Document Type: Tutorial
NI Supported: Yes

Taking Thermocouple Temperature Measurements

Overview

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

For more information, return to the Measurement Fundamentals Main Page.

Table of Contents

What Is Temperature?

Qualitatively, the temperature of an object determines the sensation of warmth or coldness felt by touching it. More specifically, temperature is a measure of the average kinetic energy of the particles in a sample of matter, expressed in units of degrees on a standard scale.

What Is a Thermocouple?

One of the most frequently used temperature sensors is the thermocouple. Thermocouples are very rugged, inexpensive devices that operate over a wide temperature range. A thermocouple is created whenever two dissimilar metals touch and the contact point produces a small open-circuit voltage as a function of temperature. This thermoelectric voltage is known as the Seebeck voltage, named after Thomas Seebeck, who discovered it in 1821. The voltage is nonlinear with respect to temperature. However, for small changes in temperature, the voltage is approximately linear, or

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

where DV is the change in voltage, S is the Seebeck coefficient, and DT is the change in temperature.

S varies with changes in temperature, however, causing the output voltages 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. A complete list of available thermocouples is shown in Table 1 below.

Table 1. Compositions and Letter Designations of the Standardized Thermocouples

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

Thermocouple Measurement and Signal Conditioning

To measure a thermocouple Seebeck voltage, you cannot simply connect the thermocouple to a voltmeter or other measurement system, because connecting the thermocouple wires to the measurement system creates additional thermoelectric circuits.

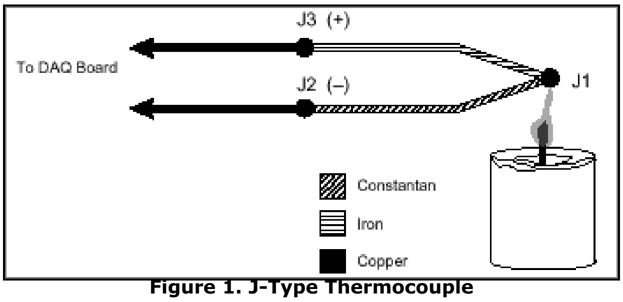

Figure 1. J-Type Thermocouple

Consider the circuit illustrated in Figure 1, in which a J-type thermocouple is in a candle flame that has a temperature you want to measure. The two thermocouple wires are connected to the copper leads of a DAQ board. Notice that the circuit contains three dissimilar metal junctions – J1, J2, and J3. J1, the thermocouple junction, generates a Seebeck voltage proportional to the temperature of the candle flame. J2 and J3 each have their own Seebeck coefficient and generate their own thermoelectric voltage proportional to the temperature at the DAQ terminals. To determine the voltage contribution from J1, you need to know the temperatures of junctions J2 and J3 as well as the voltage-to-temperature relationships for these junctions. You can then subtract the contributions of the parasitic junctions at J2 and J3 from the measured voltage at junction J1.

Thermocouples require some form of temperature reference to compensate for these unwanted parasitic "cold" junctions. The most common method is to measure the temperature at the reference junction with a direct-reading temperature sensor and subtract the parasitic junction voltage contributions. This process is called cold-junction compensation. You can simplify computing cold-junction compensation by taking advantage of some thermocouple characteristics.

By using the Thermocouple Law of Intermediate Metals and making some simple assumptions, you can see that the voltage a data acquisition system measures depends only on the thermocouple type, the thermocouple voltage, and the cold-junction temperature. The measured voltage is in fact 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 effect on the output as long as both ends of that wire are the same temperature, or isothermal.

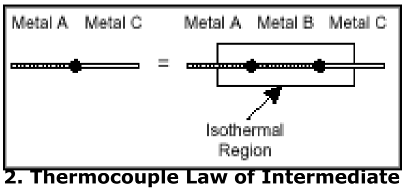

Figure 2. Thermocouple Law of Intermediate Metals

Consider the circuit in Figure 3. This circuit is similar to the previously described circuit in Figure 1, but a short length of constantan wire has been 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.

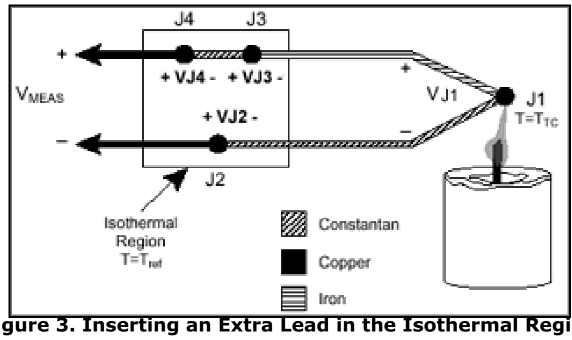

Figure 3. Inserting an Extra Lead in the Isothermal Region

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. Because of the direction of the current through the circuit, J4 contributes a positive Seebeck voltage, and J2 contributes an equal but opposite negative voltage. Therefore, the effects of the junctions cancel each other, and the total contribution to the measured voltage is zero. Junctions J1 and J3 are both iron-constantan junctions, but may be at different temperatures because they do not share an isothermal region. Because they are at different temperatures, junctions J1 and J3 both produce a Seebeck voltage, but with different magnitudes. To compensate for the cold junction J3, its temperature is measured and the contributed voltage is subtracted out of the thermocouple measurement.

Using the notation $V_{Jx}(T_y)$ to indicate the voltage generated by the junction J_x at temperature T_y, the general thermocouple problem is reduced to the following equation:

$$V_{MEAS} = V_{J1}(T_{TC}) + V_{J3}(T_{ref}) \quad (2)$$

where V_{MEAS} is the voltage the DAQ board measures, T_{TC} is the temperature of the thermocouple at J1, and T_{ref} is the temperature of the reference junction.

Notice that in Equation 2, $V_{Jx}(T_y)$ is a voltage generated at temperature T_y with respect to some reference temperature. As long as both V_{J1} and V_{J3} are functions of temperature relative to the same reference temperature, equation 2 is valid. As stated earlier, for example, NIST thermocouple reference tables are generated with the reference junction held at 0 °C.

Because junction J3 is the same type as J1 but contributes an opposite voltage, $V_{J3}(T_{ref}) = -V_{J1}(T_{ref})$. Because V_{J1} is the voltage that the thermocouple type undergoing testing generates, this voltage can be renamed V_{TC}. Therefore, Equation 2 is rewritten as follows:

$$V_{MEAS} = V_{TC}(T_{TC}) - V_{TC}(T_{ref}) \quad (3)$$

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 hot junction of the thermocouple.

There are two techniques for implementing cold-junction compensation - hardware compensation and software compensation. Both techniques require that the temperature at the reference junction be sensed with a direct-reading sensor. A direct-reading sensor has an output that depends only 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 SCXI terminal blocks include thermistors located near the screw terminals to which thermocouple wires are connected.

With hardware compensation, a variable voltage source is inserted into the circuit to cancel the parasitic thermoelectric voltages. The variable voltage source generates a compensation voltage according to the ambient temperature, and thus adds the correct voltage to cancel the unwanted thermoelectric signals. When these parasitic signals are canceled, the only signal a data acquisition system measures is the voltage from the thermocouple junction. With hardware compensation, the temperature at the data acquisition system terminals is irrelevant because the parasitic thermocouple voltages have been canceled. 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 fact makes the circuit fairly expensive. Hardware compensation is also generally less accurate than software compensation.

Alternatively, you can use software for cold-junction compensation. After a direct-reading sensor measures the reference-junction temperature, software can add the appropriate voltage value to the measured voltage to eliminate the parasitic thermocouple effects. Recall Equation 3, which 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. For this reason, 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:

$$T = a_0 + a_1 v + a_2 v^2 + \ldots + a_n v^n \quad (4)$$

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.

Eliminating Noise

Thermocouple output signals are typically in the millivolt range, making them susceptible to noise. Lowpass filters are commonly used in thermocouple data acquisition systems to effectively eliminate high frequency noise in thermocouple measurements. For instance, lowpass filters are useful for removing the 60 Hz power line noise that is prevalent in many laboratory and plant settings.

You can also significantly improve the noise performance of your system by amplifying the low-level thermocouple voltages near the signal source (measurement point). Because thermocouple output voltage levels are very low, you should choose a gain that optimizes the input limits of the analog-to-digital converter (ADC). The output range of all thermocouple types falls between -10 mV and 80 mV.

Another source of noise is due to thermocouples being mounted or soldered directly to a conductive material, like steel or water. This configuration makes thermocouples particularly susceptible to common-mode noise and ground loops. Isolation helps to prevent ground loops from occurring, and can dramatically improve the rejection of common-mode noise. With conductive material that has a large common-mode voltage, isolation is required as non-isolated amplifiers cannot measure signals with large common-mode voltages.

To see how filtering and amplification can dramatically improve the accuracy of thermocouple measurements, visit the Online Accuracy Lab.

DAQ Systems for Thermocouple Measurements

The following table contains links to recommended starter sets for thermocouple measurements in a variety of applications. Click on an "application" to learn more about the recommended system.

Thermocouple

Application	Channels	Features
Low Cost & High-Accuracy	Up to 32	Starting at $395 with 24-bit resolution
High-Channel Count	32-3000+	Modular and expandable
Isolated	Up to 96 per system	300 Vrms Isolation per channel
Ethernet	Up to 32 per network node	Rugged, industrial platform

Relevant NI Products

Customers interested in this topic were also interested in the following NI products:

LabVIEW
Data Acquisition (DAQ)
Signal Conditioning
Return to Sensor Fundamentals or the Measurement Fundamentals Main Page.

Print this Page

Related Links:
Virtual Signal Conditioning Laboratory

Reader Comments | Submit a comment »

Legal