INTRODUCTION TO TEMPERATURE MEASUREMENT SYSTEMS

1 INTRODUCTION

There are many methods of practical temperature measurement in use. Some of these have been developed for particular applications while others may simply have become outmoded. This article describes the two main types of temperature measuring systems that are currently available. These are, thermocouples and resistance thermometers. Sensors employing these techniques can be provided to fulfil most temperature measurement requirements. Thermocouples of different types can cover the range −250 to 2 000°C and beyond, while resistance thermometers can be highly accurate. An important characteristic of both methods is that the output is in the form of an electrical signal which can be readily transmitted, switched, displayed, recorded and further processed using suitable data handling equipment.

Section 2 of this article is concerned with thermocouple thermometry. It begins with the basic principles involved, the components of the practical thermocouple and goes on to measurement methods, including the averaging of a number of thermocouples. Finally, the considerations that are involved when higher accuracy is being sought with thermocouple measurements, are discussed.

Section 3 relates to the techniques associated with resistance thermometry including the basic principles, the various types of sensors, resistance measurement methods, self-heating effects, etc.

Section 4 covers some of the temperature measurement considerations that are common both to thermocouple and resistance thermometry. They include the need to link the sensor to the region of interest, response characteristics and stagnation effects.

Table 1. Thermocouple/Resistance Thermometry Comparisons

Method	Thermocouple thermometry
Advantages	Wide temperature range. Versatile, e.g. sensor can be in a robust industrial unit of mineral insulated cable or as ultra fine wires, etc. Simple application, just the junction at the tip needs to take-up the required temperature.
Disadvantages	Needs temperature reference. Needs extension cables for long runs. Needs attention to detail for high accuracy.
Method	**Resistance Thermometry**
Advantages	Potentially the most accurate method. Simple installation. Needs only copper cables for long runs.
Disadvantages	Needs energising current. Sensor types limited. High accuracy types need careful handling. Sensors larger than thermocouple junctions.

2 THERMOCOUPLE THERMOMETRY

2.1 Basic concepts

If a temperature gradient is presented in an electrical conductor, the heat flow will create a movement of electrons and an electromotive force (e.m.f.) will be generated in the region. The magnitude and direction of the e.m.f. will be dependent on the magnitude and direction of the temperature gradient and the material forming the conductor. The voltage existing across the ends of the conductor will represent the algebraic sum of the e.m.f.s generated along it. Thus, for a given overall temperature difference, T1-T2, the gradient distributions shown diagrammatically in Figures 1a, 1b and 1c will produce the same total voltage, E, providing that the conductor has uniform thermo-electric characteristics throughout its length. The output voltage of a single conductor as shown is not normally measurable as the sum of the thermal e.m.f.s around a completed circuit of a uniform conductor, in any temperature situation will, of course be zero.

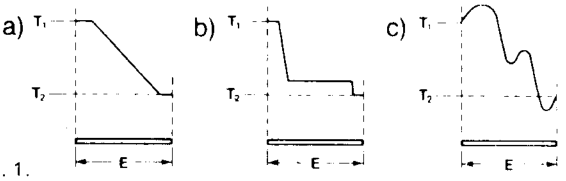


Fig. 1.

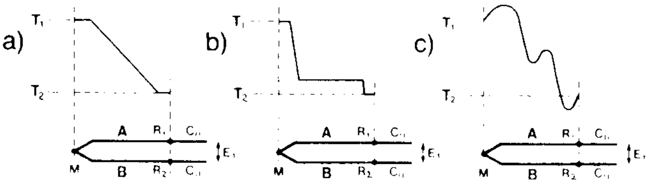


Fig. 2.

In a practical thermocouple, two materials having different e.m.f./temperature characteristics are combined to produce a usable output voltage. Thus a thermocouple comprising two dissimilar conductors A and B in the temperature gradient situation shown in Figure 2a will generate an output because of the interaction of the temperature gradient with both conductors A and B. It will produce the same output, E_T for any gradient distribution between a given temperature difference T1-T2 provided that the conductors have uniform thermo-electric characteristics throughout their lengths (Figs. 2a, 2b and 2c).

As the junctions M, R_1, R_2, represent the limits of the e.m.f. generating conductors A and B, the remaining conductors linking the measuring device being (uniform) copper wire, the output of the thermocouple will effectively become a function of the junction temperatures. This is the basis of practical thermocouple thermometry.

A thermocouple then, provides an output that is related to the temperatures of its two junctions. It is usual to designate the connection between the two dissimilar wires as the Measuring Junction and the junction (it is, in fact, more frequently a pair of junctions) linking the dissimilar wires to the copper ouput connections as the Reference Junction (M and R, respectively in Figure 2). If the reference junction is maintained at a fixed and known temperature the temperature of the measuring junction can be deduced from the thermocouple output voltage. There are calibration tables for each thermocouple combination that relate ouput voltage to the temperature of the measuring junction if the reference junction is maintained at 0°C.

Remember

a) The output of a thermocouple is generated only in the regions where the temperature gradients exist along it.

b) To ensure accurate and stable operation the thermo-electric characteristics of the thermocouple conductors must be, and remain, uniform throughout.

c) Only a circuit comprising dissimilar materials in a temperature gradient will generate an output. A circuit comprising a single uniform conductor situated in a temperature gradient will produce no output. A circuit comprising dissimilar conductors under isothermal conditions will produce no output.

d) The thermo-electric sensitivity of most materials is non-linear with temperature. Thus a given temperature difference between the measuring and reference junctions of a thermocouple will produce different outputs at different reference temperatures.

2.2 Thermocouple materials

The majority of conducting materials will produce a thermo-electric ouput but when considerations such as wide temperature range, useful output, the unambiguous relationship of output with temperature are taken into accout, the practical choice is somewhat reduced. Fortunately, the selection process has been carried out by the thermocouple suppliers and a useful range of metals and alloys is generally available in wire form or as completed sensors to cover a temperature range from −250 to higher than 2 000°C.

This temperature range cannot be covered with a single thermocouple combination. The temperature ranges of some of the more commonly used thermocouples are given in Tables 2 and 3. These have internationally recognised type designations. In general the platinum based thermocouple materials are the most stable. They have a useful temperature range from room ambient to 2 000°C, although their outputs are low compared with base metal types. Some common types of platinum thermocouples are listed in Table 2. The upper temperature limits shown in the table are nominal. They may be raised or lowered depending on the conditions, duration of exposure, the life and accuracy required, etc.

Table 2. Commonly used platinum metal thermocouples.

International type designation	Conductor Material	Temperature range (°C)
R	Pt-13% Rh (+) Pt (−)	0 to +1 600
S	Pt-10% Rh (+) Pt (−)	0 to +1 550
B	Pt-30% Rh (+) Pt-6% Rh (−)	+100 to +1 600 +1 750 Intermittent

Among the considerations involved when selecting base metal thermocouple materials (see Table 3), will be the temperature range, the sensitivity, compatibility with existing measuring equipment, etc. Your thermocouple supplier will assist with the selection for any particular application.

Table 3. Commonly used base metal thermocouples.

International type designation	Conductor material	Temperature range (°C)
K	Ni-Cr (+) Ni-Al (−)	0 to +1 100
T	Cu (+) Cu-Ni (−)	−185 to +350
J	Fe (+) Cu-Ni (−)	+20 to +700
E	Ni-Cr (+) Cu-Ni (−)	0 to +800

2.3 The practical thermocouple

For simple applications, thermocouples can be made quite readily from a length of cable which is usually supplied in coils and with insulation material suitable for the application. The measuring junction is formed at one end of a chosen length usually by welding the wires together. Soldering or twisting are less satisfactory methods although the latter method can be more secure when fitted under a clamping screw in a connecting block. The essential requirement is for a satisfactory and reliable electrical connection, bearing in mind the operating conditions for the junction (Fig. 3).

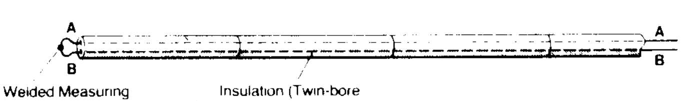


Fig. 3.

At the other end, each thermocouple wire is joined to a copper wire to form the reference junction. Here again, welding is probably the best method, but silver soldering using a small quantity in paste form and a miniature flame is a reasonable alternative. However, as with all soldering operations in thermocouple circuits, it is important to ensure that all traces of any corrosive flux are removed. The junctions might then be fitted into closed-end tubes or potted in a suitable epoxy resin for immersion in an ice-water mixture.

This method of thermocouple construction is simple, versatile and well suited to laboratory type experiments. It is likely to yield quite accurate results as each measuring junction can be placed very close to the required site and, in form, the thermocouple approaches the theoretical ideal (see Fig. 2). Nevertheless, local manufacture is not appropriate for all users and more permanent and operationally convenient systems are available. Figure 4 is a diagram of a typical industrial type thermocouple. In the following sections the functions of each of the components are described.

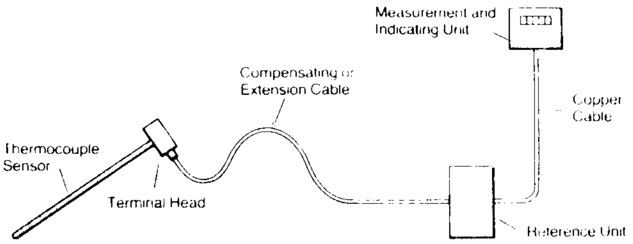


Fig. 4.

2.4 The thermocouple sensor

For most temperature measurement purposes it is convenient to purchase the thermocouple as a separate unit or sensor (see Fig. 4). The range of types and styles of thermocouple sensors is very wide to suit the needs of industry and science. Frequently, the thermocouple conductors will be fitted in a closed-end pocket or thermowell made from a suitable heat resistant alloy or refractory material (Fig. 5).

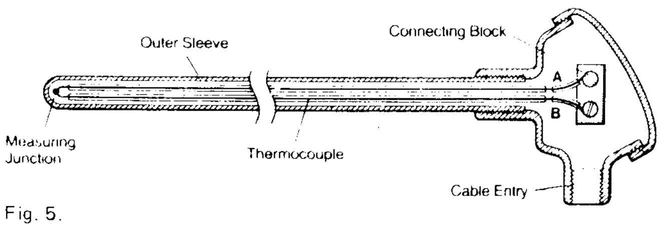


Fig. 5.

In all cases great care is taken by the suppliers to ensure that the conductors are correctly manufactured and installed in the sensor unit under closely controlled conditions. In this manner the amount of change that the heated region of the conductors may undergo during service (thus affecting the uniformity) is reduced to a minimum. This is an important consideration as it is this unit that is likely to be situated in the majority of the temperature gradient and thus the greater part of the ouput voltage is generated within it (see Section 2.2).

An alternative form of construction is using mineral insulated (M.I.) cable where the thermocouple conductors are embedded in a closely compacted, inert mineral powder and surrounded by a metal (e.g. stainless steel or nickel alloy) sheath to form a hermetically sealed assembly. The sheath functions as a useful protective cover in many situations. These types of assembly can be obtained with outer diameters ranging from as low as 0,25 up to 19,0 mm and lengths can be from a few millimetres to hundreds of metres (see Fig. 6).

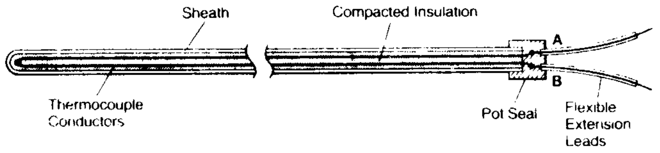


Fig. 6.

For special applications where a very rapid response is required, it is occasionally advantageous for an M.I. thermocouple to be manufactured with the junction exposed. As this may raise some strength or compatibility considerations, the advice of the supplier should be sought.

Thermocouple sensors are often furnished with a connection or terminal box which allows convenient linking to the remainder of the thermocouple circuit. Alternatively, a special plug can be fitted in which the connecting pins are made from thermoelectric materials as are those in the mating socket (see Fig. 7). This is a convenient arrangement which allows rapid fitting or exchange of sensors without sacrificing thermocouple conductor uniformity. The plugs and sockets are polarised to ensure correct connections.

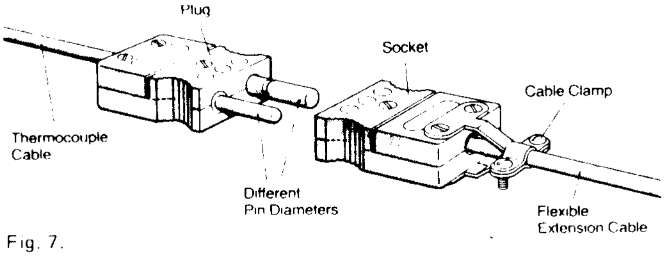


Fig. 7.

2.5 Extension cables

Extension cables are a convenient and frequently economic way of extending thermocouple circuits from the sensor to the reference unit in the form of wiring cables with similar conductor materials to those of the sensor. Alternatively they may incorporate quite different conductor materials which in combination develop similar ouputs to those of the thermocouple over the limited temperature range likely to be experienced at the thermocouple to extension wire connections. In this latter case these cables are often called compensating cables.

An obvious example of the use of compensating cables is with platinum metal thermocouples where the cost of the thermocouple materials is high and it is usually an economic necessity to extend the circuit using lower cost compensating cables. It should be borne in mind however, that if the temperature of the connecting box is allowed to increase, the output from the compensating wires will diverge from that of the platinum thermocouple and errors in the temperature determination will increase correspondingly.

Another example of the use of compensating cables is where the output of Type K thermocouples is closely matched at low temperatures by the combination of Cu/Cu-Ni conductors. As one conductor is already copper the number of reference junctions is halved, an advantage with large multi-thermocouple schemes. The loop resistance of this cable is also somewhat less than with the equivalent Type K conductors.

Extension cables are produced usually in a convenient form for carrying over long distances, e.g. as wiring cables or multicore cables. With extension cables the mis-match errors arising from high connecting box temperatures are likely to be less than with compensating cables.

3 RESISTANCE THERMOMETRY

3.1 Basic concepts

The resistance that electrical conductors exhibit to the flow of an electric current is related to their temperature. If the relationship is predictable, smooth and stable, the phenomenon can be used as a basis for temperature measurement. There are some metals that fulfil this requirement including copper, gold, nickel, platinum and silver. Of these, copper, gold and silver have inherently low values of electrical resistivity making them less suitable for resistance thermometry, although copper has almost a linear resistance relationship with temperature. Nickel and nickel alloys have a high resistivity and high resistance versus temperature coefficients but these are non-linear, sensitive to strain and they also suffer from an inflexion at around the Curie Point (358°C) which makes the derivation of the resistance to temperature expressions more complicated.

This leaves platinum which has advantages that make it well suited to resistance thermometry. It has a wide temperature range, a resistivity that is more than six times that of copper and a reasonable although non-linear resistance versus temperature coefficient. It can be drawn into fine wires or strips and can also be obtained in a very pure form. Although platinum is an expensive material only small amounts are required for resistance thermometer construction and this is not a highly significant factor in the overall cost.

An important requirement for accurate resistance thermometry is that the platinum resistance element must be, and remain in a fully annealed condition. Suitable heat treatment can produce the annealed condition. The problem for the manufacturer is to support the fine platinum wire with minimum strains being imposed even though the unit may be mounted in an operating plant. Some of the practical techniques used to achieve this are described below.

The relationship of the platinum resistance thermometer with temperature can be represented very closely by a quadratic equation,

$$R_1/R_0 = 1 + At + Bt^2$$

where R_1 = the thermometer resistance at temperature t.
R_0 = the thermometer resistance at 0°C
t = temperature (°C)

A and B are coefficients determined by calibration.

For commercially produced platimum resistance thermometers, standard tables of resistance versus temperature have been produced based on an R value of 100 ohms and a fundamental interval ($R_{100}-R_0$) of 38,5 ohms.

3.2 Types of sensor

Most users of platinum resistance thermometers will employ purpose made sensors. These are manufactured in a wide range of types and styles. As mentioned in Basic concepts, to achieve high stability the platinum sensor elements must be, and remain, in a fully annealed condition. This implies a special mounting method. For laboratory standard type instruments the element may be a thin wire, wound in a helical form and supported by frictional contact in a closely fitting glass tube. The more general purpose type sensors have wires wound on glass or ceramic formers that have similar temperature versus expansion characteristics to that of the platinum wire. The windings are secured with a coating of suitable cement or glaze. The wire coils can also be arranged in grooves in ceramic plates to produce flat sensors which have applications such as surface temperature measurement (see Fig. 8).

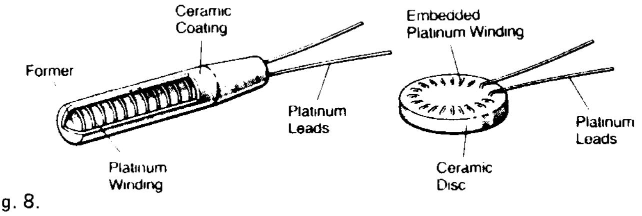


Fig. 8.

An alternative method of platinum resistance thermometer construction is by depositing the platinum material as a thin film pattern on a suitable substrate. In this way the element can be bonded to a flat or cylindrical surface (see Fig. 9).

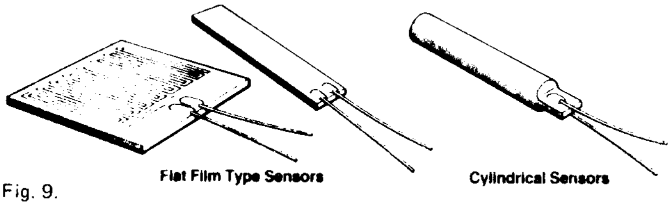


Fig. 9.

Platinum resistance sensors are available fitted into a range of protection tubes. These can be equipped with suitable terminal blocks for connection to the copper cables linking the measuring instrument. As with thermocouple type sensors the protection tube might be fitted into a thermowell for further environmental and mechanical protection (see Fig. 10).

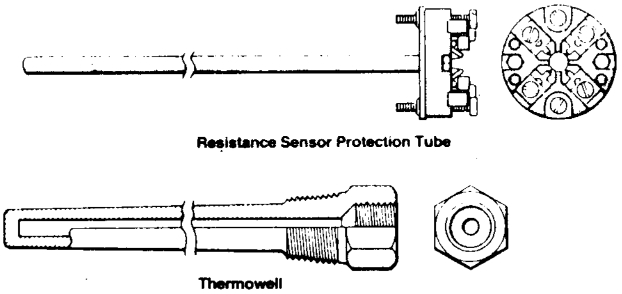


Fig. 10.

3.3 Measurement methods

There are two main instruments for determining the resistance of sensors, measuring bridges and potentiometers. Measuring bridges are used extensively in the laboratory where the bridge elements may be resistance decades, or tapped inductances in AC versions. Highly accurate measurements are also possible using a precision potentiometer. An important requirement with this method is the provision of a stable energising current.

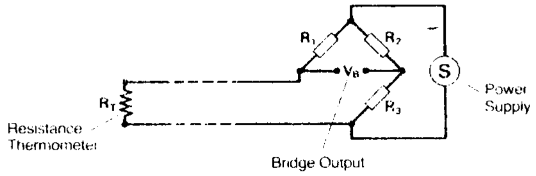


Fig. 11.

Some commercially produced industrial systems use a type of Wheatstone Bridge. The bridge is not normally balanced by altering resistance values but instead the magnitude of the out-of-balance voltage in a fixed element bridge is used to measure the applied resistance (see Fig. 11). Alternatively, the resistance thermometer might be energised from a constant current source and the voltage developed across it measured in a potentiometer type method.

The simple two wire connection shown in Figure 11 above is used only where high accuracy is not required as the resistance of the connecting wires is always included with that of the sensor.

An alternative arrangement allows for another pair of wires to be carried alongside the thermometer pair. This additional pair is connected together close to the thermometer and the loop formed is introduced into the other side of the bridge circuit. Thus the effects of the two sets of leads tend to cancel (see Fig. 12).

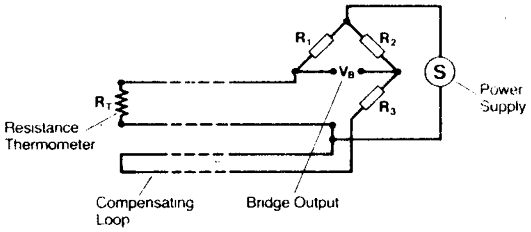


Fig. 12.

A better scheme is shown in Figure 13. Here the two leads to the sensor are on either side of the bridge and thus effectively cancel, while the third lead functions as the extended supply lead to configure the bridge in the form shown below.

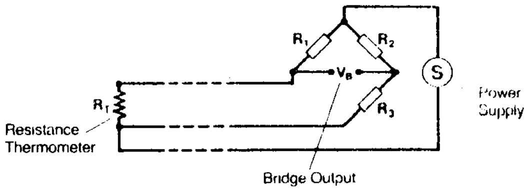


Fig. 13.

The best method of resistance determination however is by using a full four wire connection scheme (see Fig. 14).

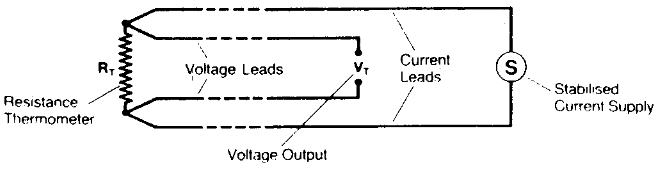


Fig. 14.

The essentials for a voltage based method are shown in Figure 14 above where S provides an accurately known current through the sensor R and the voltage developed across the sensor is measured with a high impedance voltmeter or potentiometer. In this way the resistance of the leads has a negligible effect on the measurement.

The four wire connection arrangement can be used to provide cancellation effects with a bridge type measuring technique (see Fig. 15).

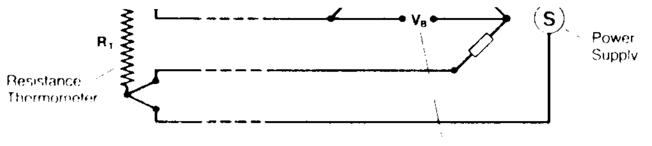


Fig. 15.

3.4 Self-heating effects

In order to measure the resistance of a platinum resistance thermometer an electric current must be passed through the sensor. The passage of such a current will produce a heating effect and the temperature of the thermometer element will be raised above the ideal equilibrium condition.

The heat generated in the thermometer by a current is directly proportional to the resistance value and proportional to the square of the applied current. The temperature rise is dependent on the quantity of heat generated, the size of the sensor and the nature of the thermal linkage between the resistance wire and the surrounding medium. Thus self-heating effects tend to become more significant when for example, slow moving gas streams are being measured rather than fast flowing liquids.

If self-heating is likely to be a problem the energising current should be reduced to a minimum consistent with adequate sensitivity. It is sometimes possible to quantify the error in temperature determination arising from self-heating effects. The resistance of the thermometer is measured at constant temperature with two energising currents. The resistance values are then plotted against the square of the currents and the line can be extrapolated to indicate the resistance value at zero current.

3.5 Installation

The design of platinum resistance sensors is inevitably a compromise between the measurement ideal of a fully annealed, unrestrained platinum wire and the practical requirement of a robust, unbreakable thermometer. The sensors produced for industrial use are remarkably robust and stable but some care should be exercised to try to ensure that they are not subjected to excessive vibration or mechanical shocks. In this regard, long overhanging pockets can be subject to vibration in an industrial plant. Furthermore the sensor should not be able to vibrate within the pocket or thermowell.

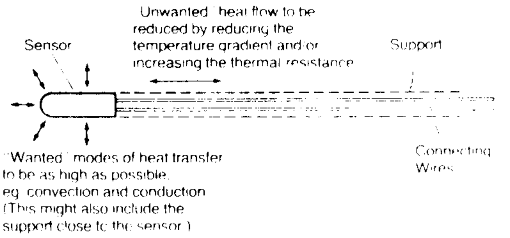
3.6 Calibration

If the accuracy of the application warrants it, regular calibration checks or a routine replacement programme can be instituted. The cost of calibration may well dictate that routine replacement programmes can be instituted. The cost of calibration may well dictate that routine replacement is to be preferred.

4 SOME APPLICATION NOTES

4.1 Thermal linkage of sensor to medium

An important requirement with any temperature measurement is that the sensor should take-up the temperature of its immediate surroundings as closely as possible. There is little advantage in providing a highly accurate means of determining the sensor temperature if it does not, itself, represent the required value. The problem is essentially one of providing a good thermal contact, i.e. high heat transfer and the main considerations are illustrated in Figure 16.



"Unwanted" heat flow to be reduced by reducing the temperature gradient and/or increasing the thermal resistance

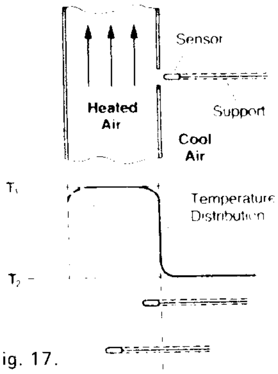
"Wanted" modes of heat transfer to be as high as possible. eg convection and conduction (This might also include the support close to the sensor.)

Fig. 16.

It can be seen that there is a need to provide good thermal paths between the sensor and the measurement region to help the sensor take-up and the local temperature. Conversely, the amount of heat flowing along the sensor stem, or support, which could modify the sensor temperature must be reduced as far as possible. Discussions with your supplier will help to decide the most suitable form of sensor for a particular application.

To obtain accurate temperature measurements the following aspects may have to be taken into account:

a) Good thermal linkage of the sensor to its surroundings. When measuring in solids this includes installing the sensor in a closely fitting hole, considering the use of cements, fillers, high conductivity greases or heat transfer fluids. On surfaces, the use of pads and greases, cements or solders. In fluids, installing in the fastest flowing region, and arranging for the sensor to be in cross-flow if possible. The depth of immersion is important and if the fluids are slow moving with respect to the sensor, external finning may be advantageous.



1) Sensor just immersed. Considerable heat flow away from the sensor along the support. Sensor indication low

2) Sensor well immersed. Long length of support receiving heat from the air stream thus, at same temperature as the sensor. Sensor indicates correctly

Fig. 17.

b) It should be recognised that any heat flow to or from the sensor along the support and connecting wires is unwanted and should be minimised. The first consideration is to reduce the temperature gradients close to the sensor. This usually implies endeavouring to provide sufficient immersion depth of the sensor into the medium (see Fig. 17). Further improvements might be made by using pockets and supports with a high axial thermal resistance, e.g. made from thin stainless steel. Additionally, small diameter and low thermal conductivity connecting wires might be used.

c) The presence of the sensor may affect the temperature that is being measured. This is more likely to be a problem with surface temperature measurements where the sensor may interrupt or modify the heat transfer process at the surface. Two fairly obvious requirements are to keep the size of the sensor to a minimum and to endeavour to make the sensor conform to the characteristics of the surface as far as possible. Usually any measures taken to reduce errors in the sensor temperature will tend also to reduce the temperature disturbance introduced by the sensor.

Heat transfer is a function of three main processes, conduction, convection and radiation. A short explanation of each process is given below.

4.1.1 *Conduction*

Thermal conduction describes the transfer of heat in a medium essentially by the molecular activity within the material. The thermal conductivity of materials differs widely with metals, notably silver and copper, being good conductors whereas gases, e.g. still air, are poor conductors. The thermal conductivity of materials is somewhat related to their electrical conductivity but the near perfect electrical insulating properties of some materials do not exist in the thermal sense. Electrical conduction is analogous to heat conduction and electrical circuits are sometimes used to design thermal layouts. Thermal conduction is the principal mode of heat transfer within the temperature sensor and associated pocket or thermowell assembly.

4.1.2 *Convection*

Convection is the mode of heat transfer between a body and a moving liquid or gas. When a fluid flows over a surface the layer of fluid that is in intimate contact with the surface is brought to rest. From the surface, the velocity initially rises steeply and then more gradually in towards the main flow. Heat transfer is by molecular conduction across the stationary boundary layer and a combination of conduction and physical mixing in the body of the fluid. The temperature distribution in the fluid is related to the velocity distribution.

Forced convection refers to a fluid being circulated by mechanical means, e.g. a pump or fan. If the fluid moves spontaneously under the influence of gravity by heat induced density changes, the phenomenon is known as natural convection. The majority of fluid temperature sensors rely on convection heat transfer at their outer boundary to take up the local fluid temperature.

4.1.3 *Radiation*

A body at a temperature above absolute zero radiates heat and therefore radiation interchange may become a consideration when installing temperature measuring sensors. The intensity of heat radiated from the surface of a body is proportional to its absolute temperature to the fourth power (T^4). Thus the radiation interchange between two surfaces is a function of their differences in temperature to the fourth power ($T_1^4 - T_2^4$). Clearly, the effect becomes more significant as temperatures increase. The radiation intensity is inversely proportional to the square of the distance to the surface; it is also influenced by the surface condition(emissivity),the angle of the surface, the nature of the transmission path, etc. When measuring temperatures in the working space of an electrically heated, high temperature furnace, heat transmission is likely to be almost entirely by radiation to both the contents and to the sensor.

Radiation can provide unwanted heat transfer when, for example, the temperature of a relatively slow moving gas stream is required. The sensor temperature will be brought towards the wanted temperature of the gas by convection heat transfer at the sensor boundary. If the gas is hotter than its surroundings the sensor will also lose heat by radiation and its temperature will be lowered. Conversely, if the gas is cooler than its surroundings the sensor will gain heat by the net interchange between the surroundings and the sensor and its temperature will be raised. To reduce radiation effects of this type the emissivity of the sensor casing might be reduced or shields fitted around the sensor to intercept the radiation.

4.2 Sensor response time

All sensors have a finite response time and this has to be recognised if the temperature of the medium is changing with time. The inherent response time of the sensor is a function of its construction and it is usually determined for a specific test condition. One such method is to plunge the sensor into rapidly moving water maintained at a different temperature. This allows comparisons to be made for different types of sensor. The controlling parameter in this case is the effective thermal diffusivity of the sensor $k/c\rho$ where k is the effective thermal conductivity, c is the effective specific heat and ρ is the density. In simple terms, the thermal diffusivity represents the rate at which a temperature change is propagated through a medium. Thus the ideal quick response sensor would be made of high conductivity material k, having a low specific heat c, and a low density ρ. Unfortunately, many constraints affect the construction of sensors, some of which may impair their response time but some practical steps can be taken by the user. These might include ensuring the lowest possible thermal resistance at the boundary (which is effectively part of k), and reducing the path length (and thus also the thermal mass of the sensor) by using a device of the smallest practical dimensions.

4.3 Stagnation temperature

As the velocity of a gas flowing over a body increases, the temperature of the layer of gas in contact with the body begins to rise. A temperature measuring sensor is such a body and the measurement of the temperature of fast moving gas flows is complicated by the addition of this dynamic heating effect. The temperature most frequently required is the free stream temperature (i.e. the gas temperature without the dynamic component). This is usually called the static temperature. The static temperature plus the dynamic heating component is called the total temperature. The total temperature is the one most usually measured, using special probes designed virtually to stagnate the gas at the sensor and thus recover the dynamic component. From the measured total temperature the static temperature, T_s can be derived from calculation using a relationship such as:

$$T_S = T_T \div [0{,}5(\gamma - 1)M + 1]$$

where T_T = the measured total temperature

γ = the ratio of the specific heats of the gas at constant volume

M = Mach number.

Some examples of the temperature rise due to dynamic heating in air at atmospheric pressure are:

1°C at 45m/s, 10°C at 145 m/s and 30°C at 245 m/s.

5 CONCLUDING REMARKS

Thermocouple and resistance thermometers provide unrivalled methods of temperature measurement for most applications. The instruments are accurate and reliable. However, by utilising some of the procedures contained in this Guide, the accuracy and reliability of your system might be improved still further.