Chapter 4

Temperature sensors and thermal transducers

4.1 Heat and temperature

The physical quantity that we call *heat* is one of the many forms of energy, and an amount of heat is measured in the usual energy units of joules. The quantity of heat contained in an object cannot be measured, but we can measure changes of heat content that take place when there is a change of *temperature* or a change of physical *state* (solid to liquid, liquid to gas, one crystalline form to another). In this sense, then, *temperature* is a measure of the level of heat for a material whose physical state has remained unchanged. The relationship between temperature and energy is very similar to that between voltage level and electrical energy.

The temperature sensors that we use all depend on changes that take place in materials as their temperatures change. Transducers for electrical to thermal energy make use of the heating effect of a current through a conductor, but transducers for thermal to electrical energy are not so direct, and in accordance with the laws of thermodynamics will require a temperature difference to operate, taking heat in at a higher temperature and discharging some heat at a lower temperature.

4.2 The bimetallic strip

sensori bimetallici

Thermal sensing is important for the detection of effects as diverse as fire, overheating, or the failure of a freezer. The simplest type of thermal sensor is the *bimetallic* type, whose principle is illustrated in Figure 4.1. A compound strip is formed by riveting or welding two layers of metals, chosen so as to have very different values of *linear expansivity*. The linear expansivity (old name, expansion coefficient) is the fractional change of length per degree change of temperature and for all metals is positive,

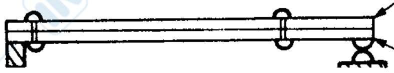

Figure 4.1 The bimetallic strip consists of two metal strips welded or riveted together. The strip can be extended into a spring shape for greater sensitivity, or can consist of two welded discs that will buckle when heated.

Table 4.1 Linear expansivity values for some metals – multiply figure shown by 10^{-5} for value. Because the metals do not expand by the same amount, however, the strip will bend as the temperature changes, as indicated in Figure 4.2.

Metal/Alloy	Expansivity	Metal/Alloy	Expansivity
Aluminium	2.4	Brass	2.1
Bronze	1.9	Chromium	0.85
Constantan	1.5	Copper	1.6
Invar	0.2	Iron	1.2
Magnesium	2.6	Manganin	1.6
Nickel	1.3	Platinum	0.90
Silver	1.9	Stainless steel	1.0
Tantalum	0.65	Tin	2.7
Tungsten	0.43	Zinc	2.6

Figure 4.2 If one metal has a higher expansivity than the other, the strip will bend when heated, with the metal of higher expansivity on the outer side of the sector of the circle.

meaning that the strip expands as the temperature increases. Table 4.1 shows expansivity values for some metals in units of $K^{-1} \times 0^{-5}$.

This bending action can be sensed by a displacement transducer of any of the types discussed in Chapter 2, but is more often used to operate switch contacts, usually with the strip itself carrying one contact. The conventional type of bimetallic strip element is still to be found in some thermostats, although the strip is very often arranged into a spiral. This allows for much greater sensitivity, since the sensitivity depends on the length of the strip. The amount of deflection can be fairly precisely proportional to temperature change if the temperature range is small.

Thermostats of this type, however, have an undesirably large *hysteresis*, so that, for example, a thermostat set for a nominal 20°C might open at 22°C

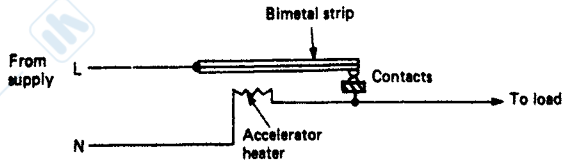

Figure 4.3 Using an accelerator with a bimetal thermostat. The accelerator ensures that the rate of rise of temperature at the thermostat is greater than that of the surroundings, so overcoming the hysteresis of the thermostat to some extent.

and close again at 18°C. This leads to undesirable temperature swings which can nullify the use of a thermostat. For example, with a bimetallic thermostat used to control room temperature the effect of the hysteresis is likely to be that the occupants of a room ignore the thermostat and turn the radiators directly on or off, or use the thermostat simply as an on/off switch. The hysteresis of the simple bimetal thermostat can be reduced by the use of an *accelerator*, consisting of a high-value resistor placed close to the element. The principle is that when the thermostat contacts close to switch on heating in a room, current is passed through the accelerator resistor (Figure 4.3) so that the rate of heating within the thermostat is faster than outside. See Chapter 10 for details of switch contacts.

This leads to the thermostat points opening before the same temperature is achieved in the room outside. The current through the accelerator resistor then switches off, and the thermostat will then cool more rapidly than the room so that the switch-on is more rapid than would otherwise be the case. The use of an accelerator, however, can lead to the desired working temperature being achieved very slowly or not at all in cold weather, and much too rapidly in hot weather. This has led to the use of more sensitive devices for thermostat use, based on thermistors (see later in this chapter).

The bimetallic strip exists in several physical forms, and one particularly useful form is the disc (Figure 4.4). For a change of temperature, a bimetallic disc will abruptly buckle giving a snap-over action that requires no form of assistance. This is the basis of the small thermal switches that are used for overheating protection in electronic equipment. These thermal switches can be bolted to heat sinks, small motors, transformers, jug-kettles, or other components that are likely to overheat and have a metallic surface.

Thermal switches can be bought as normally open or normally closed types, depending on whether they are to be used to detect rising or falling temperatures. The pre-set nominal temperatures have temperature hysteresis of the order of 3–5°C on each side of the set temperature since no accelerator is used. For more precise control, units that use long bimetal strips can be obtained with smaller hysteresis and variable setting temperature.

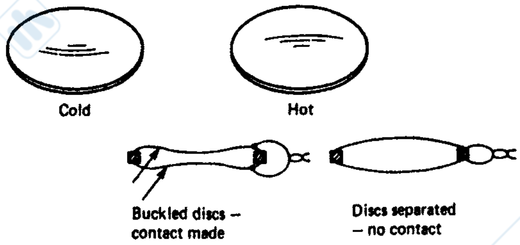

Figure 4.4 Bimetallic discs are used extensively as sensors for overheating components such as transformer windings and electric motors.

All types of long-element bimetal strip thermostats should be recalibrated at intervals, since the strip is subject to gradual changes (creep) that affect the thermostat setting.

4.3 Liquid and gas expansion

An older principle used in temperature sensing is liquid expansion in conjunction with a pressure switch, making use of the principles of the familiar mercury thermometer. The simplest sensor of this type is an adaptation of a mercury thermometer with two wire electrodes inset into the capillary (Figure 4.5). Since mercury is a conducting metal, a circuit will be made through the electrodes when the mercury level reaches the electrode whose

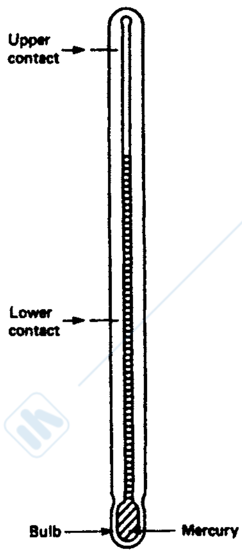

Figure 4.5 A temperature switch developed from an ordinary mercury thermometer using wire electrodes embedded in the glass tubing.

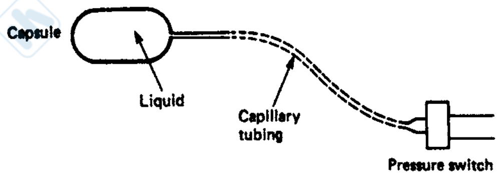

Figure 4.6 A liquid bulb and pressure sensor method for temperature sensing. The volume of liquid in the capillary tubing should be negligible compared to the volume of liquid in the bulb.

position corresponds to the higher temperature. This allows a predetermined temperature to be sensed, but for a switching action only and with no way of altering the temperature at which switching takes place other than by replacing the sensor with another one.

Although the mercury level can be used to change the frequency of an oscillating circuit and thus to provide a proportional sensing of temperature, this type of action is seldom used. The sensors that are used for temperature measurement as distinct from switching are mainly of the electronic type, including thermocouples and thermistors, and devices that make use of mechanical expansion are more likely to be used in switching circuits. The most common type is a development of the conventional bulb thermometer and has a sensing element (Figure 4.6) consisting of a capsule filled with liquid that is connected by a narrow-bore tube to the pressure switch. The liquid need not be mercury, and is nowadays more likely to be a form of synthetic oil.

Since the capsule can be remote, and involves no electrical connections, this is often a very useful method to use for hazardous environments, and the liquid can be chosen accordingly. The length of connecting tubing must be such that the volume of liquid contained in the tubing is only a small fraction of the total volume, since the temperature of the liquid in the tubing will also affect the pressure. The use of air or an inert gas in place of a liquid makes the device very much more sensitive, but the pressure switch needs to be able to respond to much lower pressures than are exerted by an expanding liquid.

One disadvantage of the system in general is that the sensing capsule needs to contain a reasonable volume of liquid and so cannot be small. In addition, since this volume of material has to be heated and cooled in order to follow temperature fluctuations, time is needed for the change, so that capsules cannot follow rapidly changing temperatures. The pressure sensor need not be a switching device, and the use of a diaphragm coupled to a potentiometer, LVDT or piezoelectric transducer can make the liquid/bulb type of temperature sensor into a fairly precise instrument, although this combination has few applications.

4.4 Thermocouples

THEORY

The thermocouple is frequently used as the sensing element in a thermal sensor or switch. The principle is that two dissimilar metals always have a (small) contact potential between them, and this contact potential changes as the temperature changes. The contact potential cannot be measured for a single connection (or junction), but when two junctions are in a circuit with the junctions at different temperatures, then a voltage of a few millivolts can be detected (Figure 4.7). This voltage will be zero if the junctions are at the same temperature, and will increase as the temperature of one junction relative to the other is changed until a peak is reached. The shape of the typical characteristic is shown in Figure 4.8, from which you can see

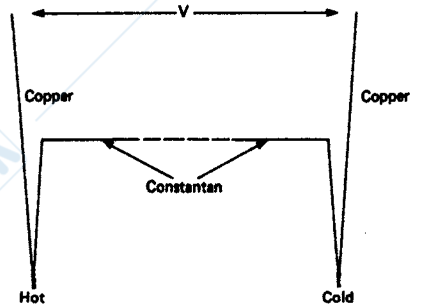

Figure 4.7 The construction of a thermocouple, in this example using copper and constantan alloy.

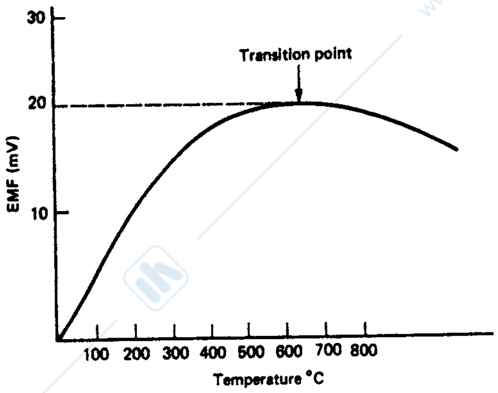

Figure 4.8 A thermocouple characteristic, showing the typical curvature and the transition point at which the characteristic reverses. A few combinations of metals (like copper/silver) have no transition, but have a very low output.

Table 4.2 The EMF (in mV) at 100°C difference for platinum/metal thermocouples.

Metal/Alloy	EMF in mV	Metal/Alloy	EMF in mV
Aluminium	0.4	Constantan	−3.3
Copper	0.75	Iron	1.88
Manganin	0.65	Molybdenum	1.2
Nickel	−1.5	Silicon	45.0
Silver	0.7	Tungsten	0.8

that the thermocouple is useful only over a limited range of temperature due to the non-linear shape of the characteristic and the reversal that takes place at temperatures higher than the turn-over point.

The thermocouple makes use of the Seebeck effect, and the theory of this leads to an equation for EMF:

$$E = a + b\theta + c\theta^2$$

where a, b and c are constants for the types of metals used in the thermocouple and θ is the temperature difference between them. If the cold junction is held at 0°C, then the EMF equation becomes:

$$E = \alpha T^2 + \beta T$$

where α and β are measured constants for the pair of metals, and T is the temperature difference. For temperatures below the transition point α is usually small, so that the EMF is almost directly proportional to temperature difference.

- The Peltier effect, see later, is the reverse of the Seebeck effect.
- The Kelvin effect is much less well-known, and it concerns EMF generated in a conductor with no junctions. In such a conductor, a temperature difference between two different parts of the conductor will cause an EMF to be developed.

When an electric current flows through a conductor whose ends are maintained at different temperatures, heat is released at a rate approximately proportional to the product of the current and the temperature gradient.

- Any practicable circuit including a thermocouple will contain more than two junctions of differing metals, and the circuits have to be designed so that only the intended junctions are at different temperatures.

The output from a thermocouple is small, of the order of millivolts for a 10°C temperature difference, and Table 4.2 shows typical EMF values for metals and alloys, using platinum as the other metal of the couple. Table 4.3 shows values of EMF and temperature difference for three commonly

Table 4.3 More detailed characteristics for three important thermocouple types, showing the useful range of temperature differences and EMF values in mV when the cold end of the thermocouple is at 0°C.

Temperature °C	Copper/ Constantan	Iron/ Constantan	Platinum/ Plat.Rhodium
−20	−0.75	−1.03	
−10	−0.38	−0.52	
0	0.00	0.00	0.00
10	0.39	0.52	0.05
20	0.79	1.05	0.11
30	1.19	1.58	0.17
40	1.61	2.12	0.23
50	2.04	2.66	0.30
60	2.47	3.20	0.36
70	2.91	3.75	0.43
80	3.36	4.30	0.50
90	3.81	4.85	0.57
100	4.28	5.40	0.64
200	9.28	10.99	1.46
300	14.86	16.57	2.39
400	20.87	22.08	3.40
500		27.59	4.46
600		33.28	5.57
700		39.30	6.74
800		45.71	7.95
900		52.28	9.21
1000		58.23	10.51
1200			13.22
1500			17.46

used thermocouple materials. Of these, the copper/constantan type is used mainly for the lower range of temperatures and the platinum/rhodium type for the higher temperatures. Because of the small voltage output, amplification is usually needed, unless the thermocouple is used for temperature measurement, together with a sensitive millivoltmeter. If the output of the thermocouple is required to drive anything more than a meter movement, then DC amplification will be needed, using an operational amplifier or chopper amplifier (see Chapter 12). The type of amplifier that is used needs to be carefully selected, because good drift stability is necessary unless the device is recalibrated at frequent intervals. This makes the chopper type of amplifier preferable for most applications.

If an on/off switching action is required, the thermocouple must be used along with a controller that uses a Schmitt trigger type of circuit which also permits adjustment of bias so that the switching temperature can be pre-set. The usual circuitry includes amplification, because the lower ranges of thermocouple outputs are comparable with the contact potentials (the same type of effect) in amplifier circuits, and attempting to use very small inputs for switching invariably leads to problems of low hysteresis and excessive sensitivity.

One particular advantage of thermocouples is that the sensing elements themselves are very small, allowing thermocouples to be inserted into very small spaces and to respond to rapidly changing temperatures. The electrical nature of the process means that the circuitry for reading the thermocouple output can be remote from the sensor itself. Note that thermocouple effects will be encountered wherever one metallic conductor meets another, so that temperature differences along circuit boards can also give rise to voltages that are comparable with the output from thermocouples. The form of construction of amplifiers for thermocouples is therefore important, and some form of zero setting is needed.

PRACTICAL USE

Thermocouples are very widely used industrially, making the thermocouple one of the most important of temperature sensors. Of the many possible combinations of metals that could be used for thermocouples, only a few are practical from the consideration of a reasonably linear scale and good resistance to high temperatures. Table 4.4 shows the most commonly used

Table 4.4 The most common thermocouple types, with their code letters.

Code	Metals	Range	mV @ 100°C	Notes
S	PtRh/Pt	0–1400°C	0.645	Needs ceramic sheath
R	PtRh/Pt	0–1400°C	0.647	Needs ceramic sheath
J	Fe/CuNi	0–800°C	5.268	Attacked by oxygen or acids
K	NiCr/NiAl	0–1100°C	4.095	Avoid reducing agents
T	Cu/CuNi	−200°C to +400°C	4.277	Low temperature use
E	NiCr/CuNi	0–800°C	6.137	High output

Notes: The S-type uses 90% platinum, 10% rhodium alloy with pure platinum as the other metal.
The R-type uses 87% platinum, 13% rhodium alloy with pure platinum as the other metal.
The J-type (or iron–constantan couple) uses copper–nickel alloy and iron.
The K-type (or chromel–alumel couple) uses nickel–chromium and nickel–aluminium alloys.
The T-type (or copper–constantan couple) uses copper and copper–nickel alloy.
The E-type (or chromel–constantan couple) uses nickel–chromium and copper–nickel alloys.

types. These fall into two groups, the *base metal* types such as iron–constantan and the *noble metal* types such as platinum–rhodium–platinum. The noble metal (originally named because of their resistance to all known acids) thermocouples are required for the higher temperatures, but have lower output levels and require ceramic sheathing to avoid oxidation damage. Thermocouples that use iron as one wire require protection against rusting and against oxidizing atmospheres generally.

The differences between thermocouple measurements and those made by other means are not always well appreciated, however. A thermocouple measurement is always a differential measurement, measuring the temperature difference between the cold or *reference* junction and the hot or *measuring* junction. When neither of the metals used in the thermocouple is the same as that used for the connecting cable, there will be two sets of junctions. Tables for thermocouple use are always made up in the assumption that the reference junction will be at 0°C. In industrial use this is very seldom true, and some form of compensation has to be used so that the output readings can be adjusted for the true temperature of the reference junction(s).

The usual method is *cold-junction compensation* incorporated into the amplifier/output portion of the instrument. A metal coil or a thermistor is used to sense the temperature at the reference junction or junctions, and the output from this sensor is used in an adding stage within the instrument to correct for the effect. This is most easily done in microprocessor-controlled equipment by using a table of correction values held in a ROM, but older analogue methods using an adding stage have been satisfactory in the past.

- Note that these methods apply a correction based on the cable that is supplied with the instrument. Changing to a different cable material (for example, extending the thermocouple connecting cable with copper cable) can make the built-in correction factor false, since two new junctions have now been added.

For precise measurements, although thermocouples are not ideal for such applications, it is more usual to have the reference junction(s) held in temperature reference units. The ice-point form of the reference unit is held at 0°C using Peltier cooling junctions (the reverse of the thermocouple effect) and precise sensors for the reference temperature, such as the bellows type which makes use of the expansion which occurs as water changes to ice. The traditional way of establishing the zero reference point was to use a vacuum flask filled with a mixture of ice and water, but this can cause large discrepancies unless used carefully.

The main objection is that ice which has been taken from a freezer will often be at 15°C or lower, and the water around it at around +5°C, so that the reference junction will quite certainly be at the wrong temperature and also at a temperature which will change considerably. The water–ice mixture is suitable if the water is demineralized (and the ice made from similar water), the ice is crushed, not in lumps, the ice has been in contact with the water for a considerable time and is constantly stirred, and the reference junction is not in contact with the ice.

The *hotbox* reference system uses a solid aluminium block with a drilled cavity into which the reference junction is placed. The block temperature is maintained constant, usually at a temperature well above ambient in the region of 55–65°C. The temperature of the block is raised quickly to its steady level by a heater which switches off when the temperature approaches the controlled level. From then on, the temperature is controlled by a thermistor and a small heating element operating in a loop with an amplifier. The instrumentation for the thermocouple must include circuitry that will correct the readings for the raised temperature of the reference junction by adding a small voltage to the output of the thermocouple.

- Another method, which is a passive system, consists of embedding the reference junction in a metal block that is well insulated, so that its temperature changes only very slowly. Another sensor in the block is connected to the instrumentation and generates the correction signal for the reference junction temperature.

The connections between the thermocouple and the reading system are important, as has been mentioned. When the distance between the thermocouple and the measuring instrument is considerable, extension or compensating cables should be used to connect these two. The difference between these two is that extension leads use the same materials as the thermocouples, and can be used at the same temperatures. Compensating cables use low-cost metals and can be used in ambient temperatures up to about 80°C only. The compensating cables must be matched to the type of thermocouple being used, and both extension and compensating cables must be connected in the correct polarity.

Cables made to the British standard (BS 1843:1952) all use codings in which the negative lead is blue, but the US ANSI cables use red for negative and the German DIN specifications use red for positive. In each case, the other colour is used for the opposite polarity (Table 4.5). Because the colours are not internationally standardized, it is important to know the country of origin of thermocouple extension or compensating cables and the market for which they were intended (cables of German origin might have been manufactured for sale in the USA and carry the ANSI colour coding).

Whatever type of thermocouple is used, many applications will require the measuring junction to be sheathed to prevent contact with such materials as molten metals, hot or corrosive gases and corrosive liquids. For some applications, the junction can be allowed to protrude outside the sheathing if a fast response is needed, particularly for gas temperature

Table 4.5 Colour codes for extension cables and compensating cables in the UK, USA and Germany.

Code		UK	USA	Germany
(a) *Extension cables*				
	Outer	Brown	Purple	—
E	Positive	Brown	Purple	—
	Negative	Blue	Red	—
	Outer	Black	Black	Blue
J	Positive	Yellow	White	Red
	Negative	Blue	Red	Blue
	Outer	Red	Yellow	Green
K	Positive	Brown	Yellow	Red
	Negative	Blue	Red	Green
	Outer	Blue	Blue	Brown
T	Positive	White	Blue	Red
	Negative	Blue	Red	Brown
(b) *Compensating cables – type U for noble metals, type VX for base metals*				
	Outer	Green	Green	White
U	Positive	White	Black	Red
	Negative	Blue	Red	White
	Outer	Red	Red	Green
VX	Positive	White	Brown	Red
	Negative	Blue	Red	Green

measurements, although this is not permissible if the gas is corrosive. The alternatives are to use the isolated type of sheathings, in which the junction is totally insulated electrically, or the grounded type, in which the junction makes contact with the sheathing. The latter type also gives good protection against corrosive materials, but with a considerably faster response.

Both the fully sheathed types must be used in high-pressure environments. Table 4.6 lists materials commonly used for sheathing thermocouples for industrial uses. The 27% chrome alloy is the most widely used type for low-temperature molten metal bath measurements, particularly for lead and zinc alloys. Stainless steel is better than nickel alloys in atmospheres that contain oxides of sulphur (exhaust gases from burning coal or oil, for example), and the ceramic materials must be used for sheathing noble metal thermocouples.

4.5 Metal-resistance sensors

All metallic conductors exhibit a change of resistivity when their tempera-

Table 4.6 Sheathing materials used for thermocouples.

Material	Max. °C	Comments
Mild steel	500–800	Depends whether cold drawn or solid drawn. Liable to oxidation
27% chrome–iron	1000	Used in molten tin or lead. Liable to oxidation
18/8 stainless steel	800	Good resistance to oxidation and corrosion
Inconel (nickel alloy)	1100	Must not be used in sulphur oxide atmosphere
Silicon carbide	1500	Outer sheath use, resists thermal shock. Can be oxidized
Alumina ceramic	1600–1900	Use for noble metals. Highly resistant to chemicals

Table 4.7 Resistance, resistivity and the change of resistance with temperature.

A wire with uniform cross-sectional area A, length s and resistivity ρ will have resistance R, given by:

$$R = \frac{\rho s}{A}$$

For a temperature rise of θ°C, the following changes occur:

length increases by $s\alpha\theta$, where α is the linear expansivity;
area increases by $2A\alpha\theta$, where A is area at 0°C;
resistivity increases by $\rho\alpha\theta$, where ρ is resistivity and α is temperature coefficient of resistivity.

For most metals, value of expansivity is of the order of $2 \times 10^{-5}\,K^{-1}$ and the temperature coefficient of resistivity is of the order of $4 \times 10^{-3}\,K^{-1}$, about 200 times larger, so that the changes in dimensions affect resistance only to a negligible extent. This allows us to use the temperature coefficient of resistivity as if it were the temperature coefficient of resistance. The formula for resistance change is therefore:

$$R_\theta = R_0(1 + \alpha\theta)$$

where R_θ = resistance at temperature θ, R_0 = resistance at 0°C, α = temperature coefficient of resistivity, θ = temperature difference.

ture changes and this change in the resistivity causes a change of resistance – Table 4.7 summarizes the relationships. The change of resistance is a more linear quantity over a large range of temperature than the output from a thermocouple. Although the characteristic shows deviation from a straight

Table 4.8 Temperature coefficients of resistance for some metals.

Metal	Coefficient ($\times 10^{-3}$)	Metal	Coefficient ($\times 10^{-3}$)
Aluminium	4.2	Copper	4.3
Iron	6.5	Nickel	6.5
Platinum	3.9	Silver	3.9

line at high temperatures, there is at least no reversal as is found in the thermocouple characteristic. The deviation is caused by the effect of the square and cube law components of the equation, and these effects are important only at high temperatures. For most metals, the first coefficient of resistance change (alpha) is close in value to the 1/273 (or 0.00366) figure for the expansivity of gases (see Table 4.8). A few metal alloys have a very low value of temperature coefficient, notably constantan with a value that is only about 10% of the average for pure metals, and manganin with an even lower value. Both of these materials are alloys of copper, nickel and manganese.

For comparatively small temperature ranges, up to 400°C or so, the resistance change of nickel or of nickel alloys can be used. For higher temperature ranges, platinum and its alloys are more suitable because of their much greater resistance to oxidation. For measurement purposes, the resistance sensor can be connected to a measuring bridge, along with a set of dummy leads whose temperature is also changed (Figure 4.9). A platinum resistance in this form can be used as a standard of temperature measurement. The National Physical Laboratory standard thermometer is a gas-expansion type, but this requires long and elaborate setting up, so

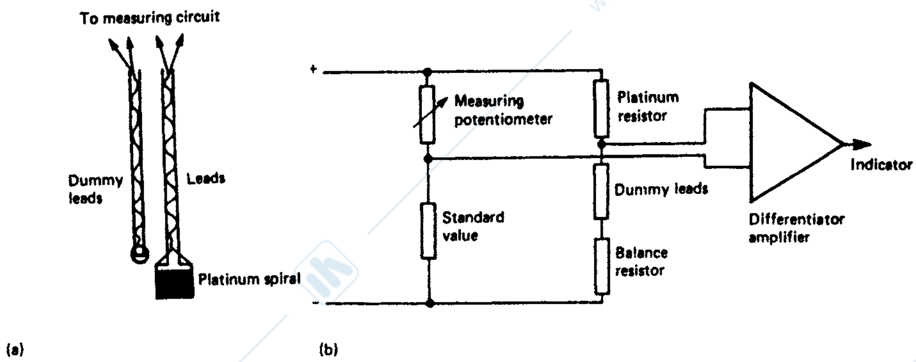

Figure 4.9 The arrangement of a platinum resistance thermometer using dummy leads to compensate for the change of resistance of the leads to the measuring element: (a) physical arrangement, (b) electrical circuit.

that platinum-resistance thermometers calibrated from the gas-thermometer standard are used extensively as secondary standards (often called, confusingly, sub-standards). The size of the sensing element and its heat capacity make the response slow compared to some of the purely electronic devices, such as the thermocouple.

When a switching action is required, the output from a bridge circuit connected to the platinum resistance thermometer can be used to operate a trigger type of circuit. This is seldom done, because the advantage of the resistance type of thermometer is its comparatively linear response, and switching can be carried out by a variety of less expensive devices.

RESISTANCE THERMOMETERS RTD

The platinum-resistance thermometer was formerly used only as a laboratory standard, but advances in the construction of these and resistance thermometers generally have led to resistance thermometers being used in many applications for which only thermocouples were once considered. In particular, many industrial processes that at one time would have been considered as being tightly controlled if the temperature variations were held to 10°C, are now required to be held to much closer limits. The days of 'spit on it and see if it sizzles' are quite definitely over, and the days of 'near enough' are almost gone as well. Emphasis on quality control and uniformity of product now require temperatures in manufacturing processes to be maintained to much closer limits than was even thought possible at one time.

Although there are several materials that can be used in resistance thermometers, platinum has the considerable advantage of being the reference material for international standards, used in the range −270°C to +660°C. The laboratory form of platinum-resistance thermometer is used for calibrating other thermometers, but is a fairly bulky piece of equipment. Miniature versions are now available which combine the accuracy of the platinum-resistance principle with the ability of platinum to withstand corrosive atmospheres. Although nickel and copper can be and are used for some purposes in the lower ranges of temperature, platinum has the advantage that it can be prepared in a very pure state, is highly resistant to corrosion (like all noble metals) and has a resistance/temperature relationship which is almost perfectly linear over a wide range of temperatures. It is also a very stable material, both electrically and mechanically, so that drift of resistance value as the material ages, and with use, is negligible.

The other factors that have led to an increase in the use of platinum-resistance thermometers are the development of instrumentation that can match the high standards of the platinum-resistance system and the comparative ease of use. Connecting cables to a platinum-resistance thermometer can be ordinary copper cable, with no need for special extension

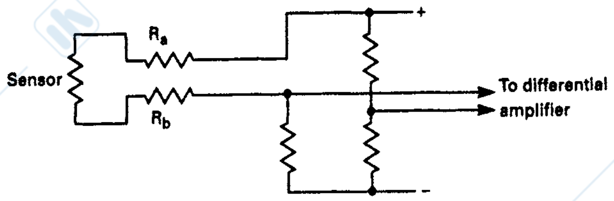

Figure 4.10 The simple Wheatstone bridge circuit used for a resistance thermometer. The cable resistance values R_a and R_b are measured in addition to the resistance of the sensor.

compensating cables. The calibration of a platinum-resistance thermometer is a once-only affair, with no need for cold-junction compensation or the use of thermostatic enclosures for a reference junction. The instrumentation portion of a thermometer can also be simpler, and adding stages to allow for compensation is unnecessary.

The construction for an industrial platinum-resistance thermometer is generally more rugged than the open coil construction used for a laboratory standard. The wire is wound in a spiral or small radius and the whole spiral sealed into a hollow alumina rod, using ceramic sealant where the wires enter the alumina. The sizes of such assemblies can be as small as 0.8 mm in diameter and 5 mm in length, and with careful monitoring of the winding resistance accuracy as close as 0.01% can be obtained. Another quite different form of construction is the use of thin films of platinum on ceramic substrates, which unlike the wound form can be mass-produced, at much lower prices. These are for many industrial purposes more suitable, although some care has to be taken with any platinum-film device to ensure that the device has no chemical catalytic action on any gases or liquids with which it is in contact.

The electrical circuit used for the platinum-resistance thermometer is a bridge circuit, and for many applications, a simple Wheatstone bridge circuit (Figure 4.10) is sufficient. In this type of circuit, the resistance $R_a + R_b$ of the two connecting leads is also measured, but if this resistance is negligible compared with that of the platinum coil (1% or less) then the error is also negligible. In some cases, however, the leads must be of a substantial length and cannot have negligible resistance, so that other circuits must be used. Although the full-compensation method of Figure 4.9 is used in laboratory equipment, a simpler system is illustrated in Figure 4.11, in which three leads are used, two carrying current and one acting as voltage sensor only. In this circuit, the added resistance is equivalent to the difference between the main connecting cables, and this quantity is, for practically all industrial measurements, negligible. The principle can be extended to a four-wire system in which two cables carry the bridge current and two others act as voltage connectors.

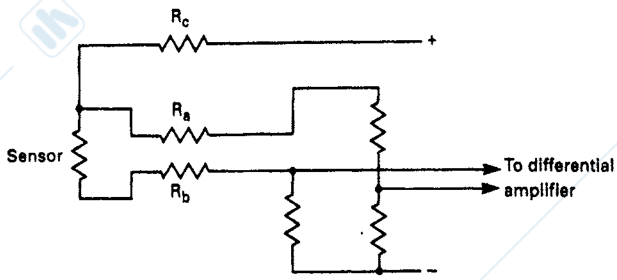

Figure 4.11 A three-wire compensating circuit in which the cable resistance is almost balanced out: only the difference in cable resistance is added to the sensor resistance.

For all resistance thermometer applications, the amount of current used in the bridge circuit must be so low that the self-heating of the platinum sensor is negligible. This creates a conflict between sensitivity and accuracy because the higher the current through the low resistance of the platinum, the greater the voltage to be measured and hence the ease of use of the bridge. Modern high-impedance electronic amplifiers make it possible to operate measuring bridges with very low currents without sacrificing sensitivity, so that this problem is much less significant than was formerly the case. Some care is needed, however, if a new platinum-resistance thermometer head is connected to an old measuring bridge, to ensure that the bridge current is low enough to avoid self-heating. The resistance of film-type sensors is higher than that of the older wire type, and lower currents will be needed for the films.

Table 4.9 compares and contrasts the merits of thermocouples and resistance thermometers as an approximate guide to specifying a temperature measuring system for industrial use.

4.6 Thermistors termistori

Thermistors are a form of temperature-sensitive resistors formed using mixtures of oxides of exotic metals. The constructional methods are similar to those used for carbon composition resistors. Some of these mixtures have positive temperature coefficients, and in most cases it would be meaningless to quote a value for temperature coefficient, positive or negative, because the value is not a constant. The thermistors with a positive temperature coefficient are very non-linear, but the more common negative temperature coefficient types follow a roughly logarithmic law with no violent changes in resistance.

Given that the resistance of a thermistor is known at one temperature θ_2, it can be calculated for another temperature θ_1 by using the formula illu-

Table 4.9 The relative merits of thermocouples and platinum resistance thermometry compared.

Thermocouple	Platinum Resistance
0.5–5°C precision	0.1–1.0°C precision
−200°C to +1750°C range	−200°C to +650°C range
Price factor 1	Price factor 2.5
Sensitive at tip	Sensitive throughout stem
50 ms–5 s response	1–50 s response
Can be very small	Larger size
Reference zero needed	—
Can be used for surface temperature	—
Vibration resistant	Affected by vibration
No power supply needed	Needs power supply
No self-heating effect	Current must be limited
Long-term drift	Excellent stability
Very robust	Can be fragile
Special leads required	Uses copper cables
Output 10–40 μV/°C	Output 0.4Ω change/°C
Screening needed	Can be unscreened

Table 4.10 Thermistor formulae that relate resistance to temperature.

The temperature coefficient of a thermistor, is not a constant, but itself varies as temperature changes. A more useful quantity is the thermistor constant B which can be used to find the resistance at any temperature in the working range provided another pair of resistance and temperature values is known.

The equation is

$$R_2 = R_1 \cdot e\left(\frac{B}{\theta_1} - \frac{B}{\theta_2}\right)$$

θ and B values are in Kelvin (K) units of temperature.

For example, if the thermistor constant B is known to be 3200K, and the resistance at 30°C is 2 kΩ, then the resistance at 45°C can be calculated as follows.

The temperatures are 293K and 318K, so that the quantity in brackets is 0.8586. Using the exp function of a calculator, $R_2 = 2 \times 2.359 = 4.719$, about 4.7.

strated in Table 4.10. The use of θ rather than T for temperature in this formula is a reminder that the temperatures must be in units of Kelvins (absolute temperatures). The Kelvin or absolute temperature is obtained by adding 273 to the Celsius temperature. If you need to work to two places of decimals of temperature, use the figure 273.16.

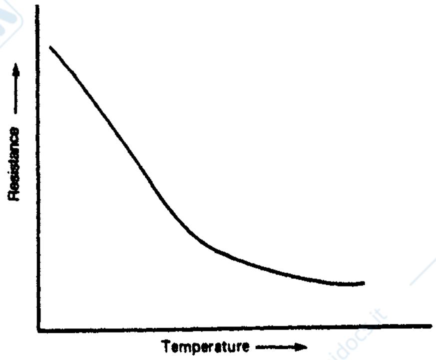

Figure 4.12 A typical resistance/temperature characteristic for an NTC thermistor. The resistance decreases as the temperature rises, and the shape of the characteristic is never linear.

Thermistors can be obtained in a variety of physical forms, as beads, miniature beads, plates, rods, and also encapsulated in metal containers. Negative temperature coefficient (NTC) thermistors are used for temperature control applications such as low-temperature oven controllers, deep-freezer thermostats, room temperature sensors and process controllers. Temperature limits range from 150°C to 200°C, with a few types able to withstand 600°C. The range of temperature that a thermistor can handle depends on the associated circuit, because the range of resistance will be very large compared to the range of temperature.

The typical NTC thermistor characteristic is shown in Figure 4.12, and it displays a negative change of resistance with increasing temperature. The shape of the characteristic is exponential rather than linear, and the useful temperature range is comparatively small.

In any of these applications, NTC thermistors have considerable advantages as compared to the old bimetal thermostat, notably the absence of any hysteresis effects (switching on at a different temperature than that for switching off). NTC thermistors can also be obtained in evacuated envelopes for use in such purposes as oscillator limiters and controllers for voltage-controlled amplifiers.

Thermistor circuits in general require the use of pre-set potentiometers in order to make working adjustments, but circuit costs can be reduced by employing curve matched thermistors whose resistance values are guaranteed to within close limits at each of a large range of temperatures. Thermistors of all types will also have quoted values of dissipation constant and time constant. The dissipation constant is the amount of power (in milliwatts) that is required to raise the temperature of the thermistor by 1°C above the ambient temperature. For the evacuated bulb type, the dissipation constant is very small, of the order of 12 μW/°C, so that the resistance

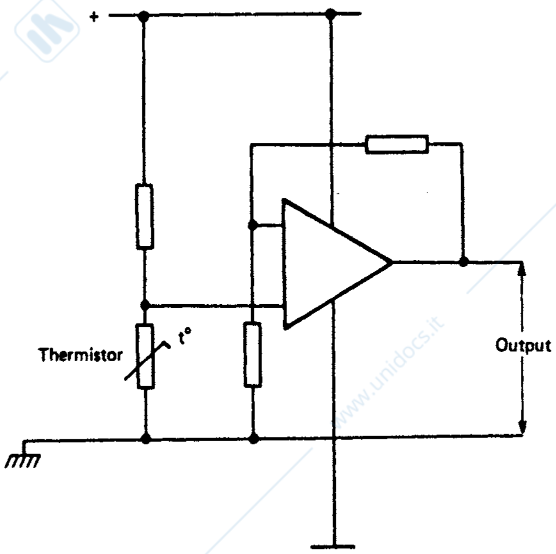

Figure 4.13 An NTC thermistor temperature sensing circuit that makes use of an operational amplifier. The sensitivity can be adjusted by altering the feedback ratio.

of this type of thermistor is substantially altered by only very small amounts of signal current. For temperature-sensing thermistors, values of dissipation constant in the range 70 = 500 μW/°C are typical.

The time constant for a thermistor is defined as the time needed for the resistance to alter by 63% of the difference between an initial value and a final value caused by a change of temperature. Time constant is measured with negligible current flowing, because otherwise the figure would be altered since part of the heating is internal rather than external. The figure of 63% may seem odd, but it corresponds to the definition of time constant for other networks, such as a capacitor and a resistor. By making the definition in this way, the value of time constant is genuinely constant over a large range of temperature changes. Time constants of 5–11 s are typical of the physically small thermistors (miniature beads and the evacuated bulb types), with much larger values for others, 18–25 s for the larger beads, and as high as 180 s for thermistors that have been assembled into temperature sensing probes.

NTC thermistors can be constructed from semiconducting materials with values of temperature coefficients that are usually much larger than the (positive) temperature coefficients of resistors. The phrase NTC resistor is used for devices with fairly small negative values of temperature coefficient, and the term thermistor is reserved for the types that have large negative values of temperature coefficient. Most of the thermistors that are incorporated into temperature-sensing circuits are of the NTC type.

PTC THERMISTORS

Positive temperature coefficient (PTC) thermistors are a more recent development, used mainly for protection circuits for sensing temperature or current. Unlike the NTC types, these PTC thermistors have a current–voltage characteristic that exhibits a change in direction, and two basic types are used, both depending on compounds of barium, lead and strontium titanates (ceramic materials). The over-temperature protection type of PTC device has a switchover point at a reference temperature (or trip temperature, T_r). At temperatures lower than the trip temperature the resistance of the PTC device is fairly constant, but around the trip temperature the PTC characteristic takes over and their resistance rises very sharply as the temperature rises. A typical graph of resistance plotted against temperature, along with a trip-sensing circuit, is shown in Figure 4.14. The sudden change in resistance can be used to operate an indicator or to switch other circuits for purposes such as motor protection or for preventing overheating of transformers.

The other type of PTC thermistor device is used for over-current protection circuits, and its resistance/temperature graph is illustrated in Figure 4.15. This characteristic follows an S-shaped curve which has two turnover points, one at a point of minimum resistance R_{min} and the other at the maximum resistance point R_{max}. Between 0°C and R_{min}, the temperature coefficient is negative, and the coefficient is also negative at the temperatures in the region higher than R_{max}. Between R_{min} and R_{max} the temperature coefficient is large and positive. In this PTC region, the change of resistance can be as large as 100% for each °C rise in temperature.

With one of these devices wired in series with a load, the load is protected against excessive current. At the working current, the PTC device is in its

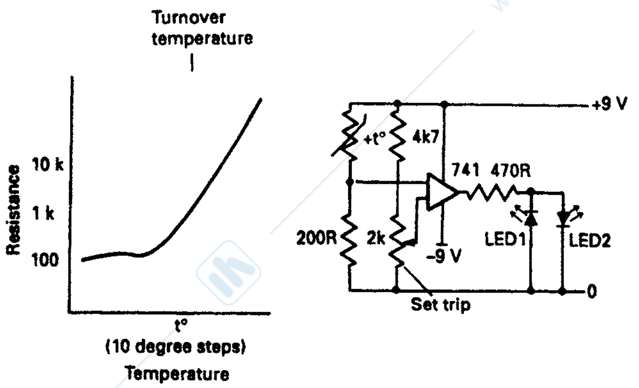

Figure 4.14 Characteristic for a PTC thermistor used for sensing excess temperature.

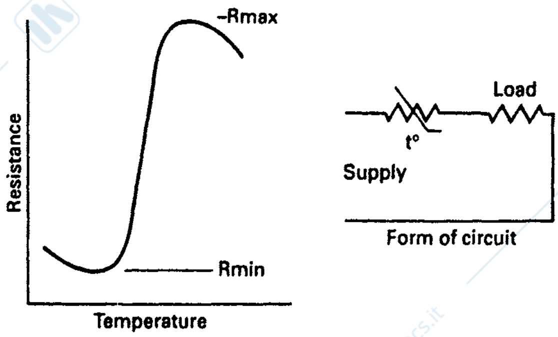

Figure 4.15 The type of characteristic used for current protection devices operated by a PTC thermistor.

low-resistance state, allowing most of the applied voltage to be across the load. When the current is increased, the thermistor will suddenly switch to its PTC mode, assisted by self-heating as more of the applied voltage will now be across the thermistor, until the current flowing in the whole circuit becomes very small. The circuit can be arranged so that it is self-resetting, returning to normal when the thermistor cools, or requires the circuit to be reset by switching off the current and allowing the thermistor to cool.

The change of resistance per unit change of temperature for a PTC thermistor can be so abrupt that circuit devices such as bridges and Schmitt triggers are sometimes not necessary. In a very few applications, the PTC thermistor can be used directly, but it is usually undesirable to have the controlled current passing through the thermistor, and more usually the thermistor is part of a transistor switch or an operational amplifier circuit. The output of such a circuit is not particularly linear, but the sensitivity can be high and the response can be rapid. One particular advantage is that the sensing element can be very small.

- Note that if an op amp with sufficient gain is used to amplify the voltage across a thermistor, any type of thermistor can be used to sense excessive temperature. The advantage of using a PTC thermistor is that many types of sensing applications can use circuits that require no op amp.

The connection of a thermistor to a switching circuit has the advantage, as compared to bimetallic strip devices, that it can be arranged so as to have zero hysteresis if this is a useful feature. For most switching purposes, however, some hysteresis is desirable in order to prevent rapid switching on and off as air currents strike the detector. The more elaborate temperature sensing systems that make use of thermistors are microprocessor controlled, and a form of time hysteresis is used. The temperature sensing output from the thermistor is monitored at short intervals, and a change registered only if the direction of temperature change is consistent. This allows much more rapid response to a temperature change than the conventional form of hysteresis, although the sensing intervals have to be adjusted to suit the type of use.

Transistors themselves can be used as sensing elements, because many transistor parameters follow an exponential negative temperature characteristic. The inherent amplification of a transistor makes the use of the temperature sensitivity of base–emitter voltage attractive as a sensing system, because the output can be taken in amplified form from the collector. The use of transistors as temperature sensors, however, is confined mainly to temperature compensation of transistor and IC circuits.

4.7 Radiant heat energy sensing

Radiant energy, which can be light, heat, radio waves or, in some instances, ionizing radiation, may need to be sensed, and a very large range of the electromagnetic spectrum is sensed by its temperature effect. The sensors for light have mainly been dealt with in the previous chapter, but there is one device, the *bolometer*, which has been held over to this chapter because its action is essentially thermal.

The bolometer principle is illustrated in Figure 4.16. A blackened material will absorb radiation well and so its temperature will rise when radiated energy falls on it. The change of temperature is then detected in the ways that have been described earlier in this chapter. The classic types of bolometers used in the nineteenth century were metal, and the effect of the temperature rise due to radiation was detected in sensitive measuring bridge circuits. Because the change of temperature due to radiated energy can be small, and the change of resistance correspondingly smaller, bolometers are usually connected into bridge circuits so that the output from an unradiated bolometer can be compared with the output from the bolometer which is deliberately exposed to radiation.

Modern bolometers can make use of semiconductor sensors, blackened for maximum absorption of radiation. The much greater change of resistance

Figure 4.16 The bolometer consists of a temperature sensor whose surface is blackened and enclosed in a container (preferably evacuated). Thermal radiation passes through the window, heating the sensor. The sensor can be a thermistor or a thermopile.

of a thermistor for a small change of temperature makes this type of material ideal for bolometer use and permits much more sensitive detection than was possible with the older types. The non-linear nature of the thermistor is less important in this type of application, because the changes of temperature are usually small.

4.8 Pyroelectric detectors

pirometro

Pyroelectric films are dielectric materials whose surfaces charge when radiated by infrared (IR). Plastics films have been used for this purpose, but the material that is favoured for modern passive infrared (PIR) detection systems is lithium tantalate. The construction of a detector is as a capacitor with one metal plate and the other a pyroelectric material with a conducting surface. Because of the effect of infrared in separating charges on the pyroelectric material (confusingly, but correctly, also called *polarization*) the charge and hence the voltage across the plates of a pyroelectric capacitor will alter as the amount of incident infrared radiation is altered.

The time constant is large, so that the response rate to alterations in IR is in the range 0.2–1 Hz. Because the detector is a capacitor, however, there is no DC response, so that a non-moving infrared emitter will not be sensed. In addition, the capacitor has a very high impedance, so that a practical pyroelectric detector consists of the capacitor and a MOSFET constructed as one unit with external connections to the source and drain of the MOSFET. The main applications for pyroelectric detectors are burglar alarms, automatic light-switching and door-opening equipment, and positioning systems.

The main parameters of a pyroelectric detector are noise-equivalent power (*NEP*), *responsivity* and frequency response. The NEP for a given source energy, signal rate of change and bandwidth express the lower limit for which the detector is useful, since signals below this limit will be below the noise level. For a typical detector for a source at a colour temperature of 500K, at a frequency of 10 Hz and 1 Hz bandwidth, the NEP figure of 10^{-9} W is quoted for a lithium tantalate pyroelectric material.

Responsivity can be quoted in terms of either voltage or current output as volts per unit radiant energy or current per unit radiant energy, at a given predominant wavelength or colour temperature of source. A typical figure of voltage responsivity is 3200 V/W. The frequency response of responsivity means the change of responsivity for different modulation frequencies (not radiated frequency), and this, as noted above, corresponds to a low-pass filter action with a peak at less than 1 Hz.

Figure 4.17 illustrates a typical PIR unit, using a DIL IC layout with four pins in a casing approximately 8 × 7.5 mm. The equivalent circuit is of two pyroelectric capacitors connected so that their voltages will add, and with the summed voltages applied to the gate of a MOSFET whose source and