity with the standard value. The fundamental purpose of measurement is to aid the process economy by improving the quality of the product.

12.1 Classification of Measurement :

Measurement is classified as :

(i) **Direct Measurement :** In which the meaning of the measurement and the purpose of the processing are the indentical.

The measurement of the physical dimensions of a equipment manufactured in a lathe machine and the purpose of the processing operation is to produce a equipment with given physical dimensions are same is an example of direct measurement.

(ii) **Indirect Measurement :** Wherein the meaning of the measurement and the purpose processing are different but are related with each other.

The measurement of the temperature of the different fractions in the fractionating column to remove different fractions is an example of indirect measurement. The purpose of the process to remove the different fractions and the meaning of the measurement to measure the temperature of the different fractions are not indentical but are related with each other. The empirical relation is generally established between the measurement actually made and the desired result.

12.2 Classification of Instrument :

The measuring instrument is a device to determine the the value of the quantity. The value determined by the instrument is generally quantitative.

The instrument generally used to convert measured variable into a displacement. The measured variable such as temperature, pressure, flow, chemical composition is converted into more useful quantity such as displacement, pressure, force and potential.

The classification of the instrument is made according to the source of power.

The instruments are classified as :

(i) Self operated instrument

(ii) Power operated instrument.

Self operated instrument : The instrument derives its power wholly from the instrument itself. A mercury-in-glass thermometer derives its power wholly from the expansion of the mercury due to change in temperature.

Power Operated Instrument : The instrument requires external source of power. The external source of power such as electricity, hydraulic supply, compressed air and mechanical source of energy are used to operate the instrument.

12.3 Static Characteristics of Instrument :

The static characteristics of Instrument are considered when the instrument is used to measure a process condition which is not varying with time.

The static characteristics are represented by the range, accuracy, drift, calibration, sensitivity, hysteresis, resolution, error and precision of the instrument.

Range of Instrument : The range of an instrument indicates the lowest and highest calibrated readings it can measure, *i.e.*, a thermometer whose scale goes from 0°C to 100°C has a range from 0°C to 100°C and the span of 100°C.

The span of an instrument is its range from the minimum to maximum scale

Accuracy of Instrument : The accuracy of an instrument is based on instrument range and the reading of the instrument.

For example a pyrometer is calibrated from 400°C to 800°C and the accuracy is stated to be 0.4 percent.

The accuracy = (800 – 400) × 0.04

= 1.6°C

Static Error of Instrument :

The static error of an instrument is the difference between actual or true value of a quantity and the value indicated by the instrument. The static error is defined when the actual or true value of the quantity do not vary with time.

Static error = Instrument Reading – True value.

If the instrument reading is greater than the true value then static error is positive.

If the instrument reading is less than the true value then static error is negative.

Static correction :

The static correction of an instrument is expressed as

Static Correction = True Value – Instrument reading

The relationship between the static error and the static correction is expressed as

Static Correction = – Static error

The error calibration of an instrument is the calibration of the instrument against a suitable standard.

Reproducibility : The reproducibility of the instrument is the degree of closeness for which the given value is repeatedly measured.

The perfect reproducibility indicates that the instrument has no drift.

Drift : The drift of the instrument is the measure of shifting of the calibration of the instrument for a long period of time. It is the change in the reading indicated by the instrument for a fixed input value.

The several kinds of drift may occur. The calibration of the whole instrument gradually shift by the same amount is called as zero drift.

The zero drift can be corrected by shifting the pointer position or by adjusting the digital indicating device.

The span drift involves a gradual change in the calibration of the instrument by a proportional amount. The span drift is due to change in the spring gradient of the instrument.

The third kind of drift may occur due to only for the one portion of the calibration change. The third kind of the drift occurs at the high end of the instrument scale due to high stress of the instrument.

The drift occurs in the orifice meter due to wear and erosion of the orifice plate. The drift occurs in the thermocouple due to corrosion and contamination of the junction of the thermocouple. The drift is caused due to temperature change in the electronic instrument.

Drift is rarely apparent. The inspection and maintenance is needed to guard the drift in the instrument.

Sensitivity : It is the ratio of change in output of the instrument to the change in the input to the instrument at steady state condition. It indicates the smallest change in the value of variable to be measured to which an instrument respond.

Dead Zone : It is the largest range of the value of the measured variable to which the instrument does not respond.

Hysteresis : It is the magnitude of error caused in the output value of the instrument for a given input value when the instrument is approached in the opposite direction. The output value is measured by increasing and then decreasing the input variable.

The difference in the reading of the output value for a given input value is the hysteresis. The hysteresis is caused due to elastic deformation consequently the change in shape and due to the frictional effect in the material of the instrument.

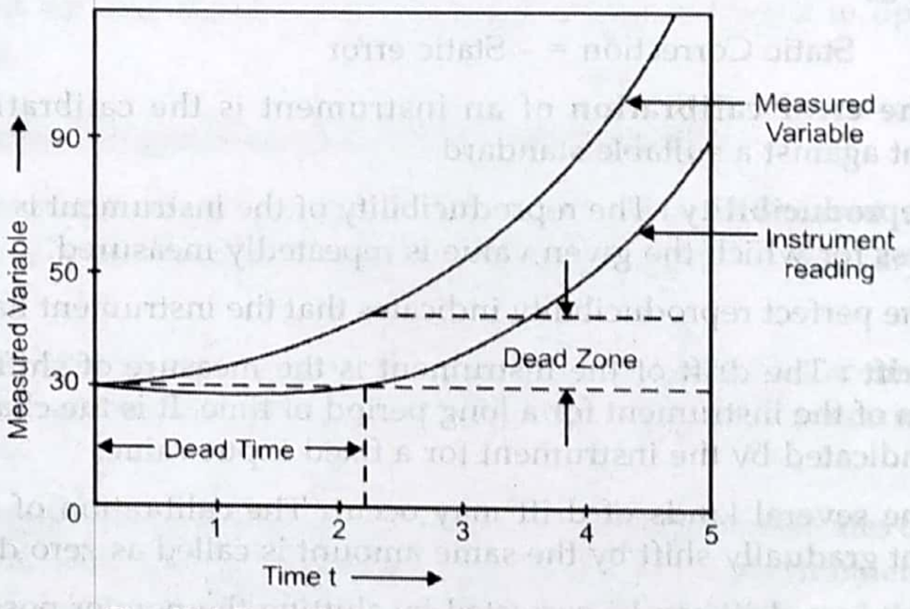


Fig. 12.1 Dead Zone and Dead Time of Instrument.

Dead Time : The dead time is the delay in the response of an instrument to the change in the measured variable.

The dead time is the time require to begin the response of the instrument for a change in measured variable. Dead time is also known as lag of the instrument.

Calibration : It is the process for determination of the correct value of the quantity by measurement or comparison of the measured value with the standard value of quantity.

Precision : It is the degree of prefection for which an instrument is designed to perform.

Resolution : It is the minimum incremental measured value of input or output that can be detected by the instrument. It is the smallest amount of a variable to which the instrument will respond.

Linearity : It is the linear variation of the output value to input value of the instrument. It is the measure of the proportionality between the input value of a variable being measured and the indicated output value of the instrument.

12.4 Dynamic Characteristics :

The instrument rarely respond instantaneously to the change in the measured quantity. The change in the measured quantity caused due to the change in the input value to the instrument. The instrument exhibit the characteristics of sluggish or slow response for the change in the measured quantity. The delay in time is often encountered when the instrument waits for the reaction to occur and such instruments are generally used for measuring the quantities that varies with time. Consequently the transient and dynamic behaviour of the instrument is relatively more important than the static characteristics of the instrument.

The dynamic characteristics of an instrument is determined by subjecting its primary element by some known magnitude of the variation of the measured quantity.

The three most common variations of the measured quantity of the instrument are :

(i) Step Change : The primary element of the instrument is subjected to an instantaneous and finite known magnitude of the variation and follows the measured quantity.

(ii) Linear Change : The primary element of the instrument is subjected to the linear variation with time and follows the measured quantity.

(iii) Sinusoidal Change : The primary element of the instrument is subjected to the sinusoidal variation of constant amplitude and follows the measured quantity.

The dynamics characteristics of the instrument are :

- Speed of response
- Measured Lag
- Fidelity
- Dynamic error

Speed of Response : It is the rapidity for instrument to respond to variation in the measured quantity.

Measuring Lag : It is the retardation or delay in the response of the instrument to the variations in the measured quantity.

Fidelity : It is the degree indicated by the instrument to the variations in the measured quantity in absence of the dynamic error.

Dynamic error : It is the difference between the actual value of the quantity varies with time and the value indicated by the instrument. The dynamic error is defined when the actual value of the quantity varies with time.

Dynamic error is defined as the difference between the input variable X(t)and the response Y (t) at steady state.

Dynamic error = X (t) – Y (t) at steady state.

= At – A (t – t)

= At where A is the slope of the linear change and t is the time constant of the first order instrument.

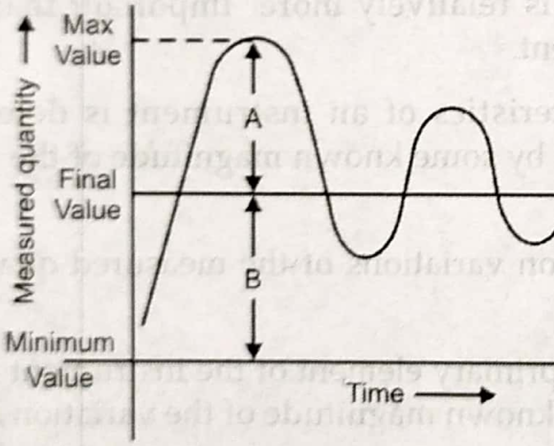


Fig. 12.2

Overshoot : It is the ratio of the the difference between the maximum and the final values of the response of the instrument to the final value of the response of the instrument.

$$\text{Overshoot} = \frac{A}{B}$$

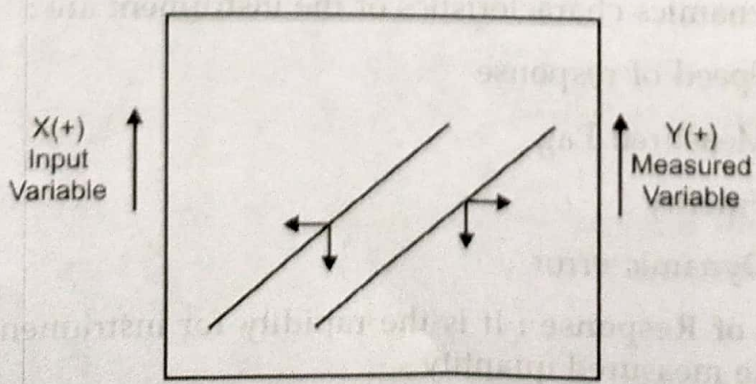


Fig. 12.3

12.5 Classification of Errors :

The errors are classified as :

1. Signal transmission error
2. Environmental error
3. Observation error
4. Operational error

1. Signal Transmission error : The error caused by the instrument while transmitting the signal of the measured quantity. It is known as instrumental error.

2. Environmental error : The errors which are caused due to the change in the environmental conditions in the area surrounding the instrument.

The change in temperature, humidity and pressure may affect the function of the instrument.

Observation Error : The error caused by the operator while recording the measured quantity indicated by the instrument.

Operational error : The errors caused due to the irregularities and variations in the process parameter.

The presence of error affects the true measurement and the efficiency of the instrument.

Minimization of errors

The errors can be minimized by the following methods :

(i) Calibration of the instrument against the standard value of the quantity.

(ii) Correct selection of instrument taking into consideration of process condition of measurement.

(iii) Correction factor considering the amount of error in the true quantity and the measured quantity.

(iv) Use of air conditioning, to minimize error.

12.6 Transducers :

It is a device which converts the energy from one form into another form. It is a device which converts the units between input and output signals. Transducers are used for the convertions of the physical quantities of one form into another form. The applications of the transducers are given below :

i) Concentration signal is transduced to a pen reading.

ii) In case of electronic controller the output signal in the form of voltage is usually fed to a transducer which converts it to a pneumatic signal in the form of pressure signal for the easy transmission of the signal in the pneumatic transmission line.

iii) In case of thermocouple the e.m.f. generated because of the bimetallic junction is measured in terms of voltage and it is calibrated in the terms of temperature. This is known as the *transducation process*.

iv) Strain gauges are used to convert a pressure signal to electrical signal. In strain gauge the electric resistance is depending on the mechanical strain. Therefore for any change in the mechanical strain there is a change in its electric resistance.

v) The potentiometer is used as a transducer in the control system which converts mechanical position into an electric voltage.

vi) The variable capacitance differential pressure transducer is used to detect and transmit pressure difference of the control system.

The application of the transducer is shown in Fig. (4.5) using a block diagram of a control system.

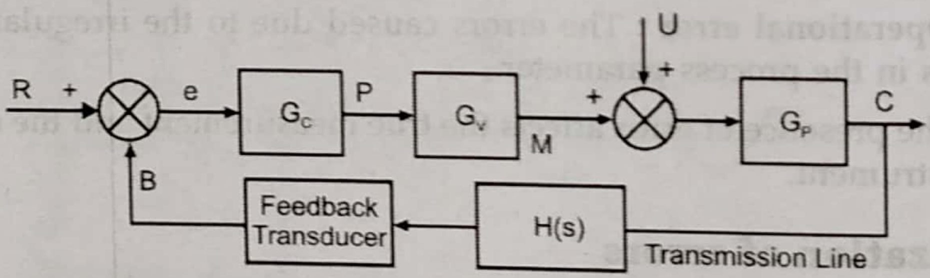


Fig. 12.4 Block diagram of control system with feedback transducer

where, G_c is the transfer function of controller.

G_v is the transfer function of control valve or final control element.

G_p is the transfer function of the process.

H is the transfer function of the measuring sensor.

If a thermocouple is used as a measuring sensor for indicating the temperature of the effluent in the terms of voltage. A feedback transducer is used to convert the electrical signal in the terms of voltage to pressure signal which can be transmitted easily in pneumatic transmission line of the control system.

12.7 Classification of Transducer :

The transducers are classified as

(i) Primary and Secondary transducers.

(ii) Analog and Digital transducers.

(iii) Active and passive transducers.

Primary and Secondary Transducers :

The primary transducer senses one quantity and convert it into another quantity.

For example the Bourdon tube pressure gauge senses the pressure and converts the pressure into the displacement of its free end. The Bourdon tube is known as primary transducer.

The secondary transducer senses the second quantity of the primary transducer and converts it into the another quantity.

For example the displacement of the free end of the Bourdon tube moves the core of a linear variable differential transformer LVDT which produces the output voltage which is proportional to the movement of the core which indicates the pressure.

Analog and Digital Transducers :

The analog transducer converts the quantity to be measured into an analog output.

For example : Thermocouple, strain gauge, Thermistor.

The digital transducers convert the quantity to be measured into an digital output.

Active and passive Transducers :

Active transducers do not require external power. The active transducers are self operating type and they develop their own electrical output. The active transducer are classified as Piezoelectric, Photoelectric, Thermoelectric.

Passive transducers require the external source of power. Passive transducers depend upon the change in the electrical parameter such as resistance, capacitance and inductance.

12.8 Active and Passive Transducers :

The transducer which is self-generating and not depending on any external source of power is known as active transducer.

Active Transducers :

Examples of the active transducers are given below.

(i) Thermocouple : The emf is generated across the junctions of the two dissimilar metals or semiconductors due to the temperature gradient of hot and cold junctions of dissimilar metals. The generated emf is calibrated in the terms of hot junction. The heat energy is converted into the electrical energy which is measured by the thermocouple. It is used to measure the temperature.

(ii) Liquid in glass thermometer : The thermal expansion in volume of the liquid in glass or liquid in metal due to the increase in the temperature of the liquid in the glass bulb can be shown as the displacement of the liquid in the capillary of the thermometer. The displacement of the liquid in the capillary of the thermometer is calibrated in terms of the temperature of the liquid. The heat energy is converted into the mechanical energy in the form displacement of liquid in the capillary of thermometer. It is used to measure the temperature.

(iii) Hot wire anemometer : The resistance of the thin wire is varied by heating or cooling by varying the flowrate of the liquid. The change in the resistance due the change in the temperature of the thin wire is calibrated in the terms of the flowrate of the liquid. The kinetic energy of the liquid is converted into the electrical energy. It is used to measure the flowrate of liquid.

(iv) Piezoelectric Transducer : The emf is generated when the external force is applied to certain crystalline material such as quartz. The generated emf is calibrated in the terms of the applied force acting on the crystalline material. The mechanical energy is converted into the electrical energy. It used to measure the force.

Passive Transducers :

The passive transducers require the external source of power. Examples of the passive transducers are given below.

Resistance Passive Transducers

(i) Resistance Thermometer : The resistance of pure metal wire with positive temperature coefficient of resistance varies with the temperature of the metal wire. The change in the resistance of the metal wire is calibrated in the terms of the temperature. The heat energy is converted into the electrical resistance. It is used to measure the temperature.

(ii) Thermistor : Resistance of certain metal oxide with the negative temperature coefficient of resistance varies with the temperature of the metal oxide. The change in the resistance of the metal oxide is calibrated in the terms of the temperature. The heat energy is converted into the electrical resistance. It is used to measure the temperature.

(iii) Potentiometer : The change in the position of the slider varies with the resistance in the potentiometer or bridge circuit by the externally applied force. The displacement of the slider is calibrated in terms of the resistance of the potentiometer. The mechanical energy is converted into the electrical energy. It is used to measure the displacement and pressure.

Resistance Strain Gauge

The resistance of the wire or semiconductor varies with the elongation or compression due to the external force, torque or displacement. The change in the resistance of the wire is calibrated in the terms of force. The mechanical energy is converted into the electrical energy. It is used to measure the force, torque and displacement.

Capacitive Passive Transducers

(i) Variable Capacitance Pressure Gauge : The capacitance varies with the change in the distance between two parallel plates by the externally applied pressure. The change in the capacitance is calibrated in the terms of the applied pressure. The pressure energy is converted into the electrical energy. It is used to measure the pressure.

(ii) Dielectric Gauge : The capacitance varies with the change in the dielectric between the plates due to the change in the liquid level. The change in the capacitance is calibrated in the terms of the liquid level. The change in the liquid level is converted into the electrical energy. It is used to measure the liquid level.

(iii) Capacitor Microphone : The capacitance varies between the fixed plate and the movable diaphragm due to the sound pressure. The variation of the capacitance is calibrated in the terms of the sound pressure. It is used for the acoustic measurement.

Inductive Passive Transducer

(i) Magnetic circuit Transducer : The mutual inductance of an a.c. coil varies due to change in the magnetic core of the coil due to externally applied pressure. The change in the inductance is calibrated in the terms of the pressure . It is used to measure the pressure and displacement.

(ii) Differential Transducer : *Linear variable differential transducer (LVDT).* The differential voltage of the two secondary windings varies linearly due to the displacement of the magnetic core by the externally applied pressure. The differential voltage is calibrated in the terms of the displacement. The mechanical energy is converted into the electrical energy. It is used to measure the displacement.

(iii) Eddy Current Gauge : The inductance of the coil varies the change in the eddy current due to the displacement of the plate. The eddy current is calibrated in the terms of the displacement. The mechanical energy is converted into the electrical energy. It is used to measure displacement.

(iv) Electrodynamic Transducer : The motion of the coil due to displacement varies with the magnetic field. The electric voltage is generated due to change in the magnetic field. The electric voltage is calibrated in the terms of the displacement. The mechanical energy is converted into the electrical energy. It is used to measure the displacement.

12.9 Units of Measurement :

The unit of measurement is defined as standard measure of every kind of physical quantity.

The types of units used in engineering are :

(i) Fundamental Units

(ii) Derived Units

The fundamental units are measures of the length *l*, mass m, time t,

The derived units are expressed in the terms of fundamental units. The quantity of derived units such volume originated from the quantity of fundamental units. The volume is expressed as V =(*l*) (b) (h)

The system of units are :

(i) FPS : Foot Pound – Second System.

(ii) CGS : Centimeter Gram - Second System

(iii) MKS : Meter Kilogram- Second System.

(iv) SI Units : The System of International Units.

The system of international unit is used worldwide for standardization.

Table 1 : The fundamental units used in SI system are :

Quantity	Unit	Meaning
Length	m	Meter
Mass	kg	Kilogram
Time	s	Second
Current	A	Ampere
Temperature	K	Kelvin
Luminous itensity	Cd	Candela

Table 2 :The Supplementary Units used in SI system are :

Quantity	Unit	Meaning
Plane angle	rad	Radian
Solid angle	sr	Steradian
Quantity of substance	mole	Mole

Table 3 : The derived units used in SI system are :

Quantity	Unit
Area	m^2
Volume	m^3
Velocity	m/s
Angular velocity	rad/s
Frequency	Hz
Density	Kg/m^3
Force	N
Pressure	N/m^2
Power	W
Work	J

Table 4 : Metric Units used in the measurement

Quantity	Name	Symbol	Equivalent
Length	angstorm	Å	1 Å = 0.1nm
Volume	stere	st	1 st = 1 m^3
Force	dyne	dyn	1 dyn = 10μm
Pressure	torr	torr	1 torr = 133 Pa
Energy	calorie	cal	1 cal = 4.1868 J
	erg	erg	1 erg = 0.1 μJ
Magnetic field strength	oersted	Oe	1 Oe = 80 A/m
Magnetic flux	maxwell	Mx	1 Mx = 0.01 μWb

Table 5 : Standard Prefixes

Multiple	Prefix	Symbol	Multiple	Prefix	Symbol
10^{12}	tera	T	10^{-2}	centi	c
10^{9}	giga	G	10^{-3}	milli	m
10^{6}	mega	M	10^{-6}	micro	m
10^{3}	kilo	k	10^{-9}	nano	n
10^{2}	hecto	h	10^{-12}	pico	p
10	deka	da	10^{-15}	femto	f
10^{-1}	deci	d	10^{-18}	atto	a

Table 6 : Units in Common Use in the FPS and and SI System

	FPS			SI		
Quantity	Name	Symbol	Units	Name	Symbol	Units
Frequency	Hertz		Hertz		Hz	S^{-1}
Energy	Foot -pound	ft-1b	1b.ft^2 s^2	Joule	J	kg.m^2/s^2
Force	Pound	1b	ib.ft/s^2	Newton	N	kg.m/s^2
Resistance	Ohm			Ohm	Ω	kg.m^2 per(s^3. A^2)
Electric Potential	Volt			Volt	V	AΩ
Pressure	Pound per in^2	psi	1b/in^2	Pascal	Pa	N/m^2
Charge	Coulomb			Coulomb	C	A.s
Inductance	Henry			Henry	H	kg.m^2 per (s^2.A^2)
Capacitance	Farad			Farad	F	s^4.A^2 per(kg.m^2)
Magnetic flux				Weber	Wb	V.s
Power	Horsepower	hp	1b.ft^2/s^3	Watt	W	J/s

Table 7 : Conversion Factors for SI Units

Length	1 in	: 25.4 mm
	1 ft	: 0.304 m
	1 yd	: 0.914 m
	1 mile	: 1.609 km
	1 Å (angstron)	: 10^{-10} m
Time	1 min	: 60 s
	1 h	3.6 ks
	1 day	: 86.4 ks
	1 year	: 31.5 Ms
Area	1 in^2	: 645 .16 mm^2
	1 ft^2	: 0.092903 m^2
	1 yd^2	: 0.8361m^2
	1 acre	: 4046.9 m^2
	1 $mile^2$	: 2.590 km^2
Volume	1 in^3	: 16.387 cm^3
	1 ft^3	: 0.02832 m^3
	1 yd^3	: 0.76453 m^3
	1 UK gal	: 4546.1 cm^3
	1 US gal	: 3785.4 cm^3
Mass	1 oz	: 28.352 g
	1 lb	0.45359237 kg
	1 cwt	: 50.802 kg
	1 ton	: 1016.06 kg
Force	1 pdl	: 0.13826 N
	1 lbf	: 4.4482 N
	1 kgf	: 9.806 N
	1 tonf	: 9.964 kN.

Energy	1 ft lbf	: 1.355 J
	1 ft pd*l*	: 0.0421 J
	1 cal	: 4.1868J
	1 erg	: 10-7 J
	1 Btu	: 1.05506 kJ
	1 hp h	: 2.6845 MJ
	1 kW h	: 3.6 MJ
	1 therm	: 105.51 MJ
	1 thermie	: 4.1855 MJ
Calorific value	1 Btu/ft^3	: 37.25 kJ/m^3
Velocity	1 ft/s	: 0.304 m/s
	1 mile/h	: 0.447 m/s
Volumetric Flowrate	1 ft^3 /s	: 0.028 m^3/s
	1 UK gal/h	: 1.2628 cm^3/s
	1 US gal/h	: 1.051 cm^3 /s
Mass flowrate	1 lb/h	: 0.126 g/s
	1 ton/h	: 0.28224 kg/s

Table 7 continue : Conversion factors for SI units

Mass per unit area	1 lb/in^2	: 703.07 kg/m^2
	1 lb/ft^2	: 4.8824 kg/m^2
	1 ton/mile^2	: 392.30 kg/km^2
Density	1lb/in^3	: 27.680 g/cm^3
	1 lb/ft^3	: 16.019 kg/m^3
	1lb/UK gal	: 99.776 kg/m^3
	1lb/US gal	: 119.83 kg/m^3
Pressure	1 lbf/in^2	: 6.894 kN/m^2
	1 tonf/in^2	: 15.444 MN/m^2
	1 lbf/ft^2	: 47.88 N/m^2
	1 standard atm	: 101.325 kN/m^2
	1 atm (1 kgf/cm^2)	: 98.0665 kN/m^2
	1 bar	: 105 N/m^2
	1 ft water	: 2.9891 kN/m^2
	1 in water	: 249.09 N/m^2
	1 in Hg	: 3.386 kN/m^2
	1 mm Hg	: 133.32 N/m^2
Power	1 hp (British)	: 745.7 W
	1 hp (metric)	: 735.5 W
	1 erg/s	: 10–7 W
	1 ft lbf/s	: 1.3558 W
	1 Btu/h	: 0.29307 W
	1 ton of refrigeration	: 3516.9 W
Momentum	1 lb ft/s	: 0.13826 kg m/s
Angular momentum	1 lb ft^2/s	: 0.042 kg m^2/s
Viscosity Dynamic	1 P (Poise)	: 0.1 N s/m^2
	1 lb/ft h	: 0.4133 mN s/m^2
	1 lb/ft s	: 1.488 Ns/m^2
Viscosity kinematic	1 ft^2/h	: 0.25806 cm^2/s

Table – 5 : Fundamental quantities in the instrumentation

Quantity	CGS	SI	FPS	Dimensions in M, L, T, θ	Enginerring System	Dimensions F. L. T. θ	Dimensions in F. M. L. T. θ
Mass	gram	kilogram	pound	M	slug	$FL^{-1} T^{2}$	M
Length	centimeter	meter	foot	L	foot	L	L
Time	second	second	second	T	second	T	T
Force	dyne	Newton	pound	MLT^{-2}	pound force	F	F
Energy	erg (= 10^{-7}jolules)	Joule	foot-pound	$ML^{2}T^{-2}$	foot-pound	FL	FL
Pressure	dyne/square centrimeter	Newtons/sq meter	Pound/foot^{2}	$ML^{-1}T^{-2}$	Pound force/foot^{2}	FL^{-2}	FL^{-2}
Power	erg/second	Watt	foot-pound/second	$ML^{2}T^{-3}$	foot- pound/second	FLT^{-1}	FLT^{-1}

1.2 MEASURING INSTRUMENTS

Measuring Instrument is simply a device for determining or ascertaining the value of some particular quantity or condition. The value determined by the instrument is generally, but not necessarily, quantitative. Measuring instrument may be required to indicate, record, register, signal or perform some operations on the value it has determined.

1.2.1 CLASSIFICATION OF INSTRUMENTS :

Measuring instruments are classified based upon their function or the mode by which they indicate any change in the quantity to be measured.

(A) Classification based on function :

1. **Indicating type :** These instruments have some kind of calibrated scale and pointer. Any change in the quantity to be measured is indicated by change in pointer position on the scale. Scale has calibrations in terms of values of the measured quantity *e.g.* Mercury thermometer.

2. **Recording type :** These instruments continuously make a written record of values of measured quantity against some other variable like time. e.g. If furnace is cooled and these cooling temperatures are sensed by recording type temperature measuring instrument, then plot or graph of furnace temperature against time is produced by the instrument.

3. **Signaling type :** These instruments only indicate that the values of the measured quantity are within certain specified range of values. They do not indicate the exact values of the quantity. e.g. Level switch indicates whether level of liquid inside the tank is too low or too high with reference to certain fixed level.

4. **Registering type :** These instruments record only discrete increments in the values of the measured quantity, by some numbers or some other symbols e.g. Some automobile speedometers register 1 km change in the distance travelled.

5. **Transmitting type :** These instruments merely carry the information regarding the measurement from the point of measurement to some remote point e.g. telephone lines.

6. **Manipulating type :** These instruments perform certain operations on the value of the quantity. e.g. (i) flow integrators integrate the rate of flow measurement, (ii) differential pressure sensors compare the pressures between two points.

A single measuring instrument can combine all these functions.

(B) **Classification based on Working :**

1. **Automatic Instruments :** These instruments do not require the manual assistance for their functioning *e.g.* Mercury thermometer, float operated level sensors.

2. **Manual Instruments :** These instruments require manual assistance for their functioning *e.g.* Resistance thermometer with Wheatstone's bridge indicator requires manual adjustment of null point to get the corresponding temperature reading.

(C) **Classification based on Source of Power :**

1. **Self–operated :** These instruments themselves generate the power required for their operation *e.g.* Mercury thermometer.

2. **Power–operated :** These instruments require external power supply for their functioning. This power may be in the form of electricity or compressed air or hydraulic supply.

(D) **Classification based on Mechanical Construction :**

1. **Self–contained :** These instruments have all of its parts enclosed in one physical assembly. *e.g.* mercury thermometer.

2. Some instruments have different elements contained in different physical assemblies connected by data transmission elements *e.g.* R.T.D.

1.2.2 PARTS OF THE MEASURING INSTRUMENTS :

Let us consider *pressure spring thermometer* (refer Fig. 2.6 page 28) that consists of a thermometer bulb, a capillary and Bourdon spring, all filled with mercury. Bourdon spring is connected to the pointer through adjustable link, sector, pinion etc.

1. **Primary Element :** This element first receives the energy from the measured medium and utilizes it to produce a condition representing the value of the measured variable.

In pressure–spring thermometer, the bulb represents the primary element. It first receives the heat energy from the hot bath, that causes expansion of mercury inside the bulb and capillary. This changes the pressure inside the Bourdon tube that represents change in temperature around the bulb.

2. **Secondary Element :** This element converts the condition produced by primary element into the condition useful for functioning of the instrument.

In pressure-spring thermometer, Bourdon spring represents secondary element because it converts change in pressure of mercury inside it into mechanical displacement of free end of the Bourdon spring which is necessary for functioning of the instrument.

3. **Manipulation element :** This element performs certain operations on the condition produced by the secondary element.

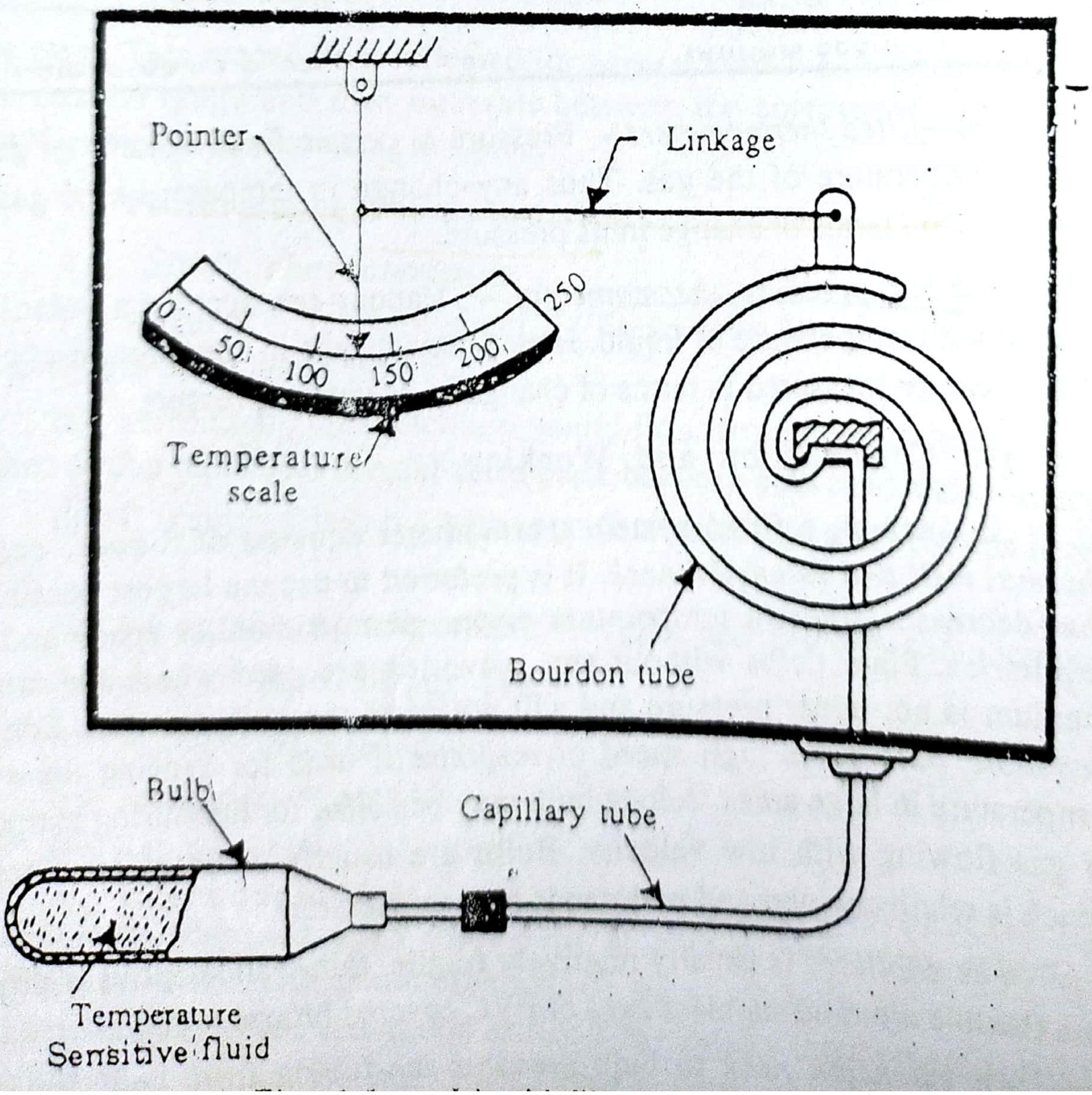
In pressure spring thermometer, adjustable link, sector, pinion, combinely act as the manipulation element because they convert linear motion of the free end of the Bourdon into proportional circular motion of the pointer.

4. **Functioning element :** This element represents the parts used for indicating, recording, signaling, registering or transmitting the measured quantity

In pressure spring thermometer, calibrated scale represents indicating element.

5. **Data Transmission element :** When primary element is far away from secondary element, then this element is essential, that transmits the condition of primary element to the secondary element.

In pressure spring thermometer, capillary acts as the data transmission element.


Pointer
Linkage
0
50
100
150
200
250
Temperature scale
Bourdon tube
Bulb
Capillary tube
Temperature Sensitive fluid

1.3 DESCRIBING AN INSTRUMENT

Any measuring instrument can be completely described with the help of following :

1. Operating principle.
2. Construction of sensing and indicating element.
3. Working of the instrument and working substances used along with their measurement ranges.
4. Calibration procedure.
5. Performance characteristics.
6. Advantages, limitations, applications, etc.

1. **Principle :** The operating principle of the instrument states the condition chosen in terms of which the measuring quantity is measured. Obviously changes in this condition should be proportional to the corresponding changes in the measuring quantity.

2. **Construction :** Actual physical construction of the instrument describes the mechanism used for measuring any changes in the condition chosen that are due to changes in the measured variable. For the instruments having separate sensing and indicating elements, they are described separately.

The information about the initial and maintenance cost of the instrument should be given.

3. **Working** : While describing working or functioning of an instrument, we imagine that sensing element of the instrument is subjected to changes in the measuring quantity, then we describe how these changes are indicated by the indicating element.

The desirable properties of working substances that can be used in the instrument are to be stated and finally list of different working substances used alongwith their advantages, limitations and measuring ranges should be given.

4. **Calibration** : Calibrating an instrument means correlating its reading or output with the corresponding value of measuring quantity. This is usually done by subjecting the primary or sensing element of the instrument to known value of measuring quantity and the corresponding pointer (in case of indicating instrument) or pen (in case of recording instrument) position is marked with this particular value in proper units. This procedure is followed for different known values of the measuring quantity and then the interval between the respective indicator markings is subdivided into suitable number of equal or unequal parts so as to prepare the scale. This being very tedious procedure usually instrument is calibrated by comparing its performance with the standard, pre-calibrated instrument when both are subjected to identical input and other conditions.

5. **Performance Characteristics** : Static as well as dynamic characteristics of an instrument are to be stated. These characteristics help us to choose the proper instrument for the specific purpose. Also the performance of different instruments for the same application can be compared. The various factors which may produce error in the instrument reading should be stated alongwith the magnitude of error and the means of minimizing these errors should be stated.

6. **Advantages, Limitations, Applications** : These points provide the basis for comparing different instruments used for same purpose. This enables proper selection of the instrument for the specific measurement.

TEMPERATURE MEASUREMENT

TEMPERATURE MEASURING INSTRUMENTS —

A. EXPANSION THERMOMETERS –

1. Solid expansion thermometers – Bimetal thermometer.
2. Liquid expansion thermometers – Liquid in glass or metal bulb thermometer.
3. Gas expansion thermometers – gas thermometers.

B. FILLED – SYSTEM THERMOMETERS (PRESSURE SPRING THERMOMETERS) —

1. Gas–filled thermometers
2. Liquid–filled thermometers
3. Vapour–pressure thermometers

C. ELECTRICAL TEMPERATURE SENSORS —

1. Resistance temperature detectors (RTD)
2. Thermistors
3. Thermocouples

D. RADIATION TEMPERATURE SENSORS — (PYROMETERS)

1. Radiation pyrometers
2. Optical pyrometers

INTRODUCTION TO TEMPERATURE MEASUREMENT :

Heat and Temperature :

Temperature of the substance represents its thermal state i.e. hotness or coldness. According to the Classical Theory *heat* is a form of energy associated with the random or chaotic thermal motion of the molecules. Temperature is a measure of heat and acts as the driving force or potential for heat transfer.

Temperature Scales

Temperature scales represent the temperature of the body quantitatively.

The International Practical Temperature Scale (IPTS) : IPTS was established by an international commission in 1948 with a text revision in 1960. A revision of the scale was finally adopted in 1968 and is reproduced in Table 2.1. The scale is defined by *fixed points* which are reproducible temperature points established by physical constants of readily available materials. Interpolation between these fixed points is made by several standard measuring instruments.

Table

Basic or Primary Fixed. Points

Temperature °C	Defining fixed point	Interpolating instrument
– 183.09	Oxygen, liquid-vapour equilibrium	Platinum resistance thermometer
0.00	Water, solid-liquid equilibrium	Platinum resistance thermometer
0.01	Water, triple point	Platinum resistance thermometer
100.00	Water, liquid-vapor equilibrium	Platinum resistance thermometer
419.58	Zinc, solid-liquid equilibrium	Platinum resistance thermometer
444.67	Sulphur, liquid-vapor equilibrium	Platinum resistance thermometer
961.62	Silver, solid-liquid equilibrium	Pt-Pt + 10 % Rh thermocouple
1064.43	Gold, solid-liquid equilibrium	Pt-Pt + 10 % Rh thermocouple

Absolute Zero Temperature : According to Classical Theory, absolute zero temperature is the state in which molecular motion is at a minimum which is related to Thermodynamics.

There are five different temperature scales used in practice viz. Centigrade or Celcius (°C), Fahrenheit (°F), Kelvin or absolute (K), Rankine or Fahrenheit absolute (°R') and Reaumur (°R).

1. **Centigrade or Celcius Scale** – (°C) : It was introduced about 1740 and is commonly used in European Countries. It has *ice-point* at 0°C and *steam-point* at 100°C. This scale depends upon the selection of working substance used.

2. **Fahrenheit Scale** (°F) : It was introduced about 1665 and is used in most English-speaking countries. It has *ice-point* at 32°F and *steam-point* at 212°F. The *zero-point* or starting point temperature is 0°F that represents temperature of certain salt-ice mixture.

°C and °F scales temperatures are related by –

$$°F = (1.8 \times °C) + 32$$

3. **Kelvin or Absolute Scale** (°K) : This is *thermodynamic* temperature scale. It was suggested by Lord Kelvin. This scale is based on mechanical work which may be obtained from a reversible Carnot heat engine working between the two temperature limits. This being thermodynamic property, is independent of the working substance used. The number of such reversible heat engines are arranged to operate on Carnot cycle such that each of them except first, receives the heat given out by its predecessor, then temperature change through each engine would represent temperature interval on the scale. The engine that discharges no heat is taken as *zero-point* of the scale. This scale has *ice-point* at 273–16°K and *steam point* at 373.16°K. °K and °C scale temperatures are related by –

$$°K = °C + 273.16$$

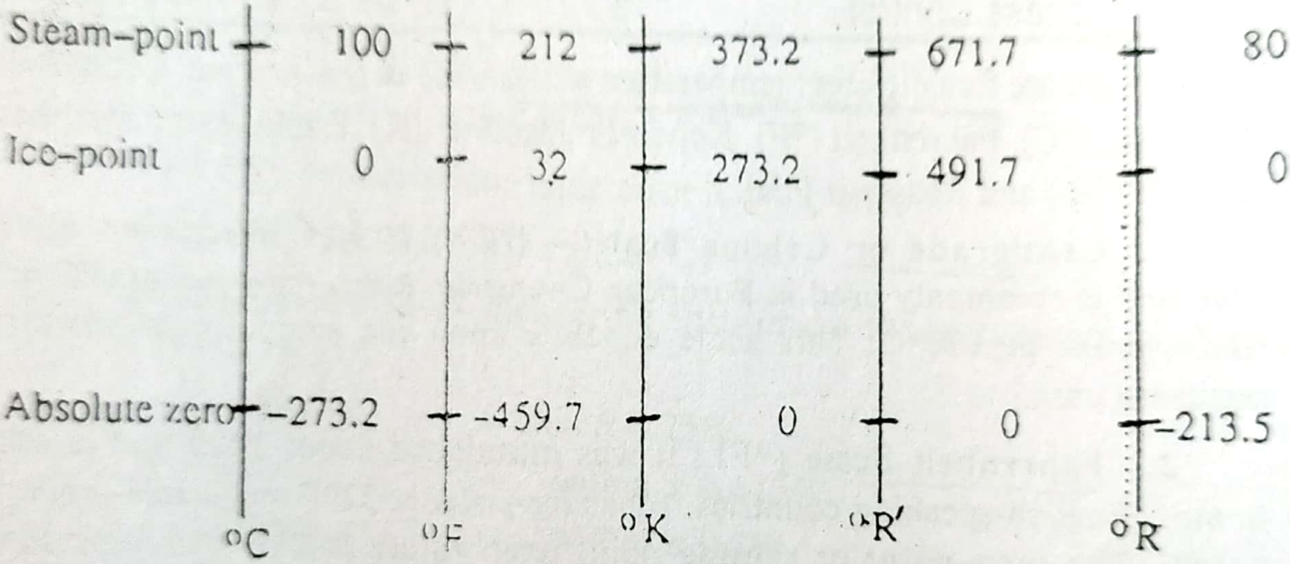
4. **Rankine Scale** (°R') : It is also called Fahrenheit absolute scale and has 491.7°R as *ice-point* and 671.7°R as *steam-point*. °R' and °F scale temperatures are related by –

$$°R' = °F + 459.7$$

This is called absolute scale because it has absolute zero as one of the reference points.

5. **Reaumur Scale** (°R) : This scale is often used in alcohol industries. It has 0°R as the *ice-point* and 80°R as the *steam-point*.

Comparison of Temperature Scales —



EXPANSION AND FILLED SYSTEM THERMOMETERS

2.1 EXPANSION THERMOMETERS

INTRODUCTION

Usually matter (solid, liquid or gas) expands or contracts with change in temperature. Hence any change in temperature of matter can be measured in terms of its volumetric expansion.

2.1.1 SOLID EXPANSION THERMOMETERS (Bimetallic thermometer)

These thermometers utilize the changes in thermal expansion of solids with temperature, for measuring temperature around the solid.

I. Principle : Solids, particularly metals change their volume with temperature, and this coefficient of change is not the same for all metals. Hence any change in temperature around the bimetal strip can be measured in terms of the free end deflection.

II. Construction and Working :

(a) Bimetallic strip :

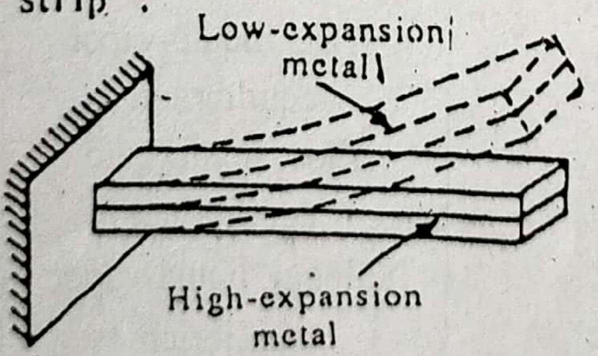


Fig. 2.1 : Bimetallic strip (Straight form)

For utilizing thermal expansion of solids for temperature measurement, bimetal strip shown in Fig. 2.1 is used. It consists of two metal strips welded together, each strip made from a metal having different coefficients of thermal expansion. In simple straight form, bimetal strip is fixed at one end in the form of cantilever beam, while its other end is free to move.

Working : Since two metals used in bimetal strip have different *coefficient of thermal expansion* (i.e. expansion per unit length per unit temperature change), the metal having high coefficient expands more in length than the metal having relatively low coefficient of thermal expansion. Since these two metals are bonded in cantilever form, as temperature around the strip increases, the strip bends towards the metal having low thermal expansion coefficient. Thus free end of the strip gets deflected and this free end deflection is nearly proportional to the change in temperature. This free end deflection is : (i) directly proportional to the square of the length of the strip, and (ii) inversely proportional to the thickness of the metal. This free end deflection is coupled with the pointer that moves on the scale calibrated in temperature.

Working substance : The metals used in bimetallic strip are – low expansion metal – Invar (64% Fe + 36% Ni), high expansion metal – Brass, Nickel, Ni–Mo alloy.

Temperature Range : Range is restricted by creeping (stressing) effect at high temperature to –75 to 540°C.

Free end deflection of the bimetal strip increases with increase in its length. Hence, to get considerably large deflection for small temperature changes, long bimetal strips are arranged in spiral of helix forms described below. Knowing the coefficient of expansion of two metals, their thickness, the desired scale length and range, the total length of spiral is computed.

(b) **Spiral bimetal element thermometer :**

In spiral arrangement, bimetal strip fixed at one end, is wound such that turn diameter goes on increasing as shown in Fig. 2.2 One end of the strip is fastened to the case while other end is connected to pointer.

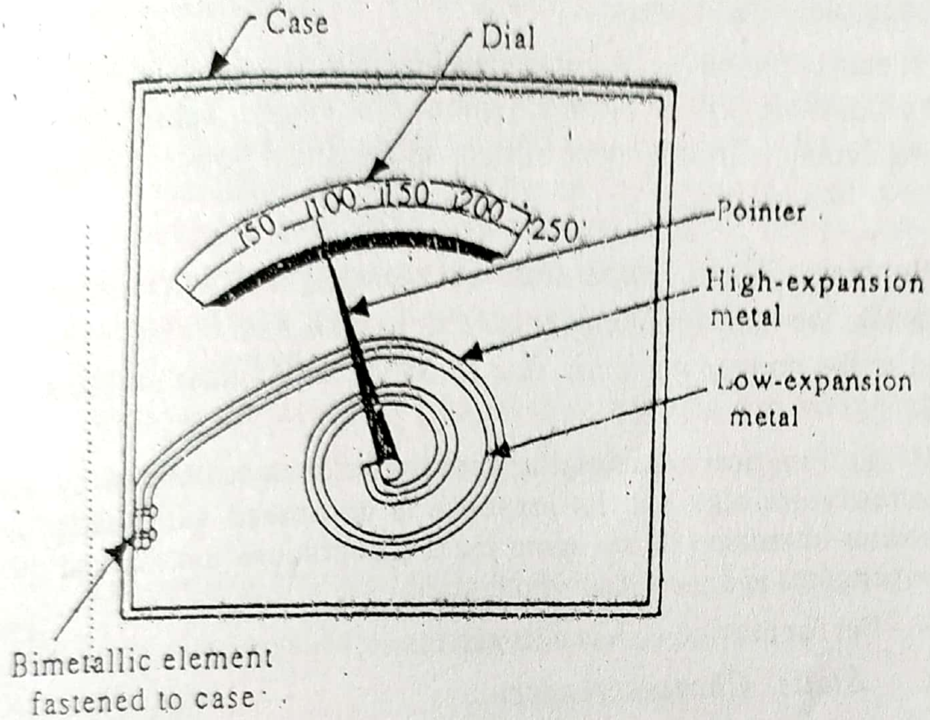


Fig. 2.2 : Spiral Bimetal element

Working : As temperature around the spiral increases the coil gets tightened or wound. This causes movement of the pointer connected to the free end.

(c) **Helix bimetal element thermometer :**

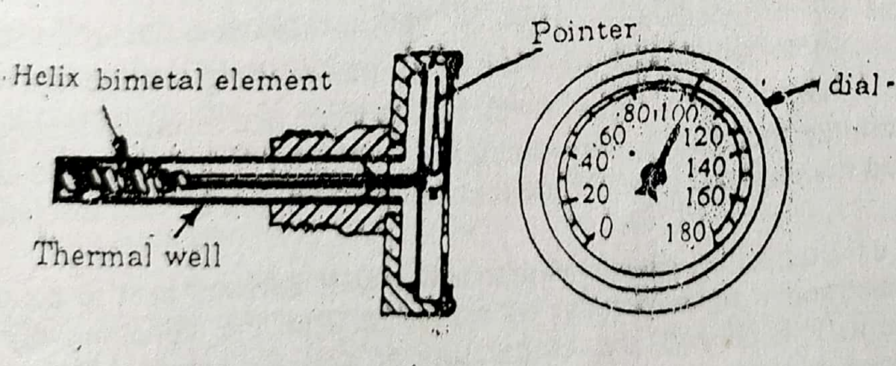


Fig. 2.3 : Helix Bimetal element

In helix arrangement shown in Fig. 2.3 bimetal strip is wound coaxially such that all turns are of same diameter. One end of the strip is fastened to the case while its other end is connected to the shaft. The shaft is connected to the pointer that moves on the calibrated scale. A metal thermal well can be used around the helix stem for protection against corrosion and breakage.

In single helix arrangement, the coil moves axially as it winds or unwinds with change in temperature. This requires clearance for vertical movement of the pointer. To overcome this difficulty, a multiple element wound coaxially is used that forms coils within coils. This construction is more costly but has an advantage in requiring less immersion depth.

The assembly is sealed using a dry gas in the dial face portion and silicone fluid in the steam around the coils that dampens the dampens the vibration and accelerates heat transfer.

Read out dials are available in ranges of 50 to 125 mm in diameter with stem length upto 600 mm.

A sturdy bimetallic element can be used to actuate a recording pen that moves on a chart driven by mechanical clockwork, behind the pen. Such a recording system is independent of outside electrical power and very reasonably priced.

Working : When temperature surrounding the helix rises, the bimetal expands and the helical bimetal rotates at its free end. This free end rotation is coupled to the pointer via shaft, due to which the pointer moves on calibrated scale.

III. **Calibration** : Bimetallic thermometer is calibrated by inserting in fixed temperature bath and its response is compared with that of a standard thermometer immersed in the same bath. Calibrations are marked for different bath temperatures and then scale is prepared.

IV. Performance Characteristics :

A. *Static Characteristics* :

1. **Accuracy** : A properly installed bimetallic thermometer has accuracy of ± 1% of span.

The factors that may introduce static error are –

(a) *Ambient temperature effect* : The ambient temperature has very little effect on the accuracy provided bimetallic element is well inserted in the hot bath.

(b) *Immersion effect* : If the bimetallic element is not well inserted in the hot bath, then conduction of heat takes place along the thermal well to the outside. This causes decrease in well temperature that results in incorrect reading. To minimize this effect, thermometer well should be well immersed in the hot bath and the exposed parts of the thermometer should be well insulated from the well.

(c) *Radiation effect* : Hot thermal well delivers heat to the cold bodies around it and it receives heat by radiation from the comparatively hot bodies around it. This changes the temperature of well and hence of bimetal. Radiation errors are minimized by consructing radiation shield around the bimetal.

2. **Reproducibility** : The factors causing calibration drift are :

(a) Mechanical and thermal stresses in bimetal strip.

(b) Fatigue and creep of bimetal strip.

3. **Sensitivity** : Dead zone depends on the starting friction in moving elements.

B. Dynamic characteristics :

The seed of response depends upon the installation conditions and characteristics of the fluid surrounding the thermometer. Time constant of response in moving air is normally larger than in a moving liquid.

V. Advantages, Limitations, Applications :

Advantages :

(a) Lowest as compared to thermal and electrical sensors.

(b) Rugged construction, less subjected to breakage.

(c) Reasonably accurate.

(d) Easy installation and little maintenance.

(e) Considerably wide temperature range.

(f) Nearly linear response.

(g) Can be equipped with recorder.

(h) Helical coil can be designed to fit into a stem more easily than the spiral.

Limitations :

(a) High accuracy can't be obtained.

(b) It is to be mounted at the point of temperature measurement.

(c) Remote indication of temperature can't be obtained.

(d) Rough handling changes calibration.

Applications : Bimetal thermometer can be used where local temperature indication is required and point of measurement is easily accessible.

2.1.2 LIQUID EXPANSION THERMOMETERS

(Liquid in metal or glass bulb thermometer)

This is the first closed thermal expansion system and has been known since Gabriel Daniel Fahrenheit investigated the expansion of mercury in eighteenth century.

I. Principle : All liquids expand with rise in temperature. This volumetric expansion of liquid is proportional to the rise in temperature, hence volumetric expansion of liquid can be taken as the measure of its temperature. The relation between volume of a liquid and its temperature is given by –

$$V_T = V_0\left(1 + \alpha T + \beta T^2 + \gamma T^3\right) \quad \ldots (1)$$

where V_0 = initial volume

V_T = final volume at T^0C,

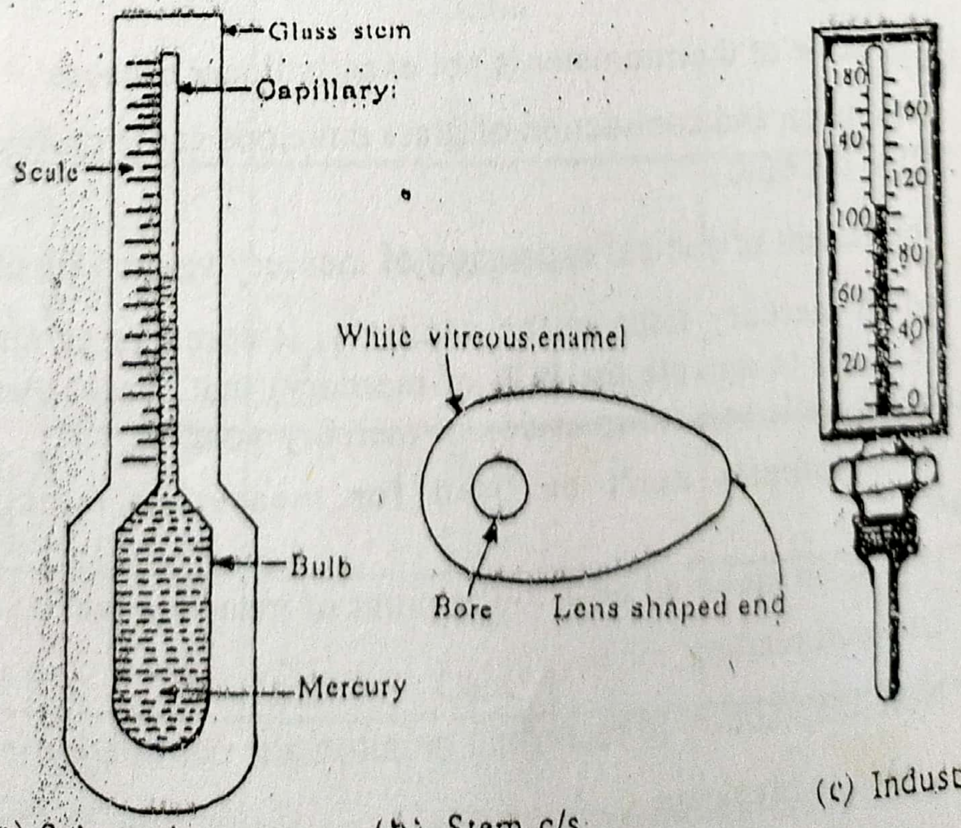
T = final temperature in ^0C

α, β, γ — coefficients of volumetric expansion.

II Construction : We describe the construction of *mercury-in-glass thermometer*, shown in Fig. 2.4 (a). It consists of a glass stem having a fine, uniform bore *capillary*, having a thin-walled *glass bulb* at lower end. The bulb may be cylindrical or spherical in shape, and has volumetric capacity very large as compared to that of the capillary. (If bulb volume is 0.5 cc, then diameter of capillary is 0.025 mm). Although bulb and capillary could be made from the same type of glass, it is more convenient to make the bulb from a glass with a good stability factor, and the capillary from a glass easier to work. For accurate measurements, the capillary must be properly annealed after it is drawn to the correct bore. Uniformity of bore is desirable but not absolutely essential if thermometer is calibrated at a sufficient number of points. The front end of the *glass stem* is lens shaped as shown in Fig. 2.4 (b) so as to magnify small diameter mercury column inside the capillary. The rear end of the stem is enameled white, that gives the background for visualising mercury column. *A clinical thermometer* has a restriction purposely placed in the capillary which prevents the mercury from returning towards the bulb when thermometer is removed from the warmer object.

The mercury (or any other working liquid) fills the bulb and the part of the capillary. After filling capillary, open end of the capillary is sealed off under vacuum such that no air is left in the capillary. Occasionally, the space above mercury inside the capillary may be filled with an inert dry gas, such as Nitrogen so as to increase the temperature range.

Industrial thermometers [shown in Fig. 2.4 (c)] have capillary enclosed in a metal case while bulb is inserted into a metal *thermal well*. The thermowell minimizes accidental breakage of the bulb without much effect on accuracy, but it may reduce the speed of response of thermometer. Thermowells are generally made of brass, steel, iron, aluminium, etc.



(a) Schematic (b) Stem c/s (c) Industrial form

Fig. 2.4 : Mercury-in-glass thermometer

Working substances and their temperature ranges : Usually *mercury* is used as working substance in liquid-in-glass thermometers. The "temperature range" of mercury-in-glass thermometer is restricted by freezing point (–39°C) and boiling point (358°C) of mercury. The upper limit of the range can be increased upto 538°C by elevating the B.P. of mercury, that is achieved by charging pressurised gas (like N_2 at 30 to 300 psi) above mercury in the capillary. For temperatures above 538°C, mercury starts boiling and vapour pressure effects play important role. *Advantages of using mercury in liquid expansion thermometers are –*

1. wide temperature range between its freezing and boiling points.
2. the coefficient of cubical expansion of mercury is nearly eight times that of glass.
3. non-wetting characteristic towards glass.

The other working substances that can be used are –

(a) Alcohol ... (–80 to 70°C)

(b) Toluene ... (–80 to 100°C)

(c) Pentane ... (–200 to 30°C)

(d) Cresole ... (–5 to 200°C)

III. Working : For temperature measurement, the bulb of mercury-in-glass thermometer is immersed in the bath to a sufficient depth. Heat energy from the hot bath is transferred to the working substance like mercury through thermal well, stem and bulb mainly by conduction. On receiving heat, mercury expands more than glass because coefficient of cubical expansion of mercury is much greater than that of glass. Since volumetric capacity of capillary is very smaller than that of the bulb, the thermal expansion of mercury causes rise in mercury level inside the capillary. *Thus mercury level inside the capillary changes with temperature of the hot bath.* The top of the mercury column read against the scale gives the bath temperature.

Working of mercury – in - glass thermometer
Change in bath temperature → mercury expands or contracts → mercury level inside the capillary rises or falls to indicate bath temperature

IV. Calibration : First ice-point is marked on the thermometer. For this the thermometer is well inserted in an ice-bath for certain period, then mercury level is marked as 0°C by observing through telescope. Usually mercury-in-glass thermometer is calibrated by comparing its performance with some other standard thermometer, provided both are dipped in the same bath under identical conditions. The type of bath depends upon the temperature range over which thermometer is to be calibrated. When both thermometers reach thermal equilibrium with bath, corresponding temperature reading is marked on the stem. This procedure is repeated for several known bath temperatures within the desired range and then intervals between the corresponding markings are equally divided by a dividing machine.

V. **Performance characteristics :**

A. *Static characteristics :*

1. **Accuracy :** ±1% of span. To achieve this accuracy thermometer bulb should be installed such that –

(a) surrounding bath medium would flow around the bulb with sufficient speed so that rapid neat transfer takes place between bath fluid and mercury.

(b) it is dipped into the bath to sufficient depth, that reduces immersion error.

(c) the surrounding temperature should be near ordinary room temperature.

Sources of static error are –

(i) Ambient temperature effect

(ii) Immersion effect

(iii) Radiation effect.

2. **Reproducibility and sensitivity :** Reproducibility of thermometer depends upon the extent of ambient–temperature effects and calibration drift. The contamination of pure working substances at high temperature also cause calibration drift. Since mercury thermometers developes a large force in thermal system, its dead zone is small i.e. within 0.05 to 0.10% of full scale.

B. ***Dynamic characteristics :***

The dynamic response of mercury thermometer is determined by the following factors :

1. *thermal characteristic of bulb, well and working substance like –*

(a) thermal capacitance,

(b) thermal conductivity,

(c) surface area per unit mass.

2. *the characteristics of bath fluid surrounding the bulb like –*

(a) outside film coefficients of heat transfer,

(b) mass flow velocity,

(c) thermal capacitance and conductivity.

For better dynamic response, bulb should have a large area, a small mass a small specific heat and a high thermal conductivity

Dip effect : If metal bulb is used then metal bulb expands suddenly with temperature rise before expansion of liquid in it. This causes temporary net contraction of volume of liquid, that causes the instrument to indicate a reverse direction of temperature change. The lag due to dip effect is 0.01 min.

Effect of bath medium : Time constant of response is larger in moving air than that in moving liquid. At higher temperatures the time constant gets reduced due to radiation effects. Time constant decreases with increasing speed of fluid past the bulb.

Effect of thermal well : Thermal well increases the time lag of the thermometer. This is mainly because due to presence of thermal well, thermometer becomes second-order system. Heat is transferred from well to bulb by conduction, convection and radiation. Since heat transfer by *conduction* depends upon area of contact between bulb and well, the space between them is often filled by metal powder, graphite, oil, or mercury. This increases speed of response of the thermometer. When liquid is filled between bulb and well, *convection* heat transfer rate increases. If space between bulb and well is not filled, then at temperatures about 540°C, most of the heat is transferred by radiation. For good radiation characteristics the radiating surfaces must be rough and well-oxidised.

VI. Advantages, Limitations, Applications :

Advantages :

(a) Low cost.

(b) Considerably wide temperature range with small bulb volume.

(c) Less space is required.

(d) Easy installation and long life.

Limitations :

(a) The scale of thermometer is not exactly linear because

(i) expansion and contraction of glass envelope cause change in volume of mercury inside the bulb.

(ii) coefficient of cubical expansion of mercury varies with temperature.

(iii) when mercury rises in the capillary, it compresses nitrogen present above it (i.e. used to elevate the B.P. of mercury) that causes elastic expansion of thermometer walls and compression of mercury volume.

(b) Thermometer can't be used for measuring rapidly fluctuating temperatures.

(c) It is to be mounted near to the point of measurement.

(d) Difficult reading.

(e) Non-adaptability to recording or automatic control.

(f) Liable to breakage.

Applications : Mercury thermometer is used for temperature measurement in –

(a) open tanks containing liquids
(b) cooking kettles
(c) molten-metal baths
(d) steam-lines
(e) air-ducts.

2.2 FILLED SYSTEM OR PRESSURE SPRING THERMOMETERS

Filled thermal elements consists of a small bore tubing having bulb connected at one end and a pressure gauge modulated in a readout instrument at the other end. The whole system is gas-tight and filled with an appropriate confined gas or liquid under pressure.

SAMA Classification of filled system : The Scientific Apparatus Maker's Association (SAMA) has classified filled system thermometers into four major categories according to filling material and then according to method of ambient temperature compensation. (Table 2.1).

Table 2.1 : SAMA classification of filled system thermometers

SAMA Category	Types of compensation	Filling medium
I	None	Liquid
I-A	Full	
I-B	Case	
II-A	Not required	Vapour
II-B		
II-C		
II-D		
III-A	Full	Gas
III-B	Case	
V-A	Full	Mercury
V-B	Case	

I. Principle :

Liquid-filled thermometers – These thermometers utilize volumetric expansion of liquid with rise in temperature for indicating temperature of liquid.

Gas-filled thermometers – Pressure of certain fixed volume of gas varies with temperature of the gas. Thus any change in temperature of gas can be measured in terms of change in its pressure.

Vapour-pressure thermometers – Vapour-pressure of a volatile liquid varies with temperature of liquid. Hence, any change in temperature of a volatile liquid can be measured in terms of change in its vapour pressure.

II. Construction and Working :

In general, a filled system thermometer consists of a *bulb, capillary, thermal well and extension neck*. It is preferred to use the largest possible bulb that decreases ambient temperature errors, permits smaller spans and larger capillaries. Plain bulbs without any covering are used where the measured medium is not under pressure and will not harm the bulb material. *Long, thin bendable bulb* gives high speed of response if used for sensing the average temperature in large areas. A long bulb may be *coiled* for measuring temperature of gas flowing with low velocity. Bulbs are usually made of stainless steel which is relatively inert and withstands high temperature.

The capillary is usually relatively fragile, thin-walled and it is protected by a flexible armored stainless steel or PVC covered bronze tubing.

An extension neck to bulb prevents the tubing from being immersed directly in the measured medium.

A. Construction and Working of Liquid filled thermometers (Class I type) :

Construction : System is completely filled with inert hydrocarbon liquids such as xylene, toluene, alcohol etc. (other than mercury) which has coefficient of expansion 6 times that of mercury and makes smaller bulbs possible. The criterion for any liquid used is that :

(i) pressure inside the system must be greater than the vapor pressure of liquid to prevent bubbles of vapors from flowing in the pressure spring; and

(ii) liquid should not be allowed to solidify even in cold storage, otherwise calibration may be affected. Figure 2.5 shows Class II type filled thermometer having a bulb, a capillary tube and a Bourdon tube with pointer mechanism. Note that in glass stem expansion thermometers, system is partially filled with working liquid, while in filled system thermometers the system is completely filled with liquid without any space left.

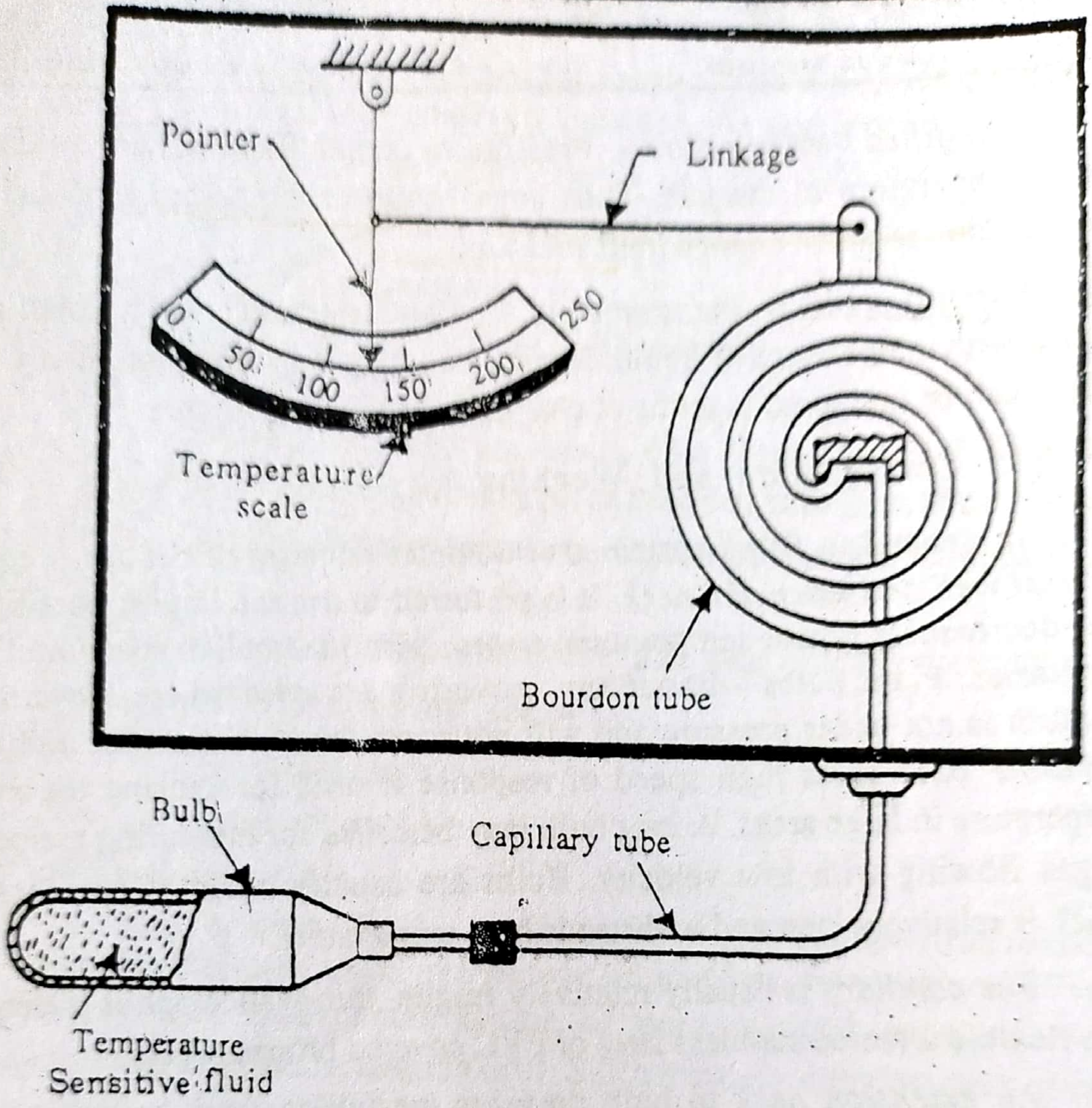


Fig. 2.5 : Liquid-filled thermometer

Class I type systems are further classified based upon the extent of ambient temperature compensation. Rise in ambient temperature causes thermal expansion and increases pressure that affects reading slightly if compensation is not provided. *The case compensation* is provided only for instrument case i. e. Bourdon spiral.

If compensation is provided for both capillary and case then it is called as *full compensation*. The further classification of Class-I type systems is given below :

ClassI-A type : These systems have full compensation against ambient temperature effect.

Class I-B type : These systems have case compensation only, against ambient temperature effect.

(Compensation detail are discussed under sources of static error at the end of this artice)

Working : When bulb is sufficiently inserted in the bath whose temperature is to be measured, the bulb liquid receives heat from the bath until its temperature equals bath temperature. With change in temperature, liquid expands or contracts that causes winding or unwinding of the Bourdon tube. This free end deflection of the Bourdon is coupled with the pointer that moves on the calibrated scale or with the pen of recorder. Thus strictly speaking liquid filled thermometer is a volume thermometer rather than pressure thermometer. The volume of liquid required in the bulb is determined by the expansion coefficients of liquid and change in volume required to operate the pointer over the full desired range.

Temperature range : – 87°C to 371° C

B. Construction and working of Vapour-pressure thermometer (Class II type) : The construction is very similar to that of liquid-filled thermometer shown in Fig. 2.6 except that a volatile liquid partially fills the system. Since vapour pressure of liquid is function of its surface temperature, its free surface must always exist at the bulb and not in the capillary or pressure spring. If bulb temperature (i.e. bath temperature) is higher than that of capillary and pressure spring then liquid volume must be large enough to fill completely the capillary and pressure spring while bulb remains partially filled. But if bulb temperature is less than that of capillary and pressure spring then bulb must be large enough to contain all the liquid. The volume of liquid required in the system should be such that –

(i) it is not too large so as to completely fill the system when all the vapour condenses at the lowest temperature range, and

(ii) it is not too small so that the entire liquid would vaporise at the highest temperature range.

Class-II type filled systems are further classified based upon relative positions of liquid space and vapour space as follows:

Class II-A type : These systems have bulb mostly filled with gas while capillary and Bourdon spiral contains liquid. These systems are used to measure temperatures.

Class II-B type : These systems have bulb mostly filled with volatile liquid while capillary and spiral contains gas. These systems are not suitable when ambient temperature is same or close to the measured temperature due to difficulty in having the vapour-liquid interface in the bulb. These systems are used to measure temperature below ambient upto – 184° C.

Class II-C type : These systems permit measurement of temperatures on both sides of the ambient temperature. These systems experience cross-ambient effect, while crossing the ambient temperature. These systems can be used above and below the ambient temperature but not through it.

Class II-D type : These systems overcome the cross-ambient effect associated with Class II-C type filled systems. Alongwith a volatile working liquid, a nonvolatile liquid is filled partly in bulb, capillary and spiral that acts as a hydraulic transmitter for transmitting vapor pressure of volatile liquid to the pressure spring. These systems can be used to measure temperatures above, below and through the ambient temperatures.

Working substance : Temperature ranges of different working substances are -

Methyl chloride	...	(0° to 50° C)
Sulphur dioxide	...	(30° to 120° C)
Ethyl alcohol	...	(90° to 170° C)
Toluene	...	(150 ° to 250° C)
Ethyl chloride	...	(30° to 100 °C)
Water	...	(120° to 220 °C)

Working : When bulb of vapour pressure thermometer is well inserted in the bath, then liquid receives heat from the bath and it vapourizes. The liquid continues to boil until pressure in the system equals the vapour pressure of the boiling liquid at that temperature. This vapour pressure is sensed by the Bourdon tube and pointer indicates the bath temperature on the calibrated scale. When temperature surrounding the bulb decreases, the vapour inside the system condenses, which results in decrease in pressure inside the system. This decreased pressure is sensed by the Bourdon tube.

C. Construction and Working of gas-filled thermometers : (Class III-type)

Construction : The construction is very similar to that of liquid filled systems. The size of bulb depends upon the type of working gas, temperature span and length of the capillary tubing. A long capillary can be avoided by terminating a short capillary at a small diaphragm chamber, that transmits the pressure with the help of spring. This arrangement is expensive but permits much smaller bulbs than could otherwise be used.

Working substance : Gas thermometers contain gases like Helium, Hydrogen, Nitrogen etc. Nitrogen is inert and cheap but it does react somewhat with steel bulb material at temperature above 427° C.

Working : For measuring hot bath temperature, the bulb of gas-filled thermometer is well inserted in the hot bath. Gas inside the bulb receives heat from the bath with corresponding change in pressure (Gay-Lussac's Law) which is indicated by moving pointer coupled with the Bourdon spiral. Hence any changes in temperature around the bulb are noticed by pointer deflections on the scale calibrated in terms of bath temperature.

Working of gas-filled thermometer.
As bath temperature changes → gas pressure changes → pointer deflects

D. Construction and Working of mercury filled thermometer : (Class V-type)

Being liquid filled system, the construction and working of mercury filled system is exactly similar to that of Class I type systems. Advantages of using mercury as filling liquid are rapid response, high accuracy, large power for operating control elements. These systems can be used at high working pressure upto 2.8 MPa at high temperature that minimizes any head effect error. Ambient temperature compensation is negligible because of incompressible nature of mercury.

III. **Calibration** : All pressure-spring thermometers are calibrated by comparing their response with that of standard thermometer, when both are dipped in same bath under identical conditions.

IV. **Performance characteristics** :

A. *Static characteristics* :

1. Accuracy : ± 0.5% of full range.
± 1% of span for gas systems.

Sources of static error are :

(a) *Ambient temperature effect : (For liquid-filled thermometers)* : Since bulb and receiving element like Bourdon are separated by long capillary tubing, any changes in ambient temperature around the capillary and receiving element causes error in temperature reading.

Ambient temperature compensation –

(i) If the ratio of the volume of liquid in the bulb to volume of liquid in the capillary and receiving element is large, say 1000 : 1, then ambient temperature effect is negligible.

(ii) *Compensation using bimetal strip* – (case compensation)

Change in ambient temperature at capillary and receiving element causes free end deflection of the Bourdon tube, that causes error in the temperature reading. This deflection is compensated by equal and opposite deflection of bimetal strip (connected as shown in Fig. 2.6) with temperature change. Thus any effect of ambient temperature is compensated or nullified.

Case compensation is adequate when case and capillary are at same temperature (near ambient) and the length of capillary is not too long.

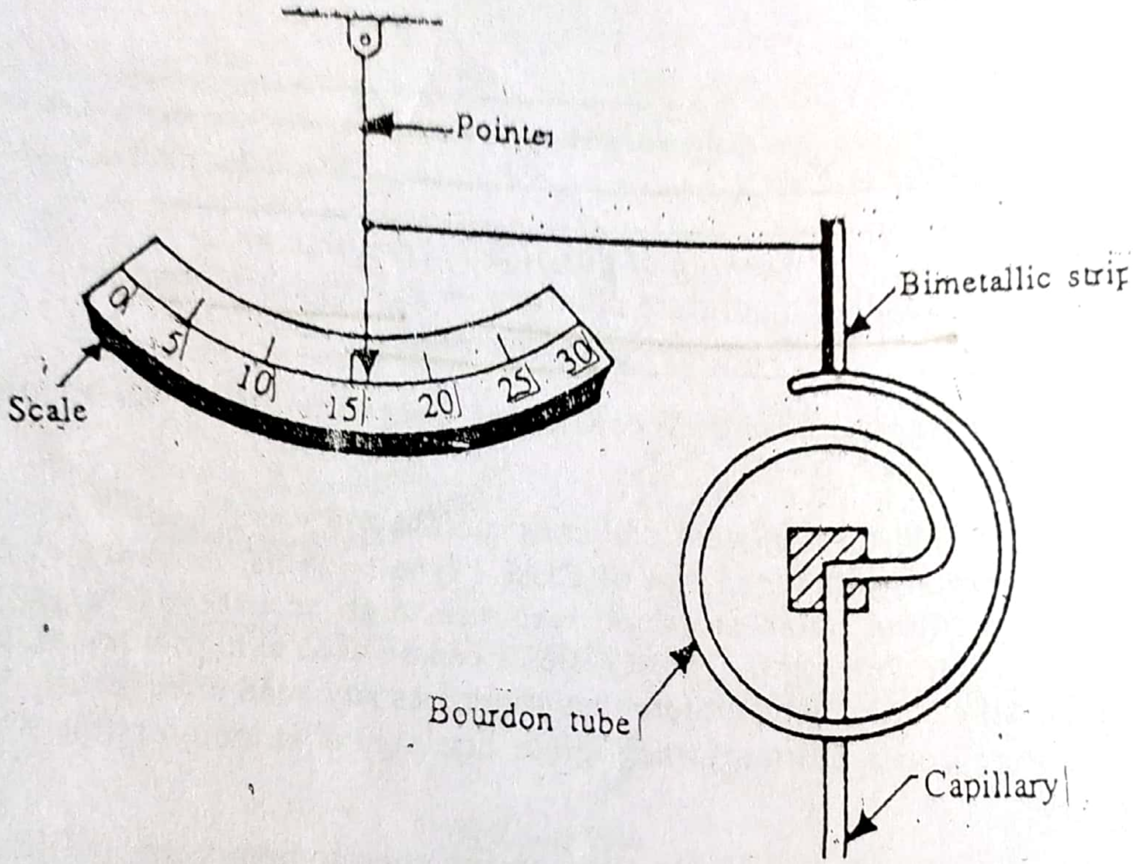


Fig. 2.6 : Ambient temperature compensation using bimetal strip

(iii) *Full Compensation (capillary and case compensation) :* This method provides compensation at the case i. e. Bourdon tube and along the capillary.

In capillary and case compensation shown in Fig. 2.7 second receiving element and capillary filled with liquid or gas is used. The capillary tubings of measuring system and compensating system both run adjacent to each other. Changes in ambient temperature cause equal deflections of the Bourdon tube. But these measuring and compensating Bourdon tubes are connected in opposition, due to which these deflections due to ambient temperature change cancel each other. Full compensation is adequate for narrow range and for small bulb, long capillary systems.

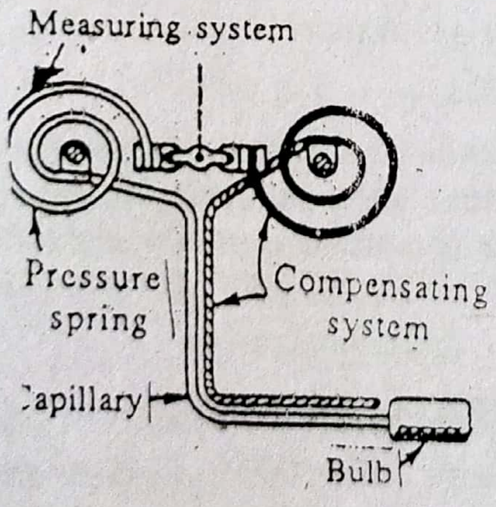


Fig. 2.7 Capillary and case compensation

Ambient temperature effect in gas-filled thermometer – Gas-thermometers have wide temperature range and hence ambient temperature effect is small as compared to liquid-filled thermometers. Compensation can be achieved by using second gas-filled capillary and receiving element.

Ambient temperature effect in vapour-filled thermometers – In vapour-actuated thermometers pressure in the thermal system is determined only by the temperature at the free surface of liquid inside the bulb. Hence, these thermometers do not require any ambient temperature compensation. Any changes in volume due to ambient temperature change are compensated by establishing a new vapour-pressure equilibrium at the liquid surface.

(b) ***Head effect*** – When thermometer bulb is at a considerably higher or lower elevation than the receiving element like Bourdon tube, then pressure head of liquid inside the capillary affects the pressure spring reading. This is called as *head effect*. Due to head effect, pressure spring shows pressure reading i.e. greater or smaller than the pressure corresponding to bulb temperature.

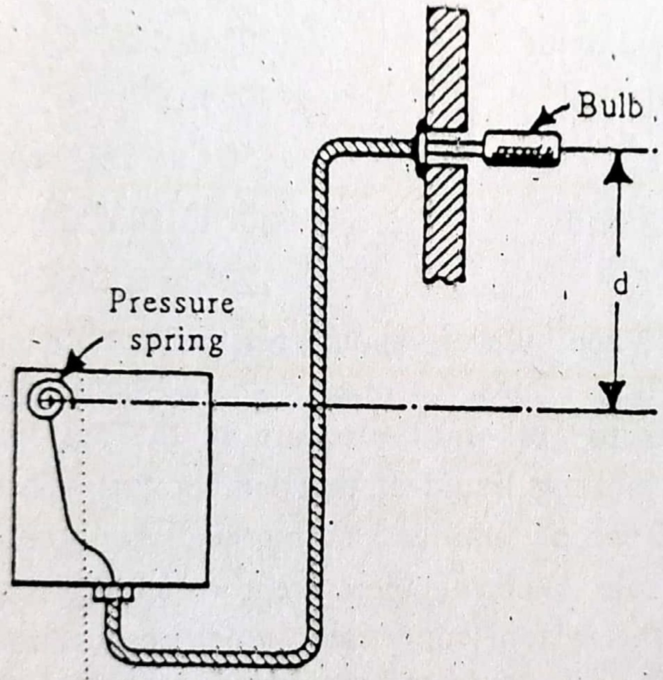


Fig. 2.8 : Head effect

Head effect in liquid-filled thermometers – In these thermometers, working liquid like mercury is filled at high pressure, say 1000 psi, hence the errror in the reading due to head effect is negligible. To correct for head effect error, the thermometer is calibrated with the bulb in its elevated or depressed position.

Head effect in gas thermometer – Head effect is negligible in gas thermometer because pressure head of gas column inside the capillary is very small as compared to pressure at which gas is filled in the system.

Head effect in vapour-thermometers – Head effect error in vapour-actuated thermometers is considerable because pressure inside the thermal system is low. Head effect is accounted by calibrating the thermometer with bulb in its elevated or depressed position.

(c) ***Immersion effect*** : When thermometer bulb is not inserted to a sufficient depth in the bath, then heat conduction takes place from the bulb towards the cold un-immersed portion of the bulb or well. This results in temperature reading smaller than the actual bath temperature. This is called as *immersion effect*. To minimize this effect in case of liquid and gas-filled thermometers, bulb and well should be well immersed in bath and extension neck of the thermometer should be well insulated from the bulb.

For vapour-actuated thermometer bulbs, it is not very essential to immerse the bulb far inside the bath. But in these thermometers, the whole free surface of volatile liquid in the bulb should be in good thermal contact with bath fluid.

(d) *Radiation effect* : While measuring temperatures of gas or air, the thermometer bulb has tendency to exchange heat with the surrounding hot or cold solid bodies. This results in error in temperature reading. To minimize radiation error a radiation shield is constructed around the bulb, that reduces radiation heat loss.

2. **Reproducibility** : The reproducibility depends upon the effectiveness of ambient temperature compensation. The calibration may drift after certain time period. Hence, the calibration should be checked periodically. The working fluids like nitrogen, mercury are used in pure from and they remain stable over long period. But these fluids may be get contaminated or decomposed at higher temperatures, that results in calibration drift.

3. **Sensitivity** : *Dead zone* of industrial pressure spring thermometers depends on the starting friction and lost motion in mechanical linkages and bearings of receiving element like Bourdon tube or between recording pen and chart paper. *Mercury thermometers* develop a larger force in the thermal system, hence they have the smallest dead zone of about 0.05 to 0.10% of full scale. *Gas and vapour thermometers* develope comparatively smaller force in the thermal system, hence they have larger dead zone of about 0.25% of full scale.

B. Dynamic characteristics : Dynamic response of pressure spring thermometers depends upon –

(i) thermal capacitance and conductivity of working fluid, bulb and thermal well.

(ii) Characteristics of bath fluid surrounding the bulb like mass velocity, thermal capacitance and conductivity. The response of the thermometer depends on the size of the bulb, its area and method of installation. For better speed of response, thermometer bulb should have a large area, small mass, small specific heat and high thermal conductivity. The time constant* for a pressure thermometer having its bare bulb placed in a well-agitated liquid is 0.1 min.

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* *Time constant* : It is the time required for the instrument to respond 63.2% of the final desired response.

Dip effect : When metal bulb containing fluid is used in pressure thermometer, then sudden expansion of the metal bulb takes place before the expansion of fluid. This causes temporary contraction of fluid volume, that results in reverse temperature reading. This is called as *dip effect.* Dip effect causes time lag of 0.01 min in *liquid-filled thermometer* while the effect is negligible in *gas and vapour-pressure thermometers.*

Effect of fluid surrounding the bulb : For a bare thermometer bulb placed in moving air, time constant is 5 to 10 times larger than that when bulb is placed in a moving liquid. At higher temperatures above 200°C, radiation heat transfer becomes predominant, that results in decreased time constant.

Cross-ambient effect in vapour-pressure thermometers –

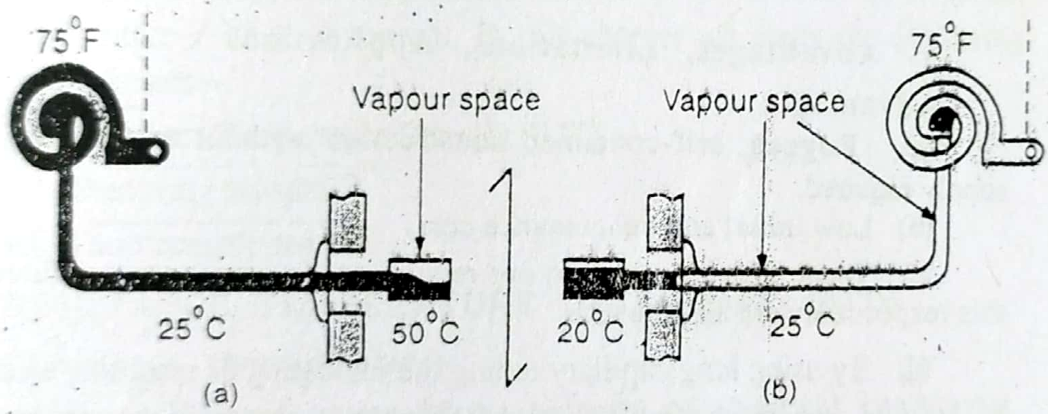


Fig. 2.9 : Cross ambient effect

Consider a vapour-actuated thermometer having capillary and receiving element at room temperature of 25°C. Now if thermometer bulb is at a higher temperature of say 50°C, then capillary and the receiving element are completely filled with liquid and vapour space is present in the bulb as shown in Fig. 2.9 (a). On the other hand if bulb is at a lower temperature of say 20°C, then vapour space is present in capillary and the receiving element as shown in Fig. 2.9 (b).

Now suppose the temperature range of the instrument is say 0° to 100°C. Then, when temperature at the bulb crosses from below to above the room temperature of 25°C, liquid must migrate from the bulb and fill the capillary and the receiving element. On the other hand when the bulb temperature drops below the room temperature of 25°C, vapour in capillary and the receiving element condenses into liquid at the bulb. This change of position of liquid and vapour space takes some time and introduces time lag in the measurement. This is called *cross-ambient* effect. Therefore vapour-pressure thermometer should not be used in cross-ambient ranges if high speed of response is desired. Cross-ambient effect can be overcome by using *dual-fill thermal system.* In dual-fill system receiving element and capillary are completely filled with a nonvapourizing liquid, which just transmits the actual vapour pressure in the bulb to the receiving element, without any condensation or evaporation. Thus the volatile working liquid is confined only to the bulb, that avoids cross-ambient effect.

Effect of thermal well – Thermal well around the thermometer bulb increases the response Lag. Heat is transferred between the bulb and well by conduction, convection and radiation. Heat transfer rate by *conduction* can be increased by filling the space between the bulb and well with a metal powder, graphite, oil or mercury. This increases the speed of response by 10%. Filling of the space between the bulb and well also prevents any heat transfer by *convection* that otherwise may introduce additional time lag. At temperature above 550°C most of the heat is transferred by radiation. Radiation being the fastest mode of heat transfer, causes very small time lag in the measurement. For effective radiation heat transfer, surfaces should be rough and well–oxidized rather than smooth and polished.

V. Advantages, Limitations, Applications :

Advantages :

(a) Rugged, self-contained construction without any external power supply required.

(b) Low initial and maintenance cost.

(c) These thermometers do not require any external power source and in this respect they are automatic.

(d) By using long capillary tubing the indicating or recording element can be located at a considerable distance from the point of measurement. Thus, remote indication can be obtained upto distance of 120 m.

(e) These thermometers generate enough power to operate the recording or indicating mechanism or controlling unit. If hand-wound clock is used for driving chart, system becomes explosion-proof.

(f) Accuracy and sensitivity are sufficient to meet most industrial requirements.

(g) Mercury thermometer has greater sensitivity than other filled thermometers.

(h) Vapour–actuated thermometers are most widely used because they are less costly and simpler to maintain. It does not require any compensation and has good speed of response.

(i) Gas thermometers has better accuracy and it can reach considerably low temperatures.

(j) Three or more separate systems can be put in a single instrument case

(k) Filled thermometers are intermediate in cost and performance between the simplest devices like glass stem and bimetallic thermometers and more complex electrical elements.

Disadvantages :

(a) Accuracy and sensitivity and temperature span are low as compared to electrical temperature sensors. For increasing accuracy, large size bulb be used, that requires larger space at the point of measurement.

(b) All pressure thermometers contain working fluid at certain fixed pressure, hence system can't be broken without affecting the calibration.

(c) In case of any breakage, the entire system should be replaced.

(d) For separation distance of more than 30 m between sensing element and indicating element, use of transmitters becomes economical.

(e) Vapour-pressure thermometers indicate only temperature at the liquid surface.

COMPARISON OF PRESSURE SPRING THERMOMETERS

Property	Mercury	Gas	Vapour
1. Scale shape	Linear	Linear	Non-linear
2. Temperature range (°C)	– 49 to 649	–268 to 760	–184 to 343
3. Smallest span (°C)	38	70	26
4. Largest span (°C)	537	426	176
5. Ambient effect	Yes	Yes	No
6. Cross-ambient effect	No	No	Yes
7. Head effect	No	No	Yes
8. Barometric effect	No	Yes	Yes
9. Dip effect	Yes	No	No
10. Immersion effect	Yes	Yes	Yes (little)
11. Response speed	Slow	Slow	Fast
12. Sensitivity	Greater	Low	Low

ELECTRICAL SENSORS FOR TEMPERATURE MEASUREMENT

The output of electrical temperature sensors is in the form of electrical signals i.e. either voltage or current. In this chapter we study the following temperature sensors –

(a) Resistance Temperature Detector (RTD)

(b) Thermistor sensors.

(c) Thermocouple sensors.

3.1 RESISTANCE TEMPERATURE DETECTORS (RTD)

(Resistance thermometers)

History : The application of the property of electrical conductors to increase electrical resistance with rise in temperature, was first described by Sir William Siemens at the Bakerian Lecture of 1871 before the Royal Society in Great Britain. The necessary methods of construction were established by Callendar, Griffiths, Holborn and Wein between 1885 to 1900.

I. Principle : Electrical resistance of a substance changes with change in its temperature. This substance can be a metal, or nonmetal like semiconductor. Hence, any changes in temperature of a metal can be measured in terms of change in its electrical resistance. The resistance of most metals increases with rise in temperature and the relationship between resistance and temperature for metals is given by

$$R_t = R_0 (1 + a_1 t + a_2 t^2 + a_3 t^3 + \ldots\ldots) \qquad \ldots (3.1)$$

where, R_t = resistance at temperature $t^{\circ}C$

R_0 = resistance at $0^{\circ}C$

a_1, a_2, a_3 = constants. i.e. coefficients of resistance.

For small temperature ranges, only constant a_1 is considered, so that relationship between temperature and resistance becomes linear.

II. Construction :

A. *Sensing element : (Resistance bulb)* – Industrial resistance thermometer bulb essentially consists of a coil of fine resistance wire wound on or inside the frame of insulating material. Different forms of the resistance bulb are described below :

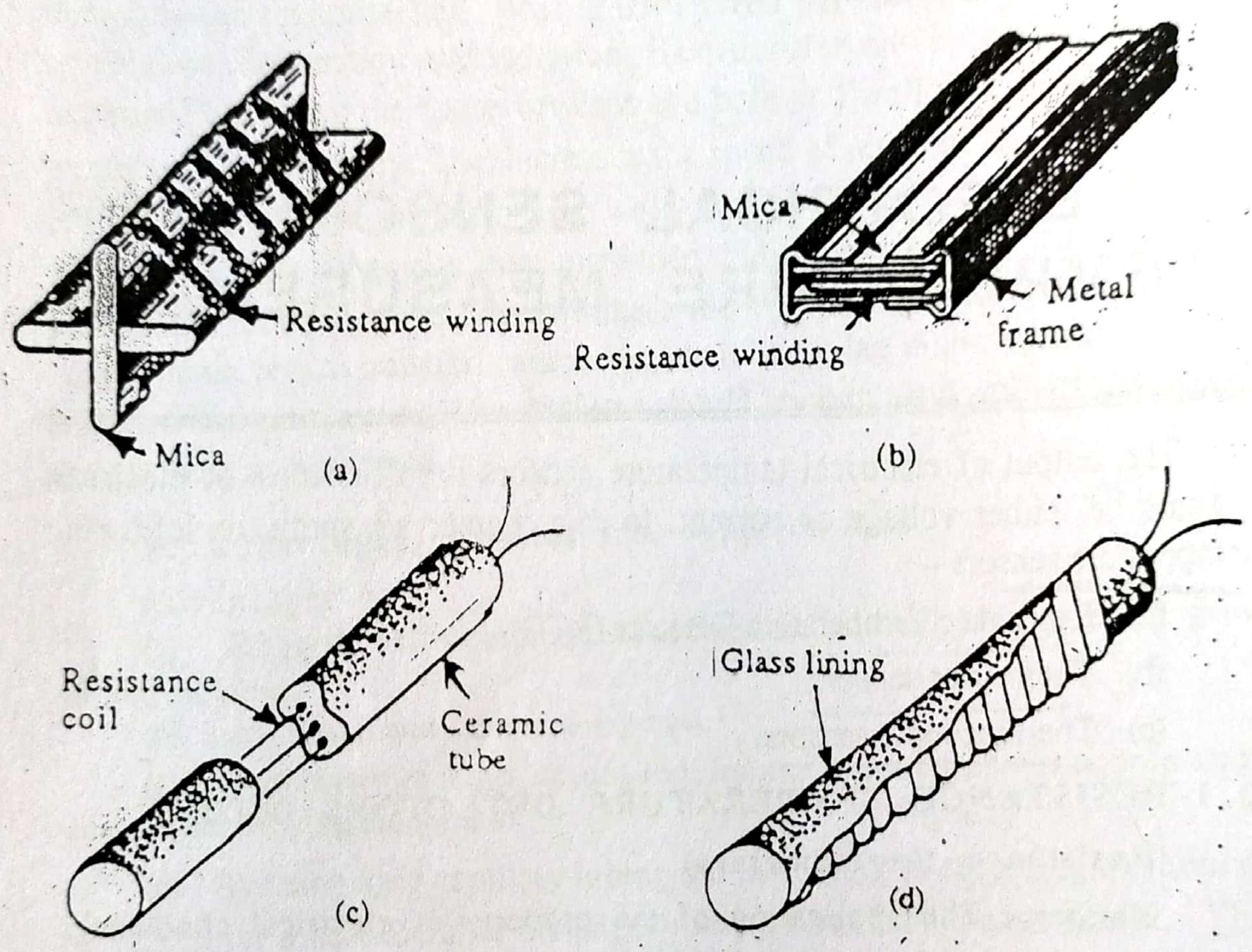


Fig. 3.1

High resistance metal wires (like platinum) are wound on a notched or perforated mica frame as shown in Fig. 3.1 (a). Such a bulb appears as a round coil.

Resistance wire is clamped between two mica plates as shown in Fig. 3.1 (b). This arrangement is more compact than that shown in Fig. 3.1 (a).

For high temperature measurement resistance wires are passed through small holes drilled in ceramic rod as shown in Fig. 3.1 (c).

The robust form of resistance bulb i.e. shown in Fig. 3.1 (d), in which resistance wire is wound on solid ceramic rod and coil is sealed by glass. This form is used in aircrafts. For surface temperature measurement,resistance element is made in the form of woven–wire mesh cloth.

Low resistance wires made of copper, nickel etc. can be wound on glass or plastic insulators, instead of using mica.

Precautions to be taken while winding resistance wire on insulating frame are –

(a) good thermal conductivity and high rate of heat transfer is obtained.

(b) the windings should be free from any physical strain, because electrical resistance of winding changes with change in mechanical stress or strain in it.

(c) the resistance wire material should have a continuous and stable relationship between resistance and temperature and also it should have a high thermal coefficient of resistance.

(d) resistance wire should be homogeneous so that entire wire would be at same, uniform temperature. This avoids generation of any localized thermo-e.m.f. due to temperature difference along the wire.

(e) while making connections of the resistance wire, the contact resistance and thermo-electric effects must be avoided. Contact resistance is avoided by soldering, fusing or welding the joints, while thermoelectric effects are avoided by maintaining all such connections at same temperature.

Working Substance (Resistance elements) : Resistance elements used are made of Platinum (Pt) or base metals such as Nickel (Ni) or Copper (C_u) or the alloys such as Balco.

(a) **Platinum Resistance Thermometers** : Pt elements are available as fine wire or as a deposited film. There are two types of Pt resistance thermometers :

(i) *Standard Pt-resistance thermometer (SPRT)* : These are used as international standard for temperature measurements between the triple point of Hydrogen (13.81 K) and the freezing point of Antimony (630°.75° C). The temperature standard of SPRT is 25.5 Ω at ice-point to stay within the range of practical Muller bridges while providing a nominal 0.1 ohm/°C sensitivity. SPRT are constructed in a manner to be almost totally strain free, using very lightly supported wires of larger size than typical in an industrial thermometer. Such elements provide high TCR and maximum thermal stability at the expense of fragility and larger size.

(ii) *The Industrial Pt-resistance Thermometer : (Industrial RTD)* : The RTD has fully supported and rugged construction that uses a reference grade wire that gives a TCR over the interval 0 to 100° C between 0.003817 to 0.003915 ohm/°C -ohm with the common value of 0.003902 ohm/ohm °C with winding over pure alumina mandrel. This value slightly differs from that of SPRT element (0.003927 ohm/ohm °C). The international grade Pt-RTD curves (temperature : Vs. resistance) are obtained with slightly doped Pt-wire having

TCR of 0.00385 ohm/ohm °C. *Wire-wound designs* are most common at ice point resistance of 100 ohm alongwith availability of 200 ohm and 500 ohm at higher cost. The *thick or thin film-type designs* are also available with ice point resistance of 100 ohm and 1000 ohm at same cost with slightly lower TCR specified at 1000 ohm.

PT 100 sensor has 100 ohm resistance at room temperature with fundamental interval of 38.5 ohms.

Resistance-temperature relationship for Pt -elements is given by Callendar equation

$$T = \left(\frac{R_T - R_0}{R_{100} - R_0}\right) 100 + \delta \left(\frac{T}{100} - 1\right) \frac{T}{100}$$

where R_0, R_T and R_{100} are resistances at 0° C, T° C and 100° C respectively.

δ = constant lying between 1.49 to 1.5 determined from sulphur point.

(iii) *Base-metal RTDs*

Nickel RTD : Second in usage to Platinum is a high purity Nickel (Ni) which offers the highest TCR, second highest temperature range and lower assembled cost than wire-wound Pt at high resistance values. Resistances of 120 and 500 ohm are most common with 1000 ohm availability. Nickel has a non-linear TCR that increases with rise in temperature. Ni is highly strain sensitive and requires great care by the manufacturer to obtain interchangeability. The TCR of Ni is highly influenced by both purity and state of anneal. There is no internationally standard temperature-resistance curve for Ni-sensors, although there are national standards, and several manufacturers can provide sensors to a common curve characteristic by TCR between 0 to 100° C of 0.00672. ohm/ohm °C.

Copper RTD : Cu -RTD's are available only at 10 or 100 ohm ice point resistance of winding wire. TCR of Cu is almost same as Pt and it is very linear above the ice point. Cu in bifilar winding is used in electrical machine due to very low inductive or capacitive reactance. There is no internationally standard recognised curve for Cu, although some national standards exit.

(iv) ***Balco RTD*** : Balco is an alloy of Fe and Ni (70 % Ni to 30 % Fe) having high specific resistance that makes possible high resistance windings without much increase in size. It has ice-pint resistance of 2000 or 10,000 ohm and second highest TCR alongwith third highest temperature capability. It does not have recognised standard curve.

Thermal well (Protective sheathing) : Thermal well is used with resistance bulb, when the thermometer is used to measure temperatures in corrosive, oxidising medium. Well is usually made of porcelain, brass or stainless steel and it is in the form of a tube that covers the bulb. Well prevents any contamination of resistance element.

Lead-wires : Lead-wires are used to connect the resistance bulb with the indicating element (Wheatstone bridge) because both are separated by distance of 100 feet or more. Lead–wires of silver or platinum have larger diameter than resistance wire and they are welded to resistance wire inside glass seal. Lead wires transmit the information regarding temperature surrounding the bulb to indicating element.

Industrial RTD sensor has 0.025 mm diameter pt-wire wound into coil and inserted into ceramic tube. The winding is embedded and fused within or on ceramic tube.

B. Indicating Element (Wheatstone Bridge Circuit) : We have seen that the electrical resistance of the sensing element i.e. of resistance bulb changes with change in temperature surrounding it. Hence, for measuring temperature around the bulb, it is necessary to measure the resistance of the bulb, which then can be correlated with the corresponding temperature value. We study Wheatstone bridge circuit used to measure resistance of the bulb.

Basic Wheatstone Bridge Circuit :

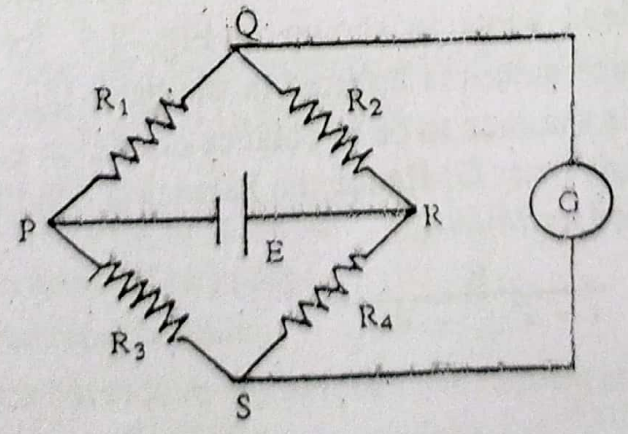


Fig. 3.2 : Wheatstone Bridge Circuit

Wheatstone bridge circuit consists of *four resistances* R_1, R_2, R_3, R_4 arranged in diamond shaped form as shown in Fig. 3.2. A *battery* of emf E is connected between terminals P and R while, a *galvanometer* G is connected between points Q and S. This circuit is said to be in *balanced condition* when galvanometer shows *null* or *zero deflection*. It can be proved that in balanced condition the resistances satisfy the relation –

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \text{ — (Balancing condition)} \quad \dots (3.2)$$

Wheatstone bridge as the indicating element for resistance thermometer –

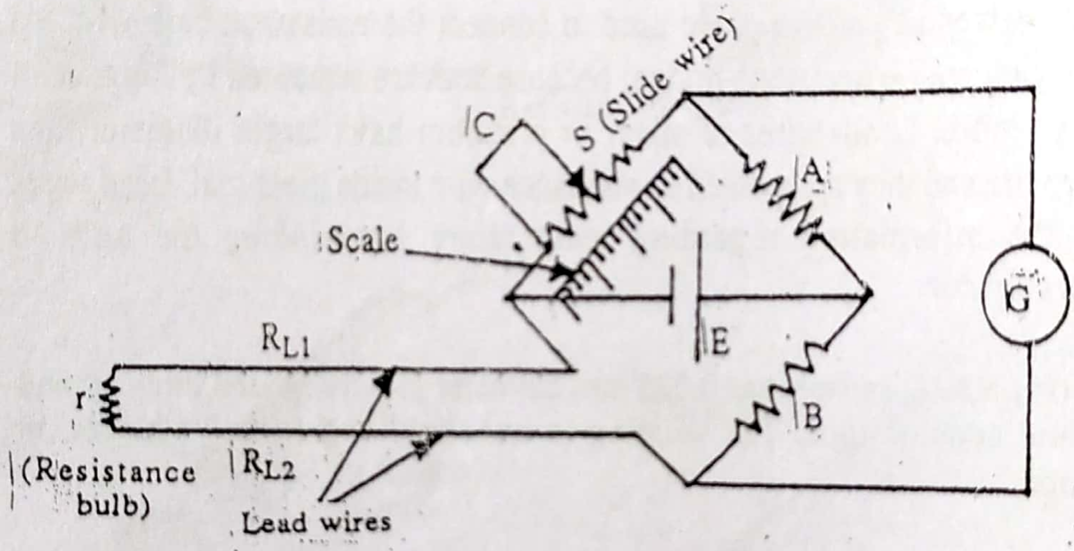


Fig. 3.3 : Indicating element of resistance thermometer

Wheatstone bridge indicating element shown in Fig. 3.3 is the modified form of basic bridge circuit shown in Fig. 3.2. In this circuit, A and B are fixed resistances while S is the variable resistance whose value can be adjusted by changing the contactor (C) position. Resistance bulb 'r' is connected in the bridge circuit with lead wires having resistances R_{L_1} and R_{L_2}. All resistances are made of Manganin so that their value does not change much with temperature.

III. Working of Resistance Thermometer :

The *sensing element* (resistance bulb) is connected to the *indicating element* (Wheatstone bridge) by lead wires as shown in Fig. 3.3. for temperature measurement using resistance bulb it is inserted in the bath. Initially at certain temperature bridge circuit is assumed to be in balance condition as indicated by null deflection in the galvanometer G. Hence the balancing condition given by equation 3.1 will get satisfied as follows :

$$\frac{A}{S} = \frac{B}{r + R_{L_1} + R_{L_2}}$$

$$\text{i. e. } \frac{A}{B} = \frac{S}{r + R_{L_1} + R_{L_2}} \quad \text{... (3.3)}$$

As temperature surrounding the bulb changes the resistance r of the bulb changes its value to say r' and this results in loss of balancing condition as indicated by non-zero galvanometer deflection. Since resistances A and B are fixed, the balancing condition can be obtained at this new value r' of bulb resistance, only by changing the value of sliding wire adjustable resistance S. Thus for every value of r, there exists certain fixed value of S, for which circuit gets balanced. Value of S can be adjusted by changing the contactor position accordingly. Thus contactor position can be marked on the scale in terms of bulb temperature. This balancing can be achieved automatically using potentiometers.

Working of resistance thermometer : Temperature around resistance bulb changes → resistance 'r' of bulb changes → loss of balancing condition → variable resistance 's' is adjusted by changing contactor position so as to restore the balancing condition → contactor position shows the temperature on the scale calibrated against slide wire.

Modified circuit (Callender - Griffith Bridge)

(Siemen's three-lead circuit) :

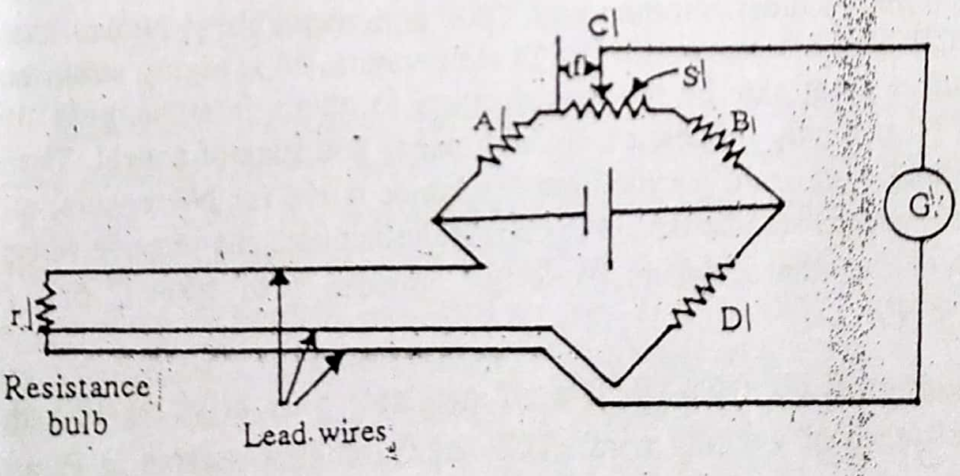


Fig. 3.4 : Callender-Griffith Bridge

We have already discussed the working of industrial resistance thermometer in which basically any change in resistance of the bulb due to change in temperature is used to determine temperature around the bulb. Hence care should be taken that the change in electrical resistance of the bulb must be only due to change in temperature around it. But there are some factors which cause change in bulb resistance without any change in temperature. These factors are –

(a) contact resistance between slidewire 's' and contactor 'c'.

(b) lead wire resistance that changes with the ambient temperature.

(c) Joule heating effect rises the temperature of the bulb that changes its resistance.

The Wheatstone bridge circuit shown in Fig. 3.3 is modified as shown in Fig. 3.4 in order to compensate for change in resistance due to above factors. This modified circuit has three lead wires and slide-wire S is placed at the top of the bridge where it may lie in both arms of the bridge. If 'f' is the fraction of slide-wire present in left arm of the bridge, then balancing condition for this modified circuit becomes –

$$\frac{r + R_L}{D + R_L} = \frac{\frac{A}{S} + f}{\frac{B}{S} + 1 - f}$$ where R_L = lead–wire resistance

(a) *Compensation of contact resistance* : In the modified circuit shown in Fig. 3.4 slide-wire 's' and contactor 'c' are not in the bridge circuit directly, but they are in galvanometer circuit. Hence, any change in contact resistance due to dirt, dust and mechanical wear causes a negligible change in galvanometer reading, while the balancing condition and hence the accuracy remains unaffected.

(b) *Compensation of change in lead–wire resistance* (Siemen's three lead method) : For achieving this compensation three lead–wires are connected as shown in Fig. 3.4, so that galvanometer is directly connected to the bulb by third lead wire. All lead wires are identical in material, size and they are passed through same cable, so that they are subjected to same ambient temperature change. Note that approximately equal length of lead-wire is present in both the arms of the bridge, that achieves compensation. It can be proved that the balance of the bridge-circuit is independent of lead-wire resistance provided –

(i) . contactor C is placed at 50% of the scale

(ii) resistances A and B are equal in magnitude.

At this particular temperature setting bulb resistance 'r' equals resistance 'D' and compensation is exact while at other temperatures the error is negligible.

(c) *Compensation of change in bulb resistance due to Joule heating of bulb* : Electrical current flowing through the bulb causes Joule heating of the resistance element with heat produced = $(\text{current})^2 \times$ resistance. This heat produced and hence the resistance varies with the current. From circuit diagram 3.4, the current through bulb would be $\left(\frac{E}{r + D}\right)$.

Therefore heat produced $H = I^2 r = \left(\frac{E}{r + D}\right)^2 r$.

But for lead wire compensation $r = D$

$$H = \frac{E^2}{4r}$$

Thus heat produced would be minimum if battery voltage is small and bulb resistance is large, that leads to negligible change in bulb resistance.

IV. Calibration : Resistance thermometers are calibrated either by reference to fixed point or by comparing the performance with the standard, reference thermometer when both are installed in identical surrounding. The reference thermometer may be a thermocouple, a liquid-in-glass thermometer or another RTD.

V. Performance characteristics :

A. Static characteristics :

(a) **Accuracy :** Accuracy of resistance thermometer is ± 0.25% of span and is better than that of other thermometers. The static error in the reading can be minimized by using the standard resistance bulb.

(b) **Reproducibility :** Reproducibility is better than thermocouple and expansion thermometers.

B. Dynamic characteristics :

Speed of response depends upon the nature of flowing medium around the bulb. The response is faster when bulb is installed in fast-flowing liquid than when the same bulb is placed in moving air. Thermal well around the bulb introduces lag in the temperature measurement. This lag is more when thermometer is installed in liquid than that in air. When thermometer is installed in air, heat transfer takes place by radiation and for effective radiation well surface should be dark and rough. It takes 6 seconds for 63.2% change when it is dipped in water heated from 0 to 50°C.

VI. Advantages, Limitations, Applications :

Advantages :

(a) Considerably wide temperature range between – 200 to 650°C that can be obtained comparatively in small size.

(b) High accurcy.

(c) No drift over long period.

(d) Fast speed of response.

(e) Good reproducibility.

(f) Does not require any ambient temperature compensation.

(g) Remote indication can be obtained.

Limitations :

(a) The coefficients of resistance in equation 3.1 vary considerably with the purity of resistance winding and its heat treatment. Hence sensing bulb requires protection against contamination and oxidation.

(b) High cost.

(c) It requires external electrical power supply.

(d) Bulb size is larger than that of thermocouple and filled thermometers.

Applications :

(a) Resistance thermometer having its galvanometer calibrated in temperature (i.e. called deflectional RTD) can be used as ambient–temperature detector.

(b) Deflectional RTD can be used in aircraft thermometers.

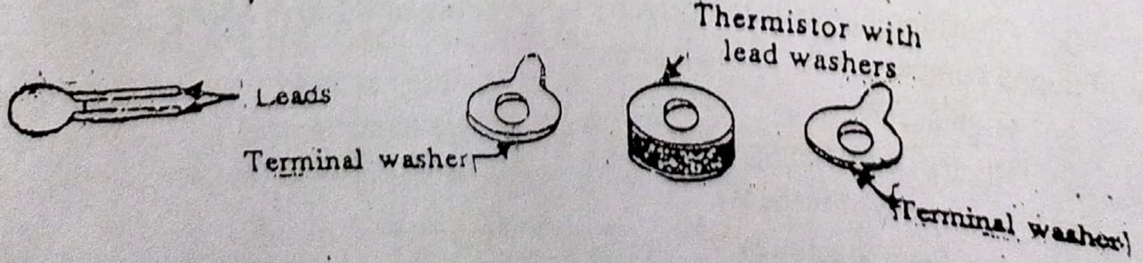
(c) RTD can be used as the standard thermometer for calibration of other thermometers.

3.2 TEMPERATURE MEASUREMENT USING THERMISTOR

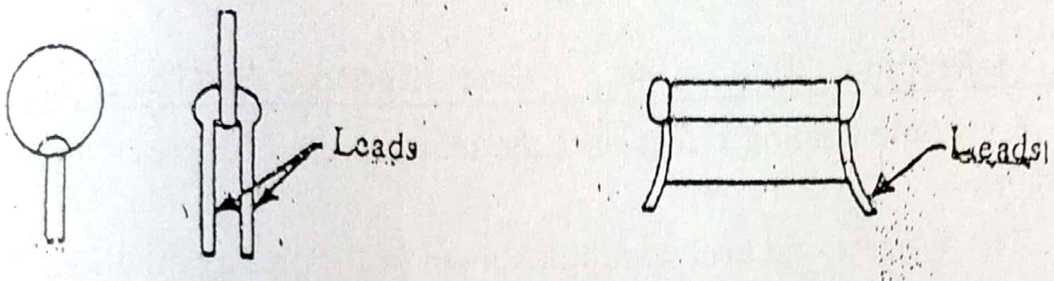
I. **Principle :** Thermistor is a semiconductor material whose electrical resistance decreases with rise in temperature around it and vice versa. Thus any change in temperature around the thermistor can be measured in terms of change in its electrical resistance.

II. Construction :

Sensing element – Thermistors are made from a specific mixture of pure oxides of Ni, Mn, Cu, Co, Fe, Mg, Ti. Thermistor was first introduced in 1940 and its name has been derived from *thermally sensitive resistors*. Thermistors have very large positive or negative TCR (temperature coefficient of resistance). For positive TCR material, its resistance increases with temperature rise, while for negative TCR material, resistance decreases with rise in temperature. The different shapes of thermistor sensors are as shown in Fig. 3.5.



(a) Bead type (b) Washer type



(c) Disc type (d) Rod type

Fig. 3.5 : Thermistor sensors

Thermistors can have bead type, washer type, disc type or rod type configuration shown in Fig. 3.5. It can also be encapsulated in plastic, cemented, soldered in bolts, encased in glass tubes. Thermistor beads are 1 to 2.5 mm in diameter, discs are 5 to 25 mm in diameter and rods are 1 to 6 mm in diameter upto 50 mm length.

Indicating element : For temperature measurement, thermistors are connected in Wheatstone bridge circuit shown in Fig. 3.3 in article 3.1.

III. **Working** : Thermistor sensing element is placed in the bath whose temperature is to be measured. As bath temperature changes electrical resistance of thermistor changes. This causes the unbalance in Wheatstone bridge circuit. This unbalance signal is indicated by galvanometer deflection. Hence, galvanometer can be calibrated in terms of bath temperature.

IV. **Calibration** : Calibration procedure is same as that for resistance thermometer discussed in art. 3.1.

V. **Performance characteristics** : All performance characteristics of thermistors are comparable with those of resistance thermometers but the response is faster than RTD.

VI. **Advantages, Limitations, Applications** :

Advantages :

(a) Low cost.

(b) Small size.

(c) For negative TCR thermistor, sensitivity is high.

(d) Due to high TCR, resistance of the sensor itself is high and hence the effect of contact resistance, lead-wire resistance is negligible.

(e) Narrow spans can be obtained.

(f) Fast speed of response.

Limitations :

(a) Non-linear response.

(b) Wide temperature span can not be obtained.

(c) Unstable at high temperatures.

Applications : Thermistors are used for protecting equipments like transformer from heavy current. For this +ve TCR thermistors are used. When current exceeds the safe limit, heat generated raises temperature of thermistor so that its resistance increases. This decreases the current through circuit to safe value.

3.3 THERMOELECTRIC TEMPERATURE MEASUREMENT

(Temperature measurement using thermocouple) :

The word *thermocouple* is a combination of *thermo* for heat requirement and *couple denoting two junctions.*

Thermocouple consists of wires of two dissimilar metals soldered or welded at the ends to form two *junctions*. The junction at higher temperature is called *hot or measuring junction* while the junction at lower temperature is called *cold or reference junction*.

I. Principle :

(a) *Seebeck effect* : In 1821, Seebeck discovered that when there is temperature difference between two junctions of the thermocouple, electromotive force (emf) is developed between the junctions. This emf causes electric current to flow through thermocouple circuit. This is called as *thermoelectric effect* by which thermal energy is converted into electrical energy. The emf developed is called as *thermo-emf* while the resulting current is called as *thermo-current*. Seebeck effect is the combined effect of Peltier and Thomson effect. This thermo-emf developed is proportional to temperature difference between junctions.

$$\therefore \quad \text{emf } e \propto (T_h - T_c)$$

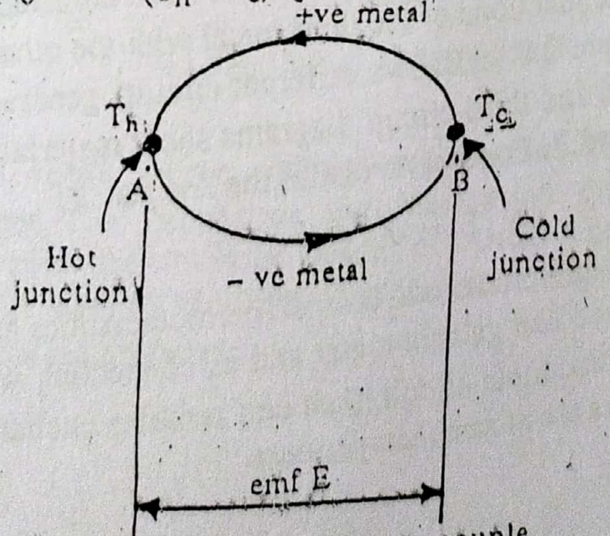


Fig. 3.6 (a) : Thermocouple

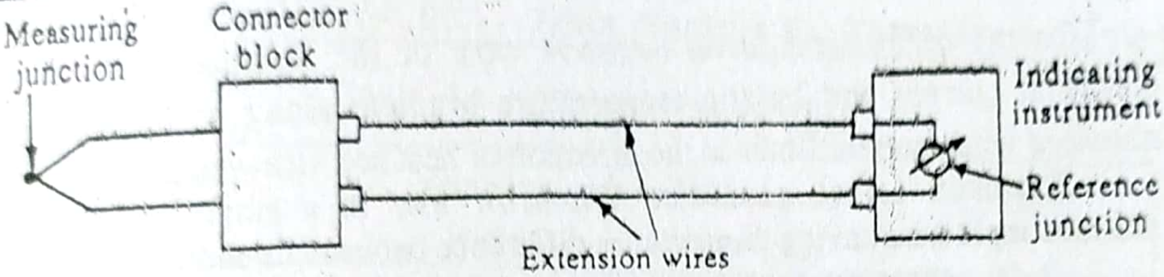


Fig. 3.6 (b)

If cold junction is maintained at fixed temperature (preferably 0°C) then emf developed can be taken as measure of the hot junction temperature.

(b) *Peltier effect* :

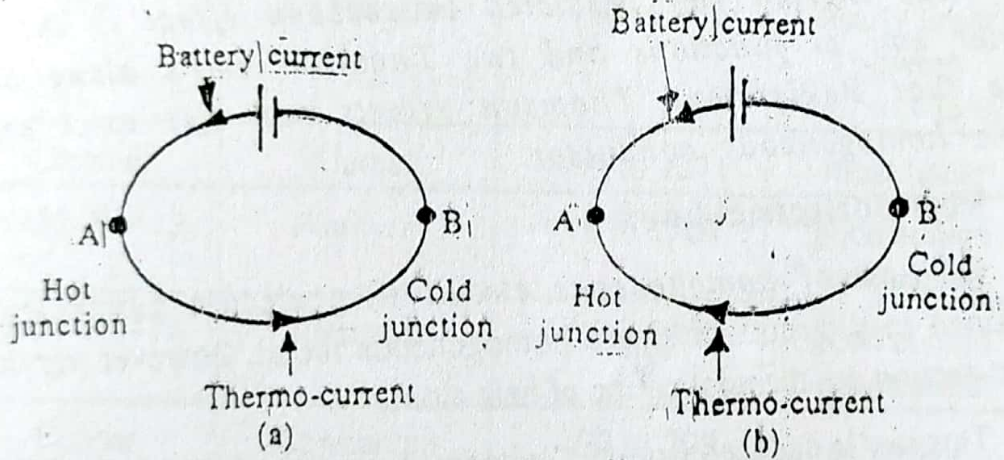


Fig. 3.7 : Peltier effect

Battery is connected in the thermocouple circuit as shown in Fig. 3.7. Battery current and thermocurrent both flow through the circuit across the junctions.

Peltier effect is defined as change in heat content when 1 coul of charge crosses the junction.

If the battery current and thermal current both flow in same direction across the junction [as shown in Fig. 3.7 (a)] then *heat is liberated at hot junction and absorbed at cold junction.*

On the other hand if battery current and thermal current both flow in opposite directions across the junction [as shown in fig. 3.7 (b)] then *heat is absorbed at hot junction and liberated at cold junction*. This is the situation when thermocouple is used in practice.

Peltier effect developes *Peltier emf* at the junctions whose magnitude and direction depends upon the junction temperature and the metals used in thermocouple.

(c) *Thomson effect* : It gives heat content of single conductor of unit cross-section when unit quantity of electricity flows through it along temperature gradient of 1K.

For a positive wire of the thermocouple carrying electrical current and having temperature gradient along its length, *heat is liberated* at any point on it where current flows in the direction of heat and vice–versa.

On the other hand *for a negative wire* of the thermocouple carrying electrical current and having temperature gradient along its length *heat is absorbed* when current flows in the direction of heat and vice–versa.

Thomson effect generates *Thomson emf* in a single homogeneous thermocouple wire having temperature difference between its ends.

It is necessary that each section of thermocouple wire in a given circuit is homogeneous, which has uniform composition and physical properties along its length. With such homogeneous wires, the circuit emf depends only upon the metals employed and the temperature of their junction, while it is independent of length and diameter of wires.

Thus thermo emf predicted in seebeck effect is the sum of Peltier emf at junctions and two Thomson emf's along the wire. Note that Peltier and Thomson effects can not exist separately for a homogeneous conductor.

Thermoelectric Laws :

(a) *Law of homogeneous circuit* : An electric current cannot be sustained in a circuit of single homogeneous metal, however varying in its cross–section, by the application of heat alone.

This law is deduced from the experiments which conclude that thermo–emf developed in the thermocouple depends only upon the hot and reference junction temperatures and it is independent of temperature distribution along the wire and intermediate temperatures along the wire.

(b) **Law of intermediate temperatures** : The law states that the thermal emf developed by thermocouple (C) with its junctions at temperatures T_1 and T_2 ($T_1 > T_2$) equals the algebraic sum of the emfs generated by two thermocouples, one (A) with its junction at T_1 and some reference temperature T_3 (lying between T_1 and T_2) and the other (B) with its junctions at same reference temperature T_3 and the measuring temperature T_2.

i. e. $T_1 \overset{E}{\,} T_2 = T_1 \overset{E}{\,} T_3 + T_3 \overset{E}{\,} T_2$

This law is used for calibration of thermocouple, because calibration can be based on temperatures of hot and cold junctions only without any reference to temperature T_i of intermediate junctions (Shown in figure 3.8 (b)).

This law is described in figure 3.8 (a)

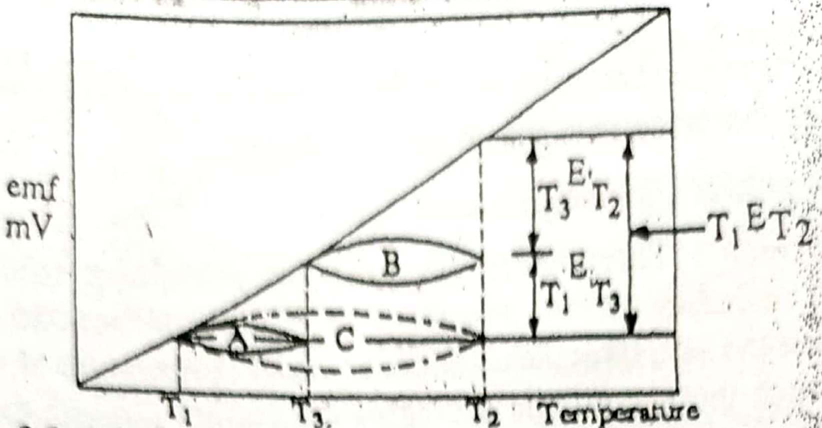


Fig. 3.8 (a) : Law of intermediate temperatures

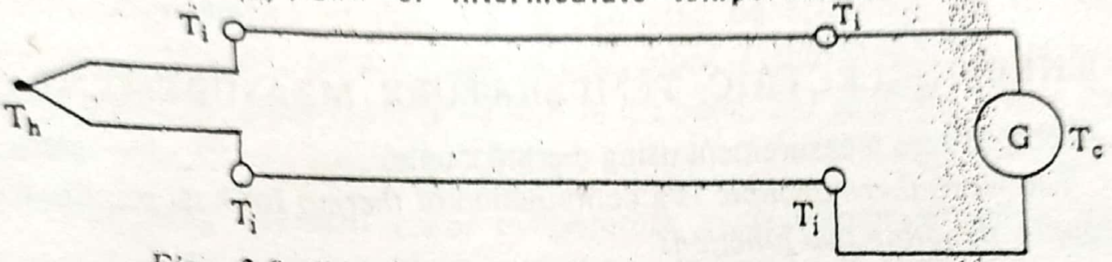


Fig. 3.8 (b) : Thermocouple Assembly

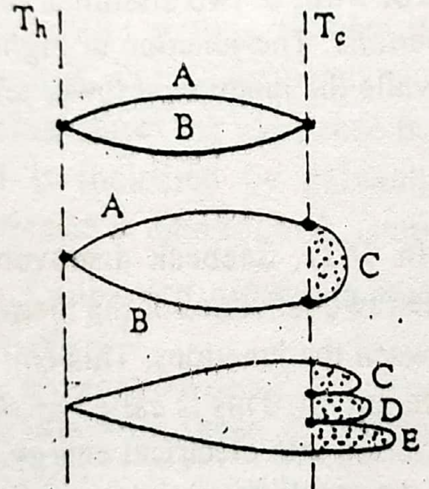


Fig. 3.8 (c) : Law of intermediate metals

(c) Law of intermediate metals : The law states that the algebraic sum of the thermoemfs in a circuit composed of any number of dissimilar metals is zero, provided all the circuit is at a uniform temperature. Hence, introduction of a third metal into the circuit of two metals will have no effect upon the emf generated so long as the junctions of the third metal with the other two are at the same temperature. Figure 3.8 (c) shows different circuits generating same emf, even though the second and third circuit diagrams show materials C, D, E, and F inserted between A and B. For second circuit the law states :

$$A\,{}^{e}B = A\,{}^{e}C + C\,{}^{e}B$$

This law is deduced from second law of Thermodynamics and it concludes that if a measuring device like galvanometer and its connecting wires connected at any point in the thermocouple circuit, then emf remains unchanged, provided all intermediate junctions are at same temperature.

II. Construction and Working :

A. Sensing element : Industrial thermocouple shown in Fig. 3.9 has two *thermocouple wires* welded or soldered to form two *junctions*. These wires are insulated from each other and covered by *protective sheathing*. *Lead-wires* connect the thermocouple to the indicating element.

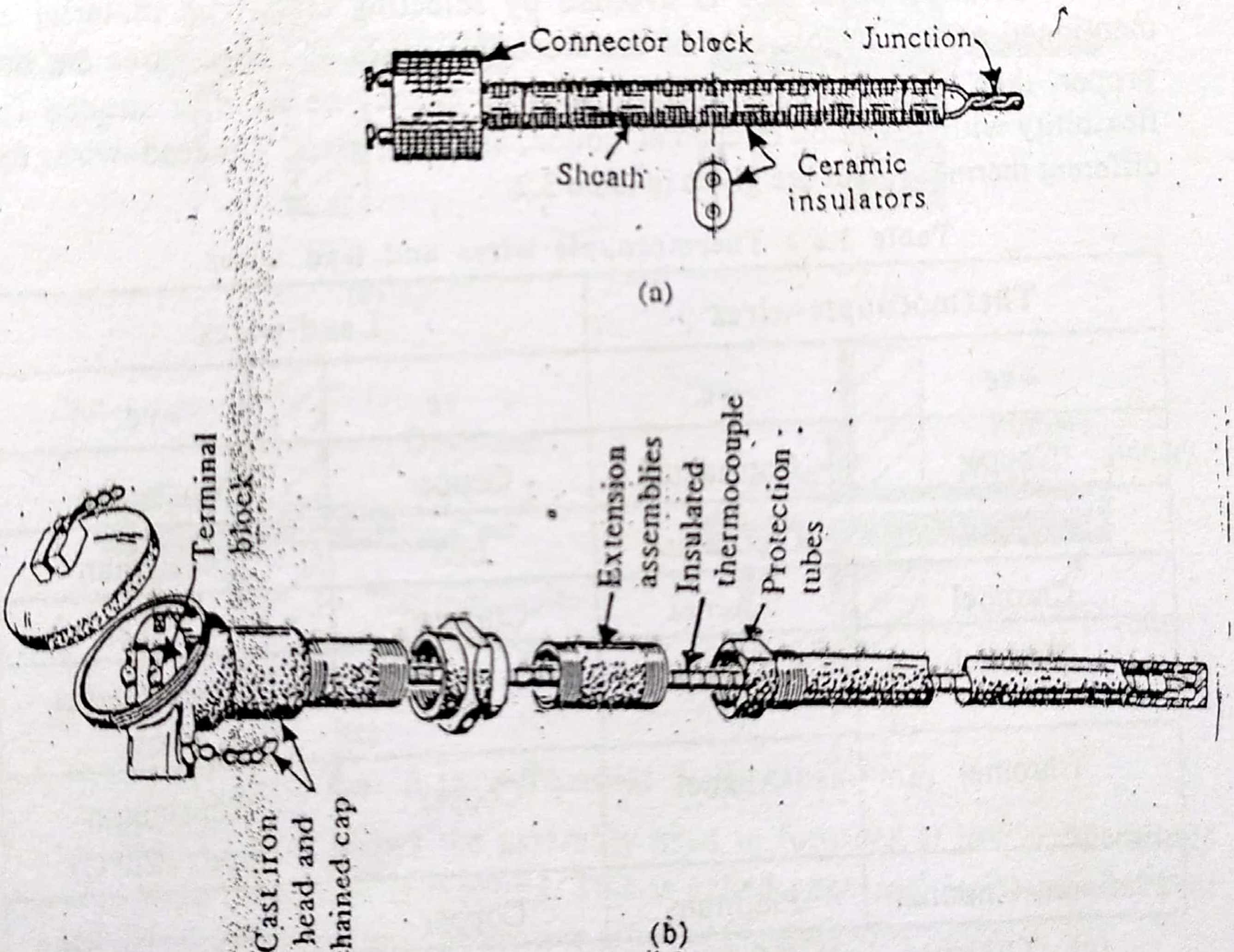


Fig. 3.9 : Thermocouple

(a) Thermocouple wires : The materials used for thermocouple wires predict its types. The properties that determine metal's usefulness in thermocouple wire are melting point, electrical conductance, stability, repeatability, cost, ease of handling, thermoelectric output in combination and reaction to various atmospheres.

Table 3.1 : Thermocouple types

Type	Positive wire	Negative wire	Temperature range (°C)	Linearity
B	pt-70–Rh–30	pt–94–Rh–6	0 to 1860	good at high temperature
E	Chromel	Constantan	(–196) to 999	good
J	Iron	Constantan	–196 to 760	nearly linear between 149 to 438°C
K	Chromel	Alumel	–190 to 1371	most linear
R	pt–87–Rh–13	Platinum	–18 to 1704	good at high temperature
S	pt 90–Rh–10	Platinum	–18 to 1760	good at high temperature
T	Copper	Constantan	–190 to 399	same as J
	Tungsten	W 74 – Re 26	–18 to 2316	same as R
	W 94 – Re 6	W 74 – Re 26	–18 to 2316	same as R
	Copper	Gold–cobalt	–268 to –18	linear above 60K
	Ir 40 – Rh 60	Ir	–18 to 2093	same as R

(pt – platinum, Rh – rhodium, W – tungsten, Re – rhenium, Ir – Irridium)

Thermocouple wires should be –

(i) homogeneous to avoid any temperature gradient along the wire.

(ii) annealed at a temperature higher than maximum range of thermocouple so as to relive internal stresses.

(iii) having size between 8 gauge to 20 gauge.

The thermocouple wires pass through ceramic insulator spacers shown in Fig. 3.9 (a) with hot junction in the bath and other ends connected to the terminal block in which positive wire terminal is marked with red colour.

Formation of measuring junctions : Measuring junction is formed by welding (twisted or butt) or soldering the wires. The twisted weld is made with larger diameter wires. The butt weld is made by fusing the two wires into a round bead.

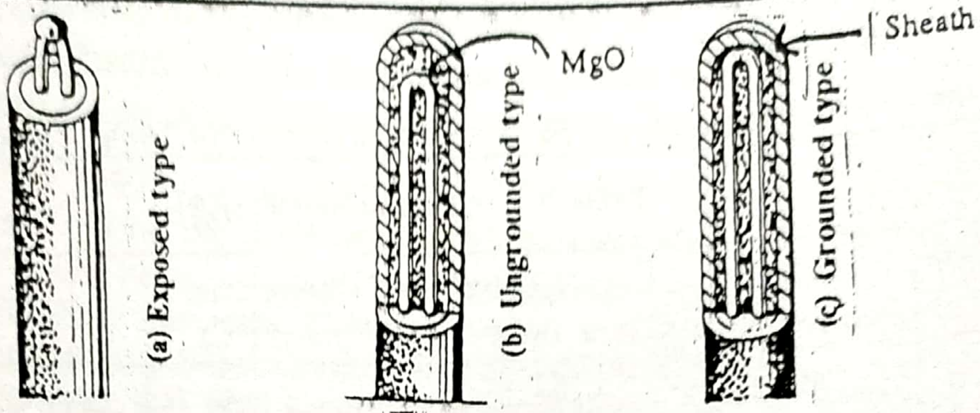


Fig. 3.10 : Types of Measuring Junctions

(i) *Exposed type* : In this type the measuring junction extends beyond the protective metallic sheath (covering) as shown in Fig. 3.10 (a). This type gives fast response and can be used for measurement of non-corrosive fluid temperature.

(ii) *Ungrounded type* : In this type measuring junction is insulated from the thermocouple sheath by soft MgO powder as shown in Fig. 3.10 (b). This junction is isolated from any external electrical noise.

(iii) *Grounded type* : In this type the measuring junction is welded to the sheath as shown in Fig. 3.10 (c). This gives faster response than ungrounded type.

Formation of reference or cold junction – The other ends of the thermocouple wires are connected to the fixing screws in the *terminal block* made of insulating material. Lead wires are connected to these screws, whose other ends are connected to thermocouple wires, so as to form reference junction, as shown in Fig. 3.11.

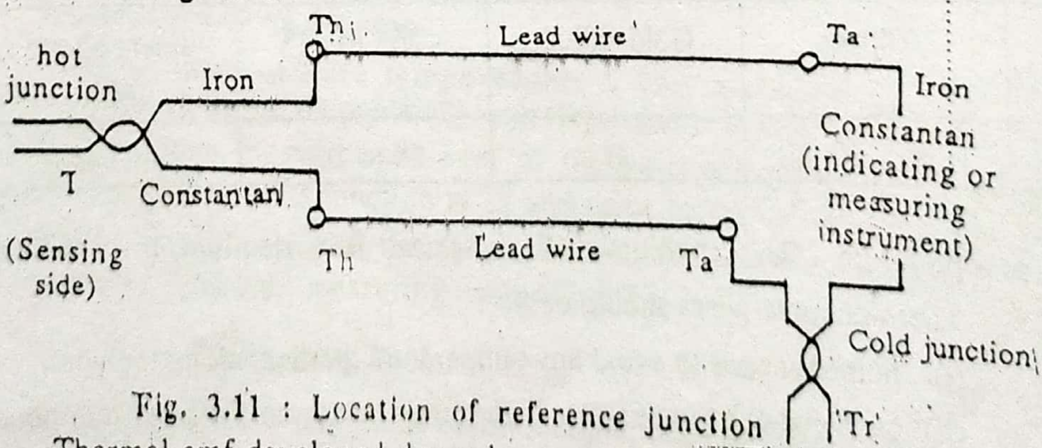


Fig. 3.11 : Location of reference junction

Thermal emf developed depends upon the difference between measuring junction and reference junction temperatures. Hence for getting emf proportional to measuring junction temperature, it is necessary to maintain reference junction at certain fixed temperature. For this purpose, the reference junction is located away from the measuring junction and usually it is located in the measuring instrument where the temperature changes are negligible. When measuring instrument is situated in temperature – controlled or air-conditioned room, this location of reference junction is more effective.

(b) **Lead-wires – (Compensating cables)** : Lead–wires connect the measuring junction of the thermocouple to the indicating instrument, because measuring junction and the indicating instrument are usually far away from each other. Ideally lead wires and thermocouple wires, both should be made of same material, but it becomes costly to use platinum lead-wires for platinum thermocouple. Hence, lead wire material is such that its thermoelectric properties should match with those of thermocouple wires.. Also lead wires should have low resistivity.

It can be observed from Fig. 3.11 that two ends of the lead–wire are not at same temperature. Since thermocouple is far away from the measuring instrument, the temperature difference (Th–Ta) may be very large. Error due to this temperature difference is avoided by selecting lead–wire material as mentioned above. If polarities of thermocouple wires and lead wires are not proper, then large error may result. Lead-wires may be solid or straded for flexibility with insulation of enamel, cotton, asbestos, glass. The lead–wires for different thermocouples are given in table 3.2.

Table 3.2 : Thermocouple wires and lead wires

Thermocouple-wires		Lead-wires	
+ve	–ve	+ ve	–ve
Copper	Constantan	Copper	Constantan
Iron	Constantan	Iron	Constantan
Chromel	Alumel	Chromel	Alumel
Chromel	Alumel	Iron	Copper–Nickel alloy
Chromel	Alumel	Copper	Constantan (upto 125°C)
Platinum–Rhodium	Platinum	Copper	Copper–Nickel

(c) **Thermal well (sheathing)** : Thermocouple measuring junction is enclosed in thermal well or protective sheathing for the following reasons –

(i) to protect the junction from oxidising and corrosive bath fluids.

(ii) to protect the junction against thermal and mechanical shocks.

Some molten–metal baths are so corrosive that one thermocouple and one well are used only for taking one quick reading and then they are replaced for next reading. Thermal wells are made of porcelain, fused silica or fire clay. Fig. 3.12 shows different types of thermo wells.

Normally used assembly is shown in Fig. 3.12 (a) that consists of a head, a mounting flange and thermocouple. It is used for *measurement of gas or air temperatures.*

Fig. 3.12 (b) shows the assembly used for *temperature measurement in pressure vessels and pipe lines containing pressurized liquids.*

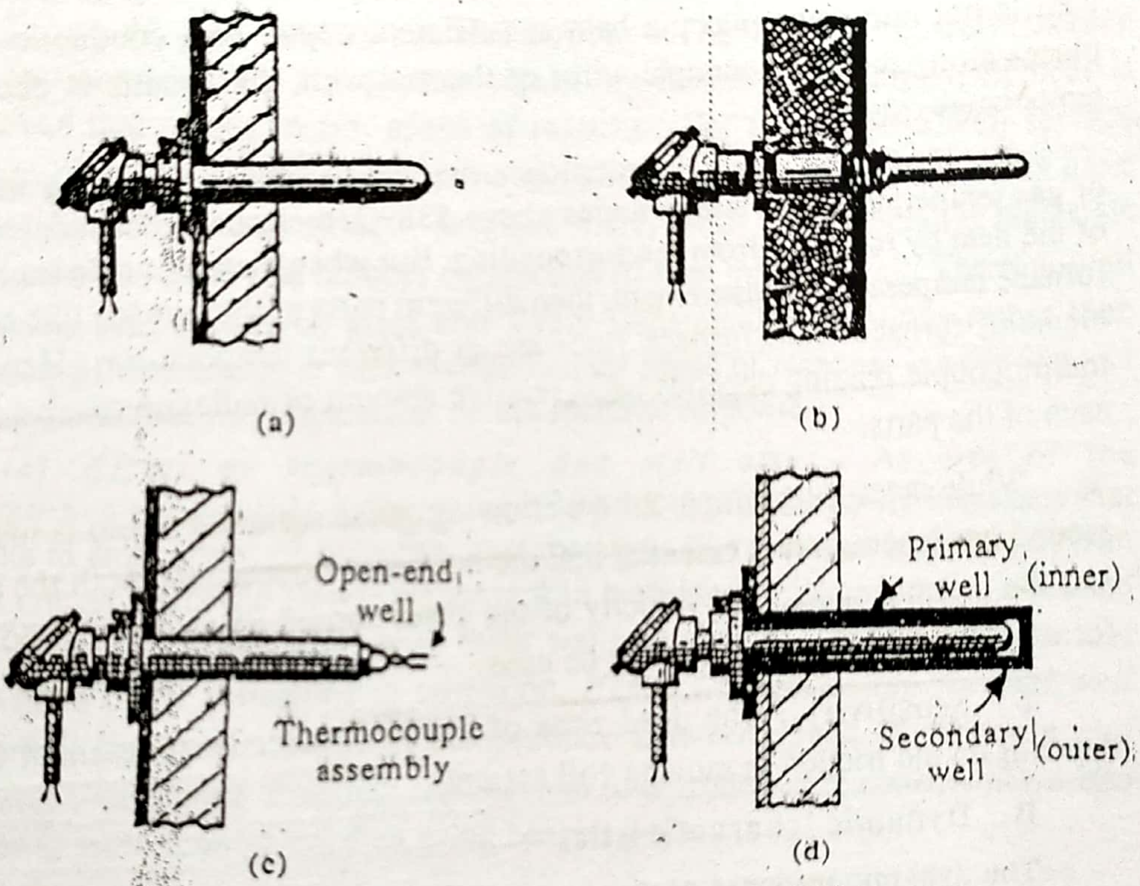


Fig. 3.12 : Thermal wells (sheathing)

Fig. 3.12 (c) shows the assembly used in furnaces at low temperatures where little protection is required. This is called *open-end well assembly* that protects the junction from the erosive effects of fast-moving gases.

Fig. 3.12 (d) shows the assembly used in baths above 1100°C where corrosion may be severe. In this system two wells, primary and secondary are used. Secondary well prevents sagging of the assembly at high temperatures and the surface of primary well is protected. Secondary wells are made of metals like Ni, Cr, Fe for oxidising atmosphere, Cr–Fe for sulphating environments. The mechanical properties to be considered while selecting a thermal well are –

(i) resistance to corrosion and oxidation.

(ii) resistance to thermal and mechanical shock.

(iii) resistance to gas leakage.

(iv) mechanical strength.

B. Indicating element (Measuring instrument) : Thermocouple generates an emf proportional to temperature difference between measuring and reference junctions. Hence to measure the measuring junction temperature it is necessary to measure the thermo–emf correctly. For this purpose the *Millivoltmeter* or the *potentiometer type instrument* is used.

The millivoltmeters : The millivoltmeter is nothing but a *calibrated dc galvanometer*. It is the simplest and least expensive indicating element for the thermocouple. The millivoltmeter consists of a *rectangular coil* pivoted at the top and bottom and this coil is placed in a steady, permanent *magnetic field* of two poles of *horse-shoe magnet*. *Hairsprings are* connected at the upper and lower ends of the coil and the springs are connected to the terminals of the millivoltmeter. When electric current passes through coil, the coil rotates and this rotation causes the pointer attached to the coil to deflect. Thus pointer deflection is proportional to the current through the coil and it is calibrated in terms of potential difference across its terminals.

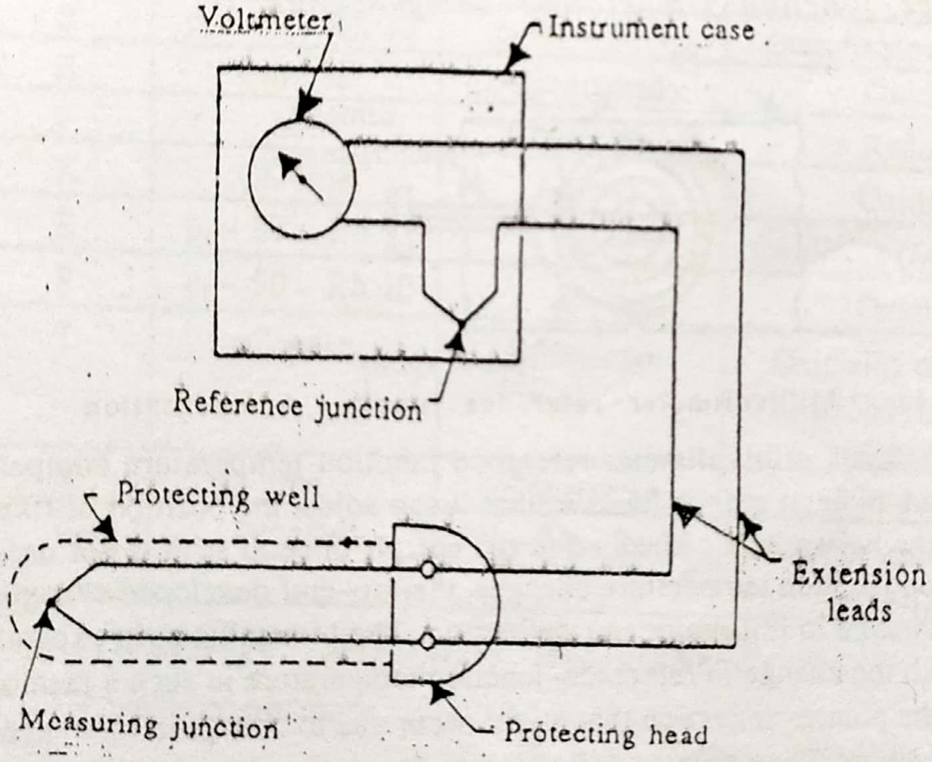


Fig. 3.13 : Thermocouple with millivoltmeter indicator

The millivoltmeter connected with the thermocouple is shown in Fig. 3.13. Figure shows *measuring junction, thermal well, terminal block, lead-wires, reference junction* located inside the millivoltmeter.

Sources of error in millivoltmeter reading :

(i) Due to electrical resistances of thermocouple, lead-wires, milli-voltmeter, the millivoltmeter (mV) reading is not exactly equal to the emf of the thermocouple but mV reads slightly less than the actual emf. In order to reduce the effect of change in external resistances, the internal resistance of the mV should be as high as possible. (about 600 ohms). Then mV is calibrated by taking certain fixed value of external resistance. Now, the error caused by change in external resistance is negligible or it can be compensated.

(ii) Change in ambient temperature may change the internal resistance of the galvanometer, that affects the calibration. This error is avoided by using Manganin resistor which has small TCR.

(iii) Ambient temperature changes cause change in reference junction temperature that results in serious error in the measuring junction temperature. The magnitude of error is proportional to the change in emf caused by change in reference junction temperature. It is very troublesome to maintain the reference junction at 0°C, hence it is usually maintained at room temperature of 24°C and the millivoltmeter is compensated for any changes in this temperature.

(iv) Since thermocouple emfs are of low level type, precautions must be taken against stray currents resulting from proximity to electrical wiring. To avoid this, best practice is never to run thermocouple wire in the same conduit with electric power wires.

Reference junction temperature compensation :

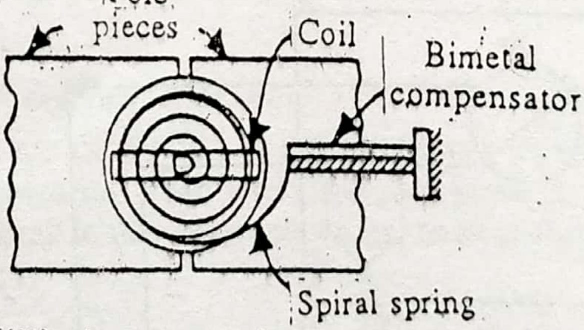


Fig. 3.14 : Millivoltmeter reference junction compensation

Fig. 3.14 shows millivoltmeter reference junction temperature compensation in which a bimetal strip is fixed so that it can adjust the position of fixed end of one of the hairsprings connected to the coil. If bimetal strip is not used, then as reference junction temperature changes, thermo–emf developed changes, that results in change in millivoltmeter deflection. The bimetallic strip expands or contracts with the change in reference–junction temperature in such a fashion that it cancels the pointer deflection that might occur due to change in reference–junction temperature. Thus pointer deflection is proportional to the difference between measuring junction temperature and the reference junction temperature at which the millivoltmeter is calibrated.

III. Calibration : A thermocouple is calibrated by comparing its performance with a standard thermometer when both are dipped in same bath under same conditions. The standard thermometer may be another thermocouple or RTD or mercury thermometer. Above 800°C thermocouple is calibrated by comparing the performance with an optical pyrometer.

IV. Performance characteristics :

A. Static characteristics :

1. Accuracy : The accuracy of the millivoltmeter and a standard iron-constantan thermocouple is ± 1.5% of full scale.

The sources of error in thermocouple reading –

(a) *Depth of immersion :* If thermocouple measuring junction and well is not immersed into the bath at sufficient depth, heat conduction takes places along the thermocouple wires or thermal well, that results in decreased temperature reading.

(b) *Rddiation effect :* Radiation errors occur while measuring high air or gas temperatures. At temperatures above 538°C, thermocouples receive most of the heat by radiation from the surrounding. But when thermocouple is used for furnace temperature measurement, then different parts of the furnace like heating element, furnace wall, furnace floor are at different temperatures. Hence the thermocouple reading depends upon relative amount of radiation received from each of the parts.

While measuring temperature of flowing gases radiation shield is installed around hot junction. It is essential that the hot gases flow around both the shield and the thermocouple. The velocity of the gases should be as high as possible for which venturi arrangement may be used.

2. Sensitivity : The dead zone of millivoltmeter is quite small but it depends on the friction in moving coil systems.

B. Dynamic characteristics :

The dynamic response of the thermocouple depends upon its heat-transfer characteristics, thermal well heat transfer characteristics, size of the thermocouple and well.

(a) Effect of heat transfer characteristics of thermocouple and well : When bare thermocouple is installed in a liquid, most of heat is transferred by conduction. But when bare thermocouple is installed in a gas at temperature less than 200°C, most of the heat is transferred by conduction, some by convection and very little by radiation. For temperatures between 200 to 530°C heat is transferred by all 3 modes, while at temperature above 530°C heat is mostly transferred by radiation, that results in fast speed of response. When a thermal well is used, air space present between the measuring junction and the well introduces time lag in heat transfer. Sometimes there is physical contact

between measuring junction and wall that improves speed of response. With few exceptions the thermocouple wire material do not affect the speed of response to great extent. Thermal capacitance of well material is important at low temperature because it decides film coefficient of resistance that in turn depends upon velocity of fluid past the thermocouple. The speed of air flow should be at least 0.6 m/s and speed of liquid flow should be at least 0.3 m/s, to get a reasonable speed of response.

(b) Effect of well material and surface - The quality of well surface decides its emissivity and greater emissivity means large amount of heat is absorbed that results in fast speed of response. For this purpose well surface should be rough instead of smooth and polished. Ceramic thermal wells have higher emissivity than smooth oxidised metal wells. Also metallic materials form an oxide scale that reduces conduction of heat through well. Thermal-well materials such as quartz, glass and Vycor transmit the radiations rather than absorbing them. Hence in such thermocouples speed of response is very fast and well material has very little effect on the speed of response.

(c) Effect of thermocouple and well size - As size of the thermocouple measuring junction increases, its thermal capacity increases that results in slow speed of response, cast materials like Nichrome, Chromel, Iron have thicker walls and slower response than machined wells of Inconel, steel and iron. Heavier thermal wells with thick walls have slow speed of response but they have better resistance to corrosion. *Hence while selecting thermal well material, there must be good compromise between speed of response and corrosion resistance.* Frequent replacement of corroded light construction wells becomes more economical than using heavier walls.

V. Advantages, Limitations and Applications :

Advantages :

(a) Rugged, inexpensive construction.

(b) Simpler to use and take the readings.

(c) Indicating instrument is compact like millivoltmeter as compared to Wheatstone bridge for RTD.

(d) Wide temperature range from –270° to 2800°C.

(e) The output is in electrical form that is suitable for indicating and controlling devices.

(f) Good accuracy and reproducibility.

(g) Electrical output can be transmitted over longer distance, hence sensing and indicating elements can be far away from each other.

(h) No danger of contaminating the process by filling fluid.

Limitations :

(a) Not suitable for spans less than 33°C.

(b) The reference junction must be maintained at constant temperature and compensation arrangements should be made.

(c) Non–linear temperature emf relationship.

(d) Temperature gradients must be avoided.

(e) Not as simple as direct reading thermometre.

(f) They can't be used bare in conducting fluid.

Applications : The thermocouple types suitable for various environments are listed below :

Thermo-couple type	+ ve wire	– ve wire	Suitable atomosphere (advantage)
B	Pt – 70 – Rh 30	Pt-94 – Rh 6	Inert or slow oxidizing
E	Chromel	Constantan	Oxidizing
J	Iron	Constantan	Reducing
K	Chromel	Alumel	Oxidizing
R	Pt – 87 – Rh 13	Pt	Oxidizing (fast response)
S	Pt – 90 – Rh 10	Pt	Oxidizing
T	Copper	Constantan	Oxidizing or reducing (Good corrosion resistance)
Y	Iron	Constantan	Reducing
–	Tungsten	W – 74 – Re 26	Inert or vacuum (high temperature)

(i) Average Temperature Measurement

Parallel combinatio

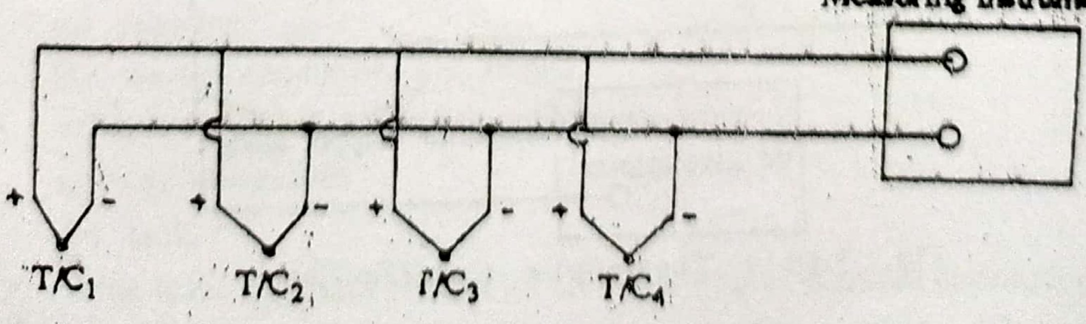


Fig. 3.15 : Average temperature measurement

(ii) Temperature difference measurement :

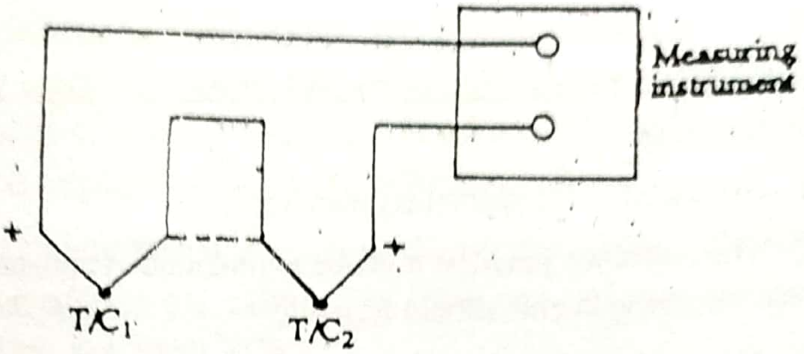


Fig. 3.16 : Temperature difference measurement

(iii) Parallel operation from common thermocouple :

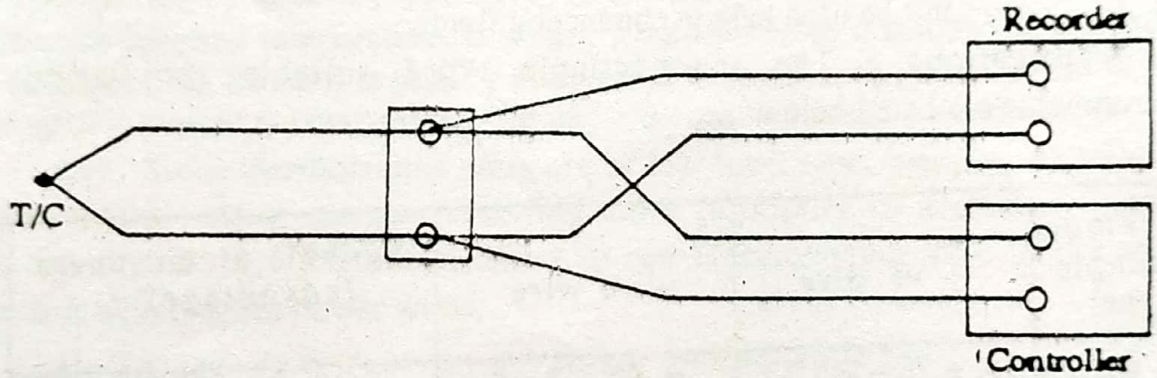


Fig. 3.17 : Parallel operation

(iv) Thermopiles : These are thermocouples connected in series with electrically insulated junction as shown in figure 3.18. Thermopilses generate large emfs thus reducing sensitivity requirements in the indicating millivoltmeter. The principal objections to the use of thermopiles are the necessity for electrical isolation of individual thermocouples and error due to short circuit of one of the thermocouples which might go unnoticed.

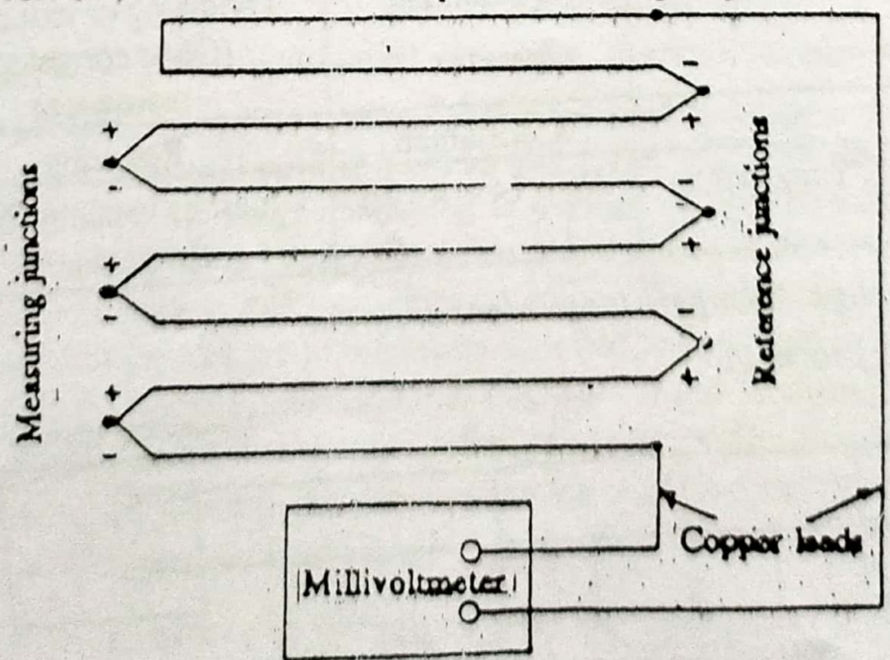


Fig. 3.18 : Thermopile Construction

THERMOCOUPLE SELECTION

While selecting a thermocouple type for temperature measurement, one should consider temperature range, sensitivity and accuracy required. The selection procedure for different components is described below:

1. Thermocouple wire size : For getting higher sensitivity smaller diameter wires are to be used but they are mechanically weak. For higher temperature measurement heavier wires are used.

2. Thermocouple length : If the thermocouple is not inserted to the sufficient depth in hot bath, then thermocouple reading shows an error called as immersion error. To avoid this, thermocouple length should be such that the tip of the thermocouple is in most turbulent region, that avoids any formation of film on well surface. In case of cylindrical pipes it is better to locate the thermocouple tip at the pipe centre while in case of tanks length should be nearly equal to ten times the diameter of thermowell.

3. Well material : Following are the well materials alongwith their temperature limits. Carbon steel (540°C) cast iron (700°C), stainless steel (980°C) Inconnel (Cr 14% + Ni 80%) (above 980°C), Ceramic tubes (upto 1650°C).

4. Lead wire material and size : Lead wires are of larger diameter than thermocouple wires so as to reduce their resistivity. Lead wire material should be, as far as possible, same as that of the thermocouple wire material, otherwise both the materials should have matching thermoelectric properties. This reduces error due to change in ambient temperature.

5. Single or duplex thermocouple : It is not recommended to split the thermocouple connections for two different devices like say recorder and controller. For this purpose duplex element is used that consists of two independent thermocouples housed in same thermal well.

USE OF THERMOCOUPLE TABLES :

All thermocouple tables showing the values of emf for various measuring junction temperatures are based upon a reference junction temperature of 0° C. Therefore direct conversion of emf reading into temperature can be made only when ice bath (at 0 °C) is used at the reference junction. If it is not possible to maintain the reference junction temperature at 0° C, a correction factor must be applied to the millivolt values given in the thermocouple tables. Note that thermocouple emf generated is decreased with decrease in temperature difference between the measuring and reference junctions. Hence emf correction is applied as follows :

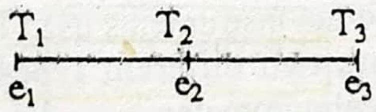
A. Converting emf (mV) obtained to equivalent temperature : (with reference junction at (say) room temperature of 25° C).

(i) From the thermocouple table for the thermocouple used, obtain the emf e_{ref} corresponding to the actual temperature of measuring junction (room temperature of 25° C).

(ii) The value obtained in step (i) is added algebraically to the emf reading obtained on millivoltmeter that gives the corrected emf.

$$e_{corrected} = e_{actual} + e_{ref}$$

(iii) Using the same thermocouple table, the temperature corresponding to corrected emf is obtained. This might require *interpolation* between two printed values in the tables. This is done by adding algebraically to the smaller value a proportionate part of the difference between two printed values.



$$\frac{T_3 - T_1}{T_2 - T_1} = \frac{e_3 - e_1}{e_2 - e_1}$$

$$e_2 = e_1 + \left(\frac{T_2 - T_1}{T_3 - T_1}\right)(e_3 - e_1)$$

B. Converting measuring junction temperature to equivalent emf : For checking the calibration of instrument it is necessary to check the emf obtained for certain hot junction temperature. For this proceed as follows :

(i) From the thermocouple table for the thermocouple used, obtain the emf e_{ref} corresponding to actual temperature (say room temperature) at the input terminals of the instrument to be checked, which is based upon 0° C reference junction temperature.

(ii) From the same table, obtain the emf e_T based upon 0° C reference junction for the temperature to be checked.

(iii) Subtract algebraically the value obtained in step (i), above, from the value obtained in step (ii) that gives corrected emf,

$$e_{corrected} = e_T - e_{ref}$$