CHAPTER 14

# Temperature Measurement

## Chapter Outline



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## 14.1 Introduction

We are probably well aware that temperature measurement is very important in all spheres of life. In engineering applications, it is particularly important in the process industries, where it is the most commonly measured process variable. It is therefore appropriate for us to devote this first chapter on measurement of individual physical variables to the subject of temperature measurement.

Unfortunately, temperature measurement poses some interesting theoretical difficulties because of its rather abstract nature. These difficulties become especially apparent when we come to consider the calibration of temperature-measuring instruments, particularly when we look for a primary reference standard at the top of the calibration chain. Foremost among these difficulties is the fact that any given temperature cannot be related to a fundamental standard of temperature in the same way that the measurement of other quantities can be related to the primary standards of mass, length, and time. If two bodies of lengths $l_1$ and $l_2$ are connected together end to end, the result is a body of length $l_1 + l_2$. A similar relationship exists between separate masses and separate times. However, if two bodies at the same temperature are connected together, the joined body has the same temperature as each of the original bodies.

This is a root cause of the fundamental difficulties that exist in establishing an absolute standard for temperature in the form of a relationship between it and other measurable quantities for which a primary standard unit exists. In the absence of such a relationship, it is necessary to establish fixed, reproducible reference points for temperature in the form of freezing and triple points of substances where the transition between solid, liquid, and gaseous states is sharply defined. The *International Practical Temperature Scale* (IPTS)[1] uses this philosophy and defines a number of *fixed points* for reference temperatures. Three examples are as follows:

- the triple point of hydrogen: $-259.35\ ^\circ C$
- the freezing point of zinc: $419.53\ ^\circ C$
- the freezing point of gold: $1064.18\ ^\circ C$

A full list of fixed points defined in the IPTS can be found in Section 14.14.

If we start writing down the physical principles that are affected by temperature, we will get a relatively long list. Many of these physical principles form the basis for temperature-measuring instruments. It is therefore reasonable for us to study temperature measurement by dividing the instruments used to measure temperature into separate classes according to

[1] The IPTS is subject to periodic review and improvement as research produces more precise fixed reference points. The latest version was published in 1990.

the physical principle on which they operate. This will give us nine classes of instrument based on the following principles:

1. The thermoelectric effect
2. Resistance change
3. Sensitivity of semiconductor device
4. Radiative heat emission
5. Thermography
6. Thermal expansion
7. Sensitivity of fiber-optic devices
8. Color change
9. Change of state of material

We will consider each of these in the following sections. The final section in this list covers MEMS sensors, which are miniature sensors that are currently based on measuring radiative heat emission.

## 14.2 Thermoelectric Effect Sensors (Thermocouples)

Thermoelectric effect sensors rely on the physical principle that, when any two different metals are connected together, an emf, which is a function of the temperature, is generated at the junction between the metals. The general form of this relationship is:

$$e = a_1T + a_2T^2 + a_3T^3 + \cdots + a_nT^n \tag{14.1}$$

where $e$ is the emf voltage generated and $T$ is the absolute temperature.

This is clearly nonlinear, which is inconvenient for measurement applications. Fortunately, for certain pairs of materials, the terms involving squared and higher powers of $T$ ($a_2T^2$, $a_3T^3$, etc.) are approximately zero and the emf–temperature relationship is approximately linear according to:

$$e \approx a_1T \tag{14.2}$$

Wires of such pairs of materials are connected together at one end, and in this form are known as *thermocouples*. Thermocouples are a very important class of device as they provide the most commonly used method of measuring temperatures in industry.

Thermocouples are manufactured from various combinations of the base metals copper and iron; the base metal alloys of alumel (Ni/Mn/Al/Si), chromel (Ni/Cr), constantan (Cu/Ni), nicrosil (Ni/Cr/Si), nisil (Ni/Si/Mn), nickel–molybdenum, and nickel–cobalt; the noble metals platinum and tungsten; and the noble metal alloys of platinum–rhodium, tungsten–rhenium, and gold–iron. Only certain combinations of these are used as thermocouples, and most standard combinations are known by internationally recognized type letters, for example, type K is chromel–alumel. The emf–temperature characteristics for some of these standard thermocouples are shown in Figure 14.1: these show reasonable linearity over at least part of their temperature-measuring ranges.

The structure of a typical thermocouple, made from one chromel wire and one constantan wire, is shown in Figure 14.2(a). For analysis purposes, it is useful to represent the thermocouple by its equivalent electrical circuit, shown in Figure 14.2(b). The emf generated at the point where the different wires are connected together is represented by a voltage source, $E_1$, and the point is known as the *hot junction*. The temperature of the hot junction is customarily shown as $T_h$ on the diagram. The emf generated at the hot junction is measured at the open ends of the thermocouple, which is known as the *reference junction*.

In order to make a thermocouple conform to some precisely defined emf–temperature characteristic, it is necessary that all metals used are refined to a high degree of pureness and all alloys are manufactured to an exact specification. This makes the materials used expensive, and consequently thermocouples are typically only a few centimeters long. It is clearly impractical to connect a voltage-measuring instrument at the open end of the thermocouple to measure its output in such close proximity to the environment whose temperature is being measured, and therefore *extension leads* up to several meters long are

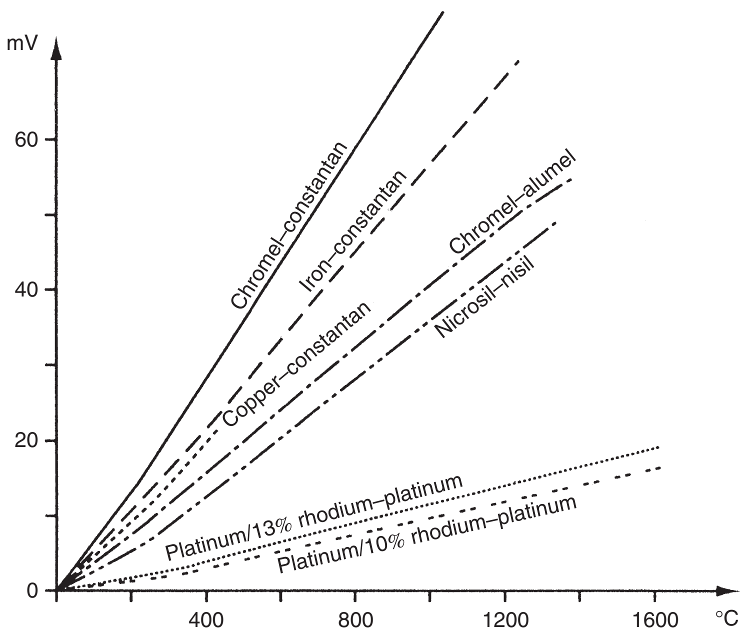


**Figure 14.1**
Emf–temperature characteristics for some standard thermocouple materials.

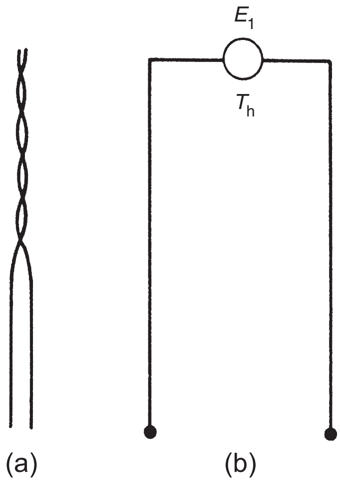


**Figure 14.2**
(a) Thermocouple and (b) equivalent circuit.

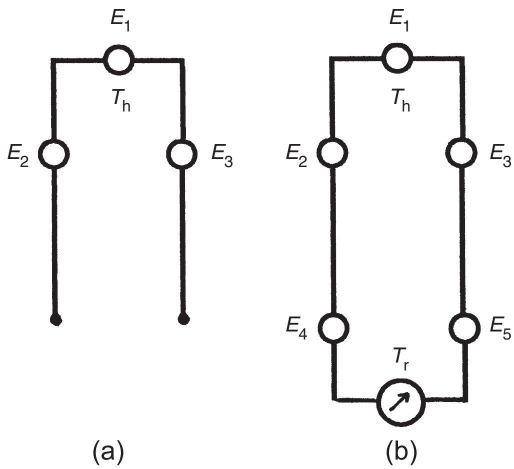


**Figure 14.3**
(a) Equivalent circuit for thermocouple with extension leads; (b) equivalent circuit for thermocouple and extension leads connected to a meter.

normally connected between the thermocouple and the measuring instrument. This modifies the equivalent circuit to that shown in Figure 14.3(a). There are now three junctions in the system and consequently three voltage sources, $E_1$, $E_2$, and $E_3$, with the point of measurement of the emf (still called the reference junction) being moved to the open ends of the extension leads.

The measuring system is completed by connecting the extension leads to the voltage-measuring instrument. As the connection leads will normally be of different materials to those of the thermocouple extension leads, this introduces two further emf-generating junctions $E_4$ and $E_5$ into the system as shown in Figure 14.3(b). The net output emf measured ($E_m$) is then given by:

$$E_m = E_1 + E_2 + E_3 + E_4 + E_5 \quad (14.3)$$

and this can be reexpressed in terms of $E_1$ as:

$$E_1 = E_m - E_2 - E_3 - E_4 - E_5 \quad (14.4)$$

In order to apply Eqn (14.1) to calculate the measured temperature at the hot junction, $E_1$ has to be calculated from Eqn (14.4). To do this, it is necessary to calculate the values of $E_2$, $E_3$, $E_4$, and $E_5$.

It is usual to choose materials for the extension lead wires such that the magnitudes of $E_2$ and $E_3$ are approximately zero, irrespective of the junction temperature. This avoids the difficulty that would otherwise arise in measuring the temperature of the junction between the thermocouple wires and the extension leads, and also in determining the emf/temperature relationship for the thermocouple/extension lead combination.

A near-zero junction voltage is most easily achieved by choosing the extension leads to be of the same basic materials as the thermocouple, but where their cost per unit length is greatly reduced by manufacturing them to a lower specification. As an alternative to using lower specification materials of the same basic type as the thermocouple, copper compensating leads are also sometimes used with certain types of base metal thermocouples. In this case, the law of intermediate metals has to be applied to compensate for the emf at the junction between the thermocouple and compensating leads.

Unfortunately, the use of extension leads of the same basic materials as the thermocouple but manufactured to a lower specification is still prohibitively expensive in the case of noble metal thermocouples. It is necessary in this case to search for base metal extension leads that have a similar thermoelectric behavior to the noble metal thermocouple. In this form, the extension leads are usually known as *compensating leads*. A typical example of this is the use of nickel/copper—copper extension leads connected to a platinum/rhodium—platinum thermocouple. It should be noted that the approximately equivalent thermoelectric behavior of compensating leads is only valid for a limited range of temperatures that is considerably less than the measuring range of the thermocouple that they are connected to.

To analyze the effect of connecting the extension leads to the voltage-measuring instrument, a thermoelectric law known as the *law of intermediate metals* can be used. This states that the emf generated at the junction between two metals or alloys *A* and *C* is equal to the sum of the emf generated at the junction between metals or alloys *A* and *B* and the emf generated at the junction between metals or alloys $B$ and $C$, where all junctions are at the same temperature. This can be expressed more simply as:

$$e_{AC} = e_{AB} + e_{BC} \tag{14.5}$$

Suppose we have an iron–constantan thermocouple connected by copper leads to a meter. We can express $E_4$ and $E_5$ in Figure 14.4 as:

$$E_4 = e_{\text{iron-copper}}; \quad E_5 = e_{\text{copper-constantan}}$$

The sum of $E_4$ and $E_5$ can be expressed as: $E_4 + E_5 = e_{\text{iron-copper}} + e_{\text{copper-constantan}}$

Applying Eqn (14.5): $e_{\text{iron-copper}} + e_{\text{copper-constantan}} = e_{\text{iron-constantan}}$

Thus, the effect of the connecting the thermocouple extension wires to the copper leads to the meter is canceled out, and the actual emf at the reference junction is equivalent to that arising from an iron–constantan connection at the reference junction temperature, which can be calculated according to Eqn (14.1). Hence, the equivalent circuit in Figure 14.3(b) becomes simplified to that shown in Figure 14.4. The emf $E_m$ measured by the voltage-measuring instrument is the sum of only two emfs, consisting of the emf generated at the hot junction temperature $E_1$ and the emf generated at the reference junction temperature $E_{\text{ref}}$. The emf generated at the hot junction can then be calculated as:

$$E_1 = E_m + E_{\text{ref}}$$

$E_{\text{ref}}$ can be calculated from Eqn (14.1) if the temperature of the reference junction is known. In practice, this is often achieved by immersing the reference junction in an ice bath to maintain it at a reference temperature of 0 °C. However, as discussed in the following section on thermocouple tables, it is very important that the ice bath remains exactly at 0 °C if this is to be the reference temperature assumed, otherwise significant

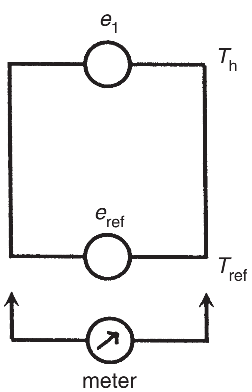


**Figure 14.4**
Effective emf sources in a thermocouple measurement system.

measurement errors can arise. For this reason, refrigeration of the reference junction at a temperature of 0 °C is often preferred.

### 14.2.1 Thermocouple Tables

Although the preceding discussion has suggested that the unknown temperature $T$ can be evaluated from the calculated value of the emf $E_1$ at the hot junction using Eqn (14.1), this is very difficult to do in practice because Eqn (14.1) is a high-order polynomial expression. An approximate translation between the value of $E_1$ and temperature can be achieved by expressing Eqn (14.1) in graphical form as in Figure 14.1. However, this is not usually of sufficient accuracy, and it is normal practice to use tables of emf and temperature values known as *thermocouple tables*. These include compensation for the effect of the emf generated at the reference junction ($E_{ref}$), which is assumed to be at 0 °C. Thus, the tables are only valid when the reference junction is exactly at this temperature. Compensation for the case where the reference junction temperature is not at zero is considered later in this section.

In Appendix 3, tables for a range of standard thermocouples are given.[2] In these tables, a range of temperatures is given in the left hand column and the emf output for each standard type of thermocouple is given in the columns to the right. In practice, any general emf output measurement taken at random will not be found exactly in the tables, and interpolation will be necessary between the values shown in the table. This is illustrated by Example 14.2.

#### Example 14.1

If the emf output measured from a chromel–constantan thermocouple is 13.419 mV with the reference junction at 0 °C, the appropriate column in the tables shows that this corresponds to a hot junction temperature of 200 °C.

■

#### Example 14.2

Suppose that the measured output emf for a chromel–constantan thermocouple (reference junction at 0 °C) is 10.72 mV. Looking at the table for a chromel–constantan

[2] The tables given in Appendix 3 are computed according to the standard thermocouple equations corresponding to the reference fixed-point temperatures given in the 1990 International Practical Temperature scale. However, since thermocouples available from manufacturers can sometimes differ slightly in the chemical composition of alloys and the purity of metals, it is always preferable to use thermocouple tables supplied in manufacturers' data sheets rather than rely on tables published elsewhere.

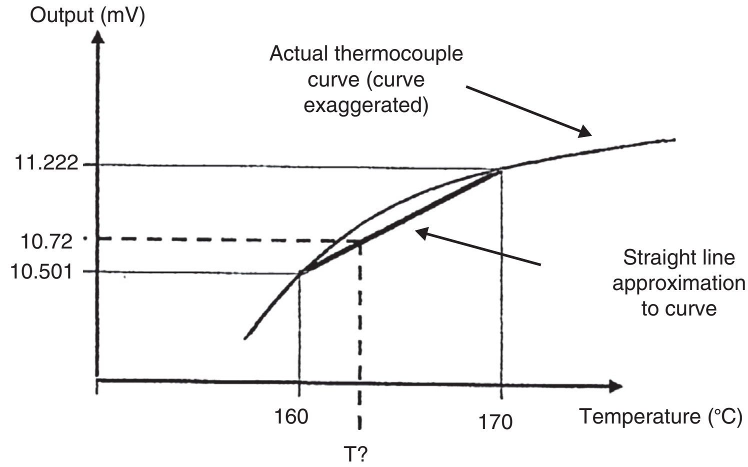


**Figure 14.5**
Procedure of interpolation between data points of a thermocouple table.

thermocouple, the value of 10.72 mV does not appear in the table. The closest emf values in the table are 10.501 mV corresponding to a temperature of 160 °C and 11.222 mV corresponding to a temperature of 170 °C. It is necessary to carry out interpolation between these values in order to determine the temperature corresponding to the emf value of 10.72 mV.

The situation is illustrated in Figure 14.5. The relationship between the thermocouple output voltage and temperature is a curve (curvature exaggerated in the figure), and the exact temperature corresponding to an output of 10.72 mV would be determined by drawing a horizontal line through the 10.72 point on the vertical axis as far as the thermocouple curve and then drawing a vertical line down from the point of intersection with the curve down to the horizontal axis, where the point of intersection would indicate the temperature. In practice, we cannot do this because we do not know the nature of the curve between these two points given by the thermocouple table (10.501 mV at 160 °C and 11.222 mV at 170 °C). The best that we can do is to draw a straight line between these two points that is an approximation to the actual curve between the points. Thus, the horizontal line through the 10.72 point on the vertical axis is drawn as far as the straight line between the points given in the table. A vertical line is then drawn from the point of intersection with this straight line down to the horizontal axis, where the point of intersection is the best indication of temperature that we can obtain.

Mathematically, this process can be explained as follows:

The emf value of 10.72 mV is 0.219 mV above the value of 10.501 mV ($10.72 - 10.501 = 0.219$).

The difference between the values of 10.501 and 11.222 mV is 0.721 mV.

Thus, the value of 10.72 mV is $\frac{0.216}{0.721} = 0.304$ of the distance between the emf values of 10.501 and 11.222. Because of the straight line approximation to the thermocouple curve, it follows that the temperature is 0.304 of the distance between the temperatures of 160 and 170.

As an equation, the temperature can be expressed as:

$$\text{Temperature} = \left(\frac{10.72 - 10.501}{11.222 - 10.501} \times 10\right) + 160 = 163.04$$

■

### 14.2.2 Nonzero Reference Junction Temperature

If the reference junction is immersed in an ice bath to maintain it at a temperature of 0 °C so that thermocouple tables can be applied directly, the ice in the bath must be in a state of just melting. This is the only state in which ice is exactly at 0 °C, and otherwise it will be either colder or hotter than this temperature. Thus, maintaining the reference junction at 0 °C is not a straightforward matter, particularly if the environmental temperature around the measurement system is relatively hot. In consequence, it is common practice in many practical applications of thermocouples to maintain the reference junction at a nonzero temperature by putting it into a controlled environment maintained by an electrical heating element. In order to still be able to apply thermocouple tables, correction then has to be made for this nonzero reference junction temperature using a second thermoelectric law known as the *law of intermediate temperatures*. This states that:

$$E_{(T_h,T_0)} = E_{(T_h,T_r)} + E_{(T_r,T_0)} \tag{14.6}$$

where $E_{(T_h,T_0)}$ is the emf with the junctions at temperatures $T_h$ and $T_0$, $E_{(T_h,T_r)}$ is the emf with the junctions at temperatures $T_h$ and $T_r$, $E_{(T_r,T_0)}$ is the emf with the junctions at temperatures $T_r$ and $T_0$, $T_h$ is the hot-junction measured temperature, $T_0$ is 0 °C, and $T_r$ is the nonzero reference junction temperature that is somewhere between $T_0$ and $T_h$.

## ■ Example 14.3

Suppose that the reference junction of a chromel—constantan thermocouple is maintained at a temperature of 80 °C and the output emf measured is 40.102 mV when the hot junction is immersed in a fluid.

The quantities given are $T_r = 80$ °C and $E_{(T_h,T_r)} = 40.102$ mV.

From the tables, $E_{(T_r,T_0)} = 4.983$ mV.

Now applying Eqn (14.6), $E_{(T_h,T_0)} = 40.102 + 4.983 = 45.085$ mV.

Again referring to the tables, this indicates a fluid temperature of 600 °C.

■

In using thermocouples, it is essential that they are connected correctly. Large errors can result if they are connected incorrectly, for example, by interchanging the extension leads or by using incorrect extension leads. Such mistakes are particularly serious because they do not prevent some sort of output being obtained, which may look sensible even though it is incorrect, and so the mistake may go unnoticed for a long period of time. The following examples illustrate the sort of errors that may arise:

## ■ Example 14.4

This example is an exercise in the use of thermocouple tables, but it also serves to illustrate the large errors that can arise if thermocouples are used incorrectly. In a particular industrial situation, a chromel—alumel thermocouple with chromel—alumel extension wires is used to measure the temperature of a fluid. In connecting up this measurement system, the instrumentation engineer responsible has inadvertently interchanged the extension wires from the thermocouple. The ends of the extension wires are held at a reference temperature of 0 °C and the output emf measured is 14.1 mV. If the junction between the thermocouple and extension wires is at a temperature of 40 °C, what temperature of fluid is indicated and what is the true fluid temperature?

■

## ■ Solution

The initial step necessary in solving a problem of this type is to draw a diagrammatical representation of the system and to mark on this the emf sources, temperatures, etc., as shown in Figure 14.6. The first part of the problem is solved very simply by looking up in thermocouple tables what temperature the emf output of 12.1 mV indicates for a chromel—alumel thermocouple. This is 297.4 °C. Then, summing emfs around the loop:

$$V = 12.1 = E_1 + E_2 + E_3 \quad \text{or} \quad E_1 = 12.1 - E_2 - E_3$$

$$E_2 = E_3 = \text{Emf}_{(\text{alumel—chromel})_{40}} = -\text{Emf}_{(\text{chromel—alumel})_{40}}{}^{3} = -1.611 \text{ mV}$$

[3] The thermocouple tables quote emfs using the convention that going from chromel to alumel is positive. Hence, the emf going from alumel to chromel is minus the emf going from chromel to alumel.

■

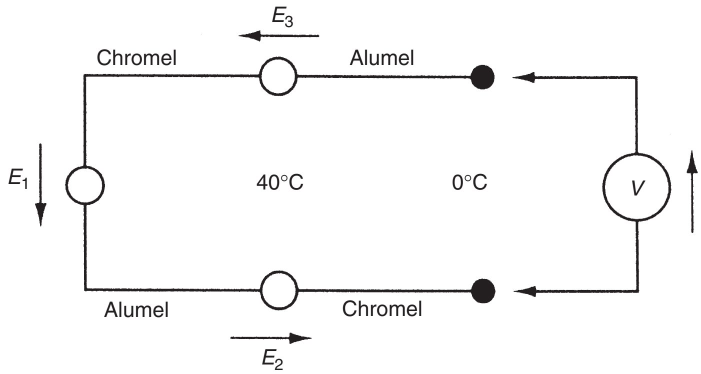


**Figure 14.6**
Diagram for solution of Example 14.4.

Hence $E_1 = 12.1 + 1.611 + 1.611 = 15.322$ mV.

Interpolating from the thermocouple tables, this indicates that the true fluid temperature is 374.5 °C.

## Example 14.5

This example also illustrates the large errors that can arise if thermocouples are used incorrectly. An iron–constantan thermocouple measuring the temperature of a fluid is connected by mistake with copper–constantan extension leads (such that the two constantan wires are connected together and the copper extension wire is connected to the iron thermocouple wire). If the fluid temperature was actually 200 °C, and the junction between the thermocouple and extension wires was at 50 °C, what emf would be measured at the open ends of the extension wires if the reference junction is maintained at 0 °C? What fluid temperature would be deduced from this (assuming that the connection mistake was not known about)?

## Solution

Again, the initial step necessary is to draw a diagram showing the junctions, temperatures, and emfs, as shown in Figure 14.7. The various quantities can then be calculated:

$$E_2 = \text{Emf}_{(\text{iron}-\text{copper})_{50}}$$

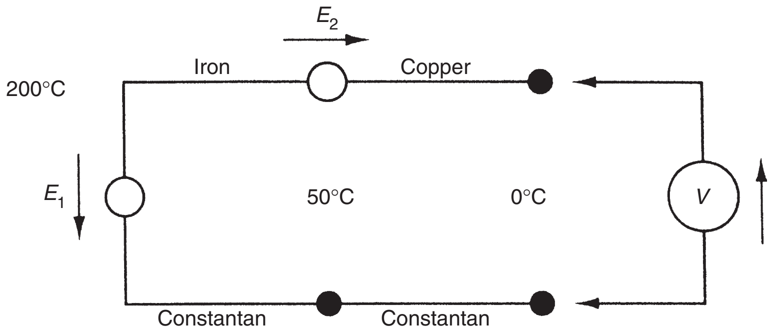


**Figure 14.7**
Diagram for solution of Example 14.5.

By the law of intermediate metals:

$$\begin{aligned} \text{Emf}_{(\text{iron-copper})_{50}} &= \text{Emf}_{(\text{iron-constantan})_{50}} - \text{Emf}_{(\text{copper-constantan})_{50}} \\ &= 2.585 - 2.035 \text{ (from thermocouple tables)} = 0.55 \text{ mV} \\ E_1 &= \text{Emf}_{(\text{iron-constantan})_{200}} = 10.777 \text{ (from thermocouple tables)} \\ V &= E_1 - E_2 = 10.777 - 0.55 = 10.227 \end{aligned}$$

Using tables and interpolating, 10.227 mV indicates a temperature of:

$$\left(\frac{10.227 - 10.222}{10.777 - 10.222}\right) 10 + 190 = 190.1\ ^\circ\text{C}$$

■

### *14.2.3 Thermocouple Types*

The five standard base metal thermocouples are chromel–constantan (type E), iron–constantan (type J), chromel–alumel (type K), nicrosil–nisil (type N), and copper–constantan (type T). These are all relatively cheap to manufacture but they become inaccurate with age and have a short life span. In many applications, performance is also affected through contamination by the working environment. To overcome this, the thermocouple can be enclosed in a *protective sheath*, but this has the adverse effect of introducing a significant time constant, making the thermocouple slow to respond to temperature changes. Therefore, as far as possible, thermocouples are used without protection.

**Chromel–constantan thermocouples (type E)** give the highest measurement sensitivity of 68 μV/°C, with an inaccuracy of ±0.5% and a useful measuring range of −200 °C up to 900 °C. Unfortunately, while they can operate satisfactorily in oxidizing environments when unprotected, their performance and life are seriously affected by reducing atmospheres.

**Iron–constantan thermocouples (type J)** have a sensitivity of 55 μV/°C and are the preferred type for general purpose measurements in the temperature range of −40 °C to +750 °C, where the typical measurement inaccuracy is ±0.75%. Their performance is little affected by either oxidizing or reducing atmospheres.

**Copper–constantan thermocouples (type T)** have a measurement sensitivity of 43 μV/°C and find their main application in measuring subzero temperatures down to −200 °C, with an inaccuracy of ±0.75%. They can also be used in both oxidizing and reducing atmospheres to measure temperatures up to 350 °C.

**Chromel–alumel thermocouples (type K)** are a widely used general purpose device with a measurement sensitivity of 41 μV/°C. Their output characteristic is particularly linear over the temperature range between 700 °C and 1200 °C and this is therefore their main application, although their full measurement range is −200 °C to +1300 °C. Like chromel–constantan devices, they are suitable for oxidizing atmospheres but not for reducing ones unless protected by a sheath. Their measurement inaccuracy is ±0.75%.

**Nicrosil–nisil thermocouples (type N)** were developed with the specific intention of improving on the lifetime and stability of chromel–alumel thermocouples. They therefore have similar thermoelectric characteristics to the latter but their long-term stability and life are at least three times better. This allows them to be used in temperatures up to 1300 °C. Their measurement sensitivity is 39 μV/°C and they have a typical measurement uncertainty of ±0.75%. A detailed comparison between type K and N devices can be found in Brookes (1985).

**Nickel/molybdenum–nickel–cobalt thermocouples (type M)** have one wire made from a nickel–molybdenum alloy with 18% molybdenum and the other wire made from a nickel–cobalt alloy with 0.8% cobalt. They can measure at temperatures up to 1400 °C, which is higher than other types of base metal thermocouple. Unfortunately, they are damaged in both oxidizing and reducing atmospheres. This means that they are rarely used except for special applications like temperature measurement in vacuum furnaces.

**Noble metal thermocouples** are expensive, but they enjoy high stability and long life even when used at high temperatures, though they cannot be used in reducing atmospheres. Unfortunately, their measurement sensitivity is relatively low. Because of this, their use is mainly restricted to measuring high temperatures unless the operating environment is particularly aggressive in low-temperature applications. Various combinations of the metals platinum and tungsten, and the metal alloys of platinum–rhodium, tungsten–rhenium, and gold–iron are used.

**Platinum thermocouples (type B)** have one wire made from a platinum−rhodium alloy with 30% rhodium and the other wire made from a platinum−rhodium alloy with 6% rhodium. Their quoted measuring range is +50 °C to +1800 °C, with a measurement sensitivity of 10 μV/°C.

**Platinum thermocouples (type R)** have one wire made from pure platinum and the other wire made from a platinum−rhodium alloy with 13% rhodium. Their quoted measuring range is 0 °C to +1700 °C, with a measurement sensitivity of 10 μV/°C and quoted inaccuracy of ±0.5%.

**Platinum thermocouples (type S)** have one wire made from pure platinum and the other wire made from a platinum−rhodium alloy with 10% rhodium. They have similar characteristics to type R devices, with a quoted measuring range is 0 °C to +1750 °C, measurement sensitivity of 10 μV/°C, and inaccuracy of ±0.5%.

**Tungsten thermocouples (type C)** have one wire made from pure tungsten and the other wire made from a tungsten/rhenium alloy. Their measurement sensitivity of 20 μV/°C is double that of platinum thermocouples and they can also operate at temperatures up to 2300 °C. Unfortunately, they are damaged in both oxidizing and reducing atmospheres. Therefore, their main application is temperature measurement in vacuum furnaces.

**Chromel−gold/iron thermocouples** have one wire made from chromel and the other wire made from a gold/iron alloy which is in fact almost pure gold but with a very small iron content (typically 0.15%). These are rare, special purpose thermocouples with a typical measurement sensitivity of 15μV/°K that are designed specifically for cryogenic (very low temperature) applications. The lowest temperature measureable is 1.2 K. Several versions are available which differ according to the iron content and consequent differences in the measurement range and sensitivity. Because of this variation in iron content, and also because of their rarity, these do not have an international type letter.

### *14.2.4 Thermocouple Protection*

Thermocouples are delicate devices that must be treated carefully if their specified operating characteristics are to be maintained. One major source of error is induced strain in the hot junction. This reduces the emf output, and precautions are normally taken to minimize induced strain by mounting the thermocouple horizontally rather than vertically. It is usual to cover most of the thermocouple wire with thermal insulation, which also provides mechanical protection, although the tip is left exposed if possible to maximize the speed of response to changes in the measured temperature. However, thermocouples are prone to contamination in some operating environments. This means that their emf/temperature characteristic varies from that published in standard tables. Contamination also makes them brittle and shortens their life.

**Figure 14.8**
Typical probe encasing a thermocouple.

Where they are prone to contamination, thermocouples have to be protected by enclosing them entirely in an insulated sheath, often called a probe. Figure 14.8 shows a photograph of a typical probe encasing a thermocouple. Some common sheath materials and their maximum operating temperatures are shown in Table 14.1. While the thermocouple is a device that has a naturally first-order type of step response characteristic, the time constant is usually so small as to be negligible when the thermocouple is used unprotected. However, when enclosed in a sheath, the time constant of the combination of thermocouple and sheath is significant. The size of the thermocouple and hence the diameter required for the sheath has a large effect on the importance of this. The time constant of a thermocouple in a 1-mm-diameter sheath is only 0.15 s and this has little practical effect in most measurement situations, whereas a larger sheath of 6 mm diameter gives a time constant of 3.9 s that cannot be ignored so easily.

**Table 14.1: Common sheath materials for thermocouples**

| Material | Maximum Operating Temperature (°C)[a] |
|---|---|
| Mild steel | 900 |
| Nickel—chromium | 900 |
| Fused silica | 1000 |
| Special steel | 1100 |
| Mullite | 1700 |
| Recrystallized alumina | 1850 |
| Beryllia | 2300 |
| Magnesia | 2400 |
| Zirconia | 2400 |
| Thoria | 2600 |

[a]The maximum operating temperatures quoted assume oxidizing or neutral atmospheres. For operation in reducing atmospheres, the maximum allowable temperature is usually reduced.

### 14.2.5 Thermocouple Manufacture

Thermocouples are manufactured by connecting together two wires of different materials, where each material is produced so as to conform precisely with some defined composition specification. This ensures that its thermoelectric behavior accurately follows that for which standard thermocouple tables apply. The connection between the two wires is affected by welding, soldering, or, in some cases, just by twisting the wire ends together. Welding is the most common technique used generally, with silver soldering being reserved for copper–constantan devices.

The diameter of wire used to construct thermocouples is usually in the range between 0.4 and 2 mm. The larger diameters are used where ruggedness and long life are required, although these advantages are gained at the expense of increasing the measurement time constant. In the case of noble metal thermocouples, the use of large diameter wire incurs a substantial cost penalty. Some special applications have a requirement for a very fast response time in the measurement of temperature, and in such cases wire diameters as small as 0.1 μm can be used.

### 14.2.6 The Thermopile

The thermopile is the name given to a temperature-measuring device that consists of several thermocouples connected together in series, such that all the reference junctions are at the same cold temperature and all the hot junctions are exposed to the temperature being measured, as shown in Figure 14.9. The effect of connecting $n$ thermocouples together in series is to increase the measurement sensitivity by a factor of $n$. A typical thermopile manufactured by connecting together 25 chromel–constantan thermocouples gives a measurement resolution of 0.001 °C.

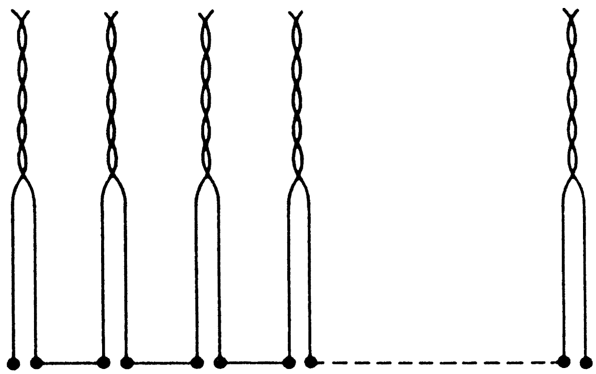

**Figure 14.9**
Thermopile.

### 14.2.7 Digital Thermometer

Thermocouples are also used in digital thermometers, of which both simple and intelligent versions exist (see Section 14.11 for a description of the latter). A simple digital thermometer is the combination of a thermocouple, a battery-powered, dual-slope digital voltmeter to measure the thermocouple output, and an electronic display. This provides a low noise, digital output that can resolve temperature differences as small as 0.1 °C. The accuracy achieved is dependent on the accuracy of the thermocouple element, but reduction of measurement inaccuracy to ±0.5% is achievable.

### 14.2.8 The Continuous Thermocouple

The continuous thermocouple is one of a class of devices that detect and respond to heat. Other devices in this class include the *line-type heat detector* and *heat-sensitive cable*. The basic construction of all these devices consists of two or more strands of wire separated by insulation within a long thin cable. While they sense temperature, they do not in fact provide an output measurement of temperature. Their function is to respond to abnormal temperature rises and thus prevent fires, equipment damage, etc.

The advantages of continuous thermocouples become more apparent if the problems with other types of heat detector are considered. The insulation in the line-type heat detector and heat-sensitive cable consists of plastic or ceramic material with a negative temperature coefficient (i.e., the resistance falls as the temperature rises). An alarm signal can be generated when the measured resistance falls below a certain level. Alternatively, in some versions, the insulation is allowed to break down completely, in which case the device acts as a switch. The major limitation of these devices is that the temperature change has to be relatively large, typically 50−200 °C above ambient temperature, before the device responds. Also, it is not generally possible for such devices to give an output that indicates that an alarm condition is developing before it actually happens, and thus allow preventative action. Furthermore, after the device has generated an alarm it usually has to be replaced. This is particularly irksome because there is a large variation in the characteristics of detectors coming from different batches and so replacement of the device requires extensive on-site recalibration of the system.

In contrast, the continuous thermocouple suffers from very few of these problems. It differs from other types of heat detector in that the two strands of wire inside it are a pair of thermocouple materials[4] separated by a special, patented mineral insulation and contained within a stainless-steel protective sheath. If any part of the cable is subjected to heat, the resistance of the insulation at that point is reduced and a "hot junction" is created

[4] Normally type E, chromel−constantan, or type K, chromel−alumel.

between the two wires of dissimilar metals. An emf is generated at this hot junction according to normal thermoelectric principles.

The continuous thermocouple can detect temperature rises as small as 1 °C above normal. Unlike other types of heat detector, it can also monitor abnormal rates of temperature rise and provide a warning of alarm conditions developing before they actually happen. Replacement is only necessary if a great degree of insulation breakdown has been caused by a substantial hot spot at some point along the detector's length. Even then, the use of thermocouple materials of standard characteristics in the detector means that recalibration is not needed if it is replaced. Calibration is not affected either by cable length, and so a replacement cable may be of a different length to the one it is replacing. One further advantage of continuous thermocouples over earlier forms of heat detector is that no power supply is needed, thus significantly reducing installation costs.

## 14.3 Varying Resistance Devices

Varying resistance devices rely on the physical principle of the variation of resistance with temperature. The devices are known as either resistance temperature devices (RTDs) or thermistors according to whether the material used for their construction is a metal or a semiconductor, and both are common measuring devices. RTDs are also known by the name of *resistance thermometers*. The normal method of measuring resistance is to use a DC bridge. The excitation voltage of the bridge has to be chosen very carefully because, although a high value is desirable for achieving high measurement sensitivity, the self-heating effect of high currents flowing in the temperature transducer creates an error by increasing the temperature of the device and so changing the resistance value.

### 14.3.1 RTD (Resistance Thermometer)

The resistance temperature device (**RTD**), which is alternatively known as a *resistance thermometer*, relies on the principle that the resistance of a metal varies with temperature according to the relationship:

$$R = R_0\left(1 + a_1T + a_2T^2 + a_3T^3 + \cdots + a_nT^n\right) \tag{14.7}$$

This equation is nonlinear and so is inconvenient for measurement purposes. The equation becomes linear if all the terms in $a_2T^2$ and higher powers of $T$ are negligible such that the resistance and temperature are related according to:

$$R \approx R_0(1 + a_1T)$$

This equation is approximately true over a limited temperature range for some metals, notably platinum, copper, and nickel, whose characteristics are summarized in

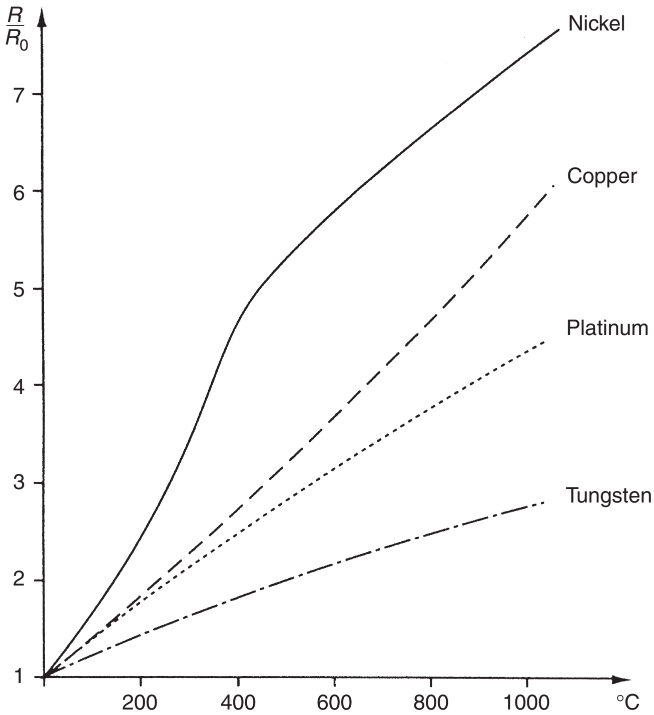


**Figure 14.10**
Typical resistance–temperature characteristics of metals.

Figure 14.10. Platinum has the most linear resistance/temperature characteristic and it also has good chemical inertness. It is therefore far more common than copper or nickel thermocouples. Its resistance–temperature relationship is linear within ±0.4% over the temperature range between −200 °C and +40 °C. Even at +1000 °C, the quoted inaccuracy figure is only ±1.2%. Platinum thermometers are made in three forms, as a film deposited on a ceramic substrate, as a coil mounted inside a glass or ceramic probe, or as a coil wound on a mandrel, though the last of these are now becoming rare. The nominal resistance at 0 °C is typically 100 Ω or 1000 Ω, though 200 Ω and 500 Ω versions also exist. Sensitivity is 0.385 Ω/°C (100 Ω type) or 3.85 Ω/°C (1000 Ω type). A high nominal resistance is advantageous in terms of higher measurement sensitivity, and the resistance of connecting leads has less effect on measurement accuracy. However, cost goes up as the nominal resistance increases. A photograph of a typical thin-film RTD is shown in Figure 14.11.

Besides having a less linear characteristic, both nickel and copper are inferior to platinum in terms of their greater susceptibility to oxidation and corrosion. This seriously limits their accuracy and longevity. However, because platinum is very expensive compared with nickel and copper, the latter are used in RTDs when cost is important. Another metal,

**Figure 14.11**
Photograph of a thin-film resistance temperature device (RTD).

tungsten, is also used in RTDs in some circumstances, particularly for high-temperature measurements. The working range of each of these four types of RTD is as shown below:

Platinum: −270 °C to +1000 °C (though use above 650 °C is uncommon)
Copper: −200 °C to +260 °C
Nickel: −200 °C to +430 °C
Tungsten: −270 °C to +1100 °C

In the case of noncorrosive and nonconducting environments, RTDs are used without protection. In all other applications, they are protected inside a sheath. As in the case of thermocouples, such protection reduces the speed of response of the system to rapid changes in temperature. A typical time constant for a sheathed platinum RTD is 0.4 s. Moisture buildup within the sheath can also impair measurement accuracy.

The frequency at which an RTD should be calibrated depends upon the material it is made from and upon the operating environment. Practical experimentation is therefore needed to determine the necessary frequency and this must be reviewed if the operating conditions change.

### 14.3.2 Thermistors

Thermistors are manufactured from beads of semiconductor material prepared from oxides of the iron group of metals such as chromium, cobalt, iron, manganese, and nickel. Normally, thermistors have a negative temperature coefficient, that is, the resistance decreases as the temperature increases, according to:

$$R = R_0 e^{[\beta(1/T - 1/T_0)]} \tag{14.8}$$

This relationship is illustrated in Figure 14.12. However, alternative forms of heavily doped thermistors are now available (at greater cost) that have a positive temperature

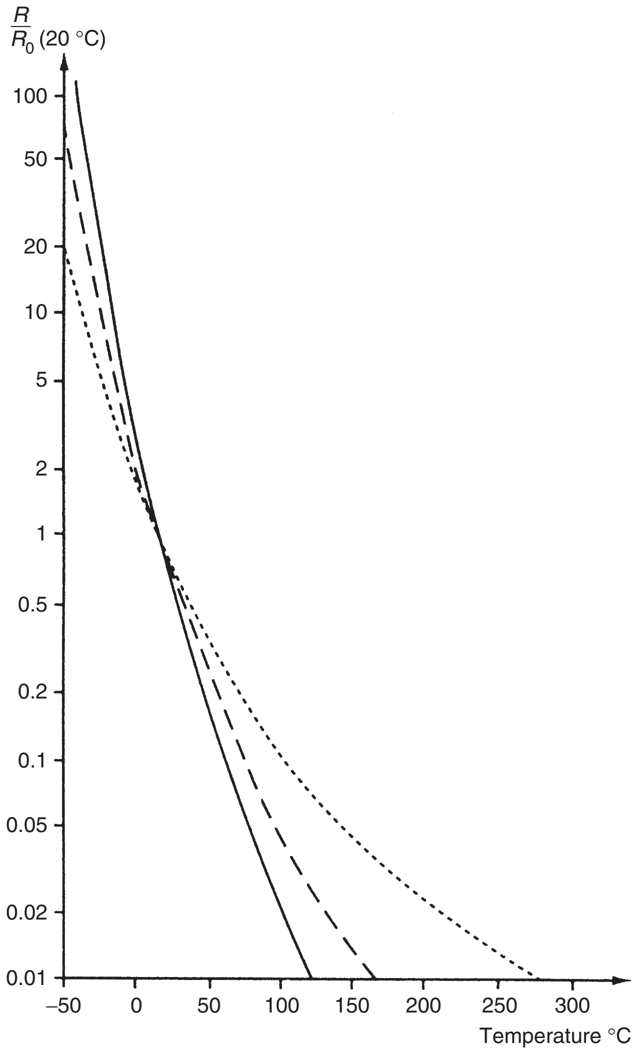


**Figure 14.12**
Typical resistance/temperature characteristics of thermistor materials.

coefficient. The form of Eqn (14.8) is such that it is not possible to make a linear approximation to the curve over even a small temperature range, and hence the thermistor is very definitely a nonlinear sensor. However, the major advantages of thermistors are their relatively low cost and their small size. This size advantage means that the time constant of thermistors operated in sheaths is small, although the size reduction also decreases its heat dissipation capability and so makes the self-heating effect greater. In consequence, thermistors have to be operated at generally lower current levels than RTDs and so the measurement sensitivity is less.

As in the case of RTDs, some practical experimentation is needed to determine the necessary frequency at which a thermistor should be calibrated and this must be reviewed if the operating conditions change.

## 14.4 Semiconductor Devices

Semiconductor devices, consisting of either diodes or integrated circuit transistors, have only been commonly used in industrial applications for a few years, but they were first invented several decades ago. They have the advantage of being relatively inexpensive, but one difficulty that affects their use is the need to provide an external power supply to the sensor.

Integrated circuit transistors produce an output proportional to the absolute temperature. Different types are configured to give an output in the form of either a varying current (typically 1 μA/K) or varying voltage (typically 10 mV/K). Current forms are normally used with a digital voltmeter that detects the current output in terms of the voltage drop across a 10-kΩ resistor. Although the devices have a very low cost (typically a few pounds) and a better linearity than either thermocouples or RTDs, they only have a limited measurement range from −50 °C to +150 °C. Their inaccuracy is typically ±3%, which limits their range of application. However, they are widely used to monitor pipes and cables, where their low cost means that it is feasible to mount multiple sensors along the length of the pipe/cable to detect hot spots.

In diodes, the forward voltage across the device varies with temperature. Output from a typical diode package is in the microamp range. Diodes have a small size, with good output linearity and typical inaccuracy of only ±0.5%. Silicon diodes cover the temperature range from −50 °C to +200 °C and germanium ones from −270 °C to +40 °C.

## 14.5 Radiation Thermometers

All objects emit electromagnetic radiation as a function of their temperature above absolute zero, and radiation thermometers (also known as radiation pyrometers) measure this radiation in order to calculate the temperature of the object. The total rate of radiation emission per second is given by:

$$E = KT^4 \tag{14.9}$$

The power spectral density of this emission varies with temperature in the manner shown in Figure 14.13. The major part of the frequency spectrum lies within the band of wavelengths between 0.3 and 40 μm, which corresponds to the visible (0.3−0.72 μm) and infrared (0.72−1000 μm) ranges. As the magnitude of the radiation varies with

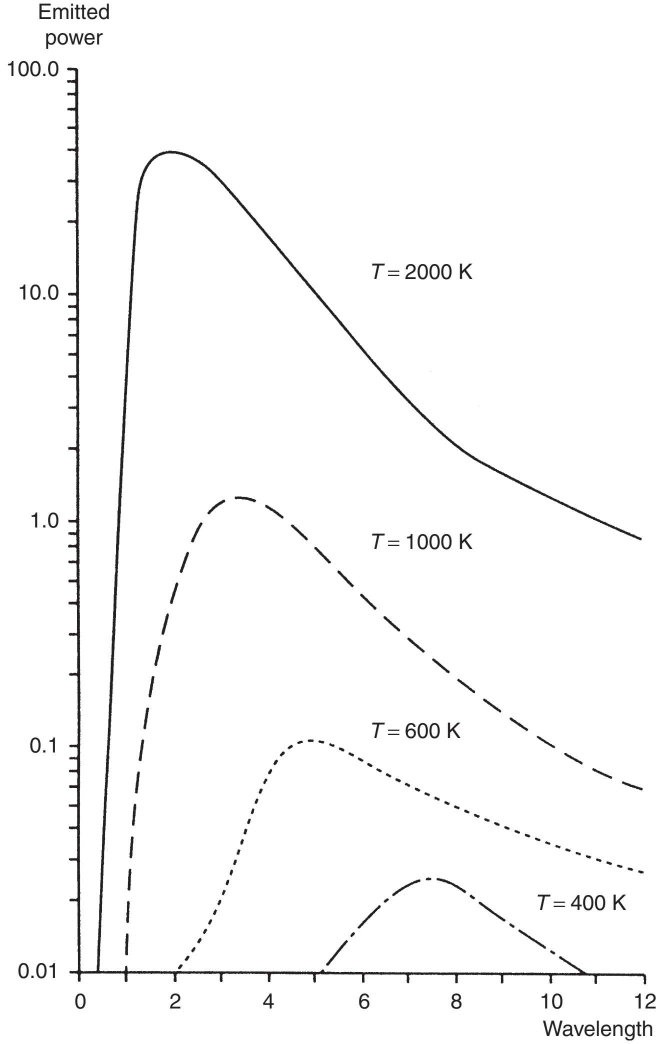


**Figure 14.13**
Power spectral density of radiated energy emission at various temperatures.

temperature, measurement of the emission from a body allows the temperature of the body to be calculated. Choice of the best method of measuring the emitted radiation depends on the temperature of the body. At low temperatures, the peak of the power spectral density function (Figure 14.13) lies in the infrared region, whereas at higher temperatures it moves toward the visible part of the spectrum. This phenomenon is observed as the red glow that a body begins to emit as its temperature is increased beyond 600 °C.

Different versions of radiation thermometers are capable of measuring temperatures between −100 °C and +10,000 °C with measurement inaccuracy as low as ±0.05% in the more expensive versions (though this level of accuracy is not obtained when measuring very high temperatures). Portable, battery-powered, hand-held versions are also available, and these are particularly easy to use. The important advantage that radiation thermometers have over other types of temperature-measuring instrument is that there is no contact with the hot body while its temperature is being measured. Thus, the measured system is not disturbed in any way. Furthermore, there is no possibility of contamination, which is particularly important in the food, drug, and many other process industries. They are especially suitable for measuring high temperatures that are beyond the capabilities of contact instruments such as thermocouples, RTDs, and thermistors. They are also capable of measuring moving bodies, for instance, the temperature of steel bars in a rolling mill. Their use is not as straightforward as the discussion so far might have suggested, however, because the radiation from a body varies with the composition and surface condition of the body as well as with temperature. This dependence on surface condition is quantified by the *emissivity* of the body. The use of radiation thermometers is further complicated by absorption and scattering of the energy between the emitting body and the radiation detector. Energy is scattered by atmospheric dust and water droplets and absorbed by carbon dioxide, ozone, and water vapor molecules. Therefore, all radiation thermometers have to be carefully calibrated for each particular body whose temperature they are required to monitor.

Various types of radiation thermometers exist, as described below. The optical pyrometer can only be used to measure high temperatures, but various types of radiation pyrometers are available that between them cover the whole temperature spectrum. Intelligent versions (see Section 14.11) also now provide full or partial solution to many of the problems described below for nonintelligent pyrometers.

### 14.5.1 Optical Pyrometer

The optical pyrometer, illustrated in Figure 14.14, is designed to measure temperatures where the peak radiation emission is in the red part of the visible spectrum, that is, where the measured body glows a certain shade of red according to the temperature. This limits the instrument to measuring temperatures above 600 °C. The instrument contains a heated tungsten filament within its optical system. The current in the filament is increased until its color is the same as the hot body: under these conditions the filament apparently disappears when viewed against the background of the hot body. Temperature measurement is therefore obtained in terms of the current flowing in the filament. As the brightness of different materials at any particular temperature varies according to the emissivity of the material, the calibration of the optical pyrometer must be adjusted according to the emissivity of the target. Manufacturers provide tables of standard material emissivities to assist with this.

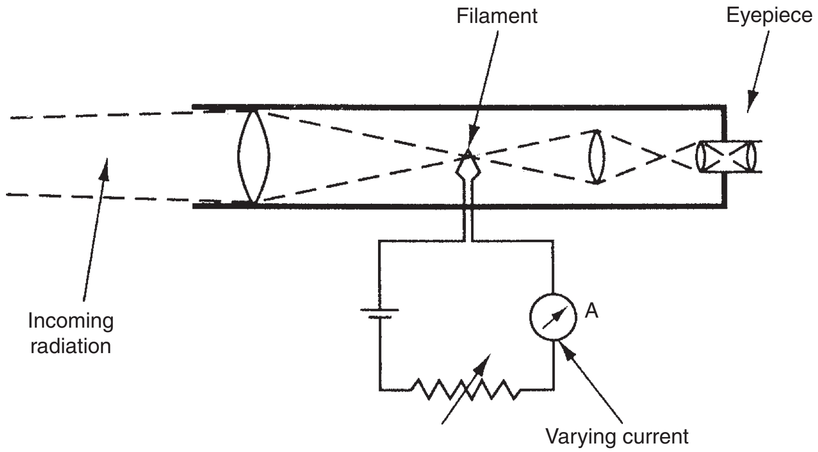


**Figure 14.14**
Optical pyrometer.

The inherent measurement inaccuracy of an optical pyrometer is ±5 °C. However, in addition to this error, there can be a further operator-induced error of ±10 °C arising out of the difficulty in judging the moment when the filament "just" disappears. Measurement accuracy can be improved somewhat by employing an optical filter within the instrument that passes a narrow band of frequencies of wavelength around 0.65 μm corresponding to the red part of the visible spectrum. This also extends the upper temperature measurable from 5000 °C in unfiltered instruments up to 10,000 °C.

The instrument cannot be used in automatic temperature control schemes because the eye of the human operator is an essential part of the measurement system. The reading is also affected by fumes in the sight path. Because of these difficulties and its low accuracy, hand-held radiation pyrometers are rapidly overtaking the optical pyrometer in popularity, although the instrument is still widely used in industry for measuring temperatures in furnaces and similar applications at present.

### *14.5.2 Radiation Pyrometers*

All the alternative forms of radiation pyrometer described below have an optical system that is similar to that in the optical pyrometer and focuses the energy emitted from the measured body. However, they differ by omitting the filament and eyepiece and having instead an energy detector in the same focal plane as the eyepiece was, as shown in Figure 14.15. This principle can be used to measure temperature over a range from −100 °C to +3600 °C. The radiation detector is either a thermal detector, which measures the temperature rise in a blackbody at the focal point of the optical system, or a photon detector.

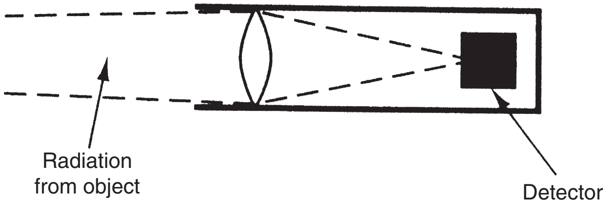


**Figure 14.15**
Structure of the radiation thermometer.

Thermal detectors respond equally to all wavelengths in the frequency spectrum, and consist of either thermopiles, RTDs, or thermistors. All of these typically have time constants of several milliseconds, because of the time taken for the blackbody to heat up and the temperature sensor to respond to the temperature change.

Photon detectors respond selectively to a particular band within the full spectrum and are usually of the photoconductive or photovoltaic type. They respond to temperature changes very much faster than thermal detectors because they involve atomic processes, and typical measurement time constants are a few microseconds.

Fiber-optic technology is frequently used in high-temperature measurement applications to collect the incoming radiation and transmit it to a detector and processing electronics that are located remotely. This prevents exposure of the processing electronics to potentially damaging, high temperature. Fiber-optic cables are also used to apply radiation pyrometer principles in very difficult applications, such as measuring the temperature inside jet engines by collecting the radiation from inside the engine and transmitting it outside (see Section 14.8). The term *fiber-optic pyrometer* is frequently used to describe devices that use fiber optics.

The size of objects measured by a radiation pyrometer is limited by the optical resolution, which is defined as the ratio of target size to distance. A good ratio is 1:300, and this would allow temperature measurement of a 1-mm-sized object at a range of 300 mm. With large distance/target size ratios, accurate aiming and focusing of the pyrometer at the target is essential. It is now common to find "through the lens" viewing provided in pyrometers, using a principle similar to SLR camera technology, as focusing and orientating the instrument for visible light automatically focuses it for infrared light. Alternatively, dual laser beams are sometimes used to ensure that the instrument is aimed correctly toward the target.

Various forms of electrical output are available from the radiation detector: these are functions of the incident energy on the detector and are therefore functions of the temperature of the measured body. While this therefore makes such instruments of use in automatic control systems, their accuracy is often inferior to optical pyrometers.

This reduced accuracy arises first because a radiation pyrometer is sensitive to a wider band of frequencies than the optical instrument and the relationship between emitted energy and temperature is less well defined. Second, the magnitude of energy emission at low temperatures gets very small, according to Eqn (14.9), increasing the difficulty of accurate measurement.

The forms of radiation pyrometer described below differ mainly in the technique used to measure the emitted radiation. They also differ in the range of energy wavelengths, and hence the temperature range, which each is designed to measure. One further difference is the material used to construct the energy-focusing lens. Outside the visible part of the spectrum, glass becomes almost opaque to infrared wavelengths, and other lens materials such as arsenic trisulfide are used.

**Broadband (unchopped) radiation pyrometers:** The broadband radiation pyrometer finds wide application in industry and has a measurement inaccuracy that varies from ±0.05% of full scale in the best instruments to ±0.5% in the cheapest. However, their accuracy deteriorates significantly over a period of time, and an error of 10 °C is common after 1–2 years of operation at high temperatures. As its name implies, the instrument measures radiation across the whole frequency spectrum and so uses a thermal detector. This consists of a blackened platinum disc to which a thermopile[5] is bonded. The temperature of the detector increases until the heat gain from the incident radiation is balanced by the heat loss due to convection and radiation. For high-temperature measurement, a two-couple thermopile gives acceptable measurement sensitivity and has a fast time constant of about 0.1 s. At lower measured temperatures, where the level of incident radiation is much less, thermopiles constructed from a greater number of thermocouples must be used to get sufficient measurement sensitivity. This increases the measurement time constant to as much as 2 s. Standard instruments of this type are available to measure temperatures between −20 °C and +1800 °C, although in theory much higher temperatures could be measured by this method.

**Chopped broadband radiation pyrometers:** The construction of this form of pyrometer is broadly similar to that shown in Figure 14.15 except that a rotary mechanical device is included that periodically interrupts the radiation reaching the detector. The voltage output from the thermal detector thus becomes an alternating quantity that switches between two levels. This form of AC output can be amplified much more readily than the DC output coming from an unchopped instrument. This is particularly important when amplification is necessary to achieve an acceptable measurement resolution in situations where the level of incident radiation from the measured body is low. For this reason, this form of instrument is the more common when measuring body temperatures associated with peak

[5] Typically manganin–constantan.

emission in the infrared part of the frequency spectrum. For such chopped systems, the time constant of thermopiles is too long. Instead, thermistors are generally used, giving a time constant of 0.01 s. Standard instruments of this type are available to measure temperatures between +20 °C and +1300 °C. This form of pyrometer suffers similar accuracy drift to unchopped forms. Its life is also limited to about 2 years because of motor failures.

**Narrowband radiation pyrometers:** Narrowband radiation pyrometers are highly stable instruments that suffer a drift in accuracy that is typically only 1 °C in 10 years. They are also less sensitive to emissivity changes than other forms of radiation pyrometer. They use photodetectors of either the photoconductive or the photovoltaic form whose performance is unaffected by either carbon dioxide or water vapor in the path between the target object and the instrument. A photoconductive detector exhibits a change in resistance as the incident radiation level changes whereas a photovoltaic cell exhibits an induced voltage across its terminals that is also a function of the incident radiation level. All photodetectors are preferentially sensitive to a particular narrow band of wavelengths in the range of 0.5–1.2 μm and all have a form of output that varies in a highly nonlinear fashion with temperature, and thus a microcomputer inside the instrument is highly desirable. Four commonly used materials for photodetectors are cadmium sulfide, lead sulfide, indium antimonide, and lead tin telluride. Each of these is sensitive to a different band of wavelengths and therefore all find application in measuring the particular temperature ranges corresponding to each of these bands.

The output from the narrowband radiation pyrometer is normally chopped into an AC signal in the same manner as used in the chopped broadband pyrometer. This simplifies the amplification of the output signal, which is necessary to achieve an acceptable measurement resolution. The typical time constant of a photon detector is only 5 μs, which allows high chopping frequencies up to 20 kHz. This gives such instruments an additional advantage in being able to measure fast transients in temperature as short as 10 μs.

**Two-color pyrometer (ratio pyrometer):** As stated earlier, the emitted radiation–temperature relationship for a body depends on its emissivity. This is very difficult to calculate, and therefore in practice all pyrometers have to be calibrated to the particular body they are measuring. The two-color pyrometer (alternatively known as a ratio pyrometer) is a system that largely overcomes this problem by using the arrangement shown in Figure 14.16. Radiation from the body is split equally into two parts, which are applied to separate narrowband filters. The outputs from the filters consist of radiation within two narrow bands of wavelength $\lambda_1$ and $\lambda_2$. Detectors sensitive to these frequencies produce output voltages $V_1$ and $V_2$, respectively. The ratio of these outputs ($V_1/V_2$) can be shown (see Dixon, 1987) to be a function of temperature and to be independent of the emissivity provided that the two wavelengths $\lambda_1$ and $\lambda_2$ are close together.

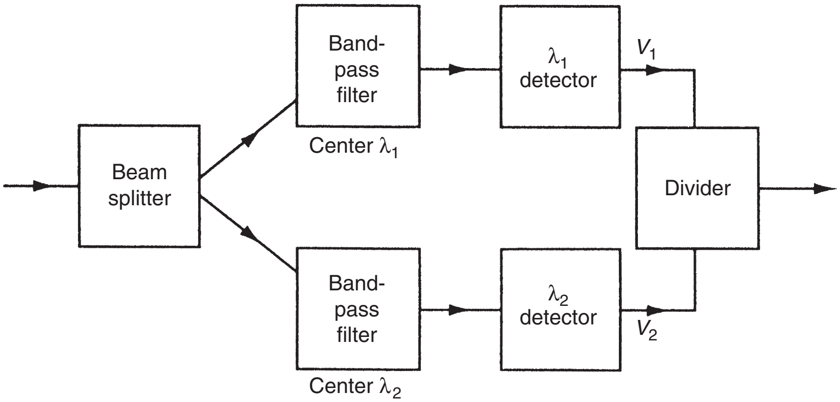


**Figure 14.16**
Two-color (ratio) pyrometer system.

The theoretical basis of the two-color pyrometer is that the output is independent of emissivity because the emissivities at the two wavelengths $\lambda_1$ and $\lambda_2$ are equal. This is based on the assumption that $\lambda_1$ and $\lambda_2$ are very close together. In practice, this assumption does not hold and therefore the accuracy of the two-color pyrometer tends to be relatively poor. However, the instrument is still of great use in conditions where the target is obscured by fumes or dust, which is a common problem in the cement and mineral-processing industries. Two-color pyrometers typically cost 50–100% more than other types of pyrometer.

**Multiwavelength pyrometer:** This is an extension of the two-color pyrometer that uses three or more separate wavelengths. By appropriate mathematical manipulation of the outputs at the detector for each frequency, an accurate temperature measurement is achieved even when the emissivity is unknown, changing, or different at each wavelength.

**Selected waveband pyrometer:** The selected waveband pyrometer is sensitive to one waveband only, for example, 5 μm, and is dedicated to particular, special situations where other forms of pyrometer are inaccurate. One example of such a situation is measuring the temperature of steel billets that are being heated in a furnace. If an ordinary radiation pyrometer is aimed through the furnace door at a hot billet, it receives radiation from the furnace walls (by reflection off the billet) as well as radiation from the billet itself. If the temperature of the furnace walls is measured by a thermocouple, a correction can be made for the reflected radiation, but variations in transmission losses inside the furnace through fumes, etc., make this correction inaccurate. However, if a carefully chosen selected waveband pyrometer is used, this transmission loss can be minimized and the measurement accuracy is thereby greatly improved.

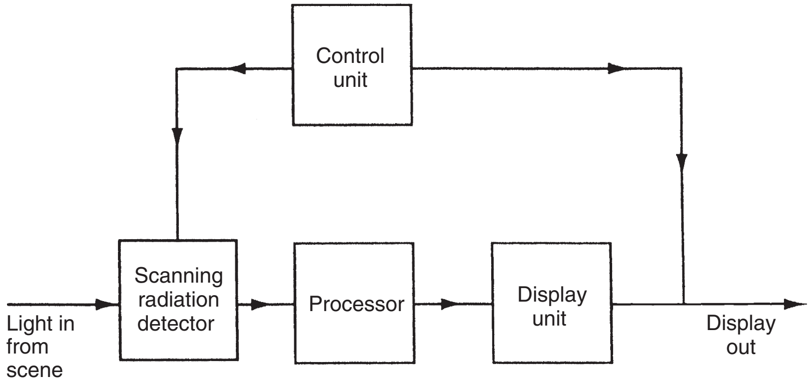


**Figure 14.17**
Thermography (thermal imaging) system.

## 14.6 Thermography (Thermal Imaging)

Thermography, or thermal imaging, involves scanning an infrared radiation detector across an object. The information gathered is then processed and an output in the form of the temperature distribution across the object is produced. Temperature measurement over the range from −20 °C up to +1500 °C is possible. Elements of the system are shown in Figure 14.17.

The radiation detector uses the same principles of operation as a radiation pyrometer in inferring the temperature of the point that the instrument is focused on from a measurement of the incoming infrared radiation. However, instead of providing a measurement of the temperature of a single point at the focal point of the instrument, the detector is scanned across a body or scene, and thus provides information about temperature distributions. Because of the scanning mode of operation of the instrument, radiation detectors with a very fast response are required, and only photoconductive or photovoltaic sensors are suitable. These are sensitive to the portion of the infrared spectrum between wavelengths of 2 and 14 μm.

Simpler versions of thermal imaging instruments consist of hand-held viewers that are pointed at the object of interest. The output from an array of infrared detectors is directed onto a matrix of red light-emitting diodes assembled behind a glass screen, and the output display thus consists of different intensities of red on a black background, with the different intensities corresponding to different temperatures. Measurement resolution is high, with temperature differences as small as 0.1 °C being detectable. Such instruments are used in a wide variety of applications such as monitoring product flows through pipework, detecting insulation faults, and detecting hot spots in furnace linings, electrical transformers, machines, bearings, etc. The number of applications is extended still further if the instrument is carried in a helicopter, where uses include scanning electrical transmission lines for faults, searching for lost or injured people, and detecting the source and spread pattern of forest fires.

More complex thermal imaging systems comprise a tripod-mounted detector connected to a desktop computer and display system. Multicolor displays are commonly used in such systems, where up to 16 different colors represent different bands of temperature across the measured range. The heat distribution across the measured body or scene is thus displayed graphically as a contoured set of colored bands representing the different temperature levels. Such color thermography systems find many applications such as inspecting electronic circuit boards and monitoring production processes. There are also medical applications in body scanning.

## 14.7 Thermal Expansion Methods

Thermal expansion methods make use of the fact that the dimensions of all substances, whether solids, liquids, or gases, change with temperature. Instruments operating on this physical principle include the liquid-in-glass thermometer, the bimetallic thermometer, and the pressure (gas) thermometer.

### 14.7.1 Liquid-in-Glass Thermometers

The liquid-in-glass thermometer is a well-known temperature-measuring instrument that is used in a wide range of applications. The fluid used is normally either mercury or colored alcohol, and this is contained within a bulb and capillary tube, as shown in Figure 14.18(a). As the temperature rises, the fluid expands along the capillary tube and the meniscus level is read against a calibrated scale etched on the tube. Industrial versions of the liquid-in-glass thermometer are normally used to measure temperature in the range between $-200\ ^\circ C$ and $+1000\ ^\circ C$, although instruments are available to special order that can measure temperatures up to $1500\ ^\circ C$.

Measurement inaccuracy is typically $\pm 1\%$ of full-scale reading, although an inaccuracy of only $\pm 0.15\%$ can be achieved in the best industrial instruments. The major source of measurement error arises from the difficulty of correctly estimating the position of the curved meniscus of the fluid against the scale. In the longer term, additional errors are introduced due to volumetric changes in the glass. Such changes occur because of creep-like processes in the glass, but occur only over a timescale of years. Annual calibration checks are therefore advisable.

### 14.7.2 Bimetallic Thermometer

The bimetallic principle is probably more commonly known in connection with its use in thermostats. It is based on the fact that if two strips of different metals are bonded

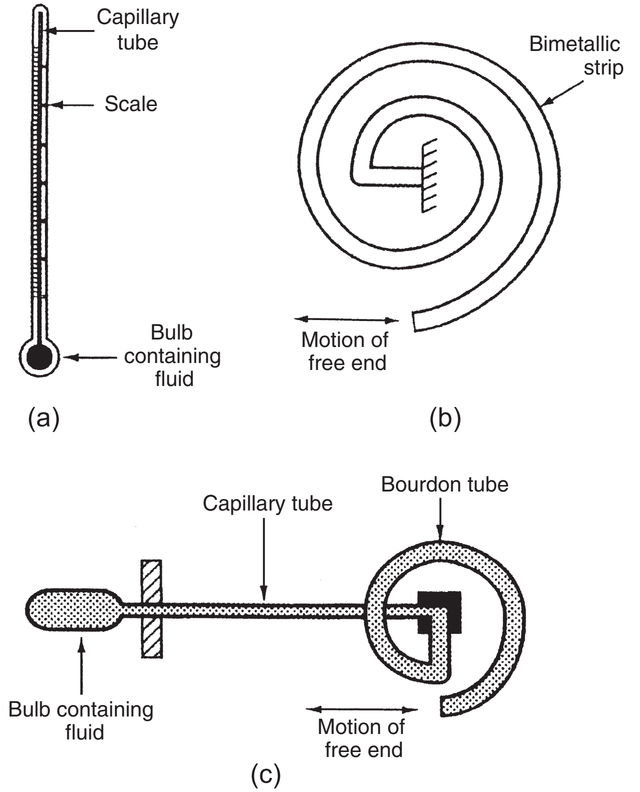


**Figure 14.18**
Thermal expansion devices: (a) Liquid-in-glass thermometer; (b) bimetallic thermometer; (c) pressure thermometer.

together, any temperature change will cause the strip to bend, as this is the only way in which the differing rates of change of length of each metal in the bonded strip can be accommodated. In the bimetallic thermostat, this is used as a switch in control applications. If the magnitude of bending is measured, the bimetallic device becomes a thermometer. For such purposes, the strip is often arranged in a spiral or helical configuration, as shown in Figure 14.18(b), as this gives a relatively large displacement of the free end for any given temperature change. The measurement sensitivity is increased further by choosing the pair of materials carefully such that the degree of bending is maximized, with invar (a nickel-steel alloy) or brass being commonly used.

The system used to measure the displacement of the strip must be carefully designed. Very little resistance must be offered to the end of the strip, otherwise the spiral or helix will distort and cause a false reading in the measurement of the displacement. The device is normally just used as a temperature indicator, where the end of the strip is made to turn a pointer that moves against a calibrated scale. However, some versions produce an electrical output, using either a linear variable differential transformer or a fiber-optic shutter sensor to transduce the output displacement.

Bimetallic thermometers are used to measure temperatures between −75 °C and +1500 °C. The inaccuracy of the best instruments can be as low as ±0.5% but such devices are quite expensive. Many instrument applications do not require this degree of accuracy in temperature measurements, and in such cases much cheaper bimetallic thermometers with substantially inferior accuracy specifications are used.

All such devices are liable to suffer changes in characteristics due to contamination of the metal components exposed to the operating environment. Further changes are to be expected arising from mechanical damage during use, particularly if they are mishandled or dropped. As the magnitude of these effects varies with their application, the required calibration interval must be determined by practical experimentation.

### 14.7.3 Pressure Thermometers

Pressure thermometers (or *gas thermometers* as they are sometimes known) have now been superseded by other alternatives in most applications, but they still remain useful in a few applications such as furnace temperature measurement when the level of fumes prevents the use of optical or radiation pyrometers. Examples can also still be found of their use as temperature sensors in pneumatic control systems. The sensing element in a pressure thermometer consists of a stainless-steel bulb containing a liquid or gas. If the fluid were not constrained, temperature rises would cause its volume to increase. However, because it is constrained in a bulb and cannot expand, its pressure rises instead. As such, the pressure thermometer does not strictly belong to the thermal expansion class of instruments but is included because of the relationship between volume and pressure according to Boyle's law: $PV = KT$. The change in pressure of the fluid is measured by a suitable pressure transducer such as the Bourdon tube (see Chapter 15). This transducer is located remotely from the bulb and connected to it by a capillary tube as shown in Figure 14.18(c).

Pressure thermometers can be used to measure temperatures in the range between −250 °C and +2000 °C and their typical inaccuracy is ±0.5% of full-scale reading. However, the instrument response has a particularly long time constant.

The need to protect the pressure-measuring instrument from the environment where the temperature is being measured can require the use of capillary tubes up to 5 m long, and the temperature gradient, and hence pressure gradient, along the tube acts as a modifying input that can introduce a significant measurement error. Errors also occur in the short term due to mechanical damage and in the longer term due to small volumetric changes in the glass components. The rate of increase in these errors is mainly use related and therefore the required calibration interval must be determined by practical experimentation.

## 14.8 Fiber-Optic Temperature Sensors

Fiber-optic cables can be used as either intrinsic or extrinsic temperature sensors, as discussed in Chapter 13, though special attention has to be paid to providing a suitable protective coating when high temperatures are measured. Cost varies from $1500 to $6000, according to type, and the normal temperature range covered is 250 °C−3000 °C, though special devices can detect down to 100 °C and others can detect up to 3600 °C. Their main application is measuring temperatures in hard-to-reach locations, though they are also used when very high measurement accuracy is required. Some laboratory versions have an inaccuracy as low as ±0.01%, which is better than a type S thermocouple, although versions used in industry have a more typical inaccuracy of ±1.0%.

While it is often assumed that fiber-optic sensors are intrinsically safe, it has been shown (Johnson, 1994) that flammable gas might be ignited by the optical power levels available from some laser diodes. Thus, the power level used with optical fibers must be carefully chosen, and certification of intrinsic safety is necessary if such sensors are to be used in hazardous environments.

One type of intrinsic sensor uses cable where the core and cladding have similar refractive indices but different temperature coefficients. Temperature rises cause the refractive indices to become even closer together and losses from the core to increase, thus reducing the quantity of light transmitted. Other types of intrinsic temperature sensors include the cross-talk sensor, phase modulating sensor, and optical resonator, as described in Chapter 13. Research into the use of distributed temperature sensing using fiber-optic cable has also been reported. This can be used to measure things like the temperature distribution along an electricity supply cable. It works by measuring the reflection characteristics of light transmitted down a fiber-optic cable that is bonded to the electrical cable. By analyzing the backscattered radiation, a table of temperature versus distance along the cable can be produced, with a measurement inaccuracy of only ±0.5 °C.

A common form of extrinsic sensor uses fiber-optic cables to transmit light from a remote targeting lens into a standard radiation pyrometer. This technique can be used with all types of radiation pyrometers, including the two-color version, and a particular advantage is that this method of measurement is intrinsically safe. However, it is not possible to measure very low temperatures, because the very small radiation levels that exist at low temperatures are badly attenuated during transmission along the fiber-optic cable. Therefore, the minimum temperature that can be measured is about 50 °C, and the light guide for this must not exceed 600 mm in length. At temperatures exceeding 1000 °C, lengths of fiber up to 20 m long can be successfully used as a light guide.

One extremely accurate device that uses this technique is known as the Accufiber sensor. This is a form of radiation pyrometer that has a black box cavity at the focal point of the lens system. A fiber-optic cable is used to transmit radiation from the black box cavity to a spectrometric device that computes the temperature. This has a measurement range of 500 °C–2000 °C, a resolution of $10^{-5}$ °C, and an inaccuracy of only ±0.0025% of full scale.

Several other types of devices that are marketed as extrinsic fiber-optic temperature sensors consist of a conventional temperature sensor (e.g., an RTD) connected to a fiber-optic cable so that the transmission of the signal from the measurement point is free of noise. Such devices must include an electricity supply for the electronic circuit that is needed to convert the sensor output into light variations in the cable. Thus, low-voltage power cables must be routed with the fiber-optic cable, and the device is therefore not intrinsically safe.

## 14.9 Color Indicators

The color of various substances and objects changes as a function of temperature. One use of this is in the optical pyrometer as discussed earlier. The other main use of color change is in special color indicators that are widely used in industry to determine whether objects placed in furnaces have reached the required temperature. Such color indicators consist of special paints or crayons that are applied to an object before it is placed in a furnace. The color sensitive component within these is some form of metal salt (usually of chromium, cobalt, or nickel). At a certain temperature, a chemical reaction takes place and a permanent color change occurs in the paint or crayon, although this change does not occur instantaneously but only happens over a period of time.

Hence, the color change mechanism is complicated by the fact that the time of exposure as well as the temperature is important. Such crayons or paints usually have a dual rating that specifies the temperature and length of exposure time required for the color change to occur. If the temperature rises above the rated temperature, then the color change will occur in less than the rated exposure time. This causes little problem if the rate of temperature rise is slow with respect to the specified exposure time required for color change to occur. However, if the rate of rise of temperature is high, the object will be significantly above the rated change temperature of the paint/crayon by the time that the color change happens. Besides wasting energy by leaving the object in the furnace longer than necessary, this can also cause difficulty if excess temperature can affect the required metallurgical properties of the heated object.

Paints and crayons are available to indicate temperatures between 50 °C and 1250 °C. A typical exposure time rating is 30 min, that is, the color change will occur if the paint/crayon is exposed to the rated temperature for this length of time. They have the advantage of low cost, typically a few pounds per application. However, they adhere strongly to the heated object, which can cause difficulty if they have to be cleaned off the object later.

Some liquid crystals also change color at a certain temperature. According to the design of sensors using such liquid crystals, the color change can either occur gradually during a temperature rise of perhaps 50 °C or else change abruptly at some specified temperature. The latter kind of sensors are able to resolve temperature changes as small as 0.1 °C and, according to type, are used over the temperature range from −20 °C to +100 °C.

## 14.10 Change of State of Materials

Temperature-indicating devices known as Seger cones or pyrometric cones are commonly used in the ceramics industry. They consist of a fused oxide and glass material that is formed into a cone shape. The tip of the cone softens and bends over when a particular temperature is reached. Cones are available that indicate temperatures over the range from 600 °C to +2000 °C.

## 14.11 Intelligent Temperature-Measuring Instruments

Intelligent temperature transmitters have now been introduced into the catalogs of almost all instrument manufacturers, and they bring about the usual benefits associated with intelligent instruments. Such transmitters are separate boxes designed for use with transducers that have either a DC voltage output in the millivolt range or an output in the form of a resistance change. They are therefore suitable for use in conjunction with thermocouples, thermopiles, RTDs, thermistors, and broadband radiation pyrometers. Transmitters normally have nonvolatile memories where all constants used in correcting output values for modifying inputs, etc., are stored, thus enabling the instrument to survive power failures without losing such information. Other facilities in intelligent transmitters include adjustable damping, noise rejection, self-adjustment for zero and sensitivity drifts, and expanded measurement range. These features allow an inaccuracy level of ±0.05% of full scale to be specified.

Mention must be made particularly of intelligent pyrometers, as some versions of these are able to measure the emissivity of the target body and automatically provide an emissivity-corrected output. This particular development provides an alternative to the two-color pyrometer when emissivity measurement and calibration for other types of pyrometer poses difficulty.

Digital thermometers (see Section 14.2.7) also exist in intelligent versions, where the inclusion of a microprocessor allows a number of alternative thermocouples and RTDs to be offered as options for the primary sensor.

The cost of intelligent temperature transducers is significantly more than their nonintelligent counterparts, and justification purely on the grounds of their superior accuracy is hard to make. However, their expanded measurement range means immediate savings are made in terms of the reduction in the number of spare instruments needed to cover a number of measurement ranges. Their capability for self-diagnosis and self-adjustment means that they require attention much less frequently, giving additional savings in maintenance costs. Many transmitters are also largely self-calibrating in respect of their signal processing function, although appropriate calibration routines still have to be applied to each sensor that the transmitter is connected to.

## 14.12 MEMS Temperature Sensors

The latest development in temperature measurement is the introduction of MEMS-based devices. These are usually noncontact devices that are based on thermocouples or thermopile sensors (a thermopile is a number of thermocouples connected in series), with polysilicon–gold thermocouples being a common choice. The sensor is powered by a battery that has a very long life owing to the very low power consumption of the device.

Figure 14.19 shows the typical structure of a thermopile-based sensor, in which the hot junctions of a number of thermocouples are placed in the central region of the sensor exposed to the radiated heat from a body, and with the reference junctions situated in the

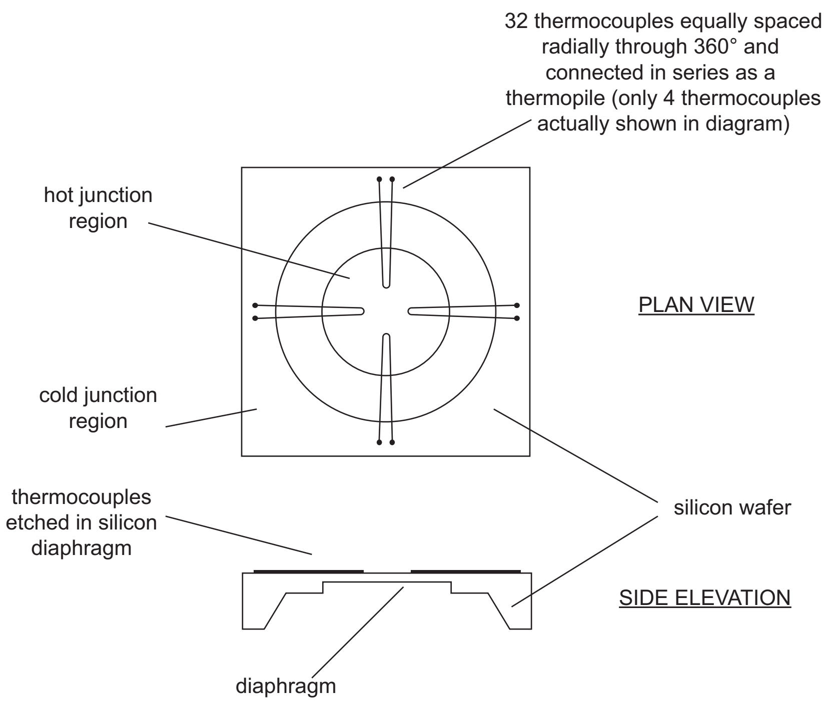


**Figure 14.19**
Thermopile-based MEMS temperature sensor.

cool outer part of sensor. All the thermocouples are connected in series to create the thermopile. Such thermal MEMS sensors frequently have integrated signal conditioning within the package. A typical commercially available device contains 32 thermocouples within a 4 × 4 mm package, with a measurement range from −40 °C up to +125 °C and a typical measurement inaccuracy of ±1 °C.

## 14.13 Choice between Temperature Transducers

The suitability of different instruments in any particular measurement situation depends substantially on whether the medium to be measured is a solid or a fluid. For measuring the temperature of solids, it is essential that good contact is made between the body and the transducer unless a radiation thermometer is used. This restricts the range of suitable transducers to thermocouples, thermopiles, RTDs, thermistors, semiconductor devices, and color indicators. On the other hand, fluid temperatures can be measured by any of the instruments described in this chapter, with the exception of radiation thermometers.

The most commonly used device in industry for temperature measurement is the base metal thermocouple. This is relatively cheap, with prices varying widely from a few pounds upward according to the thermocouple type and sheath material used. Typical inaccuracy is ±0.5% of full scale over the temperature range of −250 °C to +1200 °C. Noble metal thermocouples are much more expensive, but are chemically inert and can measure temperatures up to 2300 °C with an inaccuracy of ±0.2% of full scale. However, all types of thermocouple have a low-level output voltage, making them prone to noise and therefore unsuitable for measuring small temperature differences.

RTDs are also in common use within the temperature range of −270 °C to +650 °C, with a measurement inaccuracy of ±0.5%. While they have a smaller temperature range than thermocouples, they are more stable and can measure small temperature differences. The platinum RTD is generally regarded as offering the best ratio of price to performance for measurement in the temperature range of −200 °C to +500 °C, with prices starting from $20.

Thermistors are another relatively common class of devices. They are small and cheap, with a typical cost of around $5. They give a fast output response to temperature changes, with good measurement sensitivity, but their measurement range is quite limited.

Semiconductor devices have a better linearity than thermocouples and RTDs and a similar level of accuracy. Thus, they are a viable alternative to these in many applications. Integrated circuit transistor sensors are particularly cheap (from $10 each), although their accuracy is relatively poor and they have a very limited measurement range (−50 °C to +150 °C). Diode sensors are much more accurate and have a wider temperature range (−270 °C to +200 °C), though they are also more expensive (typical costs are anywhere from $60 to $700).

A major virtue of radiation thermometers is their noncontact, noninvasive mode of measurement. Costs vary from $300 up to $4000 according to type. Although calibration for the emissivity of the measured object often poses difficulties, some instruments now provide automatic calibration. Optical pyrometers are used to monitor temperatures above 600 °C in industrial furnaces, etc., but their inaccuracy is typically ±5%. Various forms of radiation pyrometers are used over the temperature range between −20 °C and +1800 °C and can give measurement inaccuracies as low as ±0.05%. One particular merit of narrowband radiation pyrometers is their ability to measure fast temperature transients of duration as small as 10 μs. No other instrument can measure transients anywhere near as fast as this.

The range of instruments working on the thermal expansion principle is mainly used as temperature-indicating devices rather than as components within automatic control schemes. Temperature ranges and costs are mercury-in-glass thermometers up to +1000 °C (cost from a few dollars), bimetallic thermometers up to +1500 °C (cost $60 to $150), and pressure thermometers up to +2000 °C (cost $150 to $750). The usual measurement inaccuracy is in the range of ±0.5% to ±1.0%. The bimetallic thermometer is more rugged than liquid-in-glass types but less accurate (however, the greater inherent accuracy of liquid-in-glass types can only be realized if the liquid meniscus level is read carefully).

Fiber-optic devices are more expensive than most other forms of temperature sensor (costing up to $6000) but provide a means of measuring temperature in very inaccessible locations. Inaccuracy varies from ±1% down to ±0.01% in some laboratory versions. Measurement range also varies with type, but up to +3600 °C is possible.

Color indicators are widely used to determine when objects in furnaces have reached the required temperature. These indicators work well if the rate of rise of temperature of the object in the furnace is relatively slow but, because temperature indicators only change color over a period of time, the object will be above the required temperature by the time that the indicator responds if the rate of rise of temperature is large. Cost is low, for example a crayon typically costs $4.

The latest devices in temperature measurement are MEMS sensors. These are low-cost devices with very small size and low-temperature consumption. Apart from their use as temperature sensors, they are also used for heat detection as a means of turning lights on and off when humans move in and out of an area.

## 14.14 Calibration of Temperature Transducers

The fundamental difficulty in establishing an absolute standard for temperature has already been mentioned in the introduction to this chapter. This difficulty is that there is no practical way in which a convenient relationship can be established that relates the temperature of a body to another measurable quantity that is expressible in primary standard units. Instead, it is necessary to use a series of reference calibration points for temperature that are very well defined. These points have been determined by research and international discussion and are published as the *International Practical Temperature Scale*. They provide fixed, reproducible reference points for temperature in the form of the freezing points and triple points[6] of substances where the transition between solid, liquid, and gaseous states is sharply defined. The full set of defined points is as follows:

- Triple point of hydrogen −259.3467 °C
- Triple point of neon −248.5939 °C
- Triple point of oxygen −218.7916 °C
- Triple point of argon −189.3442 °C
- Triple point of mercury −38.8344 °C
- Triple point of water +0.0100 °C
- Melting point of gallium +29.7646 °C
- Freezing point of indium +156.5985 °C
- Freezing point of tin +231.928 °C
- Freezing point of zinc +419.527 °C
- Freezing point of aluminum +660.323 °C
- Freezing point of silver +961.78 °C
- Freezing point of gold +1064.18 °C
- Freezing point of copper +1084.62 °C

For calibrating intermediate temperatures, interpolation between the fixed points is carried out by one of the following reference instruments:

A helium gas thermometer for temperatures below 24.6 K.
A platinum RTD for temperatures between 13.8 K and 961.8 °C.
A narrowband radiation thermometer for temperatures above +961.8 °C.

The triple point method of defining fixed points involves the use of a triple point cell. The cell consists of a sealed cylindrical glass tube that is filled with a highly pure version of the reference substance (e.g., mercury). This must be at least 99.9999% pure (such that contamination is less than one part in one million). The cell has a well that allows insertion of the thermometer being calibrated. It also has a valve that allows the cell to be evacuated down to the required triple point pressure.

The freezing point method of defining fixed points involves the use of an ingot of the reference metal (e.g., tin) that is better than 99.99% pure. This is protected against

[6] The triple point of a substance is the temperature and pressure at which the solid, liquid, and gas phases of that substance coexist in thermodynamic equilibrium. For example, in the case of water, the single combination of pressure and temperature at which solid ice, liquid water, and water vapor coexist in a stable equilibrium is a pressure of 611.73 mbars and temperature of 273.16 K (0.01 °C).

oxidation inside a graphite crucible with a close fitting lid. It is heated beyond its melting point and allowed to cool. If its temperature is monitored, an arrest period is observed in its cooling curve at the freezing point of the metal. The melting point method is similar but involves heating the material until it melts (this is only used for materials like gallium where the melting point is more clearly defined than the freezing point). Electric resistance furnaces are available to carry out these procedures. Up to 1100 °C, a measurement uncertainty of less than ±0.5 °C is achievable.

The accuracy of temperature calibration procedures is fundamentally dependent on how accurately points on the IPTS can be reproduced. The present limits are as follows:

| | | | |
|---|---|---|---|
| 1 K | 0.3% | 800 K | 0.001% |
| 10 K | 0.1% | 1500 K | 0.02% |
| 100 K | 0.005% | 4000 K | 0.2% |
| 273.15 K | 0.0001% | 10000 K | 6.7% |

### 14.14.1 Reference Instruments and Special Calibration Equipment

The primary reference standard instrument for calibration at the top of the calibration chain is either a helium gas thermometer, a platinum RTD, or a narrowband radiation thermometer according to the temperature range of the instrument being calibrated, as explained at the end of the last section. However, at lower levels within the calibration chain, almost any instrument from the list of instrument classes given in Section 14.1 might be used for workplace calibration duties in particular circumstances. Where involved in such duties, of course, the instrument used would be one of high accuracy that was reserved solely for calibration duties. The list of instruments that are suitable for workplace-level calibration therefore includes mercury-in-glass thermometers, base metal thermocouples (type K), noble metal thermocouples (types B, R, and S), platinum RTDs, and radiation pyrometers. However, a subset of this is commonly preferred for most calibration operations. Up to 950 °C, the platinum RTD is often used as a reference standard. Above that temperature up to about 1750 °C, a type S (platinum/rhodium–platinum) thermocouple is usually employed. Type K (chromel–alumel) thermocouples are also used as an alternative reference standard for temperature calibration up to 1000 °C.

Although no special types of instrument are needed for temperature calibration, the temperature of the environment within which one instrument is compared with another has to be carefully controlled. This requires purpose-designed equipment, which is available commercially from a number of manufacturers.

For calibration of all temperature transducers other than radiation thermometers above a temperature of 20 °C, a furnace consisting of an electrically heated ceramic tube is commonly used. The temperature of such a furnace can typically be controlled within limits of ±2 °C over the range from 20 °C to 1600 °C.

Below 20 °C, a stirred water bath is used to provide a constant reference temperature, and the same equipment can in fact be used for temperatures up to 100 °C. Similar stirred liquid baths containing oil or salts (potassium/sodium nitrate mixtures) can be used to provide reference temperatures up to 600 °C.

For the calibration of radiation thermometers, a radiation source which approximates as closely as possible to the behavior of a blackbody is required. The actual value of the emissivity of the source must be measured by a surface pyrometer. Some form of optical bench is also required so that instruments being calibrated can be held firmly and aligned accurately.

The simplest form of radiation source is a hot plate heated by an electrical element. The temperature of such devices can be controlled within limits of ±1 °C over the range from 0 °C to 650 °C, and the typical emissivity of the plate surface is 0.85. Type R noble metal thermocouples embedded in the plate are normally used as the reference instrument.

A blackbody cavity provides a heat source with a much better emissivity. This can be constructed in various alternative forms according to the temperature range of the radiation thermometers to be calibrated, though a common feature is a blackened conical cavity with a cone angle of about 15°.

For calibrating low-temperature radiation pyrometers (measuring temperatures in the range of 20 °C−200 °C), the blackbody cavity is maintained at a constant temperature (±0.5 °C) by immersing it in a liquid bath. The typical emissivity of a cavity heated in this way is 0.995. Water is suitable for the bath in the temperature range of 20 °C−90 °C and a silicone fluid is suitable for the range of 80 °C−200 °C. Within these temperature ranges, a mercury-in-glass thermometer is commonly used as the standard reference calibration instrument, although a platinum RTD is used when better accuracy is required.

Another form of blackbody cavity is one lined with a refractory material and heated by an electrical element. This gives a typical emissivity of 0.998 and is used for calibrating radiation pyrometers at higher temperatures. Within the range of 200 °C−1200 °C, temperatures can be controlled within limits of ±0.5 °C and a type R thermocouple is generally used as the reference instrument. At the higher range of 600 °C−1600 °C, temperatures can be controlled within limits of ±1 °C and a type B thermocouple (30% rhodium−platinum/6% rhodium−platinum) is normally used as the reference instrument. As an alternative to thermocouples, radiation thermometers can also be used as a standard within ±0.5 °C over the temperature range from 400 °C to 1250 °C.

To provide reference temperatures above 1600 °C, a carbon cavity furnace is used. This consists of a graphite tube with a conical radiation cavity at its end. Temperatures up to 2600 °C can be maintained with an accuracy of ±5 °C. Narrowband radiation thermometers are used as the reference standard instrument.

Again, the above equipment merely provides an environment in which radiation thermometers can be calibrated against some other reference standard instrument. To obtain an absolute reference standard of temperature, a fixed-point, blackbody furnace is used. This has a radiation cavity consisting of a conical-ended cylinder which contains a crucible of 99.999% pure metal. If the temperature of the metal is monitored as it is heated up at a constant rate, an arrest period is observed at the melting point of the metal where the temperature ceases to rise for a short time interval. Thus the melting point, and hence the temperature corresponding to the output reading of the monitoring instrument at that instant, is defined exactly. Measurement uncertainty is of the order of ±0.3 °C. The list of metals, and their melting points, was presented earlier at the start of Section 14.14.

In the calibration of radiation thermometers, knowledge of the emissivity of the hot plate or blackbody furnace used as the radiation source is essential. This is measured by special types of surface pyrometer. Such instruments contain a hemispherical, gold-plated surface which is supported on a telescopic arm that allows it to be put into contact with the hot surface. The radiation emitted from a small hole in the hemisphere is independent of the surface emissivity of the measured body and is equal to that which would be emitted by the body if its emissivity value was 100. This radiation is measured by a thermopile with its cold junction at a controlled temperature. A black hemisphere is also provided with the instrument which can be inserted to cover the gold surface. This allows the instrument to measure the normal radiation emission from the hot body and so allows the surface emissivity to be calculated by comparing the two radiation measurements.

Within this list of special equipment, mention must also be made of standard tungsten strip lamps which are used for providing constant known temperatures in the calibration of optical pyrometers. The various versions of these provide a range of standard temperatures between 800 °C and 2300 °C to an accuracy of ±2 °C.

### 14.14.2 Calculating Frequency of Calibration Checks

The simplest instruments from a calibration point of view are liquid-in-glass thermometers. The only parameter able to change within these is the volume of the glass used in their construction. This only changes very slowly with time, and hence only infrequent (e.g., annual) calibration checks are required.

The required frequency for calibration of all other instruments is either (1) dependent upon the type of operating environment and the degree of exposure to it or (2) use related. In some cases, both of these factors are relevant.

RTDs and thermistors are examples of instruments where the drift in characteristics depends on the environment they are operated in and on the degree of protection they have from that environment. Devices such as gas thermometers suffer characteristics drift which is largely a function of how much they are used (or misused!). Any instruments not mentioned so far suffer characteristics drift due to both environmental and use-related factors. The list of such instruments includes bimetallic thermometers, thermocouples, thermopiles, and radiation thermometers. In the case of thermocouples and thermopiles, error in the required characteristics is possible even when the instruments are new, and therefore their calibration must be checked before they are used for the first time.

As the factors responsible for characteristics drift vary from application to application, the required frequency of calibration checks can only be determined experimentally. The procedure for doing this is to start by checking the calibration of instruments used in new applications at very short intervals of time, and then to progressively lengthen the interval between calibration checks until a significant deterioration in instrument characteristics is observed. The required calibration interval is then defined as that time interval which is predicted to elapse before the characteristics of the instrument have drifted to the limits which are allowable in that particular measurement application.

Working and reference standard instruments and ancillary equipment must also be calibrated periodically. An interval of 2 years is usually recommended between such calibration checks, although monthly checks are advised for the blackbody cavity furnaces used to provide standard reference temperatures in pyrometer calibration. Standard RTDs and thermocouples may also need more frequent calibration checks if the conditions (especially of temperature) and frequency of use demand them.

### *14.14.3 Procedures for Calibration*

The standard way of calibrating temperature transducers is to put them into a temperature-controlled environment together with a standard instrument, or to use a radiant heat source of controlled temperature with high emissivity in the case of radiation thermometers. In either case, the controlled temperature must be measured by a standard instrument whose calibration is traceable to reference standards. This is a suitable method for most instruments in the calibration chain but is not necessarily appropriate or even possible for the process instruments at the lower end of the chain.

In the case of many process instruments, their location and mode of fixing makes it difficult or sometimes impossible to remove them to a laboratory for calibration checks to be carried out. In this event, it is standard practice to calibrate them in their normal operational position, using a reference instrument which is able to withstand whatever hostile environment may be present. If this practice is followed, it is imperative that the working standard instrument is checked regularly to ensure that it has not been contaminated.

Such *in situ calibration* may also be required where process instruments have characteristics which are sensitive to the environment in which they work, so that they are calibrated under their usual operating conditions and are therefore accurate in normal use. However, the preferred way of dealing with this situation is to calibrate them in a laboratory with ambient conditions (of pressure, humidity etc.) set up to mirror those of the normal operating environment. This alternative avoids having to subject reference calibration instruments to harsh chemical environments which are commonly associated with manufacturing processes.

For instruments at the lower end of the calibration chain, that is, those measuring process variables, it is common practice to calibrate them against an instrument which is of the same type but of higher accuracy and reserved only for calibration duties. If a large number of different types of instruments have to be calibrated, however, this practice leads to the need to keep a large number of different calibration instruments. To avoid this, various reference instruments are available which can be used to calibrate all process instruments within a given temperature-measuring range. Examples are the liquid-in-glass thermometer (0 °C to +200 °C), platinum RTD (−200 °C to +1000 °C), and type S thermocouple (+600 °C to +1750 °C). The optical pyrometer is also often used as a reference instrument at this level for the calibration of other types of radiation thermometers.

For calibrating instruments further up the calibration chain, particular care is needed with regard to both the instruments used and the conditions they are used under. It is difficult and expensive to meet these conditions and hence this function is subcontracted by most companies to specialist laboratories. The reference instruments used are the platinum RTD in the temperature range of −200 °C to +1000 °C, the platinum−platinum/10% rhodium (type S) thermocouple in the temperature range of +1000 °C to +1750 °C, and a narrowband radiation thermometer at higher temperatures. An exception is *optical pyrometers*, which are calibrated as explained in the final paragraph of this section about calibration. A particular note of caution must be made where platinum−rhodium thermocouples are used as a standard. These are very prone to contamination and, if they need to be handled at all, this should be done with very clean hands.

Before ending this chapter, it is appropriate to mention one or two special points that concern the calibration of thermocouples. The mode of construction of thermocouples means that their characteristics can be incorrect even when they are new, due to faults in either the homogeneity of the thermocouple materials or in the construction of the device. Therefore, calibration checks should be carried out on all new thermocouples before they are put into use. The procedure for this is to immerse both junctions of the thermocouple in an ice bath and measure its output with a high accuracy digital voltmeter ($\pm 5\ \mu V$). Any output greater than $5\ \mu V$ would indicate a fault in the thermocouple material and/or its construction. After this check on thermocouples when they are brand new, the subsequent rate of change of thermoelectric characteristics with time is entirely dependent upon the operating environment and the degree of exposure to it. Particularly relevant factors in the environment are the type and concentration of trace metal elements and the temperature (the rate of contamination of thermocouple materials with trace elements of metals is a function of temperature). A suitable calibration frequency can therefore only be defined by practical experimentation, and this must be reviewed whenever the operating environment and conditions of use change. A final word of caution when calibrating thermocouples is to ensure that any source of electrical or magnetic fields is excluded, since these will induce erroneous voltages in the sensor.

Special comments are also relevant regarding the calibration of a *radiation thermometer.* As well as the normal accuracy checks, its long-term stability must also be verified by testing its output over a period which is 1 h longer than the manufacturer's specified "warm-up" time. This shows up any components within the instrument which are suffering from temperature-induced characteristics drift. It is also necessary to calibrate radiation thermometers according to the emittance characteristic of the body whose temperature is being measured and according to the level of energy losses in the radiation path between the body and measuring instrument. Such emissivity calibration must be carried out for every separate application that the instrument is used for, using a surface pyrometer.

Finally, it should be noted that the usual calibration procedure for *optical pyrometers* is to sight them on the filament of a tungsten strip lamp in which the current is accurately measured. This method of calibration can be used at temperatures up to 2500 °C. Alternatively, they can be calibrated against a standard radiation pyrometer.

## 14.15 Summary

Our review at the start of the chapter revealed that there are 10 different physical principles that are commonly used as the basis for temperature-measuring devices. During the course of the chapter, we have then looked at how each of these principles is exploited in various classes of temperature-measuring devices.

We started off by looking at the thermoelectric effect and its use in thermocouples and thermopiles, and also the derived devices of digital thermometers and continuous thermocouples. Thermocouples are the most commonly used device for industrial applications of temperature measurement. However, despite their relatively simple operating concept of generating an output voltage as a function of the temperature they are exposed to, proper use of thermocouples requires an understanding of two thermoelectric laws. These laws were presented and their application was explained by several examples. We also saw how the output of a thermocouple has to be interpreted by thermocouple tables. We went on to look at the different types of thermocouples that are available, which range from a number of cheap, base metal types to expensive ones based on noble metals. We looked at the typical characteristics of these and discussed typical applications. Moving on, we noted that thermocouples are quite delicate devices that can suffer from both mechanical damage and chemical damage in certain operating environments, and we discussed ways of avoiding such problems. We also briefly looked at how thermocouples are made.

Our next subject of study concerned RTDs and thermistors, both of these being devices that convert a change in temperature into a change in the resistance of the device. We noted that both of these are also very commonly used measuring devices. We looked at the theoretical principles of each of these and discussed the range of materials used in each class of device. We also looked at the typical device characteristics for each construction material.

Next, we looked at semiconductor devices in the form of diodes and transistors and discussed their characteristics and mode of operation. This discussion revealed that, although these devices are cheaper and more linear than both thermocouples and RTDs, their typical measurement range is relatively low. This limits their applicability and means that they are not used as widely as they would be if their measurement range was greater.

Moving on, we looked at the class of device known as radiation thermometers (alternatively known as radiation pyrometers), which exploit the physical principle that the peak wavelength of radiated energy emission from a body varies with temperature. The instrument is used by pointing it at the body to be measured and analyzing the radiation emitted from the body. This has the advantage of being a noncontact mode of temperature measurement, which is highly attractive in the food and drug industries and any other application where contamination of the measured quantity has to be avoided. We also observed that different versions of radiation thermometers are capable of measuring temperatures between $-100\,^{\circ}\mathrm{C}$ and $+10{,}000\,^{\circ}\mathrm{C}$, with measurement inaccuracy as low as $\pm 0.05\%$ in the more expensive versions. Despite these obvious merits, careful calibration of the instrument to the type of body being measured is essential, since the characteristics of radiation thermometers are critically dependent on the emissivity of the measured body, which varies widely between different materials.

This stage in the chapter marked the end of discussion of the four most commonly used types of temperature-measuring device. The remaining techniques all have niche applications but not of these are "large volume" uses. The first one covered of these "other techniques" was thermography. Also known as thermal imaging, this involves scanning an infrared radiation detector across either a single object or a scene containing several objects. The information gathered is then processed and an output in the form of the temperature distribution across the object is produced. It thus differs from other forms of temperature sensors in providing information on temperature distribution across an object or scene rather than the temperature at a single discrete point. Temperature measurement over the range from $-20\ ^\circ C$ up to $+1500\ ^\circ C$ is possible.

Our next subject of study concerned the liquid-in-glass thermometer, the bimetallic thermometer, and the pressure thermometer. These are all usually classed as thermal expansion-based devices, although this is not strictly true in the case of the last one, which is based on the change in pressure of a fluid inside a fixed-volume stainless-steel bulb. The characteristics and typical applications of each of these were discussed.

Moving on, we then looked at fiber-optic temperature sensors. We saw that their main application is measuring temperatures in hard-to-reach locations, though they are also used when very high measurement accuracy is required.

Next, we discussed color indicators. These mainly consist of special paints or crayons that change color at a certain temperature. They are primarily used to determine when the temperature of objects place in a furnace reach a given temperature. They are relatively cheap, and different paints and crayons are available to indicate temperatures between $50\ ^\circ C$ and $1250\ ^\circ C$. In addition, certain liquid crystals that change color at a certain temperature are also used as color indicators. These have better measurement resolution than paints and crayons and, while some versions can indicate low temperatures down to $-20\ ^\circ C$, the highest temperature that they can indicate is $+100\ ^\circ C$.

Finally, our discussion of the application of different physical principles in temperature measurement brought us to Seger cones. Also known as pyrometric cone, these have a conical shape where the tip melts and bends over at a particular temperature. They are commonly used in the ceramics industry to detect a given temperature is reached in a furnace.

The chapter then continued with a look at intelligent measuring devices. These are designed for use with various sensors such as thermocouples, thermopiles, RTDs, thermistors, and broadband radiation pyrometers. Intelligence within the device gives them features like adjustable damping, noise rejection, self-adjustment for zero and sensitivity drifts, self-fault diagnosis, self-calibration, reduced maintenance requirement, and an expanded measurement range. These features reduce typical measurement inaccuracy down to $\pm 0.05\%$ of full scale.

This completion of the discussion on all types of intelligent and non-intelligent devices allowed us to go on to consider the mechanisms by which a temperature-measuring device is chosen for a particular application. We reviewed at the characteristics of each type of device in turn and looked at the sort of circumstances in which each might be used.

Our final subject of study in the chapter was that of calibrating temperature-measuring devices. We noted first of all that there was a fundamental difficulty in establishing an absolute standard for temperature and that, in the absence of such a standard, fixed reference points for temperature were defined in the form of the freezing points and triple points of certain substances. We then went on to look at the calibration instruments and equipment that are used in workplace calibration. We also established some guidelines about how the frequency of calibration should be set. Finally, we looked in more detail at the appropriate practical procedures for calibrating various types of sensors.

## 14.16 Problems

14.1 Briefly discuss the different physical principles that are used in temperature-measuring instruments and give examples of instruments that use each of these principles.

14.2 (a) How are thermocouples manufactured? (b) What are the main differences between base metal and noble metal thermocouples? (c) Give six examples of the materials used to make base metal and noble metal thermocouples, (d) Specify the international code letter used to designate the thermocouples made from each pair of materials that you give in your answer to part (c).

14.3 Explain what each of the following are in relation to thermocouples: (a) extension leads, (b) compensating leads, (c) law of intermediate metals, (d) law of intermediate temperature.

14.4. What type of base metal thermocouple would you recommend for each of the following applications?

- (i) measurement of subzero temperatures
- (ii) measurement in oxidizing atmospheres
- (iii) measurement in reducing atmospheres
- (iv) where high sensitivity measurement is required

14.5 Why do thermocouples need protection from some operating environments and how is this protection given? Discuss any differences between base metal and noble metal thermocouples in the need for protection.

14.6 The temperature of a fluid is measured by immersing an iron–constantan thermocouple in it. The reference junction of the thermocouple is maintained at 0 °C in an ice bath and an output emf of 5.812 mV is measured. What is the indicated fluid temperature?

14.7 The output emf from a chromel–alumel thermocouple (type K), with its reference junction maintained at 0 °C, is 12.207 mV. What is the measured temperature?

14.8 The temperature of a fluid is measured by immersing a type K thermocouple in it. The reference junction of the thermocouple is maintained at 0 °C in an ice bath and an output emf of 6.435 mV is measured. What is the indicated fluid temperature?

14.9 (a) Draw a graph of the output emf from a nicrosil–nisil thermocouple (type N) over the temperature range from 0 °C to 650 °C by reading appropriate data from a thermocouple table. Assume that the reference junction of the thermocouple is maintained at 0 °C in an ice bath.

(b) Calculate the measurement sensitivity of the thermocouple over the temperature range from 450 °C to 650 °C.

14.10 The output emf from a nicrosil–nisil thermocouple (type N), with its reference junction maintained at 0 °C, is 4.21 mV. What is the measured temperature?

14.11 The output emf from a chromel–constantan thermocouple whose hot junction is immersed in a fluid is measured as 18.25 mV. The reference junction of the thermocouple is maintained at 0 °C. What is the temperature of the fluid?

14.12 A type S, platinum/10% rhodium–platinum thermocouple is used to measure the temperature of a furnace. The output emf is 17.62 mV with its reference junction maintained at 0 °C. What is the temperature of the furnace?

14.13 (a) Draw a graph of the output emf from a chromel–alumel thermocouple (type K) and from a copper–constantan thermocouple (type T) over the temperature range from 0 °C to 550 °C by reading appropriate data from a thermocouple table. Assume that the reference junction of the thermocouple is maintained at 0 °C in an ice bath. Draw the graphs for both thermocouples on the same piece of graph paper.

(b) Calculate the measurement sensitivity of each thermocouple over the temperature range from 250 °C to 400 °C.

14.14 A copper–constantan thermocouple is connected to copper–constantan extension wires and the reference junction exposed to a room temperature of 20 °C. If the output voltage measured is 6.537 mV, what is the indicated temperature at the hot junction of the thermocouple?

14.15 A nicrosil–nisil thermocouple is connected to nicrosil–nisil extension wires and the reference junction exposed to a room temperature of 21 °C. If the output voltage measured is 10.37 mV, what is the indicated temperature at the hot junction of the thermocouple?

14.16 A platinum/10% rhodium–platinum (type S) thermocouple is used to measure the temperature of a furnace. The output emf, with the reference junction maintained at 50 °C, is 5.975 mV. What is the temperature of the furnace?

14.17 (a) Draw a graph of the output emf from a chromel–constantan thermocouple (type E) and from a platinum/10% rhodium–platinum thermocouple (type S) over the temperature range from 0 °C to 600 °C by reading appropriate data from a thermocouple table. Assume that the reference junction of the thermocouple is maintained at 0 °C in an ice bath. Draw the graphs for both thermocouples on the same piece of graph paper.

(b) Calculate the measurement sensitivity of each thermocouple over the temperature range from 250 °C to 600 °C.

14.18 A chromel–alumel (type K) thermocouple is used to measure the temperature of a hot fluid. The output emf, with the reference junction maintained at 30 °C, is 33.6 mV. What is the temperature of the fluid?

14.19 A chromel–constantan (type E) thermocouple is used to measure the temperature of a furnace. The output emf, with the reference junction maintained at 18 °C, is 16.75 mV. What is the temperature of the furnace?

14.20 A iron–constantan (type J) thermocouple is used to measure the temperature of a hot fluid. The output emf, with the reference junction maintained at 16 °C, is 24.58 mV. What is the temperature of the fluid?

14.21 In a particular industrial situation, a nicrosil–nisil thermocouple with nicrosil–nisil extension wires is used to measure the temperature of a fluid. In connecting up this measurement system, the instrumentation engineer responsible has inadvertently interchanged the extension wires from the thermocouple. The ends of the extension wires are held at a reference temperature of 0 °C and the output emf measured is 21.0 mV. If the junction between the thermocouple and extension wires is at a temperature of 50 °C, what temperature of fluid is indicated and what is the true fluid temperature?

14.22 A copper–constantan thermocouple measuring the temperature of a hot fluid is connected by mistake with chromel–constantan extension wires (such that the two constantan wires are connected together and the chromel extension wire is connected to the copper thermocouple wire). If the actual fluid temperature was 150 °C, the junction between the thermocouple and extension wires was at 80 °C, and the reference junction was at 0 °C, calculate the emf measured at the open ends of the extension wires. What fluid temperature would be deduced from this measured emf (assuming that the error of using the wrong extension wires was not known about)? (Hint: apply the law of intermediate metals for the thermocouple extension lead junction).

14.23 In a particular industrial situation, a chromel–constantan thermocouple with chromel–constantan extension wires is used to measure the temperature of a fluid. In connecting up this measurement system, the instrumentation engineer responsible has inadvertently interchanged the extension wires from the thermocouple. The ends of the extension wires are held at a reference temperature of 0 °C and the output emf measured is 28.62 mV. If the junction between the thermocouple and extension wires is at a temperature of 40 °C, what temperature of fluid is indicated and what is the true fluid temperature?

14.24 Suppose that an engineer has installed a chromel–constantan thermocouple but has incorrectly used copper–constantan extension leads (such that the two constantan wires were connected together and the copper extension wire was connected to the chromel thermocouple wire). If the thermocouple was measuring a hot fluid whose real temperature is 150 °C, the junction between the thermocouple and the extension leads was at 80 °C and the reference junction was at 0 °C:

(a) Calculate the emf (voltage) measured at the open ends of the extension wires.

(b) What fluid temperature would be deduced from this measured emf (assuming that the error in using the incorrect leads was not known about)?

14.25 While installing a chromel–constantan thermocouple to measure the temperature of a fluid, it is connected by mistake with copper–constantan extension leads (such that the two constantan wires are connected together and the copper extension wire is connected to the chromel thermocouple wire). If the fluid temperature was actually 250 °C, and the junction between the thermocouple and extension wires was at 80 °C, what emf would be measured at the open ends of the extension wires if the reference junction is maintained at 0 °C? What fluid temperature would be deduced from this (assuming that the connection mistake was not known about)?

14.26 In connecting extension leads to a chromel–alumel thermocouple which is measuring the temperature of a fluid, a technician connects the leads the wrong way round (such that the chromel extension lead is connected to the alumel thermocouple lead and vice versa). The junction between the thermocouple and extension leads is at a temperature of 100 °C and the reference junction is maintained at 0 °C in an ice bath. The technician measures an output emf of 12.212 mV at the open ends of the extension leads.

(a) What fluid temperature would be deduced from this measured emf?

(b) What is the true fluid temperature?

14.27 A chromel–constantan thermocouple measuring the temperature of a fluid is connected by mistake with copper–constantan extension leads (such that the two constantan wires are connected together and the copper extension lead wire is connected to the chromel thermocouple wire. If the fluid temperature was actually 250 °C and the junction between the thermocouple and extension leads was at 90 °C, what emf would be measured at the open ends of the extension leads if the reference junction is maintained at 0 °C? What fluid temperature would be deduced from this (assuming that the connection error was not known about)?

14.28 The extension leads used to measure the output emf of an iron–constantan thermocouple measuring the temperature of a fluid are connected the wrong way round by mistake (such that the iron extension lead is connected to the constantan thermocouple wire and vice versa). The junction between the thermocouple and extension leads is at a temperature of 120 °C and the reference junction is at room temperature of 21 °C. The output emf measured at the open ends of the extension leads is 27.390 mV.

(i) What fluid temperature would be deduced from this measured emf (assuming that the mistake of connecting the extension leads the wrong way round was not known about)?

(ii) What is the true fluid temperature?

14.29 The temperature of a hot fluid is measured with a copper–constantan thermocouple but, by mistake, this is connected to chromel–constantan extension wires (such that the two constantan wires are connected together and the chromel extension wire is connected to the copper thermocouple wire. If the actual fluid temperature was 200 °C, the junction between the thermocouple and extension wires was at 50 °C and the reference junction was at 0 °C, calculate the emf measured at the open ends of the extension wires. What fluid temperature would be deduced from this measured emf (assuming that the error of using the wrong extension wires was not known about)?

14.30 In a particular industrial situation, a chromel–alumel thermocouple with chromel–alumel extension wires is used to measure the temperature of a fluid. In connecting up this measurement system, the instrumentation engineer responsible has inadvertently interchanged the extension wires from the thermocouple (such that the chromel thermocouple wire is connected to the alumel extension lead wire etc.). The open ends of the extension leads are held at a reference temperature of 0 °C and are connected to a voltmeter which measures an emf of 18.75 mV. If the junction between the thermocouple and extension wires is at a temperature of 38 °C:

(i) What temperature of fluid is indicated?

(ii) What is the true fluid temperature?

14.31 A copper–constantan thermocouple measuring the temperature of a hot fluid is connected by mistake with iron–constantan extension wires (such that the two constantan wires are connected together and the iron extension wire is connected to the copper thermocouple wire). If the actual fluid temperature was 200 °C, the junction between the thermocouple and extension wires was at 160 °C and the reference junction was at 0 °C, calculate the emf measured at the open ends of the extension wires. What fluid temperature would be deduced from this measured emf (assuming that the error of using the wrong extension wires was not known about)?

14.32 In a particular industrial situation, a nicrosil–nisil thermocouple with nicrosil–nisil extension wires is used to measure the temperature of a fluid. In connecting up this measurement system, the instrumentation engineer responsible has inadvertently interchanged the extension wires from the thermocouple (such that the nicrosil thermocouple wire is connected to the nisil extension lead wire etc.). The open ends of the extension leads are held at a reference temperature of 0 °C and are connected

to a voltmeter which measures an emf of 17.51 mV. If the junction between the thermocouple and extension wires is at a temperature of 140 °C:
(i) What temperature of fluid is indicated?
(ii) What is the true fluid temperature?

14.33 Explain what the following are: thermocouple, continuous thermocouple, thermopile, digital thermometer.

14.34 What is the International Practical Temperature Scale? Why is it necessary in temperature sensor calibration and how is it used?

14.35 RTDs and thermistors are both temperature-measuring devices that convert the measured temperature into a resistance change. What are the main differences between these two types of devices in respect of the materials used in their constructions, their cost, and their operating characteristics?

14.36 Discuss the main types of radiation thermometers that are available. How do they work and what are their main applications?

14.37 Name three kinds of temperature-measuring devices that work on the principle of thermal expansion. Explain how each works and what their typical characteristics are.

14.38 Explain how fiber-optic cables can be used as temperature sensors.

14.39 Discuss the calibration of temperature sensors, mentioning what reference instruments are typically used.

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