

# Module 2

# Measurement Systems

Lesson

4

Temperature  
Measurement

## Instructional Objective

The reader, after going through the lesson would be able to

1. Name different methods for temperature measurement
2. Distinguish between the principles of operation of RTD and thermistor
3. Explain the meaning of *lead wire compensation* of RTD
4. Differentiate characteristics of a PTC thermistor from a NTC thermistor
5. Select the proper thermocouple for a particular temperature range
6. Design simple *cold junction compensation* schemes for thermocouples.

### 1. Introduction

The word *temper* was used in the seventeenth century to describe the quality of steel. It seems, after the invention of crude form of thermometer, the word *temperature* was coined to describe the degree of hotness or coolness of a material body. It was the beginning of seventeenth century when the thermometer – a temperature measuring instrument was first developed. Galileo Galilei is credited with the construction of first thermometer, although a Dutch scientist Drebbel also made similar instrument independently. The principle was simple. A bulb containing air with long vertical tube was inverted and dipped into a basin of water or coloured liquid. With the change in temperature of the bulb, the gas inside expanded or contracted, thus changing the level of the liquid column inside the vertical tube. A major drawback of the instrument was that it was sensitive not only to variation of temperature, but also to atmospheric pressure variation.

Successive developments of thermometers came out throughout seventeenth and eighteenth century. The liquid thermometer was developed during this time. The importance of two reference fixed temperatures was felt while graduating the temperature scales. Boiling point of water and melting point of ice provided two easily available references. But some other references were also tried. Fahrenheit developed a thermometer where, it seems, temperature of ice and salt mixture was taken as  $0^{\circ}$  and temperature of human body as  $96^{\circ}$ . These two formed the reference points, with which, the temperature of melting ice came as  $32^{\circ}$  and that of boiling water as  $212^{\circ}$ . In Celsius scale, the melting point of ice was chosen as  $0^{\circ}$  and boiling point of water as  $100^{\circ}$ . The concept of Kelvin scale came afterwards, where the absolute temperature of gas was taken as  $0^{\circ}$  and freezing point of water as  $273^{\circ}$ .

The purpose of early thermometers was to measure the variation of atmospheric or body temperatures. With the advancement of science and technology, now we require temperature measurement over a wide range and different atmospheric conditions, and that too with high accuracy and precision. To cater these varied requirements, temperature sensors based on different principles have been developed. They can be broadly classified in the following groups:

1. Liquid and gas thermometer
2. Bimetallic strip
3. Resistance thermometers (RTD and Thermistors)
4. Thermocouple

5. Junction semiconductor sensor
6. Radiation pyrometer

Within the limited scope of this course, we shall discuss few of the above mentioned temperature sensors, that are useful for measurement in industrial environment.

## 2. Resistance Thermometers

It is well known that resistance of metallic conductors increases with temperature, while that of semiconductors generally decreases with temperature. Resistance thermometers employing metallic conductors for temperature measurement are called *Resistance Temperature Detector (RTD)*, and those employing semiconductors are termed as *Thermistors*. RTDs are more rugged and have more or less linear characteristics over a wide temperature range. On the other hand Thermistors have high temperature sensitivity, but nonlinear characteristics.

### Resistance Temperature Detector

The variation of resistance of metals with temperature is normally modeled in the form:

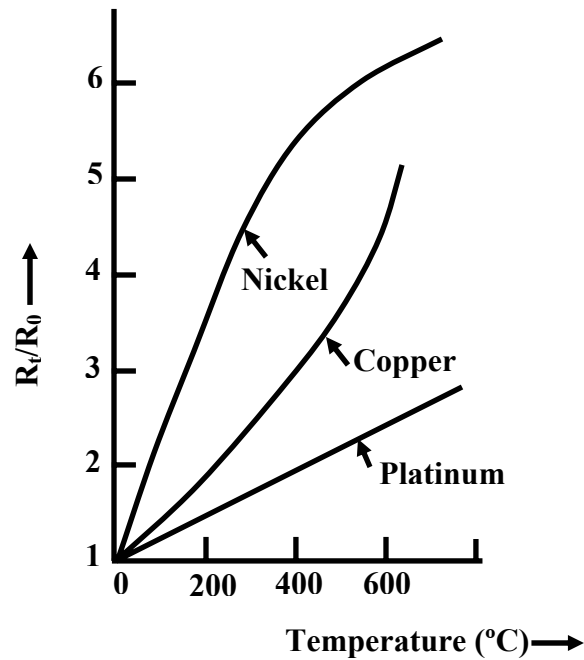
$$R_t = R_0[1 + \alpha(t - t_0) + \beta(t - t_0)^2 + \dots] \quad (1)$$

where  $R_t$  and  $R_0$  are the resistance values at  $t^\circ\text{C}$  and  $t_0^\circ\text{C}$  respectively;  $\alpha$ ,  $\beta$ , etc. are constants that depends on the metal. For a small range of temperature, the expression can be approximated as:

$$R_t = R_0[1 + \alpha(t - t_0)] \quad (2)$$

For Copper,  $\alpha = 0.00427/^\circ\text{C}$ .

Copper, Nickel and Platinum are mostly used as RTD materials. The range of temperature measurement is decided by the region, where the resistance-temperature characteristics are approximately linear. The resistance versus temperature characteristics of these materials is shown in fig.1, with  $t_0$  as  $0^\circ\text{C}$ . Platinum has a linear range of operation upto  $650^\circ\text{C}$ , while the useful range for Copper and Nickel are  $120^\circ\text{C}$  and  $300^\circ\text{C}$  respectively.



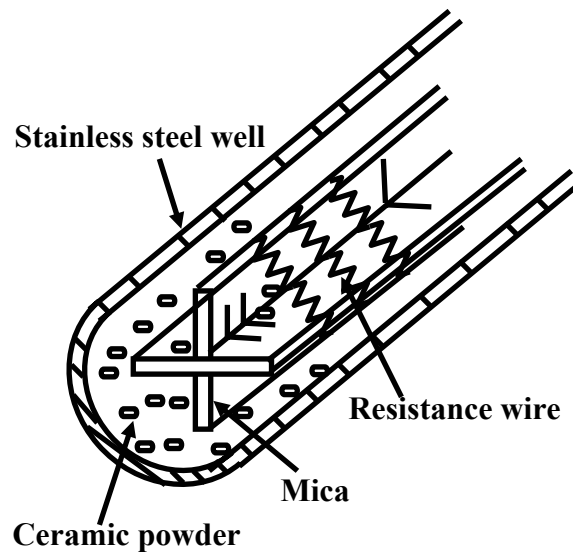
**Fig. 1 Resistance-temperature characteristics of metals**

## Construction

For industrial use, bare metal wires cannot be used for temperature measurement. They must be protected from mechanical hazards such as material decomposition, tearing and other physical damages. The salient features of construction of an industrial RTD are as follows:

- The resistance wire is often put in a stainless steel well for protection against mechanical hazards. This is also useful from the point of view of maintenance, since a defective sensor can be replaced by a good one while the plant is in operation.
- Heat conducting but electrical insulating materials like mica is placed in between the well and the resistance material.
- The resistance wire should be carefully wound over mica sheet so that no strain is developed due to length expansion of the wire.

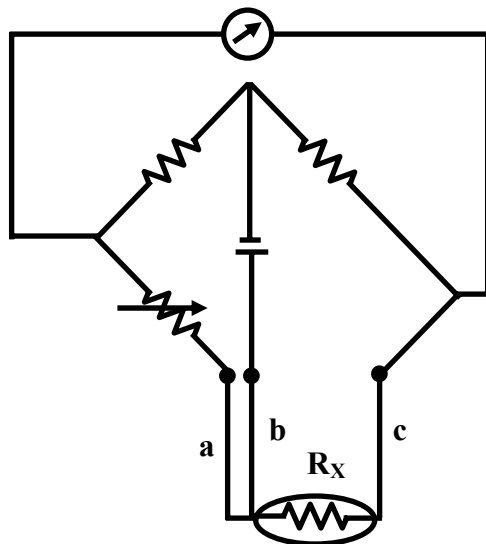
Fig. 2 shows the cut away view of an industrial RTD.



**Fig. 2 Construction of an industrial RTD**

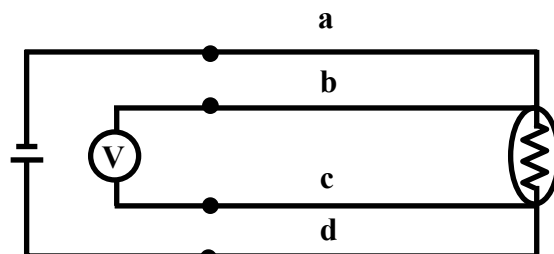
## Signal conditioning

The resistance variation of the RTD can be measured by a bridge, or directly by volt-ampere method. But the major constraint is the contribution of the lead wires in the overall resistance measured. Since the length of the lead wire may vary, this may give a false reading in the temperature to be measured. There must be some method for compensation so that the effect of lead wires is resistance measured is eliminated. This can be achieved by using either a *three wire RTD*, or a *four wire RTD*. Both the schemes of measurement are shown in fig. 3. In three wire method one additional dummy wire taken from the resistance element and connected in a bridge (fig. 3(a)) so that the two lead wires are connected to two adjacent arms of the bridge, thus canceling each other's effect. In fig. 3(b) the four wire method of measurement is shown. It is similar to a four terminal resistance and two terminals are used for injecting current, while two others are for measuring voltage.



**a. b. c: lead wires**

**Fig. 3(a) Three wire RTD**



**a. b. c: lead wires**

**Fig. 3(b) Four wire RTD**

## Thermistor

Thermistors are semiconductor type resistance thermometers. They have very high sensitivity but highly nonlinear characteristics. This can be understood from the fact that for a typical  $2000\ \Omega$  the resistance change at  $25^\circ\text{C}$  is  $80\ \Omega/^\circ\text{C}$ , whereas for a  $2000\ \Omega$  platinum RTD the change in resistance at  $25^\circ\text{C}$  is  $7\ \Omega/^\circ\text{C}$ . Thermistors can be of two types: (a) Negative temperature co-efficient (NTC) thermistors and (b) Positive temperature co-efficient (PTC) thermistors. Their resistance-temperature characteristics are shown in fig. 4(a) and 4(b) respectively.

The NTC thermistors, whose characteristics are shown in fig. 4(a) is more common. Essentially, they are made from oxides of iron, manganese, magnesium etc. Their characteristics can be expressed as:

$$R_T = R_0 e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)} \quad (3)$$

where,

$R_T$  is the resistance at temperature  $T$  (K)

$R_0$  is the resistance at temperature  $T_0$  (K)

$T_0$  is the reference temperature, normally  $25^\circ\text{C}$

$\beta$  is a constant, its value is decided by the characteristics of the material, the nominal value is taken as 4000.

From (3), the resistance temperature co-efficient can be obtained as:

$$\alpha_T = \frac{1}{R_T} \frac{dR_T}{dT} = -\frac{\beta}{T^2} \quad (4)$$

It is clear from the above expression that the negative sign of  $\alpha_T$  indicates the negative resistance-temperature characteristics of the NTC thermistor.

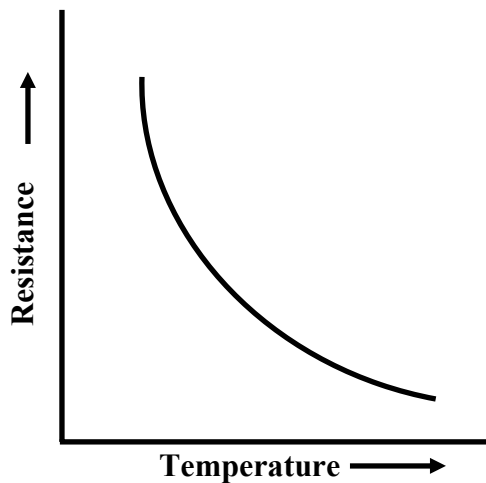


Fig. 4(a) Characteristics of a NTC thermistor

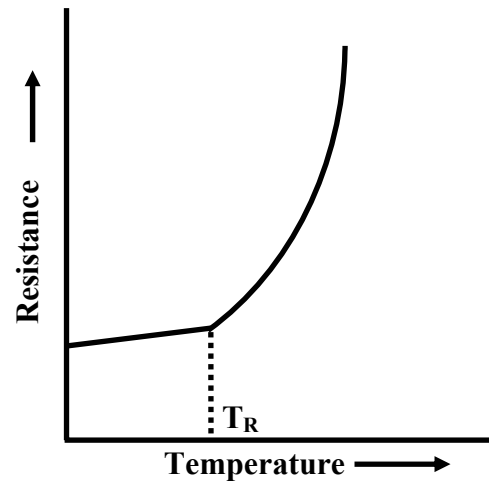


Fig. 4(b) Characteristics of a PTC thermistor

Useful range of themistors is normally  $-100$  to  $+300^\circ\text{C}$ . A single thermistor is not suitable for the whole range of measurement. Moreover, existing thermistors are not interchangeable. There is a marked spread in nominal resistance and the temperature coefficient between two thermistors of same type. So, if a defective thermistor is to be replaced by a new thermistor similar type, a fresh

calibration has to be carried out before use. Commercially available thermistors have nominal values of 1K, 2K, 10K, 20K, 100K etc. The nominal values indicate the resistance value at 25°C. Thermistors are available in different forms: bead type, rod type disc type etc. The small size of the sensing element makes it suitable for measurement of temperature at a point. The time constant is also very small due to the small thermal mass involved.

The nonlinear negative temperature characteristics also give rise to error due to *self-heating effect*. When current is flowing through the thermistor, the heat generated due to the  $I^2R$ -loss may increase the temperature of the resistance element, which may further decrease the resistance and increase the current further. This effect, if not tackled properly, may damage the thermistor permanently. Essentially, the current flowing should be restricted below the specified value to prevent this damage. Alternatively, the thermistor may be excited by a constant current source.

The nonlinear characteristics of thermistors often creates problem for temperature measurement, and it is often desired to linearise the thermistor characteristics. This can be done by adding one fixed resistance parallel to the thermistor. The resistance temperature characteristics of the equivalent resistance would be more linear, but at the cost of sensitivity.

The Positive Temperature Coefficient (PTC) thermistor have limited use and they are particularly used for protection of motor and transformer windings. As shown in fig. 4(b), they have low and relatively constant resistance below a threshold temperature  $T_R$ , beyond which the resistance increases rapidly. The PTC thermistors are made from compound of barium, lead and strontium titanate.

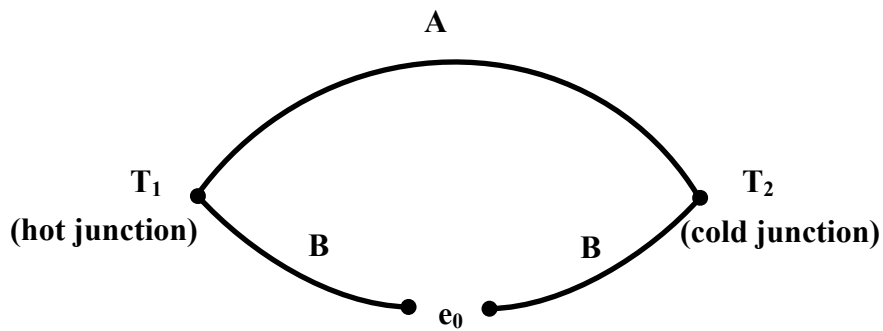
### 3. Thermocouple

Thomas Johan Seebeck discovered in 1821 that thermal energy can produce electric current. When two conductors made from dissimilar metals are connected forming two common junctions and the two junctions are exposed to two different temperatures, a net thermal emf is produced, the actual value being dependent on the materials used and the temperature difference between hot and cold junctions. The thermoelectric emf generated, in fact is due to the combination of two effects: *Peltier effect* and *Thomson effect*. A typical thermocouple junction is shown in fig. 5. The emf generated can be approximately expressed by the relationship:

$$e_0 = C_1(T_1 - T_2) + C_2(T_1^2 - T_2^2) \mu\text{v} \quad (5)$$

where  $T_1$  and  $T_2$  are hot and cold junction temperatures in K.  $C_1$  and  $C_2$  are constants depending upon the materials. For Copper/ Constantan thermocouple,  $C_1=62.1$  and  $C_2=0.045$ .





**Fig. 5 A typical thermocouple**

Thermocouples are extensively used for measurement of temperature in industrial situations. The major reasons behind their popularity are: (i) they are rugged and readings are consistent, (ii) they can measure over a wide range of temperature, and (iii) their characteristics are almost linear with an accuracy of about  $\pm 0.05\%$ . However, the major shortcoming of thermocouples is low sensitivity compared to other temperature measuring devices (e.g. RTD, Thermistor).

## Thermocouple Materials

Theoretically, any pair of dissimilar materials can be used as a thermocouple. But in practice, only few materials have found applications for temperature measurement. The choice of materials is influenced by several factors, namely, sensitivity, stability in calibration, inertness in the operating atmosphere and reproducibility (i.e. the thermocouple can be replaced by a similar one without any recalibration). Table-I shows the common types of thermocouples, their types, composition, range, sensitivity etc. The upper range of the thermocouple is normally dependent on the atmosphere where it has been put. For example, the upper range of Chromel/ Alumel thermocouple can be increased in oxidizing atmosphere, while the upper range of Iron/ Constantan thermocouple can be increased in reducing atmosphere.

**Table-1 Thermocouple materials and Characteristics**

Type	Positive lead	Negative lead	Temperature range	Temperature coeff. variation $\mu\text{v}/^\circ\text{C}$	Most linear range and sensitivity in the range
R	Platinum-Rhodium (87% Pt, 13% Rh)	Platinum	0-1500 $^\circ\text{C}$	5.25-14.1	1100-1500 $^\circ\text{C}$ 13.6-14.1 $\mu\text{v}/^\circ\text{C}$
S	Platinum-Rhodium (90% Pt, 10% Rh)	Platinum	0-1500 $^\circ\text{C}$	5.4-12.2	1100-1500 $^\circ\text{C}$ 13.6-14.1 $\mu\text{v}/^\circ\text{C}$
K	Chromel (90%Ni, 10% Cr)	Alumel (Ni <sub>94</sub> Al <sub>2</sub> Mn <sub>3</sub> Si)	-200-1300 $^\circ\text{C}$	15.2-42.6	0-1000 $^\circ\text{C}$ 38-42.9 $\mu\text{v}/^\circ\text{C}$

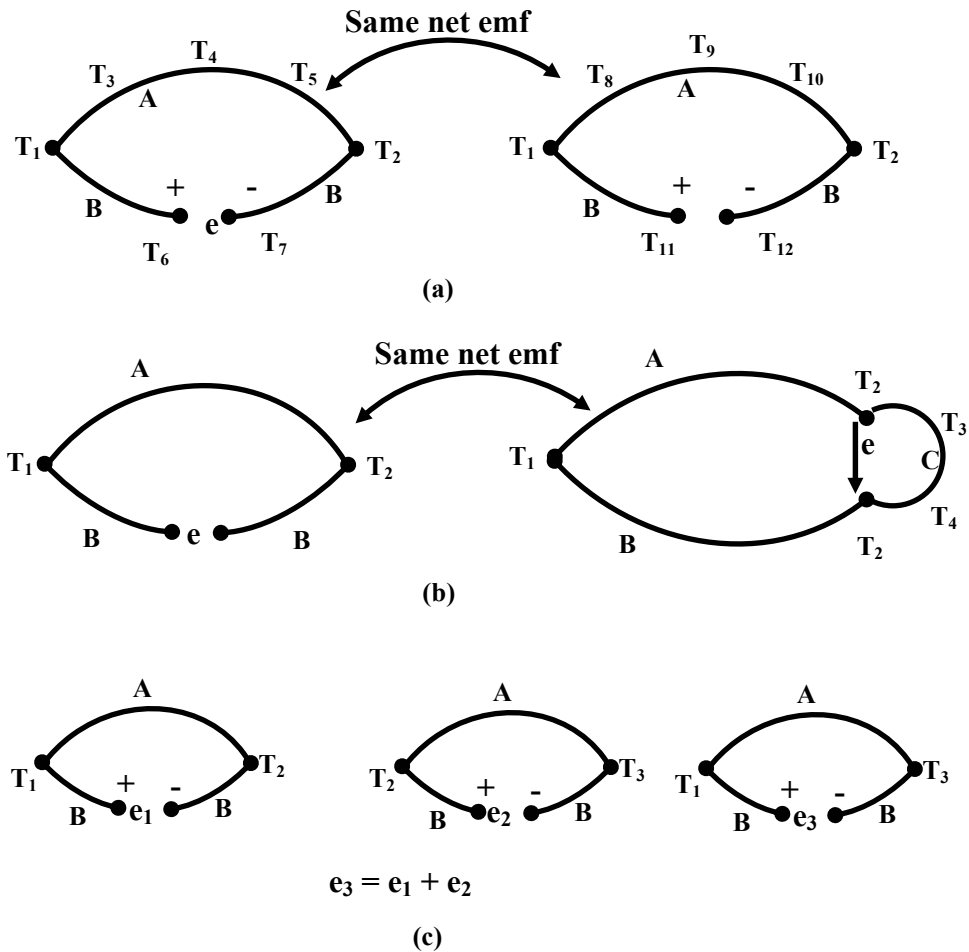
E	Chromel	Constantan (57%Cu, 43%Ni)	-200-1000°C	25.1-80.8	300-800 °C 77.9-80.8 μv/°C
T	Copper	Constantan	-200-350°C	15.8-61.8	nonlinear
J	Iron	Constantan	-150-750°C	21.8-64.6	100-500 °C 54.4-55.9

## Laws of Thermocouple

The Peltier and Thompson effects explain the basic principles of thermoelectric emf generation. But they are not sufficient for providing a suitable measuring technique at actual measuring situations. For this purpose, we have three laws of thermoelectric circuits that provide us useful practical tips for measurement of temperature. These laws are known as *law of homogeneous circuit*, *law of intermediate metals* and *law of intermediate temperatures*. These laws can be explained using fig. 6.

The first law can be explained using fig. 6(a). It says that the net thermo-emf generated is dependent on the materials and the temperatures of two junctions only, not on any intermediate temperature.

According to the second law, if a third material is introduced at any point (thus forming two additional junctions) it will not have any effect, if these two additional junctions remain at the same temperatures (fig. 6(b)). This law makes it possible to insert a measuring device without altering the thermo-emf.



**Fig. 6 Laws of Thermocouple**

The third law is related to the calibration of the thermocouple. It says, if a thermocouple produces emf  $e_1$ , when its junctions are at  $T_1$  and  $T_2$ , and  $e_2$  when its junctions are at  $T_2$  and  $T_3$ ; then it will generate emf  $e_1+e_2$  when the junction temperatures are at  $T_1$  and  $T_3$  (fig. 6(c)).

The third law is particularly important from the point of view of reference junction compensation. The calibration chart of a thermocouple is prepared taking the cold or reference junction temperature as  $0^\circ\text{C}$ . But in actual measuring situation, seldom the reference junction temperature is kept at that temperature, it is normally kept at ambient temperature. The third law helps us to compute the actual temperature using the calibration chart. This can be explained from the following example.

### Example-1

The following table has been prepared from the calibration chart of *iron-constantan* thermocouple, with reference temperature at  $0^\circ\text{C}$ .

Temperature (°C)	15	30	40	.....	180	190	200	208	210
emf (mv)	0.778	1.56	2.11	.....	9.64	10.25	10.74	11.20	11.32

Suppose, the temperature of the hot junction is measured with a *iron-constantan* thermocouple, with the reference junction temperature at 30°C. If the voltage measured is 9.64mv, find the actual temperature of the hot junction.

## Solution

Referring fig. 6(c), for this problem,  $T_1$  is the unknown temperature,  $T_2= 30^\circ\text{C}$ ,  $T_3= 0^\circ\text{C}$ . The voltages are  $e_1=9.64\text{mv}$  (measured) and  $e_2= 1.56\text{mv}$  (from chart). Therefore,  $e_3= e_1+e_2= 11.20\text{mv}$ . Hence, from the calibration chart, the actual hot junction temperature is  $T_1 = 208^\circ\text{C}$ .

## Reference Junction Compensation

From above discussions, it is imminent that the thermocouple output voltage will vary if the reference junction temperature changes. So, for measurement of temperature, it is desirable that the cold junction of the thermocouple should be maintained at a constant temperature. Ice bath can be used for this purpose, but it is not practical solution for industrial situation. An alternative is to use a thermostatically controlled constant temperature oven. In this case, a fixed voltage must be added to the voltage generated by the thermocouple, to obtain the actual temperature. But the most common case is where the reference junction is placed at ambient temperature. For high temperature measurement, the error introduced due to variation of reference junction temperature is not appreciable. For example, with a thermocouple measuring  $1500^\circ\text{C}$ , if the ambient temperature variation is within  $25 \pm 15^\circ\text{C}$ , then the error introduced in the reading due to this variation would be around 1%. Such a typical scheme is shown in fig. 7. Here a constant voltage corresponding to the ambient temperature is added through the offset of the op-amp. The thermocouple voltage is also amplified by the same op-amp.

A more accurate method for reference junction temperature compensation is shown in fig. 8. Here a thermistor, or a RTD is used to measure the ambient temperature and compensate the error through a bridge circuit. The bridge circuit is balanced at  $0^\circ\text{C}$ . When the ambient temperature goes above  $0^\circ\text{C}$ , the emf generated in the thermocouple is reduced; at the same time bridge unbalanced voltage is added to it in order to maintain the overall voltage at the same value.

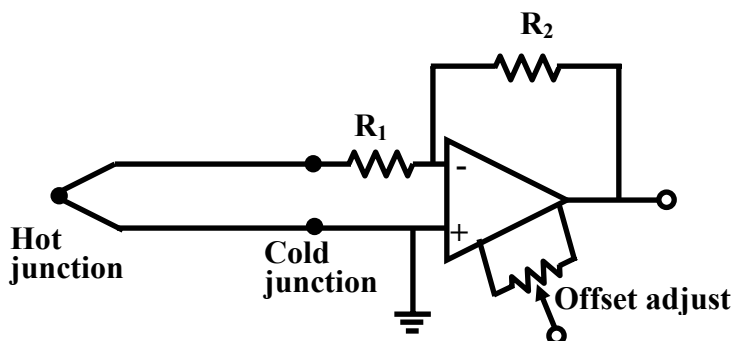
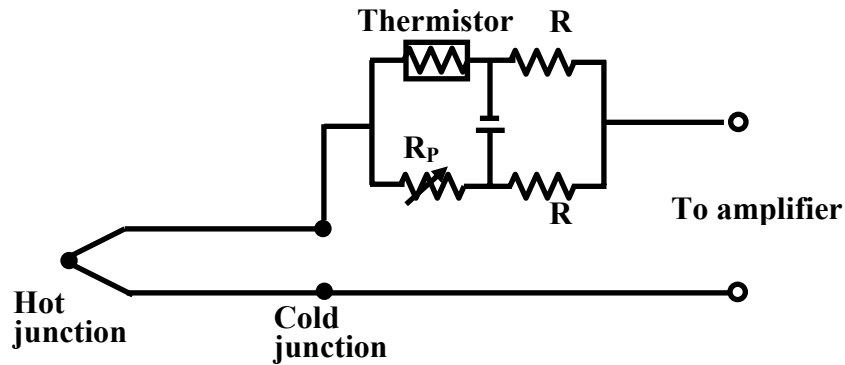


Fig.7 Simple method for reference junction compensation



**Fig. 8 Compensation scheme using wheatstone bridge**

As referred to Fig.8, the cold junction compensation is normally kept along with the signal conditioning circuits, away from the measuring point. This may require use of long thermocouple wires to the compensation circuit. In order to reduce the length of costly thermocouple wires (platinum in some case) low-cost compensating wires are normally used in between the thermocouple and the compensation circuit. These wires are so selected that their temperature emf characteristics match closely to those of the thermocouple wires around the ambient temperature.

## 4. Conclusion

Temperature is the most important process variable that requires continuous measurement and monitoring in a process industry. Among the different types of temperature transducers, the most commonly used ones are RTDs and thermocouples. Their popularity is mainly due to their ruggedness, repeatability and wide range of operation. Bare RTDs and thermocouples are rarely used in practice; instead, they are put in protective metallic sheaths. The signal conditioning circuits should be properly designed, so as to avoid the errors due to lead wires in RTDs and variation of cold junction temperatures in thermocouples. There are several cases where the temperature to be measured is more than 2000°C, the conventional measuring techniques fail to measure the high temperature. Instead, the measurement is carried out from a distance. Radiation pyrometers are used in these situations. However, its principle of operation has not been included in this lesson.

## Review Exercise

1. Name the materials commonly used for RTDs. Which one has the most linear characteristics?
2. What do you mean by lead wire compensation of RTD. How can they be achieved?
3. PT-100 is a Platinum RTD whose resistance at 0°C is 100Ω. If the resistance
4. temperature co-efficient of Platinum is  $3.91 \times 10^{-3} / ^\circ\text{C}$ , then find its resistance at 100°C.
5. What is the difference between a NTC thermistor and a PTC thermistor?
6. A thermistor is more suitable for measurement of temperature within a small range-justify.

7. Name three types thermocouples and their suitable temperature range.
8. State and explain the laws of thermocouple.
9. What do you mean by cold junction compensation of a thermocouple? Suggest two methods for compensation.
10. A thermocouple has a linear sensitivity of  $30\mu\text{v}/^\circ\text{C}$ , calibrated at a cold junction temperature of  $0^\circ\text{C}$ . It is used measure an unknown temperature with the cold junction temperature of  $30^\circ\text{C}$ . Find the actual hot junction temperature if the emf generated is 3.0 mv.

## Answers

1. Platinum, Copper, Nickel; Platinum.
3.  $139\Omega$ .
9.  $130^\circ\text{C}$ .