# MSL Technical Guide 14

# Making Sense of Thermocouples

## Introduction

Thermocouples are the most widely used of all temperature sensors. The simplicity of two wires connected to a meter has an obvious appeal. However, when high confidence is required, thermocouples can be a liability. Unlike other temperature sensors, thermocouple faults are often not obvious and calibration of thermocouples can be a waste of time.

The purpose of this technical guide is to provide thermocouple users with a simple explanation of how thermocouples really work, their problems, and how to get the best from thermocouple measurements.

## How Thermocouples Work

Numerous text-books and manufacturers' application notes cite the thermocouple junction as the source of the thermocouple voltage. In fact, in a well-designed thermocouple installation, **the junction contributes nothing to the voltage**. The junction is required only to complete the electrical circuit.

The thermocouple voltage arises because electrons in metals are responsible for carrying both heat and electricity (hence thermo-electric effect). In fact, the voltage is a side effect of heat flow. When there is a temperature difference between two parts of a piece of metal, electrons in the metal diffuse rapidly, carrying the heat, and helping the temperature to equalise. However, the electrons in the hot and cold zones diffuse differently. This means that where a temperature difference exists, there is also a charge imbalance – and a voltage is generated. This is the Seebeck effect. Most importantly, the effect occurs in the bulk of the metal and has nothing to do with any junction.

A good analogy of the thermocouple is a water-filled tube, as shown in Figure 1. Within the tube, the pressure is generated where there are gradients in the elevation of the tube. If the fluid within the tube is the same density throughout, then the pressure generated depends only on the elevations of the two ends.

Similarly, in any conductor, the Seebeck voltage is generated only at temperature gradients. If the conductor is homogeneous ('undamaged', we define this term shortly), the total voltage depends only on the end temperatures.

An important feature of thermocouples is that defects in the wires will only have an effect if they are in a part of the wire exposed to a temperature gradient. A section of wire all at the same temperature is said to be isothermal. Isothermal wires generate no voltage.

In a thermocouple, the two different wires generate different voltages, and the voltmeter measures the difference between the two voltages.

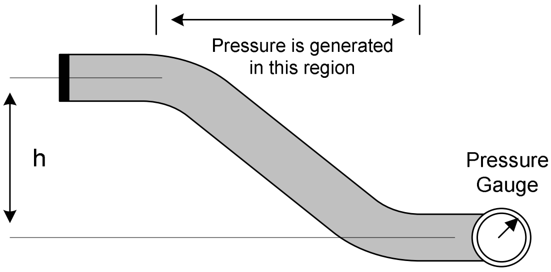


**Figure 1.** A hydraulic analogue model of a thermocouple wire. The pressure in the tube is generated only at gradients, but the total pressure depends only on the elevation of the ends.

The function of the junction in a thermocouple is simply to ensure there is an electrical connection between the two wires. So long as the junction and the damaged wire associated with the junction is isothermal, it will not generate a signal. It does not matter how the junction is made, e.g., by welding, brazing, crimping, etc, as long as it has the mechanical strength to ensure a reliable electrical connection.

## Homogeneous Wires

In order for the thermocouple voltage to be dependent on the end temperatures only, the Seebeck coefficient, which is temperature dependent and relates the voltage generated to the temperature gradient, must be the same for all sections of wire. Such wire is said to be **homogeneous**. Unfortunately, almost all of the problems with thermocouples arise from localised changes in the wire due to mechanical, thermal, and chemical damage. For example:

- A single bend, located at a temperature gradient, in a Type K thermocouple has been observed to cause a 3 °C shift in the temperature reading.
- Type K thermocouples operated at high temperatures and deprived of oxygen develop 'green rot' due to preferential oxidation of chromium. Prolonged exposure may cause a 30 % decrease in the Seebeck coefficient. This will result in errors of up to 30 °C at 100 °C.
- Type K thermocouples cycled between temperatures below 250 °C and above 550 °C will exhibit hysteresis of between 2.5 °C and 8 °C, depending on wire composition and rate of change of temperature.
- The Seebeck coefficient, for bare Type K wires in normal use in an oxidizing environment, increases about 1 % for every 1000 hours at 1000 °C.

While these examples all apply to Type K thermocouples, similar effects can be observed in all thermocouples; it happens that Type K thermocouple materials are amongst the most susceptible to these effects.

## Thermocouple Circuits

To overcome the problems with inhomogeneities, there are two guiding principles for all thermocouple circuits:

1. Where the wire is exposed to temperature gradients, e.g., where the thermocouple passes through a furnace wall, ensure it is physically and chemically protected so it is maintained in a homogenous condition.
2. Where wire is inhomogeneous, e.g., the damaged wire near the measurement and reference junctions, ensure it is maintained in an isothermal environment. If there is no temperature gradient there can be no voltage generated.

The first of these principles can be impossible to satisfy in some circumstances. In long-term and high-temperature installations, particularly, most thermocouples suffer changes in the Seebeck coefficient due to the migration of impurities, chemical changes with oxidation, or metallurgical phase changes. Further, these changes are often localized so that changes in immersion conditions or removal of the thermocouple for calibration can change the temperature reading considerably.

Where high confidence and/or high accuracy are required, thermocouples should be:

(i) fixed in place,
(ii) calibrated *in situ*, and
(iii) used only for a single installation.

Figure 2 shows a simplified circuit for a thermocouple. Following the two guidelines, the measurement junction, the reference junction and the voltmeter (a complex inhomogeneous device) are maintained in isothermal environments. In this state there are four sections of wire that generate a voltage. The two homogeneous copper leads to the meter, because they generate equal and opposite voltages, have no net effect on the measurement. The remaining voltages are due to the homogeneous wires A and B, which generate net voltage according to their end temperatures:

$$V_{\text{meas}} = [V_{\text{A}}(t_{\text{m}}) - V_{\text{A}}(t_{\text{r}})] - [V_{\text{B}}(t_{\text{m}}) - V_{\text{B}}(t_{\text{r}})] .$$

Note that if the materials A and B are the same then the net voltage is zero for all temperatures. This equation is simplified by associating the materials A and B as a thermocouple pair and by defining $V$(0 °C) = 0 for all thermocouple wire. The equation then simplifies to

$$V_{\text{meas}} = V_{\text{AB}}(t_{\text{m}}) ,$$

and this is the deceptively simple relationship defined by thermocouple standards.

Where the reference junction is at a temperature $t_r$ instead of 0 °C, the net voltage from the thermocouple is

$$V_{\text{meas}} = V_{\text{AB}}(t_{\text{m}}) - V_{\text{AB}}(t_{\text{r}}) .$$

Correction of the measured voltage to account for the temperature of the reference junction not being at 0 ºC is usually referred to as '**cold junction compensation**'. It requires an independent measure of the reference junction temperature and the addition of a voltage. In most modern instrumentation this is carried out automatically by the instrument.

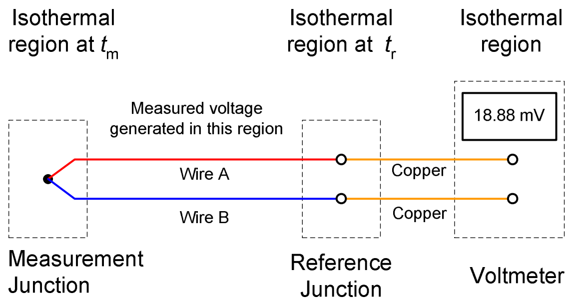


**Figure 2.** A simple thermocouple circuit.

## Calibration

Calibration of thermocouples can be a waste of time. If the wire is inhomogeneous, the thermocouple voltage will change as a temperature gradient is moved to different sections of wire (e.g., by changing the immersion into an oil bath). This means that the calibration is only useful if it is carried out with the same temperature profile along the thermocouple as when the thermocouple is used.

We can therefore identify several situations where thermocouple calibration is useful:

- *In situ*. Base-metal thermocouples with alloy wires (Types E, J, K, N, T) are prone to developing inhomogeneities when used above about 200 ºC. In these cases, an additional **heat treatment in a calibration furnace will alter the wire**. It will also not reproduce the temperature gradient in use. Both effects will lead to errors in the wire calibration. In these cases, *in situ* calibration is the only practical method. This is done by inserting a reference thermometer (platinum resistance or rare-metal thermocouple) along side the thermocouple being calibrated, and comparing the readings. The installation may have to be designed with calibration in mind for this approach to be practical.
- As a representative sample. If a large number of thermocouples are being installed, it is worthwhile getting them made from the same batch of wire, and getting a few calibrated. Since the remaining thermocouples will be brand new and in a homogeneous state, the sample calibrations will be applicable to the thermocouples being installed.
- Rare-metal thermocouples and low-temperature thermocouples. Thermocouple Types B, R, and S use pure platinum or platinum-rhodium alloys. As might be expected they also suffer from inhomogeneities, but the effects are small, perhaps only 0.3 °C. For rare-metal thermocouples, calibrations are meaningful to this level of accuracy. Base metal thermocouples used only at temperatures below 200 °C (Type K below 120 °C) generally do not exhibit large inhomogeneities so they too can be usefully calibrated off site.

## Leads and Connectors

In many industrial installations the temperature measurement may be made some distance from the indicator. In these cases it may be necessary to have many tens of metres of thermocouple wire between the measurement and reference junctions. To facilitate installation, some of the thermocouple circuit may consist of extension leads. These are flexible multi-strand thermocouple cables made from materials the same as, or similar to, the thermocouple materials. Note that the extension leads still contribute to the thermocouple voltage if they pass through temperature gradients. Extension leads are also only specified for a narrow temperature range, typically 0 °C to 50 °C, so they should not be used outside this range. If you cannot keep your hand on them they are too hot.

All thermocouple connections should be made with or via thermocouple materials. Plugs, sockets, and connecting blocks made from the appropriate materials are available for all of the letter-designated thermocouples.

## Choice of Thermocouple

Over the years, many hundreds of different thermocouples have been developed. Those in most common use are the so-called letter-designated thermocouples: Types E, J, K, N, and T are called base-metal thermocouples and are low cost (a few dollars per metre). Type B, R, and S are called rare-metal thermocouples since they are made from platinum and rhodium, and are usually expensive (up to $1000 per metre or more). In general the rare-metal thermocouples are more accurate but they have a lower signal level and are also more susceptible to contamination.

All types are readily available in many different wire diameters, insulation materials, sheath materials, and sheath designs. But none are suitable for all applications. Therefore it will be necessary to consult your local thermocouple manufacturer for advice. Further advice can be sought from your National Measurement Institute or found in a number of good books – see the reading list at the end of this guide.

One particularly useful thermocouple form is the Mineral Insulated Metal Sheathed (MIMS) thermocouple. The assembly is flexible, and most thermocouple types are readily available with a range of MIMS sheaths suited to different temperatures and environments.

## Installation Examples

To emphasise the key aspects of thermocouple installation we give here two examples, one good and one bad.

Figure 3 shows an example of a bad installation for the measurement of pipe temperature (e.g., for a hot water pipe). The errors with this type of installation can be 10% or higher (e.g. the thermocouple indicates 90 °C when the pipe is at 100 °C). Unfortunately, this type of installation is recommended in some books and manufacturers' guides. It suffers from two problems. Firstly, heat conducted down the sheath of the thermocouple causes localised cooling of the pipe. Secondly, because of the heat flow, there is a temperature gradient over the junction of the thermocouple. Both effects can cause large errors.

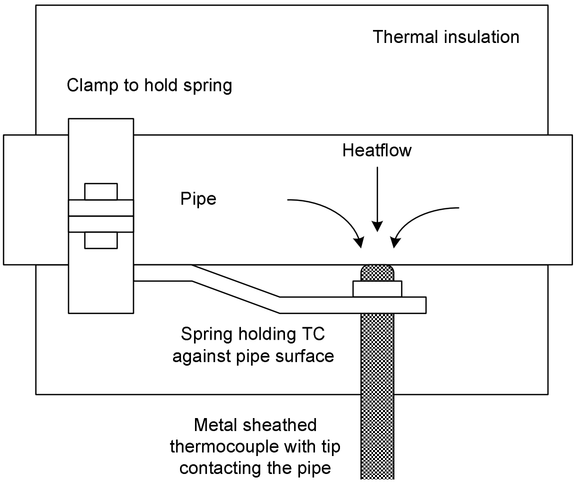


**Figure 3.** A poor thermocouple installation susceptible to poor thermal connection with the pipe and gradients across thermocouple junction

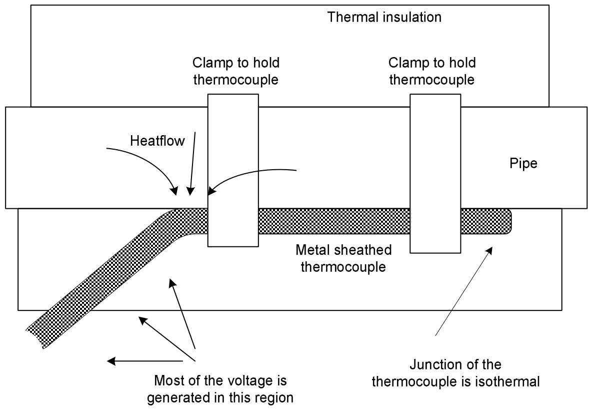


**Figure 4.** A good thermocouple installation that ensures good thermal connection with the pipe and no gradient over the junction

Figure 4 shows a good installation for a pipe temperature measurement. In this case, the area of pipe cooled by the heat loss down the thermocouple is well removed from the junction area. That is, the thermocouple junction is in an isothermal zone at the same temperature as the pipe. This ensures that the damaged wire at the junction does not generate any spurious voltages.

## Helpful Tips

Many industrial installations require both an indicator and a controller. If these are operated with separate thermocouples, then it is possible to measure the drift rates of the thermocouples. To do this, the thermocouples should be replaced occasionally, every six months perhaps, but they should not be replaced at the same time. Instead **stagger the replacement schedules**.

When one thermocouple is to be replaced, record the difference between the indicator and controller readings. Replace just one thermocouple, and note again the difference between the controller and indicator readings. The change in the difference will indicate how much the replaced thermocouple had drifted during its use. Note that the best accuracy in this approach is obtained when the thermocouples are from the same batch. You can now adjust the replacement schedule according to your accuracy requirements and the observed drift.

When a new thermocouple installation is assembled it is worthwhile checking the thermocouple circuit with a hot air blower. Put the thermocouple in an ice point (see MSL Technical Guide 1), the indicator should read close to 0 °C. Now take the hot air gun and wave it over all connections and joins in the thermocouple circuit. If the thermocouple wires, the extension leads, and connector materials are of the correct type, and the connections are all correct, then the thermocouple reading should not change and continue to read near 0 °C. If you see large changes in the reading, then something is wrong.

Although thermocouple wires and many sheathed assemblies are designed to be flexible, care should be taken with the placement of bends. If possible, make sure that the wire exposed to large temperature gradients, e.g. through furnace walls, is not bent. If bends must be located in temperature gradients, keep the bending radius of the wire as large as practical.

## Further Reading

### *Advice on thermocouple types and problems:*

American Society for Testing and Materials, *Manual on the use of Thermocouples in Temperature Measurement*, 4th Ed., 1993.

G W Burns, M G Scroger, G F Strouse, M C Croarkin, W F Guthrie, NIST Monograph 175, National Institute of Standards and Technology, Washington 1993. The voltage–temperature tables from this monograph are available at the NIST website: http://srdata.nist.gov/its90/main/.

R E Bentley, *Handbook of Temperature,* Vol. 3, Springer, Singapore, 1998.

### *For voltage vs temperature tables see also:*

American Society for Testing and Materials, E 1751-00, *Standard Guide for Temperature Electromotive Force (emf) Tables for Non-letter Designated Thermocouples*, 2005 (available at http://www.astm.org/).

International Electrotechnical Commission, International Standard 60584 *Thermocouples-Part 1: Reference tables*, 1995 (available at http://www.iec.ch/).

### *General thermometry:*

J V Nicholas and D R White, *Traceable Temperatures: An Introduction to Temperature Measurement and Calibration*, 2nd Ed., John Wiley & Sons, Chichester, 2001.

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