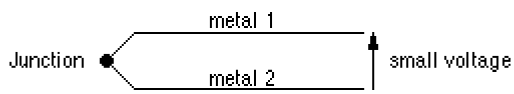
The Basics of Thermocouples

Introduction

The thermocouple is one of the most basic of all sensors. It consists of two wires of dissimilar metals joined near the measurement point. The output is a small voltage measured between the two wires.



The Thermocouple

While simple in concept the theory behind the thermocouple and its applications are much more involved than they appear on the surface so the basics that need to be understood cannot be overlooked for the most effective use of the sensor.

The following sections give a basic understanding of the some fundamentals.

History

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 voltage produced at each junction cancel each other out and no current flows in the circuit. With different temperatures at each junction, different voltage is 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 utilized.

Thermocouple theory

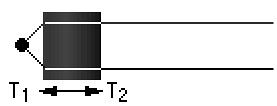
A thermocouple circuit has at least two junctions: the measurement junction and a reference junction. Typically, the reference junction is created where the two wires connect to the measuring device. This second junction it is really two junctions: one for each of the two wires, but because they are assumed to be at the same temperature (isothermal) they are considered as one (thermal) junction. It is the point where the metals change - from the thermocouple metals to what ever metals are used in the measuring device - typically copper.

The output voltage is related to the temperature difference between the measurement and the reference junctions. This is phenomena is known as the Seebeck effect.

In practice the Seebeck voltage is made up of two components: the Peltier voltage generated at the junctions, plus the Thomson voltage generated in the wires by the temperature gradient.

The Peltier voltage is proportional to the temperature of each junction while the Thomson voltage is proportional to the square of the temperature difference between the two junctions. It is the Thomson voltage that accounts for most of the observed voltage and non-linearity in thermocouple response.

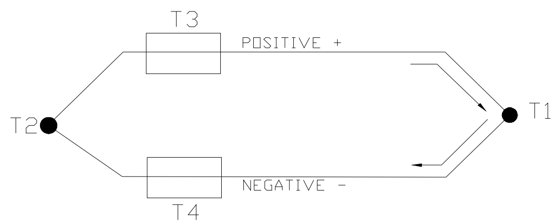
Each thermocouple type has its own characteristic Seebeck voltage curve. The curve is dependent on the metals, their purity, their homogeneity and their crystal structure. In the case of alloys, the ratio of constituents and their distribution in the wire is very important. These potential inhomogeneous characteristics of metal are why thicker wire thermocouples can be more accurate in high temperature applications, when the thermocouple metals and their impurities become more mobile by diffusion.



Signal Generated by Temperature Gradient

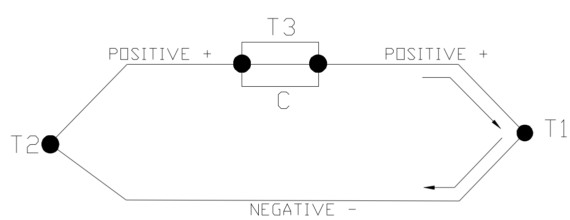
The Basic Laws of Thermoelectric Circuits

1. ***The law of homogeneous circuits*** *states that an electric current cannot be sustained in a circuit of a single homogeneous metal, however varying in section, by the application of heat alone. Any current detected when the wire is heated is taken as evidence that the wire is in homogeneous.*



A consequence of this law is that if one junction of two dissimilar metals is maintained at a temperature T1 and the other junction is at T2, the thermal EMF developed at the junction will not be affected by the temperature of the lead wires even though a temperature distribution exists along the lead wires. Meaning the EMF is not affected by temperatures T3 and T4.

2. ***The law of intermediate metals*** *states that the algebraic sum of the thermo electromotive forces (EMF) in a circuit composed of any number of dissimilar metals is zero if the circuit is at a uniform temperature.*



In a circuit as shown consisting of two dissimilar metals with their junctions at temperatures T1 and T2, a third metal is introduced by cutting and forming two junctions as shown. If the temperature of the third metal introduced is uniform over its entire length, the total electromotive force will be unaffected. As a consequence of this law any measuring device or lead wire can be added to the circuit without affecting the accuracy as long as the new junctions are at the same temperature. This law also permits soldering or brazing of thermocouple junctions.

3. ***The law of successive or intermediate temperatures*** states that if two dissimilar homogeneous metals produce a thermal EMF of E1 when the junctions are at temperatures T1 and T2, and a thermal EMF of E2 when the junctions are at temperatures T2 and T3, then the thermal EMF generated when the junctions are temperatures T1 and T3 will be E1 plus E2. This law permits the determination of an unknown temperature based on a certain reference junction temperature when the reference junction is at a different, but known, temperature from the unknown. It also makes feasible the use of oven controlled and electrically simulated reference junctions.

The practical considerations of thermocouples

The above theory of thermocouple operation has important practical implications that are well worth understanding:

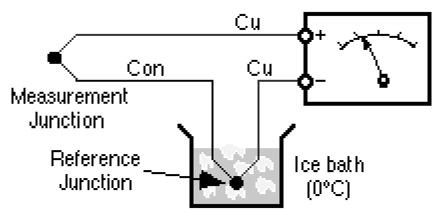
1. A third metal may be introduced into a thermocouple circuit and have no impact, provided that both ends are at the same temperature as shown in the laws above. This means that the thermocouple measurement junction may be soldered, brazed or welded without affecting the thermocouple's calibration, as long as there is no net temperature gradient along the third metal.

Further, if the measuring circuit metal (usually copper) is different to that of the thermocouple, then provided the temperature of the two connecting terminals is the same and known the reading will not be affected by the presence of copper.

2. The thermocouple's output is generated by the temperature gradient along the wires. Therefore it is important that the quality of the wire be maintained where temperature gradients exists. Wire quality can be compromised by contamination from its operating environment and the insulating material. For temperatures below 400℃, contamination of insulated wires is generally not a problem. At temperatures above 1000℃, the choice of insulation and sheath materials, as well as the wire thickness, become critical to the calibration stability of the thermocouple.

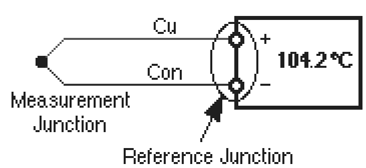
The fact that a thermocouple's output is not generated at the junction should call attention to other potential problem areas if they arise.

3. The voltage generated by a thermocouple is a function of the temperature difference between the measurement and reference junctions. Traditionally the reference junction was held at 0℃ by an ice bath:



Traditional Thermocouple Measurement

The ice bath is now considered impractical and is replaced by a reference junction compensation arrangement. This can be accomplished by measuring the reference junction temperature with an alternate temperature sensor (typically an RTD or thermistor) and applying a correcting voltage to the measured thermocouple voltage before scaling to temperature.



Modern Thermocouple Measurement

The correction can be done electrically in hardware or mathematically in software. The software method is preferred as it is universal to all thermocouple types (provided the characteristics are known) and it allows for the correction of the small non-linearity over the reference temperature range.

4. The low-level output from thermocouples requires that care be taken to avoid electrical interference from motors, power cable and transformers. Twisting the thermocouple wire pair (approx. 1 twist per 10 cm) can greatly reduce magnetic field pickup. Using shielded cable or running wires in metal conduit can reduce electric field pickup. The measuring device should provide signal filtering, either in hardware or by software, with strong rejection of the line frequency (50/60 Hz) and its harmonics.

5. The operating environment of the thermocouple needs to be considered. Exposure to oxidizing or reducing atmospheres at high temperature can significantly degrade some thermocouples.

The advantages and disadvantages of thermocouples

Because of their physical characteristics, thermocouples are the preferred method of temperature measurement in many applications. They can be very rugged, are immune to shock and vibration, are useful over a wide temperature range, require no excitation power, there is no self heating and they can be made very small. No other temperature sensor provides this degree of versatility.

On the down side, the thermocouple produces a relative low output signal that is non-linear. These characteristics require a sensitive and stable measuring device that is able provide reference junction compensation and linearization. Also the low signal level demands that a higher level of care be taken when installing to minimize potential noise sources.

The measuring hardware requires good noise rejection capability. Ground loops can be a problem with non-isolated systems, unless the common mode range and rejection is adequate.

Types of thermocouple

About eight 'standard' thermocouple types are commonly used. They have been given internationally recognized letter type designators. The letter type designator refers to the emf table, not the composition of the metals - so any thermocouple that matches the emf table within the defined tolerances may receive that table's letter designator.

Some of the non-recognized thermocouples may excel in particular niche applications and have gained a degree of acceptance for this reason, as well as due to effective marketing by the alloy manufacturer. Some of these have been given letter type designators by their manufacturers that have been partially accepted by industry.

Each thermocouple type has characteristics that can be matched to applications. Industry generally prefers K and J types because of their suitability to high temperatures, while others often prefer the T type due to its sensitivity, low cost and ease of use.

Thermocouple Type Basic Application Information

E Recommended for continuously oxidizing or inert atmospheres. Sub-zero limits of error not established. Highest thermoelectric output of the common thermocouple types.

J Suitable for vacuum, reducing or inert atmospheres, oxidizing atmospheres with reduced life. Iron oxidizes rapidly above 1000℉ (538℃) heavier gauge wire is recommended for high temperature. Bare elements should not be exposed to sulfurous atmospheres above 1000℉ (538℃).

K Recommended for continuous oxidizing or neutral atmospheres. Mostly used above 1000℉ (538℃). Subject to failure if exposed to sulfur. Preferential oxidation of chromium in positive leg at certain low oxygen concentrations causes “green rot” and large negative calibration drifts most serious in the 1500 - 1900℉ (816 - 1038℃) range. Ventilation or inert sealing of the protection tube can prevent this.

N Can be used in applications where Type K elements have shorter life and stability problems due to oxidation and the development of “green rot”.

T Usable in oxidizing, reducing, or inert atmospheres as well as vacuum. Not subject to corrosion in moist atmospheres. Limits of error established for sub-zero temperature ranges.

R & S Recommended for high temperature. Must be protected in a non-metallic protection tube and ceramic insulators. Continued high temperature usage causes grain growth which can lead to mechanical failure. Negative calibration drift caused by rhodium diffusion to the pure leg of platinum as well as from rhodium volatilization.

B Same as R & S but has a lower output. Also, has a higher maximum temperature and less susceptible to grain growth.

A table with more details on temperature ranges, accuracy and material selection is shown in the "Technical Info" section of this website:

Accuracy of thermocouples

Thermocouples will function over a wide temperature range – from well below zero to their melting point, however they are normally only characterized over their stable range. Thermocouple accuracy is a difficult subject due to a range of factors. In principal and in practice a thermocouple can achieve excellent results if calibrated, used well below its nominal upper temperature limit and if protected from harsh atmospheres. At higher temperatures many variables must be evaluated in order to maintain stability.

As mentioned previously, the temperature and voltage scales were redefined in 1990. The eight main thermocouple types - B, E, J, K, N, R, S and T - were re-characterized in 1993 to reflect the scale changes. (See: NIST Monograph 175 for details). The remaining types such as W, W3 & W5 ("C") have been informally re-characterized.

Thermocouple wire grades

There are different grades of thermocouple wire. The principal divisions are between thermocouple grades and extension grades. The thermocouple grade has the highest purity and should be used where the temperature gradient is significant. The standard thermocouple grade is most commonly used. Special thermocouple grades ("Premium") are available with accuracy about twice the standard measurement grades.

The extension thermocouple wire grades are designed for connecting the thermocouple to the measuring device. The extension wire may be of different metals to the measurement grade, but are chosen to have a matching response over a much reduced temperature range - typically -40℃ to 120℃. The reason for using extension wire in some cases is reduced cost - they can be 60% to 70% of the cost of equivalent thermocouple grades. Further cost savings are possible by using thinner gauge extension wire and a lower temperature rated insulation.

Note: When temperatures within the extension wire's rating are being measured, it is sometimes possible to use the extension wire for the entire circuit. Although not usually recommended this is occasionally done with T type extension wire, which is accurate over the -60 to 100℃ range.

Thermocouple wire gauge

At high temperatures, thermocouple wire can under go irreversible changes in the form of modified crystal structure, selective migration of alloy components and chemical changes originating from the surface metal reacting to the surrounding environment. With some types, mechanical stress and cycling can also induce changes.

Increasing the diameter of the wire where it is exposed to the high temperatures can reduce the impact of these effects.

At higher temperatures, the thermocouple wire should be protected as much as possible from hostile gases. Reducing or oxidizing gases can corrode some thermocouple wire very quickly. The purity of the thermocouple wire is most important where the temperature gradients are greatest. It is with this part of the thermocouple wiring where the most care must be taken.

Other sources of wire contamination include the insulating materials and the protective metal sheath. Metallic vapor diffusion can be significant problem at high temperatures. Platinum wires should only be used inside a nonmetallic sheath, such as high-purity alumna or mullite.

High temperature measurement is very difficult in some situations. Sometimes in these cases non-contact methods are used. However this is not always possible as the site of temperature measurement is not always visible to these types of sensors.

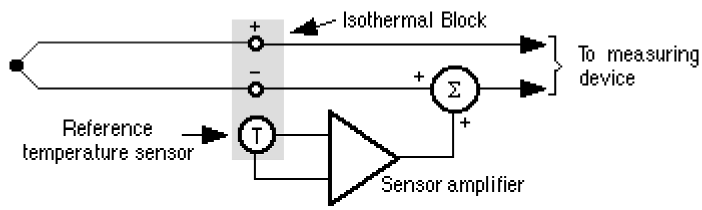
Color coding of thermocouple wire

The color coding of thermocouple wire is somewhat confusing. There are at least seven different standards. There are some inconsistencies between standards, which seem to further the confusion. For example the color red in the USA standard is always used for the negative lead, while in German and Japanese standards it is always the positive lead. The British, French and International standards avoid the use of red entirely.

Thermocouple compensation and linearization

As mentioned above, it is possible to provide reference junction compensation in hardware or in software. The principal is the same in both cases: adding a correction voltage to the thermocouple output voltage, proportional to the reference junction temperature. To this end, the connection point of the thermocouple wires to the measuring device (i.e. where the thermocouple materials change to the copper of the circuit electronics) must be monitored by a sensor. This area must be design to be isothermal, so that the sensor accurately tracks both reference junction temperatures.

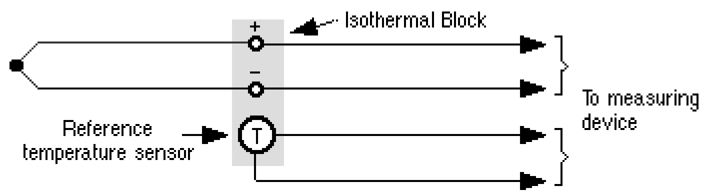
The hardware solution is simple but not always as easy to implement as one might expect.



Hardware Reference Junction Compensation

The circuit needs to be designed for a specific thermocouple type and hence lacks the flexibility of the software approach.

The software compensation technique simplifies the hardware requirement, by eliminating the reference sensor amplifier and summing circuit (although a multiplexer may be required).



Software Reference Junction Compensation

The software algorithm to process the signals needs to be carefully written.

A good resource for thermocouple emf tables and coefficients is either in the “technical pages” of this site or at the US Commerce Dept's NIST web site. It covers the B, E, J, K, N, R, S and T types.