

Thermocouple, Cold-Junction Compensation— Analog Approach

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ABSTRACT

Temperature is the most commonly measured physical parameter in a variety of systems, including automotive, industrial, and consumer domains. There are various temperature transducers available to address the need of accurate temperature measurement. Thermocouples are widely popular because they are inexpensive, have a wide range, are small in size, and do not need excitation. This application note discusses the thermocouple temperature-sensing requirements, particularly cold junction compensation and how to achieve the same compensation using analog components.

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1 Introduction to Thermocouples

Thermocouples are a popular type of temperature measurement device. A relatively low price, wide temperature range, lack of required excitation, long-term stability, and proficiency with contact measurements make these devices very common in a wide range of applications. While achieving extremely high accuracy with a thermocouple can be more difficult than a resistance temperature detector (RTD), the low cost and versatility of a thermocouple often make up for this difficulty in precision. Additionally, in contrast with thermistors and RTDs, the use of thermocouples often simplifies application circuitry because they require no excitation. That is, these devices generate voltage without any additional active circuitry. Thermocouples do, however, require a stable voltage reference and some form of ice-point or cold-junction compensation.

A thermocouple is a cable of two wires made from two dissimilar conductors (usually alloys) that are soldered or welded together at one end, as shown in [Figure 1](#). The composition of the conductors used varies widely and depends on the required temperature range, accuracy, life span, and environment being measured. However, all thermocouple types operate based on the same fundamental theory: the thermoelectric or Seebeck effect. Whenever a conductor experiences a temperature gradient from one end of the conductor to the other, a voltage potential develops. This voltage potential arises because free electrons within the conductor diffuse at different rates, depending on temperature. Electrons with higher energy on the hot side of the conductor diffuse more rapidly than the lower energy electrons on the cold side. The net effect is that a buildup of charge occurs at one end of the conductor and creates a voltage potential from the hot and cold ends. This effect is shown in [Figure 2](#).

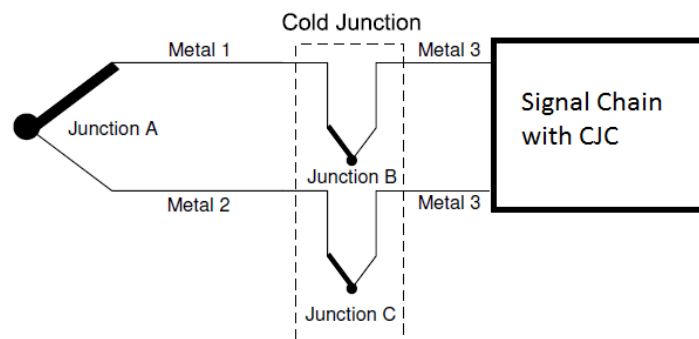


Figure 1. Thermocouple Junction Diagram

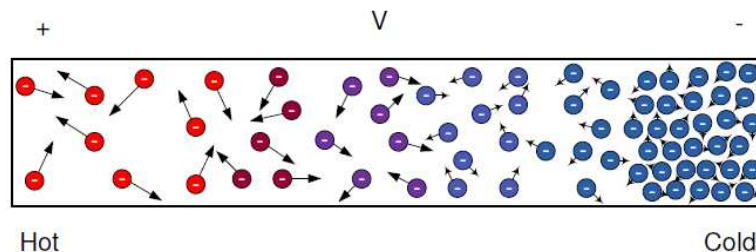


Figure 2. Seebeck Effect Diagram

Different types of metals exhibit this effect at varying levels of intensity. When two different types of metals are paired together and joined at a certain point (junction A in [Figure 1](#)), the differences in voltage on the end opposite of the short (junctions B and C) are proportional to the temperature gradient formed from either end of the pair of conductors. The implication of this effect is that thermocouples do not actually measure an absolute temperature; they only measure the temperature difference between two points, commonly known as the hot and cold junctions. Therefore, in order to determine the temperature at either end of a thermocouple, the exact temperature of the opposite end must be known.

In a classical design, one end of a thermocouple is kept in an ice bath (junctions B and C in [Figure 1](#)) in order to establish a known temperature. In reality, for most applications, providing a true ice point reference is not practical. Instead, the temperature of junctions B and C of the thermocouple are continuously monitored and used as a point of reference to calculate the temperature at junction A at the other end of the thermocouple. These junctions are known as the cold junctions or ice point for historical reasons, although they do not need to be kept cold or near freezing. These endpoints are referred to as junctions because they connect to some form of terminal block that transitions from the thermocouple alloys into the traces used on the printed circuit board (PCB), which is usually copper. This transition back to copper is what creates the cold junctions B and C. Because of the law of intermediate metals, junctions B and C can be treated as a single reference junction, provided that they are held at the same temperature or isothermal. When the temperature of the reference junction is known, the absolute temperature at junction A can be calculated. Measuring the temperature at junctions B and C and then using that temperature to calculate a second temperature at junction A is known as cold-junction compensation.

In many applications, the temperature of junctions B and C are measured using a diode, thermistor, or RTD. As with any form of cold-junction compensation, two conditions must be met to achieve accurate thermocouple measurements:

1. Junctions B and C must remain isothermal or be held at the same temperature. This condition can be achieved by keeping junctions B and C in very close proximity to each other and away from any sources of heat that may exist on a PCB. Many times, isothermal blocks are used to keep the junctions at the same temperature. A large mass of metal offers a very good form of isothermal stabilization. For other applications, maximizing the copper fill around the junctions may be sufficient. By creating an island of metal fill on both the top and bottom layers, joined with periodically placed vias, a simple isothermal block can be created. Ensure that this isothermal block is not affected by parasitic heat sources from other areas in the circuit, such as power conditioning circuitry.
2. The isothermal temperature of junctions B and C must be accurately measured. The closer a temperature sensor (such as a diode, RTD, or thermistor) can be placed to the isothermal block, the better. Air currents can also reduce the accuracy of the cold-junction compensation measurement. To achieve best performance, TI recommends ensuring that the cold junction be kept within an enclosure and that air currents be kept to a minimum near the cold junction. In applications where air currents are unavoidable, a useful alternative may be to use some form of shielding or other mechanical method to cover the cold junction measurement unit and connector block to protect the cold junction from air currents. An important note to remember is that the orientation of the PCB can affect the accuracy of the cold-junction compensation. If there are heat-generating elements physically below the cold junction, for example, inaccuracies can become significant when heat from those elements rises.

2 Thermocouple Temperature Measurement

The thermocouple temperature measurements involve two important factors: measurement of the thermal gradient from the cold junction available from the thermocouple based on the Seebeck effect and the actual cold junction measurement. The thermocouple output coefficient is a few $\mu\text{V}/^\circ\text{C}$. For a high accuracy system the processing blocks are required, which are able to have very high resolution to resolve effectively in microvolts. The other option is to gain the output through a low-noise and low-offset amplifier. This option is preferred because of the system complexity reduction for further stages. The gain of the amplifier can be adjusted to the required slope and span of the temperature measurement.

Cold junction temperature measurement accuracy is very important because the error is directly added to the temperature gradient and cannot be corrected. Cold junction temperature measurements can be achieved using a local diode, RTD, thermistor, or device-based temperature sensors. RTDs and thermistors require excitation sources and additional signal processing. Diode-based temperature sensors do not have a linear output and are linear for a very small temperature range. Device-based temperature sensors are popular because of their linear output, relatively low cost, and high accuracy. The device-based temperature sensors usually have slope in the range of $5\text{ mV}/^\circ\text{C}$ or $10\text{ mV}/^\circ\text{C}$.

A measurement system with an analog-to-digital converter (ADC) and controller can measure the individual signals (that is, the thermocouple amplified signal and cold junction signal). The controller can then take care of different slopes of the thermocouple signal and cold junction signal in the software to arrive at the cold-junction compensated temperature gradient and, thus in turn, the hot junction temperature.

The system sometimes may need to perform a cold junction compensation in the analog domain instead of the digital domain because of various system restrictions (such as the ADC or ADC channels not being available, SW overheads, system complexity cost, and so forth).

Figure 3 helps achieve the required output voltage for a given temperature range. Section 3 helps design the various component values according to the output range, temperature range, type of thermocouple, and so forth. Section 3.2 discusses the design calculations in detail. Figure 3 can be updated with calculated values to verify the design.

The design is a two-stage implementation, where each stage is implemented using an instrumentation amplifier (INA) that has very low offset at high gains, low offset drift, and low noise. An example of such an INA is the INA333 from Texas Instruments. The INA333 has a supply voltage range of up to 5 V. For higher output voltage swings, choose an INA with higher supply voltage capability.

For cold-junction temperature measurement, an IC-based analog output device (such as the LM35) is chosen. This device has linear output with a 10-mV/°C slope.

The TINA-TI simulation design in Figure 3 implements the cold-junction compensation method discussed in this application note. The TINA simulation design is available at SBOC445.

VS2 is replaced by the thermocouple chosen in the final design. VS1 is replaced by a cold-junction measurement device, such as the LM35. V5 and V6 function as positive and negative references for stage 2.

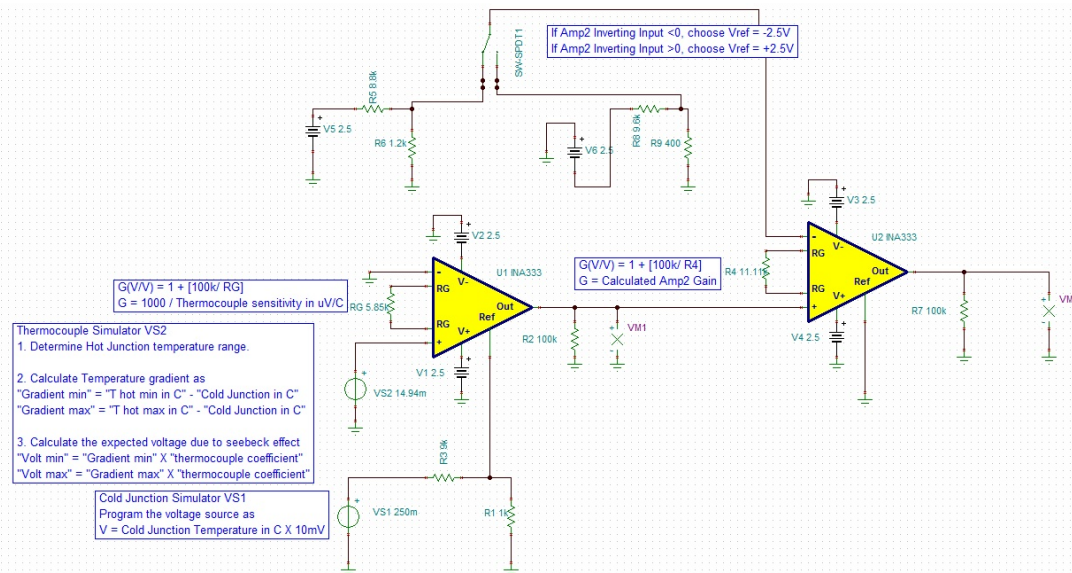


Figure 3. TINA-TI Simulation

3 Design Calculations

The design calculations listed in this section calculate the passive component values used in the design. An excel sheet is also made available to perform the calculations. The excel sheet is available at [SBOC445](#).

The XLS utility includes the J-type thermocouple gradient table and the calculations for the J-type thermocouple. Based on the type of thermocouple used in the end application, the table must be updated.

3.1 Design Specifications

- Type of thermocouple = J
- Thermocouple Seebeck coefficient = 52.17 $\mu\text{V}/^\circ\text{C}$
- Hot-junction temperature range = -100°C to 400°C
- Cold-junction temperature = 25°C
- Cold-junction temperature gradient = 10 $\text{mV}/^\circ\text{C}$
- Output voltage range = 0 V to 2 V

3.2 Calculations:

Choose a suitable slope V/C for the stage 1 output. Select a value less than the cold-junction measurement device slope. 1 $\text{mV}/^\circ\text{C}$ was chosen in this design.

Hot-junction temperature gradient = hot-junction temperature – cold-junction temperature.

Calculate these values for the range.

That is, -125°C to 375°C .

Thermocouple output voltage = hot-junction gradient \times Seebeck coefficient.

Calculate these values for the range.

That is, -6.521 mV to 19.5645 mV .

CJC output voltage = cold-junction temperature \times cold-junction temperature gradient = 250 mV.

CJC output attenuation = cold-junction temperature gradient / stage 1 output slope chosen = 10.

Choose a total resistance of $R1 + R3$ as a starting point for the CJC attenuation = 10000 Ω .

$R1 = (R1 + R3) / \text{CJC attenuation} = 1000 \Omega$.

$R3 = \text{total resistance} - R1 = 9000 \Omega$.

Stage 1 gain = stage 1 output slope / Seebeck coefficient = 19.17.

$RG = 100 \text{ k}\Omega / (\text{stage 1 gain} - 1) = 5504 \Omega$.

This formula is applicable for the INA333 only. If you choose another INA, use the formula specified in that INA data sheet.

Stage 1 output = (thermocouple output voltage \times stage 1 gain) + (CJC output voltage / CJC output attenuation).

Stage 1 output = -100 mV to 400 mV .

Stage 2 gain = (output voltage range) / (stage 1 output range) = 4.

$R4 = 100 \text{ k}\Omega / (\text{stage 2 gain} - 1) = 33333 \Omega$.

This formula is applicable for the INA333 only. If you choose another INA, use the formula specified in that data sheet.

Stage 2 inverting input = stage 1 minimum output = -100 mV .

If a positive offset is needed, choose a positive V_{ref} higher than the required offset. If a negative offset is needed, choose a negative V_{ref} .

Choose a total resistance of R5 + R6 or R8 + R9 as a starting point for the Vref attenuation = 10000 Ω.

$$R6 = (R5 + R6) \times \text{inverting voltage} / V_{\text{ref}} = 400 \Omega.$$

$$R5 = \text{total resistance} - R6 = 9600 \Omega.$$

The design created with these values was simulated and the simulation results are as shown in Figure 4.

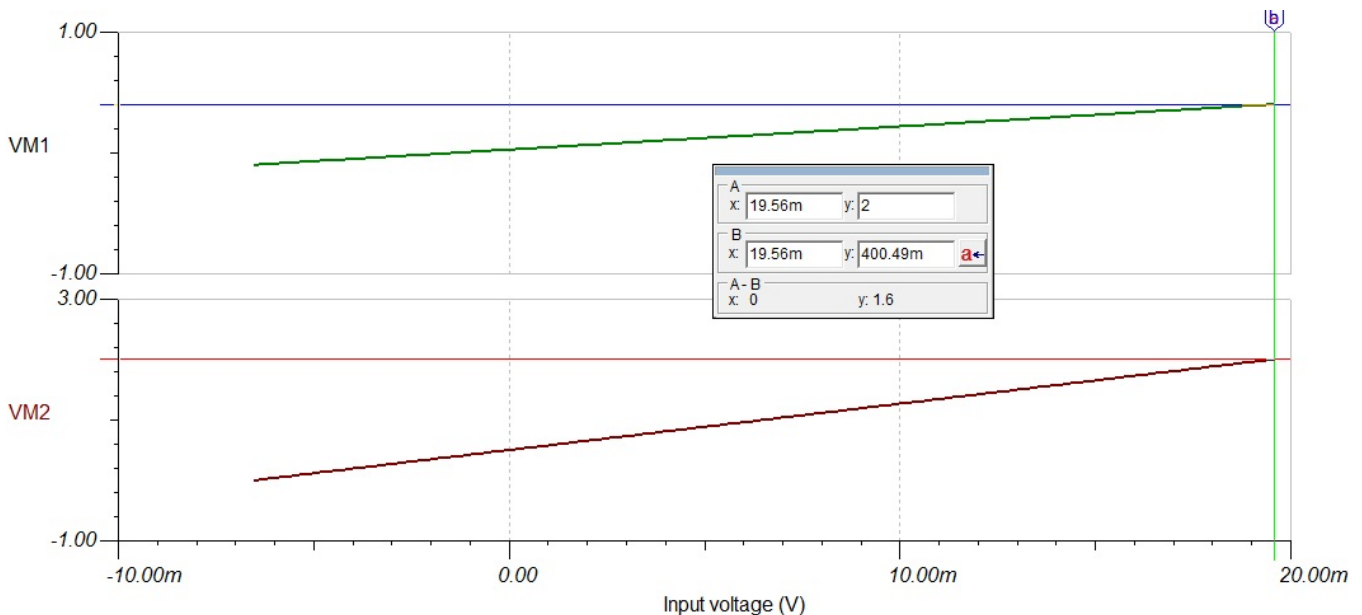


Figure 4. Simulation Design

4 Conclusion

Figure 3 can be used for thermocouple cold-junction compensation which can be modified for a given temperature range of measurement and a given output voltage range expected by following the simple design equations provided in Section 3. The output can then be transmitted as a voltage or converted into a current loop to create a simple, low-cost, low-power temperature transmitter.

The overall accuracy of the output is dependent on the thermocouple Seebeck coefficient chosen. Because the Seebeck coefficient is different at different temperature gradients, there is a tradeoff regarding the value chosen. You can either choose a coefficient at a particular temperature gradient or have an average of all the applicable gradients or an average of gradients at extreme ends. An exercise was conducted with simulation tools and the results are available at [SBOC445](#).

Another factor that plays an important role is the accuracy of passive components. Cost versus accuracy comparisons are needed before arriving at a final solution.

5 References

Precision Thermocouple Measurement with the ADS1118, [SBAA189](#)

LM35 Data Sheet, [SNIS159](#)

INA333 Data Sheet, [SBOS445](#)

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