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Taking Thermocouple Temperature Measurements

Overview

This tutorial is part of the National Instruments Measurement Fundamentals series. Each tutorial in this series teaches a specific topic about common measurement applications by explaining theoretical concepts and providing practical examples. This document introduces thermocouples, which are inexpensive temperature sensing devices that are widely used with PC-based data acquisition systems. It also includes some specific thermocouple examples.

For more in-depth guidance on making a thermocouple measurement, visit the how-to guide.

To find more information on the Measurement Fundamentals series, return to the Measurement Fundamentals Main Page.

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What Is Temperature?

Qualitatively, the temperature of an object is determined by the sensation of heat or cold felt by touching an object. Technically, temperature is a measure of the average kinetic energy of the particles in a sample of matter, expressed in units of degrees on a standardized scale.

What Is a Thermocouple?

The basis of thermocouples was established by Thomas Johann Seebeck in 1821 when he discovered that a conductor generates a voltage when it is subjected to a temperature gradient. Measuring this voltage requires the use of a second conductor material that generates a different voltage under the same temperature gradient. If the same material is used for the measurement, the voltage generated by the measuring conductor simply cancels that of the first conductor. The voltage difference generated by the two dissimilar materials can be measured and related to the corresponding temperature gradient. Based on Seebeck's principle, it is clear that thermocouples can only measure temperature differences and they need a known reference temperature to yield the absolute readings.

The Seebeck effect describes the voltage or electromotive force (EMF) induced by the temperature gradient along the wire. The change in material EMF with respect to a change in temperature is called the Seebeck coefficient or thermoelectric sensitivity. This coefficient is usually a nonlinear function of temperature.

However, for small changes in temperature over the length of a conductor, the voltage is approximately linear, which is represented by the following equation where ΔV is the change in voltage, S is the Seebeck coefficient, and ΔT is the change in temperature:

$$\Delta V \approx S\Delta T \quad (1)$$

A thermocouple is created whenever two dissimilar metals touch at one end and are measured at the other, creating a small open-circuit voltage as a function of the temperature difference between the contact point and the measurement point of the metals. The measured voltage from the thermocouple is the difference between the Seebeck voltage across each conductor, represented by the above equation. S varies with changes in temperature, which causes the output voltage of thermocouples to be nonlinear over their operating ranges.

Several types of thermocouples are available, and different types are designated by capital letters that indicate their composition according to American National Standards Institute (ANSI) conventions. For example, a J-Type

thermocouple has one iron conductor and one constantan (a copper-nickel alloy) conductor. You can see a complete list of thermocouples in Table 1.

Thermocouple Type	Conductors – Positive	Conductors – Negative
B	Platinum-30% rhodium	Platinum-6% rhodium
E	Nickel-chromium alloy	Copper-nickel alloy
J	Iron	Copper-nickel alloy
K	Nickel-chromium alloy	Nickel-aluminum alloy
N	Nickel-chromium-silicon alloy	Nickel-silicon-magnesium alloy
R	Platinum-13% rhodium	Platinum
S	Platinum-10% rhodium	Platinum
T	Copper	Copper-nickel alloy

Table 1. *Compositions and Letter Designations of the Standardized*

Thermocouple Measurement and Signal Conditioning

To measure the temperature using a thermocouple, you cannot simply connect the thermocouple to a voltmeter or other measurement system, because the voltage measured is proportional to the temperature difference between the primary junction and the junction where the voltage is being measured. Therefore, to know the absolute temperature at the thermocouple tip, the temperature where the thermocouple is connected to the measurement device must also be known.
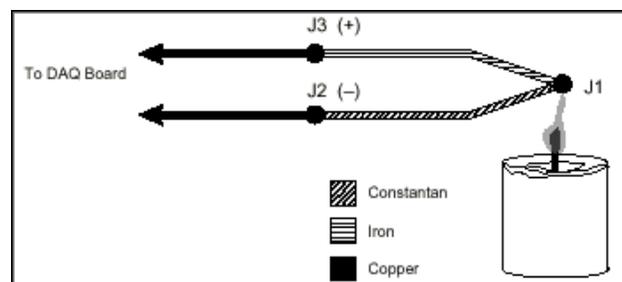
Figure 1. *J-Type Thermocouple*

Figure 1 illustrates a J-Type thermocouple in a candle flame that has a temperature you want to measure. The two thermocouple wires are connected to the copper leads of a data acquisition device. The circuit contains three dissimilar metal junctions: J1, J2, and J3. This results in a Seebeck voltage between J3 and J2 that is proportional to the temperature difference between J1, which is sensing the temperature of the candle flame, and J2 and J3. J2 and J3 should be close enough together so that they can be assumed to be at the same temperature. Because copper wire is connected to both J2 and J3, there is no additional voltage contributed between the temperature difference of the J2/J3 junction and the point where the voltage is measured by the data acquisition device. To determine the temperature at J1, you must know the temperatures of junctions J2 and J3. You can then use the measured voltage and the known temperature of the J2/J3 junction to infer the temperature at J1.

Thermocouples require some form of temperature reference to compensate for the *cold* junctions. The most common method is to measure the temperature at the reference junction with a direct-reading temperature sensor then apply this cold-junction temperature measurement to the voltage reading to determine the temperature measured by the thermocouple. This process is called cold-junction compensation (CJC). Because the purpose of CJC is to compensate for the known temperature of the cold junction, another less-common method is forcing the junction from the thermocouple metal to copper metal to a known temperature, such as 0 ºC, by submersing the junction in an ice-bath, and then connecting the copper wire from each junction to a voltage measurement device. When using the first method, you can simplify computing CJC by taking advantage of the following thermocouple characteristics.

By using the Thermocouple Law of Intermediate Metals and making some simple assumptions, you will find that the measured voltage depends on the thermocouple type, thermocouple voltage, and the cold-junction temperature. The measured voltage is independent of the composition of the measurement leads and the cold junctions, J2 and J3.

According to the Thermocouple Law of Intermediate Metals, illustrated in Figure 2, inserting any type of wire into a thermocouple circuit has no influence on the output as long as both ends of that wire are the same temperature, or isothermal.
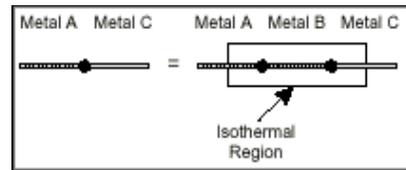
Figure 2. *Thermocouple Law of Intermediate Metals*

The circuit in Figure 3 is similar to the previously described circuit in Figure 1, except that a short length of constantan wire is inserted just before junction J3 and the junctions are assumed to be held at identical temperatures. Assuming that junctions J3 and J4 are the same temperature, the Thermocouple Law of Intermediate Metals indicates that the circuit in Figure 3 is electrically equivalent to the circuit in Figure 1. Consequently, any result taken from the circuit in Figure 3 also applies to the circuit illustrated in Figure 1.
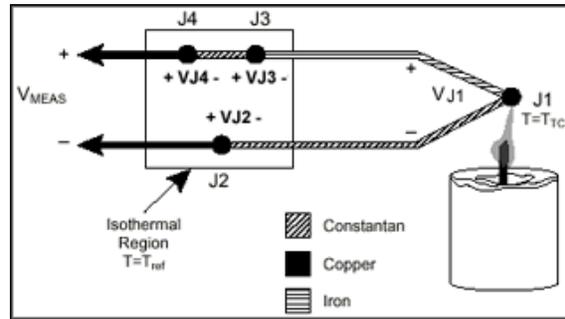

Figure 3. *Inserting an Extra Lead in the Isothermal Region*

In Figure 3, junctions J2 and J4 are the same type (copper-constantan). Because both are in the isothermal region, J2 and J4 are also the same temperature.

NIST thermocouple reference tables are generated with the reference junction held at 0 °C, therefore, to determine the temperature at the thermocouple junction you can start with Equation 2 shown below, where V_{MEAS} is the voltage measured by the data acquisition device, and V_{TC} ($T_{TC} - T_{ref}$) is the Seebeck voltage created by the difference between T_{TC} (the temperature at the thermocouple junction) and T_{ref} (the temperature at the reference junction):

Equation 2: $V_{MEAS} = V_{TC} (T_{TC} - T_{ref})$

You can rewrite Equation 2 as shown in Equation 3 where V_{TC} (T_{TC}) is the voltage measured by the thermocouple assuming a reference junction temperature of 0 °C, and V_{TC} (T_{ref}) is the voltage that would be generated by the same thermocouple at the current reference temperature assuming a reference junction of 0 °C:

Equation 3: $V_{MEAS} = V_{TC} (T_{TC}) - V_{TC} (T_{ref})$

Equation 4: $V_{TC} (T_{TC}) = V_{MEAS} + V_{TC} (T_{ref})$

In Equation 4, the computed voltage of the thermocouple assumes a reference junction of 0 °C. Therefore, by measuring V_{MEAS} and T_{ref}, and knowing the voltage-to-temperature relationship of the thermocouple, you can determine the temperature at the primary junction of the thermocouple.

There are two techniques for implementing CJC when the reference junction is measured with a direct-reading sensor: hardware compensation and software compensation. A direct-reading sensor has an output that depends on the temperature of the measurement point. Semiconductor sensors, thermistors, or RTDs are commonly used to measure the reference-junction temperature. For example, several National Instruments thermocouple measurement devices include high-accuracy thermistors located near the screw terminals where thermocouple wires are connected.

With hardware compensation, a variable voltage source is inserted into the circuit to cancel the influence of the cold-junction temperature. The variable voltage source generates a compensation voltage according to the ambient temperature that allows the temperature to be computed assuming a constant value for V_{TC} (T_{ref}) in Equations 3 and 4. With hardware compensation, you do not need to know the temperature at the data acquisition system terminals when computing the temperature of the thermocouple. This simplifies the scaling equation. The major disadvantage of hardware compensation is that each thermocouple type must have a separate compensation circuit that can add the correct compensation voltage. This disadvantage results in additional expense in the circuit. Hardware compensation is often less accurate than software compensation.

Alternatively, you can use software for CJC. After a direct-reading sensor measures the reference-junction temperature, software can add the appropriate voltage value to the measured voltage that compensates for the cold-junction temperature. Equation 3 states that the measured voltage, V_{MEAS}, is equal to the difference between the voltages at the hot junction (thermocouple) and cold junction.

Thermocouple output voltages are highly nonlinear; the Seebeck coefficient can vary by a factor of three or more over the operating temperature range of some thermocouples. Therefore, you must either approximate the thermocouple voltage-versus-temperature curve using polynomials, or use a look-up table. The polynomials are in the following form where v is the thermocouple voltage in volts, T is the temperature in degrees Celsius, and a_0 through a_n are coefficients that are specific to each thermocouple type:

$$\textbf{Equation 5}: T = a_0 + a_1v + a_2v^2 + ... + a_nv^n$$

Data Acquisition Systems for Thermocouple Measurements

Thermocouple measurements are very common but the application requirements can vary greatly. Therefore, National Instruments provides many options to measure temperature from one to 1,000+ channels. Read the Advantages of NI Sensor Measurement Systems white paper to learn about the different platforms for thermocouple measurements.

Table 2 contains links to recommended starter sets for thermocouple measurements in a variety of application types. Select an application to learn more about the recommended system.

Thermocouple Starter Sets		
Platform	**Channels**	**Features**
NI USB TC-01	1	Low cost, Starting at $99 USD
NI C Series	Up to 16	USB, wireless, ethernet Starting at $588 USD with 24-bit resolution
NI CompactDAQ	16 - 128	USB Data Acquisition, Low-to-medium channel count
NI SC Express	32 - 1,000+	High accuracy(~0.3°C), PXI Platform, Medium-to-high channel count
SCXI	32–1,000+	300 V_{rms} isolation, Medium- to high-channel

Table 2. *Recommended Starter Sets for Thermocouple Measurements*