THERMOCOUPLE THEORY AND PRACTICE

THERMOCOUPLE THEORY AND PRACTICE

Basic Theory

In 1821 a German physicist named Seebeck discovered the thermoelectric effect which forms the basis of modern thermocouple technology. He observed that an electric current flows in a closed circuit of two dissimilar metals if their two junctions are at different temperatures. The thermoelectric voltage produced depends on the metals used and on the temperature relationship between the junctions. If the same temperature exists at the two junctions, the voltages produced at each junction cancel each other out and no current flows in the circuit. With different temperatures at each junction, different voltages are produced and current flows in the circuit. A thermocouple can therefore only measure temperature differences between the two junctions, a fact which dictates how a practical thermocouple can be utilised.

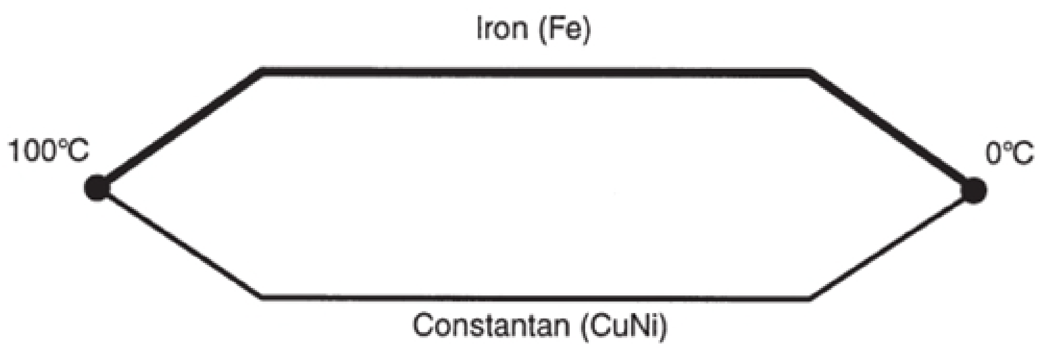

Fig 1: Thermoelement Circuit

It is important to designate each of the junctions for practical purposes; the measuring junction (often referred to as the “hot” junction) is that which is exposed to measured temperature. The reference junction is the other junction which is kept at a known temperature; this is often referred to as the “cold” junction. The term thermocouple refers to the complete system for producing thermal voltages and generally implies an actual assembly (i.e., a sheathed device with extension leads or terminal block.) The two conductors and associated measuring junction constitute a thermoelement and the individual conductors are identified as the positive or negative leg.

Developments in theoretical aspects of thermoelectricity under the influence of solid-state physics has resulted in a rather different explanation of thermocouple activity. This is that the thermoelectric voltage is generated in the thermocouple wires only in the temperature gradient existing between the “hot” and “cold” junctions and not in the junctions themselves. Whilst this is a fundamental conceptual difference to established theory the way in which thermocouples are currently used is generally successful in practical terms. However, this explanation of thermocouple behaviour must be borne in mind when calibrating the sensor or indeed when using them for relatively high precision thermometry.

Thermoelectric voltages are very small and at best attain a few tens of microvolts per degree Centigrade. In consequence, practical thermocouples are mainly used at elevated temperatures, above say 100°C and at depressed temperatures, below - 50°C; however, with appropriate measuring instruments they can be used at any value within their operational range. In some applications, the reference junction may be held at some temperature other than 0°C, for example in liquid gas or a heated enclosure; in any event, the measured "output" will correspond to the difference temperature between the two junctions (fig 2)

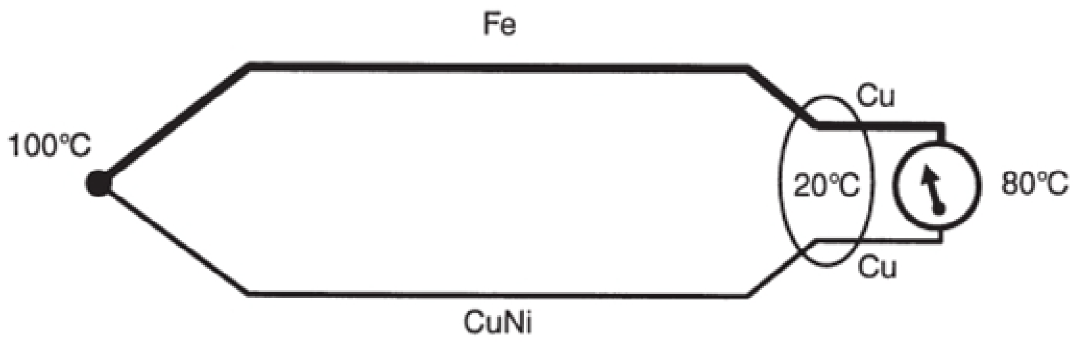

Fig 2: Thermoelement with Connecting Wires

Note Thermocouples are always formed when two different metals are connected. For example, when the thermoelement conductors are joined to copper cable or terminals, thermal voltages can be generated at the transition (see fig. 2). In this case, the second junction can be taken as located at the connection point (assuming the two connections to be thermally common). The temperature of this connection point (terminal temperature) if known, allows computation of the temperature at the measuring junction. The thermal voltage resulting from the terminal temperature is added to the measured voltage and their sum corresponds to the thermal voltage against a 0°C reference.

e.g., If the measuring junction is at 300°C and the terminal temperature is 25°C, the measured thermal voltage for the type K thermoelement (Nickel-Chromium v Nickel-Aluminium) is 11.18mV. This corresponds to 275°C difference temperature. A positive correction of 25°C refers the temperature to 0°C; 300°C is thus indicated.

THERMOCOUPLE PRACTICE

Terminating the Thermocouple

A practical industrial or laboratory thermocouple consists of only a single (measuring) junction; the reference is always the terminal temperature. If the terminal temperature is other than controlled and stable, procedures are necessary to deal with the situation. Possible measures are: -

a) Measure the terminal temperature accurately and compensate accordingly in calculating the measured value.

b) Locate the terminals in a thermally controlled enclosure

c) Terminate not in copper cable but use compensating or actual thermocouple wire to extend the sensor termination to the associated instrumentation (compensating cable uses low-cost alloys which have similar thermoelectric properties to the actual thermoelement). On this basis, there is no thermal voltage at the thermocouple's termination. The transition to copper then occurs only at the instrument terminals where the ambient temperature can be measured by the instrument; the reference junction can then be compensated for electronically.

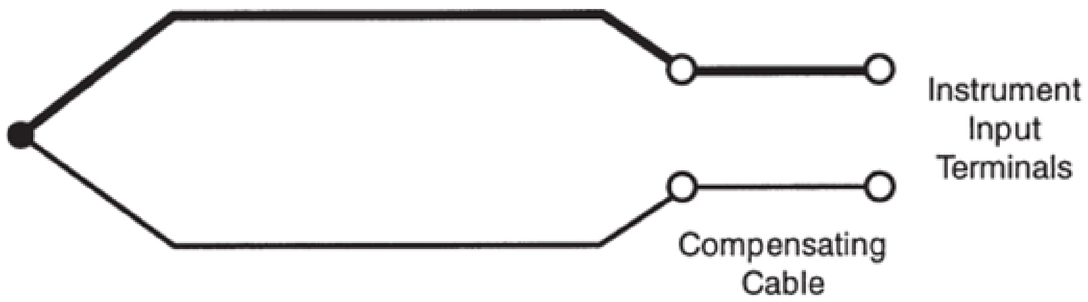

Fig 3: Thermoelement with Compensating Cable

Note: It is essential to use only compensating or specific extension cables (these have the correct thermoelectric properties) appropriate to the thermocouple otherwise an additional thermocouple is formed at the connection point. The reference junction is formed where the compensating or extension cable is connected to a different material. The cable used must not be extended with copper or with compensating cable of a different type.

d) Use a temperature transmitter at the termination point. This is effectively bringing instrumentation close to the sensor where electronic reference junction techniques can be utilised. However, this technique is convenient and often used on plant; a transmitter produces an amplified "corrected" signal which can be sent to remote instruments via copper cable of any length.

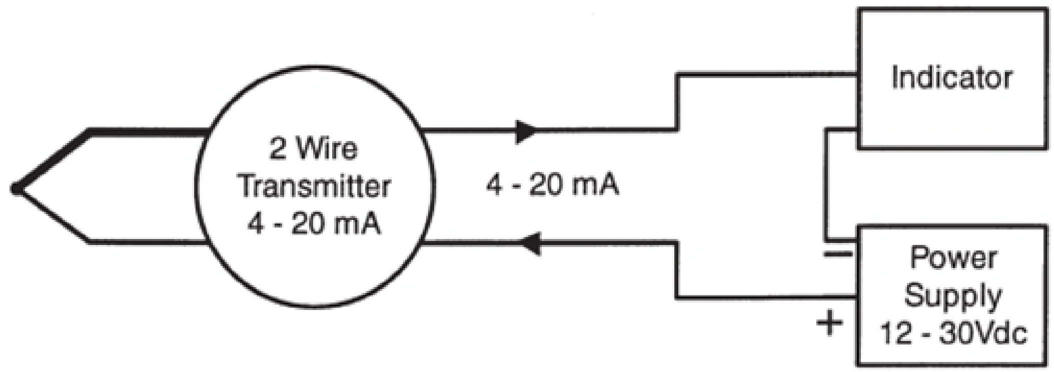

Fig 4: Temperature Transmitter – 2 Wire

External Reference Junction Techniques

Reference junction technology is usually considered as one of the main problems of any thermocouple installation. Individual instruments with thermocouples are generally provided with automatic 'CJC' (cold junction compensation). These devices sense the temperature at the point where the thermocouple is joined to the copper wiring of the instrument and apply a corrective signal. Scanning devices such as data loggers are increasingly using this method.

Where optimum accuracy is needed and to accommodate multi-thermocouple installations, larger reference units are used. These are claimed to have an accuracy of +0.1°C or better and allow the cables to the instrumentation to be run in copper, with no further temperature corrective device needed. The reference units are contained basically under three techniques.

a) The Ice Point. This is a method of feeding the emf from the thermocouple to the measuring instrumentation via the ice-point reference which is usually operated under one of two methods, the bellows type, and the temperature sensor type.

The bellows type utilises the precise volumetric increase which occurs when a known quantity of ultra-pure water changes state from liquid to solid. A precision cylinder actuates expansion bellows which control power to a thermoelectric cooling device.

The temperature sensor switch type uses a metal block of high thermal conductance and mass, which is thermally insulated from ambient temperatures. The block temperature is lowered to 0°C by a cooling element and maintained there by a temperature sensing device. A feature of this unit is its quick "pull down" time to 0°C. Special thermometers are obtainable for the checking of 0°C reference units, and alarm circuits that detect any movement from the zero position can be fitted. For calibration purposes the triple point cell which shows the equilibrium temperature between liquid water, ice and water vapour, and can be reproduced to extreme accuracy, is used.

The traditional Dewar flask filled with melting ice should be used with caution. Unless care and expertise are used in the making up and maintenance of the flask, comparatively large errors can result. When available a 0°C reference unit should be used.

b) The "Hot Box". Thermocouples are calibrated in terms of emf generated by the measuring junctions relative to the reference junction at 0°C, referencing at another temperature therefore does present problems. However, the ability of the hot box to work at very high ambient temperatures, plus a good reliability factor has led to an increase in its usage.

The unit can consist of a solid-state aluminium block thermally insulated in which the reference junctions are embedded. The block temperature is controlled by a closed loop electronic system, and a heater is used as a booster when initially switching on. This booster drops out before the reference temperature, usually between 40°C and 65°C, is reached.

c) Isothermal Systems. The thermocouple junctions being referenced are contained in a block which is heavily thermally insulated. The junctions are allowed to follow the mean ambient temperature, which varies slowly. This variation is accurately sensed by electronic means, and signal is produced for the associated instrumentation. The high reliability factor of this method has favoured its use for long term monitoring.

THERMOCOUPLE INSTALLATION AND APPLICATION

Sheathed Thermocouples – Measuring Junctions

Many alternative sheath materials are used to protect thermoelements and some examples are indicated in a separate chapter. Additionally, three alternative tip configurations are usually offered:

a) An exposed (measuring) junction is recommended for the measurement of flowing or static non-corrosive gas temperature when the greatest sensitivity and quickest response is required.

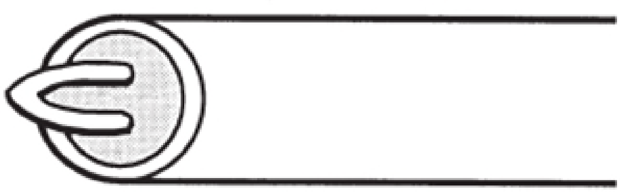

Fig 5: Exposed Junction

b) An insulated junction is more suitable for corrosive media although the thermal response is slower. In some applications where more than one thermocouple connects to the associated instrumentation, insulation may be essential to avoid spurious signals occurring in the measuring circuits.

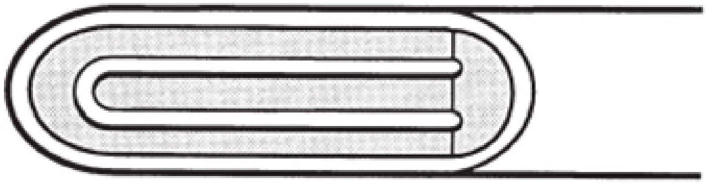

Fig 6: Insulated Junction

c) An earthed (grounded) junction is also suitable for corrosive media and for high pressure applications. It provides faster response than the insulated junction and protection not afforded by the exposed junction.

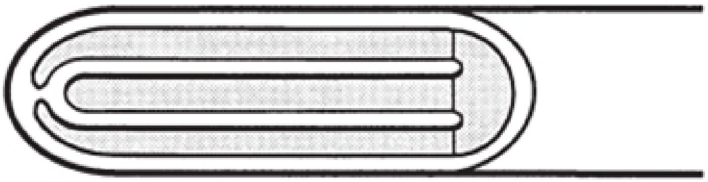

Fig 7: Earthed Junction

Connecting Thermocouples to Instruments

In industrial installations where the measuring and control instruments are located remotely from the thermocouples, compensating cable can be used between the sensor and instrument to reduce cabling costs.

Compensating cable resembles the thermoelectric characteristic of the relevant thermocouple over a limited ambient temperature range, 0° to 80°C typically. Since these cables are made from low-cost materials, cost savings can be achieved on plant installations compared with running true thermocouple extension cable.

Extension cable (true thermocouple material) should be used for maximum accuracy.

Installation Notes:

a) Always observe colour codes and polarity of connections for each type of thermocouple. If the current lead is used but crossed at both ends, the associated instrument will show an error equal to twice the temperature difference between the thermocouple termination and the instrument ambient.

b) Avoid introducing “different” metals into the cabling, preferably use compensating colour coded connectors for the greatest accuracy, reliability, and convenience of installation.

c) Avoid subjecting compensating cable to high temperatures to avoid inaccuracies. Extension cable is superior in this respect.

d) Do not form thermo-junctions using compensating cable; only extension cable is valid for this purpose.

e) Use screened or braided cable connected to ground in any installation where ac pick-up or relay contact interference is likely. “Twisted pair” construction is useful in such situations.

f) For very long cable runs, ensure that cable resistance can be tolerated by the instrumentation without resulting in measurement errors. Modern electronic instruments usually accept up to 100 Ohms or so; they will usually tolerate higher lead resistance, but some error will result. Refer to relevant instrument specifications for full details.

g) Cabling is usually available with many different types of insulation material and outer covering to suit different applications. Choose carefully in consideration of ambient temperature, the presence of moisture or water and the need for abrasion resistance.

h) If errors or indicator anomalies occur, be sure to check the thermocouple, the cable, interconnections, and the instrument. Many such problems are due to incorrect wiring or instrument calibration error rather than the sensor.

Interchangeability is facilitated using plug and socket interconnections. Special connectors are available for this purpose and thermocouple alloys, or compensating materials are used for the pins and receptacles to avoid spurious thermal voltages. Such connectors are usually colour coded to indicate the relevant thermocouple type and are available as “standard” size with round pins or “miniature” size with flat pins.

Fig 8: Plug and Socket Interconnections

Guide to Wire and Cable Insulation and Coverings

Which insulation Material?	Usable Temperature Range	Application Notes
PVC	-10°C to 105°C	Good general-purpose insulation for “light” environments. Waterproof and very flexible.
PFA (extruded)	-75°C to 250°C	Resistant to oils, acids other adverse agents and fluids. Good mechanical strength and flexibility. PTFE better for steam/elevated pressure environments
PTFE (taped & wrapped)	-75°C to 250/300°C	Resistant to oils, acids other adverse agents and fluids. Good mechanical strength and flexibility.
Glassfibre (varnished)	-60°C to 350/400°C	Good temperature range but will not prevent ingress of fluids. Fairly flexible but does not provide good mechanical protection.
High temperature glass fibre	-60°C to 700°C	Will withstand temperature up to 700°C but will not prevent ingress of fluids. Fairly flexible, not good protection against physical disturbance.
Ceramic Fibre	0 to 1000°C	Will withstand high temperature, up to 1000°C. Will not protect against fluids or physical disturbance.
Glassfibre (varnished) stainless steel overbraid	-60°C to 350/400°C	Good resistance to physical disturbance and high temperature (up to 400°C). Will not prevent ingress of fluids.

Single or multi-strand?

The choice is mainly determined by the application (e.g., termination considerations and internal diameter of associated sheath). Generally, single strand wires are used for hot junctions, and multi-strand or thicker single strand for extensions of the thermocouple. The greater the effective conductor diameter, the lower the value of thermocouple loop resistance, an important consideration with long cable runs.

Performance Considerations When Connecting Thermocouples

a) Length of cable runs and loop resistance.

The resistivity of extension and compensating cables varies according to the different conductor metals; the limit to cable lengths which can be accommodated by measuring instruments therefore depends on both the thermocouple type and instrument specifications. A general rule for electronic instruments is that up to 100 Ohms loop cable resistance (i.e., total of both legs) will not result in measurement errors.

The table of loop resistances shown in the reference chapter gives values for the popular types of thermocouple. One example is that of Type K extension cable which has a combined loop resistance of 4.5Ohms/m with 7/0.2mm conductors; in this case, 20 to 25 (100÷4.5) metres is the maximum permissible cable run. The use of larger gauge wires will permit greater lengths of course.

b) Interference and Isolation.

With long runs, the cables may need to be screened and earthed at one end (at the instrument) to minimise noise pick-up (interference) on the measuring circuit.

Alternative types of screened cable construction are available, and these include the use of copper or mylar screening. Twisted pair configurations are offered, and these can incorporate screening as required.

With mineral-insulated cables the use of the sheath for screening may raise problems. In certain forms the measuring point is welded to the sheath to reduce the response time; the screen is then connected directly to the sensor input of the instrument and is therefore ineffective. In thermocouples where the measuring point is welded to the protection tube it may be necessary to take special precautions against interference since the sheath tube can in this case act as an aerial.

Even if the measuring point is not welded to the protection tube it is inadvisable to use the sheath of a mineral-insulated thermocouple as a screen. Since it consists of non-insulated material there is a possibility with electrically heated furnaces that it can carry currents between the furnace material and the earthing point. These may result in measurement errors.

Generally, thermocouples in electrical contact with the protection tube can easily suffer interference from external voltages through voltage pick-up. In addition, two such inputs form a current loop through which the two inputs are connected. Since such current loops form a preferred path for the introduction of interference, thermocouples should under these conditions always be isolated from each other, i.e., the amplifier circuits must have no electrical connection to the remaining electronics. This is already provided on most instruments intended for connection to thermocouples.

Ceramic materials used for insulating the thermocouples inside the protection tube suffer a definite loss of insulation resistance above 800 to 1000°C. The effects described can therefore appear at high temperatures even in thermocouples where the measuring junction is not welded to the protection tube. Here again full isolation is strongly recommended.

With electrically heated furnaces in the high-temperature range it is also necessary to consider that the increased conductivity of the ceramic insulating materials may cause the supply voltage to leak into the thermocouple. Here again full isolation against supply and earth potential with an insulating voltage exceeding the peak voltage of the supply (heater voltage) is essential.

The isolation of the inputs becomes especially important when electrically heated furnaces are fitted with several thermocouples which are linked to one or several instruments.

c) Thermal Voltages and terminals.

The use of brass or copper terminals in the thermocouple circuit may or may not introduce thermal voltages depending on how they are used. Interposing one or two terminations in one or both legs is permissible provided that the temperature on both sides of the termination is the same.

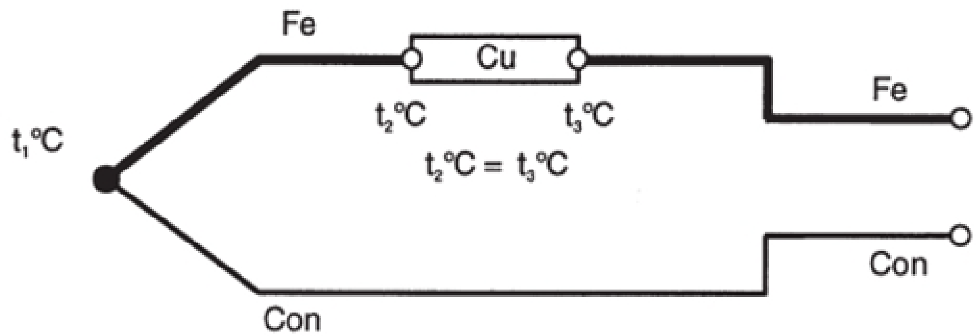

Fig 9: Using a Copper Terminal(s) in a Thermocouple Circuit

The thermal voltages produced at the junctions of Iron – Copper and Copper – Iron cancel each other at the same temperature because they are of opposite polarity, regardless of the actual temperature and of the material. This is only the case if the temperatures at both ends of the termination are the same.

With the usual two terminations, one for each core of the cable, the temperature of each can be different; it is vital though that the same temperature exists on both sides of a given termination.

Where a connection is made under circumstances of temperature variation; it is essential to use connectors free of thermal voltage effects; these are widely available.

DIFFERENT THERMOCOUPLE TYPES

The materials are made according to internationally accepted standards as laid down in IEC 584 1,2 which is based on the international Practical Temperature scale ITS 90. Operating temperature maxima are dependent on the conductor thickness of the thermoelements. The thermocouple types can be subdivided in 2 groups, base metal and rare (noble) metal:

-200°C up to 1200°C – These thermocouples use base metals

Type K – Chromel-Alumel

The best known and dominant thermocouple belonging to the group chromium-nickel aluminium is type K. Its temperature range is extended (-200 up to 1100°C). Its e.m.f./ temperature curve is reasonably linear, and its sensitivity is 41µV/°C.

Type J – Iron-Constantan

Though in thermometry the conventional type J is still popular it has less importance in Mineral Insulated form because of its limited temperature range, - 200C to +750°C. Type J is mainly still in use based on the widespread applications of old instruments calibrated for this type. Their sensitivity rises to 55µV/°C.

Type E – Chromel-Constantan

Due to its high sensitivity (68µV/°C) Chromel-Constantan is mainly used in the cryogenic low temperature range (-200 up to +900°C). The fact that it is non-magnetic could be a further advantage in some special applications.

Type N – Nicrosil-Nisil

This thermocouple has very good thermoelectric stability, which is superior to other base metal thermocouples and has excellent resistance to high temperature oxidation.

The Nicrosil-Nisil thermocouple is ideally suited for accurate measurements in air up to 1200°C. In vacuum or controlled atmosphere, it can withstand temperatures more than 1200°C. Its sensitivity of 39µV/°C at 900°C is slightly lower than type K (41µV/°C). Interchangeability tolerances are the same as for type K.

Type T – Copper-Constantan

This thermocouple is used less frequently. Its temperature range is limited to -200°C up to +350°C. It is however very useful in food, environmental and refrigeration applications. Tolerance class is superior to other base metal types and close tolerance versions are readily obtainable. The e.m.f/temperature curve is quite non-linear especially around 0°C and sensitivity is 42µV/°C.

0°C up to +1600°C – Platinum-Rhodium (Noble metal) Thermocouples

Type S – Platinum rhodium 10% Rh-Platinum

They are normally used in oxidising atmosphere up to 1600°C. Their sensitivity is between 6 and 12 µV/°C.

Type R – Platinum rhodium 13% Rh-Platinum

Similar version to type S with a sensitivity between 6 and 14µV/°C.

Type B – Platinum rhodium 30% Rh-Platinum rhodium 6% Rh

It allows measurements up to 1700°C. Very stable thermocouple but less sensitive in the lower range. (Output is negligible at room temperature).

Historically these thermocouples have been the basis of high temperature in spite of their high cost and their low thermoelectric power. Until the launching of the Nicrosil-Nisil thermocouples, type N, they remained the sole option for good thermoelectric stability.

Additionally, there are specialised thermocouple types which are not described here; these include Tungsten Rhenium types, Pallaplat, Nickel Molybdenum and other Platinum Rhodium alloys.

THERMOCOUPLE CONSTRUCTION

Many alternative configurations exist for thermocouple assemblies; basically, two general types of construction describe most industrial thermocouples – fabricated and mineral insulated.

Fabricated Thermocouples are assembled using insulated thermocouple wire, sheathing (usually stainless steel) and some form of termination (extension lead, connecting head or connector for example)

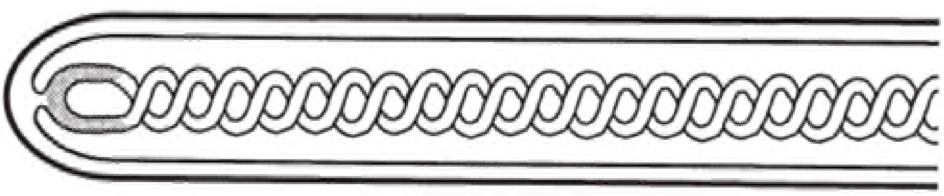

Fig 10: Fabricated Thermocouple
Insulated, Twisted Pair Thermocouple inside Stainless Steel Sheath.
Measuring junction earthed in this example.

Mineral Insulated Thermocouples consist of thermocouple wire embedded in a

densely packed refractory oxide powder insulant all enclosed in a seamless, drawn.

metal sheath (usually stainless steel).

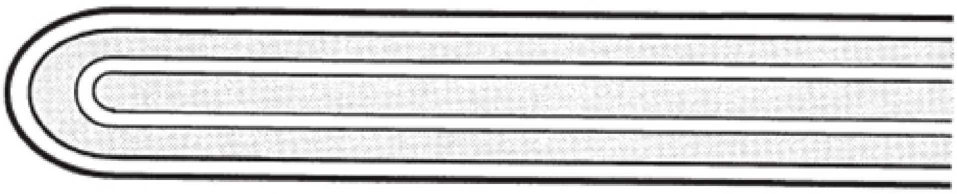

Fig 11: Mineral Insulated Thermocouple
Thermocouple wire insulated by compressed mineral oxide powder.
Insulated measuring junction shown in this example.

Effectively, the thermoelement, insulation and sheath are combined as a flexible cable which is available in different diameters, usually from 0.5mm to 8mm.

At one end, the cores and sheath are welded and form a “hot” junction. At the other end, the thermocouple is connected to a “transition” of extension wires, connecting head or connector.

Advantages of Mineral Insulated Thermocouples are:

a) Small overall dimension and high flexibility which enable temperature measurement in locations with poor accessibility.

b) Good mechanical strength

c) Protection of the thermoelement wires against oxidation, corrosion, and contamination.

d) Fast thermal response

The mineral oxides used for insulation are highly hygroscopic and open-ended cable must be effectively sealed (usually with epoxy resins) to prevent moisture take-up. A carefully prepared mineral insulated thermocouple will normally have a high value of insulation resistance (many hundreds of MOhms).

ACCURACY AND RESPONSE

High Accuracy Thermocouple Measurement

With thermocouple tolerances quoted at say ±2.5°C plus other variations it would appear a poor case could be made out for high accuracy thermocouple measurement, for example in research and high industrial technology. The key to accuracy in this field lies in the careful selection of methods and materials, and the heat treatment and calibration of the thermocouples. While application conditions do alter techniques, the following factors are suggested for consideration.

1. Obtain thermocouples with insulated measuring junctions.

2. Specify “same melts” for large installations.

3. Thermocouple reference junctions should be monitored in a reference unit with an accuracy of ±0.1°C or better.

4. Great care to be taken in running thermocouple circuitry against "pick-up" etc. with the minimum number of joins in the wiring.

5. Heat treats thermocouples to their most stable condition.

6. Calibrate thermocouples.

Thermocouple Response Times

The response time for a thermocouple is usually defined as the time taken for the thermal voltage (output) to reach 63% of maximum for the step change temperature in question. It is dependent on several parameters including the thermocouple dimension, construction, tip configuration and the nature of the medium in which the sensor is located. If the thermocouple is plunged into a medium with a high thermal capacity and heat transfer is rapid, the effective response time will be practically the same as for the thermocouple itself.

(The intrinsic response time). However, if the thermal properties of the medium are poor (e.g., still air) the response time can be 100 times greater.

Sheath Outside Diameter	Types of Measuring Junction	Response Time – Seconds Tip Temperature °C					
		100	250	350	430	700	850
6.0mm	insulated	3.2	4.0	4.7	5.0	6.4	16.0
6.0mm	earthed	1.6	2.0	2.3	2.5	3.15	8.0
3.0mm	insulated	1.0	1.1	1.25	1.4	1.6	4.5
3.0mm	earthed	0.4	0.46	0.5	0.56	0.65	1.8
1.5mm	insulated	0.25	0.37	0.43	0.50	0.72	1.0
1.5mm	earthed	0.14	0.17	0.185	0.195	0.22	0.8
1.0mm	insulated	0.16	0.18	0.19	0.21	0.24	0.73
1.0mm	earthed	0.07	0.09	0.11	0.12	0.16	0.6

Values shown are for a closed end sheath.
For exposed measuring junctions, divide the values shown by 10.

Fig 12: Table of Typical Thermocouple Response Times.

Thermocouples with grounded junctions display response times some 20 to 30% faster than those with insulated junctions. Very good sensitivity is provided by fine gauge unsheathed thermocouples. With conductor diameter in the range 0.025mm to 0.81mm, response times in the region of 0.05 to 0.40 seconds can be realised.

Immersion Length

Thermocouple assemblies are “tip” sensing devices which lends them to both surface and immersion applications depending on their construction. However, immersion types must be used carefully to avoid errors due to stem conduction; this heating flow to or from the sheath and into or away from the process which can result in a high or low reading respectively. A general rule is to immerse into the medium to a minimum of 4 times the outside diameter of the sheath; no quantitative data applies but care must be exercised to obtain meaningful results (e.g., have regard for furnace wall thickness and such like).

The ideal immersion depth can be achieved in practice by moving the probe into or out of the process medium incrementally; with each adjustment, note any apparent change in indicated temperature. The correct depth will result in no change in indicated temperature.

Surface Temperature Measurement

Although thermocouple assemblies are primarily tip sensing devices, the use of protection tubes (sheaths) renders surface sensing impractical. Physically, the probe does not lend itself to surface presentation and stem conduction would cause reading errors. If a thermocouple is to be used reliably for surface sensing, it must be in either exposed, welded junction form with very small thermal mass or be housed in a construction which permits true surface contact whilst attaching to the surface. Locating a thermocouple on a surface can be achieved in various ways including the use of an adhesive patch, a washer and stud, a magnet for ferrous metals and pipe clips. Examples of surface sensing thermocouples are shown below:

Fig 13: Thermocouples for Surface Temperature Sensing

If it is possible to provide lagging (thermal insulation) around the sensor assembly, accuracy will be improved. Thermocouples are ideal for such applications since their measuring junctions have a very small thermal mass and are physically small.