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APPLICATION NOTE 6550

THE BASICS OF THERMOCOUPLES

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Abstract: This application note examines how thermocouples are constructed and the physics behind how they work, providing readers with an understanding that will help them improve the accuracy of thermocouple readings.

Introduction

Thermocouples are a common type of temperature sensor used in applications ranging from lab test benches to industrial environments. However, as is also commonly the case with many types of sensors, acquiring accurate data with thermocouples can be challenging. This application note examines how thermocouples are constructed and the physics behind how they work, providing an understanding that will help readers improve the accuracy of their readings.

How Thermocouples Are Created

A combination of two dissimilar conductors forming "hot" and "cold" junctions creates a thermocouple (**Figure 1**). Maintaining the two junctions at different temperatures produces an electromotive force (EMF), also known as the thermoelectric voltage. EMF is measured in the millivolts range and is the product of a physical phenomenon known as the Seebeck effect, which describes the voltage that results from the thermocouple materials and the temperature difference between the hot and cold junctions.

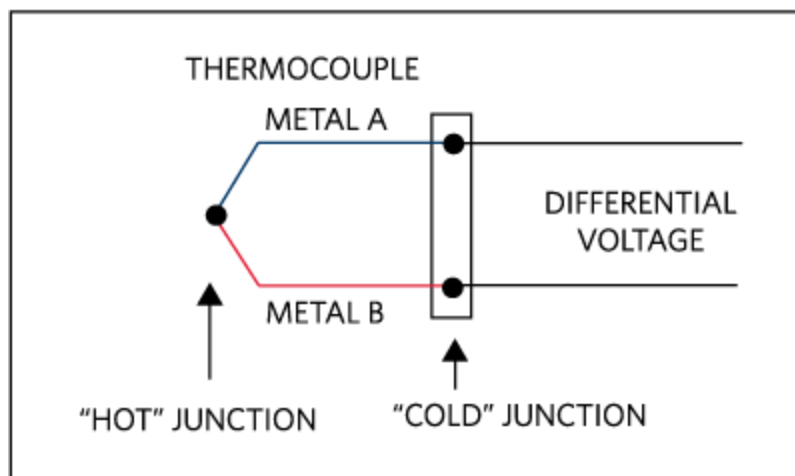


Figure 1. A fundamental thermocouple.

Equation 1 provides a linear approximation of the Seebeck effect.

$$\Delta V = S \times (T_h - T_c) \quad (\text{Eq. 1})$$

ΔV : Voltage difference between two dissimilar metals

S: Seebeck coefficient in V/K (commonly in $\mu\text{V}/^\circ\text{C}$)

$T_h - T_c$: Temperature difference between hot and cold junctions

The Seebeck coefficient is specific to the two conductors that are used to construct the thermocouple. It has a non-linear dependence on the temperature. Using a linear approximation of the Seebeck effect can produce significant measurement errors. Modern thermocouple measurement techniques should take this non-linearity into account. It is important to understand that a temperature measurement cannot be determined solely from the EMF generated by the thermocouple. Instead, the following three parameters must be known:

- The thermoelectric voltage due to thermal gradient between the hot and cold junctions
- The thermocouple type
- The cold junction temperature

If any of these variables are unknown, the temperature at the thermocouple sensing junction cannot be determined. **Equation 2** shows an updated calculation for measuring the temperature at the hot junction of a thermocouple, taking the above parameters into account:

$$T_h = \frac{V_{\text{thermocouple}}}{\alpha(T_c)} + T_c \quad (\text{Eq. 2})$$

T_h : The hot junction temperature in $^\circ\text{C}$

T_c : The cold junction temperature in $^\circ\text{C}$

$\alpha(T_c)$: Seebeck coefficient as a function of T_c in $\mu\text{V}/^\circ\text{C}$

Factors that Impact Accuracy of Thermocouple Readings

Having the fundamentals in mind makes it easier to understand the factors that can affect the accuracy of thermocouple measurements. With the three necessary parameters mentioned above, it is relatively easy to generate hot junction temperature measurements from a thermocouple. The method for acquiring these parameters, however, may introduce inaccuracies into the measurement. The following factors may affect the temperature reading at different stages of measurement and to varying degrees:

- Thermocouple characteristics
- Cold junction measurement
- Noisy environments
- Linearization

Thermocouple Characteristics

Sometimes, problems with the thermocouple itself lead to inaccurate readings. These problems may emerge from damage that occurs as a thermocouple ages. Some common issues to be aware of include:

- **Poor hot junction thermal/electrical connection**—The wrong thermoelectric voltage might be generated if the two conductors are not properly joined together at the hot junction. Bare wire junctions, insulated junctions, and grounded junctions are the most common types of hot junctions in thermocouples. They are further described below:
 - *Bare wire thermocouples*—Two leads can be joined together in different ways. Leads can be twisted together, soldered together, or welded together. For applications with excessive mechanical vibrations, twisting leads together is not recommended. For high-temperature applications, the junction should not be soldered together due to the possibility of solder reflow. Cold welding leads together is often the best option.
 - *Insulated junctions*—Based on the construction of the junction, insulated junctions are more mechanically sturdy and corrosion-resistant compared to bare wire-type thermocouples. However, because there is no metallic surface directly exposed to the measurement temperature, the thermal resistance of the hot junction increases. This slows down the thermocouple response to any change in temperature. Therefore, where there is a need to respond quickly to temperature changes, insulated junctions are not recommended. Slow response can be advantageous in some cases, as it helps to filter out “noise.” Insulated junctions also are not recommended for materials with low thermal conductivity (as is common for some gases).
 - *Grounded junctions*—Construction is similar to that of insulated junction thermocouples, with the added feature that the junction is electrically connected to the protective sheath. While the construction type is mechanically sturdy and protects against corrosion, grounded junctions have faster response times than insulated junctions, due to the metallic connection to the protective sheath (because of the thermal mass of the sheath, though, they can still be slow). However, since the tip of the thermocouple is welded directly to the protective sheath, the whole surface is susceptible. If the sheath were to come in contact with an electrical signal, it would render the EMF signal coming from the thermocouple unreliable. This side effect is

typically overlooked, and careful planning is required for applications using a grounded junction. Another important consideration is that the potential of the “grounded” sheath can be mV or even V different from the system ground potential. Generally, the power supply for the signal conditioning circuitry will need to be isolated.

- **Series resistance along the lines of the thermocouple**—Because thermocouples are conductors, the parasitic resistance in the conductors or attached circuitry may impact the signal. If the leads are too long or too thin, the total series resistance may cause signal degradation before the EMF reaches the cold junction. One way to resolve this is by using a special type of thermocouple wire known as “extension grade,” which is designed to carry the thermoelectric circuit over a longer distance.
- **Low-grade materials used to construct the thermocouple**—Some cheaper thermocouples are made of low metallurgical graded materials. The use of such materials could result in impurities in the construction that affect each batch of metal differently, producing variable Seebeck coefficients.
- **Electrical isolation issues along the length of the leads**—Several problems could emerge if the wrong type of insulation or poor-quality insulation is used to separate the two leads of the thermocouple. In high-temperature applications, if a non-temperature-resistant type of insulation is used, the insulation can melt, resulting in exposure to the leads. A break in a section of insulation may also expose the thermocouple leads. Once the thermocouple leads are exposed to the elements, they may corrode, cause shorts or line faults, or introduce other electrical signals into the lines. It is also possible for the positive and negative leads to be shorted together, which would create a premature hot junction that still gives temperature readings of the wrong location.
- **Thermocouple type**—Each thermocouple type has a specified temperature measurement range. A given thermocouple must be able to withstand the environmental conditions in which it will be applied. With a wide range of operation and inexpensive construction, K-type thermocouples are some of the most common types in use. Some thermocouple solutions only apply to a given thermocouple type. Integrated solutions such as the [MAX31856](#) are configurable to support all common thermocouple types.

The list above presents a few common issues that can result in a loss of accuracy based on the selection of the thermocouple. Some errors, however, cannot be prevented, even when a good thermocouple is selected.

Measuring Cold Junction Temperature

When using thermocouples to derive a hot junction temperature, it is critical to achieve an accurate cold junction temperature measurement. To maintain a consistent and known temperature of 0°C, traditional cold junctions would be chilled in an ice-cold water bath (hence the name “cold junction”). Modern thermocouple-to-digital ICs such as the MAX31856 use cold junction compensation to compensate for the effect of cold junction temperature through calculation and temperature measurement. A temperature sensor is typically used to measure the cold junction temperature.

When using artificial cold junction compensation, one important consideration for accuracy is to place the temperature sensor as close as possible to the true cold junction. Also, be sure that the cold junction and measurement IC are at the same temperature. One way to do this is by maximizing the thermal conductivity between the two devices and placing them away from any heat sources. Whether thermocouple leads are soldered directly to a board or connected through terminal blocks, minimizing the thermal gradient between the leads and a temperature sensor improves the accuracy of all temperature readings.

Addressing Noisy Environments

Because the signals generated by a thermocouple are so small, thermocouple measurements are susceptible to impact from noise. Differentials in magnetic flux or exposure to electromagnetic interference (EMI) along the length of the leads can generate noise in a thermocouple signal. Thermocouples are commonly used in industrial environments, which are places rife with opportunities for noise to be introduced into a signal. A common source of noise results from the magnetic field's flux differential coming from line noise at either 60Hz or 50Hz, depending on the country. These fields induce a current along the thermocouple's leads, and can introduce errors into a signal. To combat this, ICs such as the MAX31856 implement designs including internal filters with configurable notch frequencies at either 50Hz or 60Hz. Using internal filter circuitry, interference induced into the signal from the mains power frequencies can be minimized.

For higher frequencies, ferrite beads and differential filters can be used to reduce the noise coupled into thermocouple leads. Installing a 100nF differential capacitor between the positive and negative leads as close to the artificial cold junction as possible helps mitigate some of the noise caused in the thermocouple lines. In applications with higher noise levels, especially high-intensity RF fields, additional 10nf capacitors should be placed between each lead and ground.

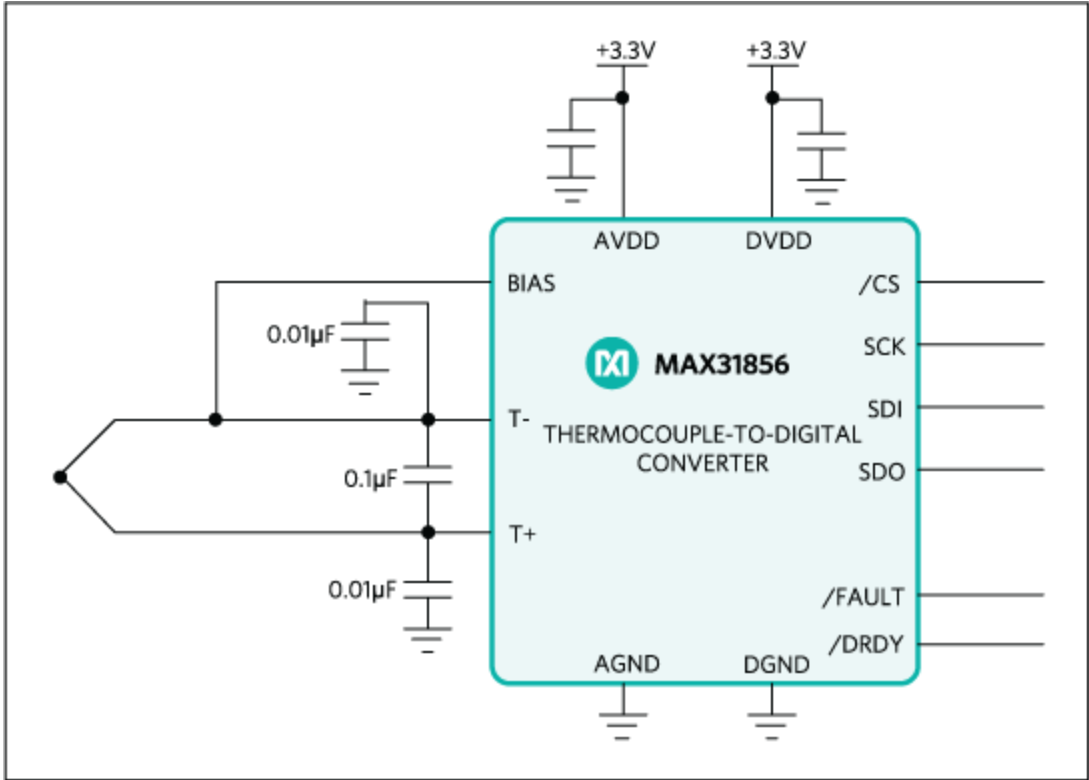


Figure 2. Thermocouple IC with filter capacitors on the thermocouple inputs.

Power-supply coupled noise can appear in thermocouple measurements. To minimize the effects of this type of noise, a 0.1µF ceramic bypass capacitor can be placed as close to the DVDD and AVDD pins and

GND as possible. Doing so helps prevent spikes in power supply voltage from affecting the temperature conversions. **Figure 2** shows a typical application circuit for the MAX31856 thermocouple sensing IC, with filtering capacitors applied to the thermocouple inputs. Additionally, twisting the thermocouple wires when possible keeps capacitively coupled noise from appearing as a differential noise voltage term.

Support for Multiple Conversion Methods

As previously discussed, the Seebeck coefficient for any thermocouple type depends on the temperature of the thermocouple, which creates a non-linear transfer function of voltage to temperature. The National Institute of Standards and Technology (NIST) maintains a published database of voltage-to-temperature conversions used for calibrating and testing each thermocouple type. The database comprises several different conversion methods. One method is a voltage-to-temperature look-up table that maps a th differential thermoelectric voltage to a temperature value over the entire temperature range for each thermocouple type (assuming the cold junction is at 0°C). The other method is a series of 9 - or 10 - order polynomial equations used to convert voltage to temperature or temperature to voltage.

In most applications, after the ADC digitizes the raw thermocouple voltage, the ADC output code must be translated to a temperature reading, either through a look-up table or with several floating-point calculations. Using a look-up table for a large temperature range consumes significant memory. On the other hand, performing many floating-point calculations consumes a significant amount of processing power in low-cost microcontroller applications. The MAX31856 offers flexibility by allowing either type of conversion method. It features an internal look-up table that provides linearized and cold-junction compensated temperature readings, or the ability to read back raw ADC results for further processing and filtering in microcontroller firmware.

Summary

Getting highly accurate temperature readings from a thermocouple requires careful consideration of many factors. The effects of noise, sheath conductivity, and thermal insulation of the hot junction must be properly addressed when performing thermocouple construction and placement. Proper shielding, RF filtering, decoupling, and series resistance minimization of the thermocouple leads must be applied to properly treat the corresponding thermoelectric voltage. Once the thermoelectric signal reaches a PCB or measurement device, accurate cold junction compensation, line frequency filtering, digitization, and translation from voltage-to-temperature are critical for reducing measurement errors. Using a thermocouple-to-digital converter IC such as the MAX31856 can simplify the acquisition of highly accurate thermocouple readings by addressing, in a single IC, all the challenges discussed in this application note.

A similar version of this application note appeared on [Power Systems Design](#) on November 1, 2017.

Related Parts

[MAX31856](#)

Precision Thermocouple to Digital Converter with Linearization

[Free Samples](#)

More Information

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APPLICATION NOTE 6550, AN6550, AN 6550, APP6550, Appnote6550, Appnote 6550

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