Thermocouples: What one needs to know

By Thomas W. Kerlin and Mitchell P. Johnson

Typical thermocouples are very simple, consisting only of two dissimilar conductors joined at one end and connected to instrumentation at the other end. Thermocouples are rugged and inexpensive. They are widely used and will continue to be. They typically provide satisfactory temperature measurements, but are not foolproof. Problems in applications can happen when users are unaware of some simple facts about thermocouple properties and principles or are careless or uninformed during installation.

Here are the 12 essential facts:

1. Thermocouple measurements have significant uncertainties due to manufacturing tolerances. For example, the tolerance on a standard grade Type K thermocouple at 1000oC (1832oF) is ±7.5oC (±13.5oF), indicating two sensors could differ by 15oC (27oF). Errors at the extreme of the tolerance range are possible but unlikely because manufacturers strive to build sensors with nominal calibrations.

2. Thermocouples do not produce a voltage at the junction. Rather, the voltage produced occurs along the length of wires that are in a temperature gradient.

3. Thermocouple thermometry requires measurement of the voltage produced by the thermocouple while no current flows in the circuit. (We need to have the "open circuit voltage.") Consequently, read-out instrumentation must have a large input impedance to adequately approximate open circuit conditions.

4. Thermocouples can decalibrate in use. This is usually a gradual process and can easily go unnoticed. Decalibration can impact process performance.

5. The most likely cause of decalibration is creation of inhomogeneous sections in one or more wires caused by chemical attack that alters the wire composition or mechanical effects that alter the wire metallurgy. Such an inhomogeneous section causes errors if, and only if, it experiences a temperature gradient.

6. Recalibration of used thermocouples is ineffective and a waste of time. Errors due to inhomogeneities, the likely cause of decalibration, depend on the temperature gradient when in use and duplicating that gradient in a calibration facility is not possible.

7. Metal-sheathed thermocouples and thermowells that house sensors conduct heat along their length. This can cause the sensor to read a temperature that lies between the process temperature and the temperature at the back end of the sensor. This problem increases with shorter, fatter sensors.

8. Sensors and thermowells can suffer mechanical failure due to vibration, stress, or pressure. Software is available to enable selection of components that are unlikely to experience these problems.

9. The time response of a sensor immersed in a process depends strongly on fluid conditions around the sensor. Time constant values reported by sensor manufacturers apply only for the conditions at which they made a measurement.

10. Thermocouple voltage depends on the temperature difference between the junction and the back end where the voltage is measured. But the thermocouple tables are based on a back end temperature of 0oC. Determining temperature requires compensation for departure of the back end temperature from 0oC. Dedicated thermocouple instruments handle this automatically, but using a voltmeter requires an understanding of the compensation procedure.

11. Thermocouple loop analysis is a simple method whose use explains all aspects of thermocouple use and misuse. Every serious user of thermocouples should learn and use this method.

12. The so-called “Laws of Thermoelectricity” should be forgotten. They have been part of the folklore for decades but are of little or no value in making good measurements. Thermocouple loop analysis is the way to go.

Thermocouple loop analysis

A homogeneous section of a conductor that experiences a temperature T0 at one end and a temperature T1 at the other end experiences a voltage difference, V, between the two ends. The voltage, V, is given by the following equation:

$V = S (T_1 – T_0)$ (1)

where

S = the Seebeck coefficient (μV/°C)

The Seebeck coefficient (also called the “thermoelectric power”) is the fundamental thermoelectric property related to thermocouple thermometry. It is a physical property of a material, like its density, thermal conductivity, or electrical resistivity. It is independent of the size and shape of the conductor but does vary with temperature. Because of this temperature dependence, the relation shown in Equation 1 is an approximation. This approximation is adequate for the qualitative analysis of thermocouple circuits but is inadequate for predicting the voltage that would be observed for a specific thermocouple in a specific temperature gradient. However, for understanding how various thermocouple configurations work, it is quite satisfactory.

The simple relation between voltage and temperature difference along the conductor may be used to predict thermocouple performance, analyze thermocouple configurations, and troubleshoot problems with thermocouple thermometry. This procedure is called thermocouple loop analysis. The procedure may be illustrated for the basic thermocouple shown in Figure 1. The approach is simply to sum up the voltage contributions for each homogeneous portion of the conductor. For example, if we choose to start the summing process at the open end of conductor A, the voltage is as follows:

$V = S_A(T_1 – T_0) + S_B(T_0 – T_1)$ (2)

This is algebraically the same as

$$V = (S_A - S_B)(T_1 - T_0) \qquad (3)$$

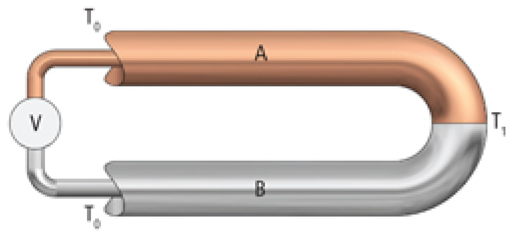

Figure 1

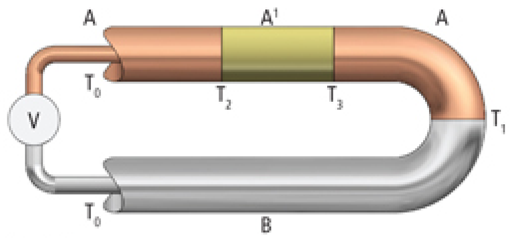

Figure 2

Note the difference in the Seebeck coefficients for the two conductors appears in Equation 3. This always happens in thermocouple loop analysis, and it is the property that is of practical interest in thermocouple thermometry. It is called the relative Seebeck coefficient (between material A and material B) and is written “S_{AB}.” That is,

$$S_{AB} = S_A - S_B \qquad (4)$$

Consequently, Equation 4 may be written as follows:

$$V = S_{AB}(T_1 - T_0) \qquad (5)$$

This is the fundamental relation in thermocouple thermometry.

Thermocouple loop analysis enables the thermocouple user to characterize any thermocouple configuration. It explains the consequences of damage to any part of a thermocouple circuit.

Reference temperature compensation

The thermocouple tables and mathematical functions for voltage vs. temperature give temperature for measured voltage when the reference end (the point where the voltage is measured) is at 0^oC. Since the reference temperature is not 0^oC in typical applications, a correction must be made before determining the junction temperature. Using thermocouple loop analysis, we may write

$$V(T_2-0) = V(T_1-0) + V(T_2 - T_1). \qquad (6)$$

That is, we must add the voltage that would have been observed if the junction was at temperature T_1 and the reference temperature was at 0^oC (the first term in Equation 7). Thermocouple readout instruments perform this correction automatically. Of course the reference temperature, T_1, must be known. Instruments include a sensor (usually an integrated circuit sensor or a thermistor) to provide T_1. The instrument then determines the voltage, V(T_1-0) from a stored formula for voltage as a function of temperature, and adds it to the measured voltage in order to obtain the voltage that would have been measured if the reference temperature was 0^oC.

The inhomogeneity problem

In the case in which chemical or metallurgical changes occur only along a portion of the thermocouple wire, the Seebeck coefficient is unchanged, except over the length of wire where the chemical or metallurgical changes occurred. A simplified depiction of the situation is shown in Figure 2, where the changes in Seebeck coefficient occur abruptly. Thermocouple loop analysis gives the following:

$$V = S_{AB}(T_1 - T_0) + S_{A'A}(T_2 - T_3) \qquad (7)$$

The first term is the voltage that would have been produced if the thermocouple had not undergone attack. Consequently, the second term is the error caused by the inhomogeneous region. If the relative Seebeck coefficient between the unaffected wire and the altered wire is nonzero, then a measurement error will occur if T_2 is not equal to T_3. That is:

An inhomogeneous section in a thermocouple wire will cause a measurement error if, and only if, it resides in a temperature gradient.

This is a very important result. Process or environmental conditions usually cause alterations only along some portion of a wire. This makes the measurement error dependent on the temperature profile along the wires. One consequence of this is it confounds any attempts to recalibrate used thermocouples. This is because in a calibration facility it is impossible to duplicate the temperature profile that the thermocouple system will experience when it is being used in a process.

The error caused by the development of an inhomogeneous section in a thermocouple circuit may be positive or negative. As can be seen in Equation 7, the polarity depends on the relative Seebeck coefficient between the affected and unaffected segments (since $S_{AA'} = S_A - S_{A'}$,$S_{AA'}$ can be positive or negative). Also, the polarity depends on the temperature difference, T_2-T_3, across the affected region, and this can be positive or negative.
Conclusions

Thermocouples are widely used and are here to stay. Problems are infrequent, but potentially serious. Users need to know how to use thermocouples properly and to troubleshoot effectively when problems arise. Thermocouple loop analysis is simple (eighth grade mathematics), comprehensive, and effective. It is an essential tool for all who are responsible for ensuring temperature measurements are correct.

ABOUT THE AUTHORS

Thomas W. Kerlin is Professor Emeritus from The College of Engineering at The University of Tennessee where he served as Professor and Head of The Nuclear Engineering Department before retirement. He has published numerous articles and two books on temperature measurement. **Mitchell P. Johnson** is president of JMS Southeast, Inc., a 31 year manufacturer of thermocouples and related products. He serves as a member of ISA, the ASTM Temperature Measurement committee, the ASME Thermowells committee and has published articles and presentations on temperature measurement through ISA.

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