Chapter 7

Thermocouples

TEC/NOT/010

This paper outlines temperature measurement using thermocouples. In particular the concepts of reference junctions and firmware compensation are discussed.

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7.1 Overview

In 1821, Thomas Seebeck discovered that a junction of two dissimilar metals produced a thermoelectric voltage (thermal emf) that was a function of the temperature of the junction.

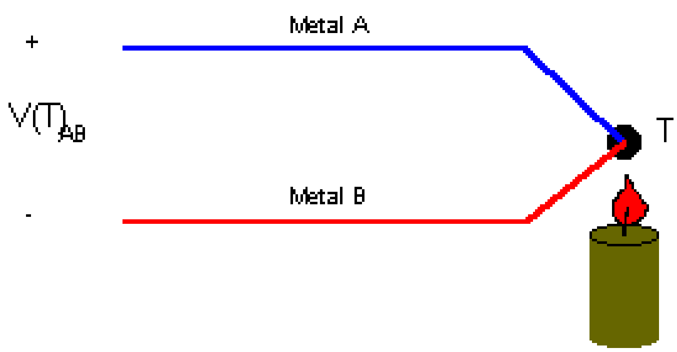

Figure 7-1: The Seebeck (thermoelectric) voltage

This method is still popular as a means of measuring temperature because it is relatively inexpensive, rugged, can be made into many shapes and has a wide temperature range (-276 to 1500°C).

7.2 Thermocouple theory

The Seebeck voltage is due to different valency levels in different metals. Electrons drop from the higher valency level to the lower until enough charge (voltage) builds up to stop the flow of electrons. This voltage is the thermoelectric voltage. One important corollary of this is the *Law of Intermediate Metals* that states that a third metal (for example a wire to a voltmeter) can be placed between two metals and does not affect the voltage produced if the temperature at each end is the same.

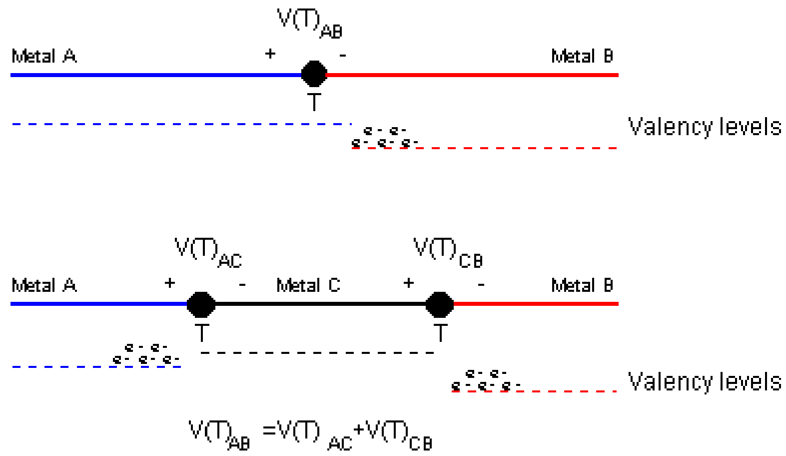

Figure 7-2: An illustration of the Law of Intermediate Metals

The following figure illustrates the thermal emfs produced about the circuit connecting a thermocouple probe to an ideal instrumentation amplifier.

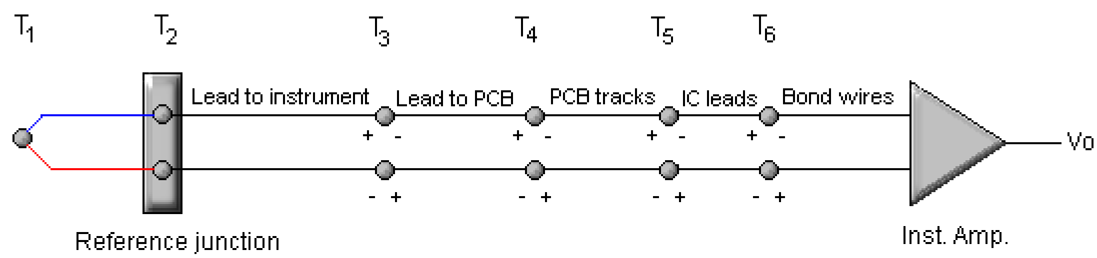

Figure 7-3: A thermocouple connected to an amplifier via a reference junction block

Because the metals used from the reference junction to the IC leads (inclusive) are usually of similar metals (copper), and at low temperature (-45° to +85°C), the thermal emfs produced are small. More importantly, providing the leads are kept close together at the same temperature, the thermal emfs produced are the same and cancel out.

Electrically the circuit is as shown in the following figure and the *Law of Intermediate Metals* can be used to remove metal C.

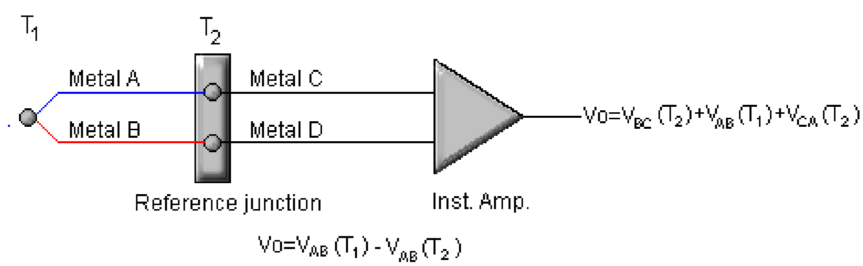

Figure 7-4: Summing the voltages about the thermocouple loop

NOTE: The net voltage produced is the voltage A and B produce at temperature T_1 (the measurand temperature) minus the voltage that A and B would produce at T_2 (the temperature of the reference junction).

In other words:

$$Eq1 \Rightarrow V_0 = V(T_{meas}) - V(T_{ref})$$

The voltage produced for a pair of metals is a non-linear function of the temperature of the junction. The function is so non-linear that an eighth-order polynomial can still have 0.5°C errors for certain metals and ranges. For this reason, the National Bureau of Standards (NBS) has drawn up thermocouple tables for the voltage produced about a loop for various combinations of metals. These tables of voltage versus temperature assume the reference junction is at a known fixed temperature (the Ice Point).

In other words:

$$V_{NBS}(T) = V(T) - V(0°)$$

This can be rewritten as:

$$V(T) = V_{NBS}(T) + V(0°)$$

Putting this in equation I:

$$V_0 = [V_{NBS}(T_{meas}) + V(0°)] - [V_{NBS}(T_{ref}) + V(0°)] = V_{NBS}(T_{meas}) - V_{NBS}(T_{ref})$$

Finally:

$$T_{meas} = V_{NBS}^{INVERSE}(V_0 + V_{NBS}(T_{ref}))$$

If V_0 and T_{ref} are known, T_{meas} can be obtained by using the NBS table to convert temperature to voltage and voltage to temperature.

NOTE: In Curtiss-Wright's KAD/TDC/002, a full 65536 point table, from temperature to voltage, and another 65536 point table, from voltage to temperature, is downloaded to EEPROM for any type of thermocouple.
The reference junction ACC/CJB/001 has a linear temperature sensor for measuring T_{ref}.

7.3 Types of thermocouples

The American Institute for Standards (ANSI) has approved letters for some types of thermocouples. The following table displays the composition and range for some of the more popular types.

Table 7-1: Some popular thermocouple combinations and their ANSI designation

Type	Composition	Range (ºC)	Range (mV)	Sensitivity at 0ºC (µV/ºC)
J	Iron Vs. Copper-Nickel	-210 +760	-8.096 +42.922	50
K	Nickel-Chromium Vs. Nickel-Aluminum	-270 +1370	-6.458 +54.807	39
E	Nickel-Chromium Vs. Copper-Nickel	-270 +1000	-9.835 +76.358	59
T	Copper Vs. Copper-Nickel	-270 +400	-6.258 +20.869	39
S	Platinum Vs. Platinum-10% Rhodium	+1760	18.612	5

The following figure graphs the output voltage (mV) versus the junction temperature (°C) from tables produced by the NBS.

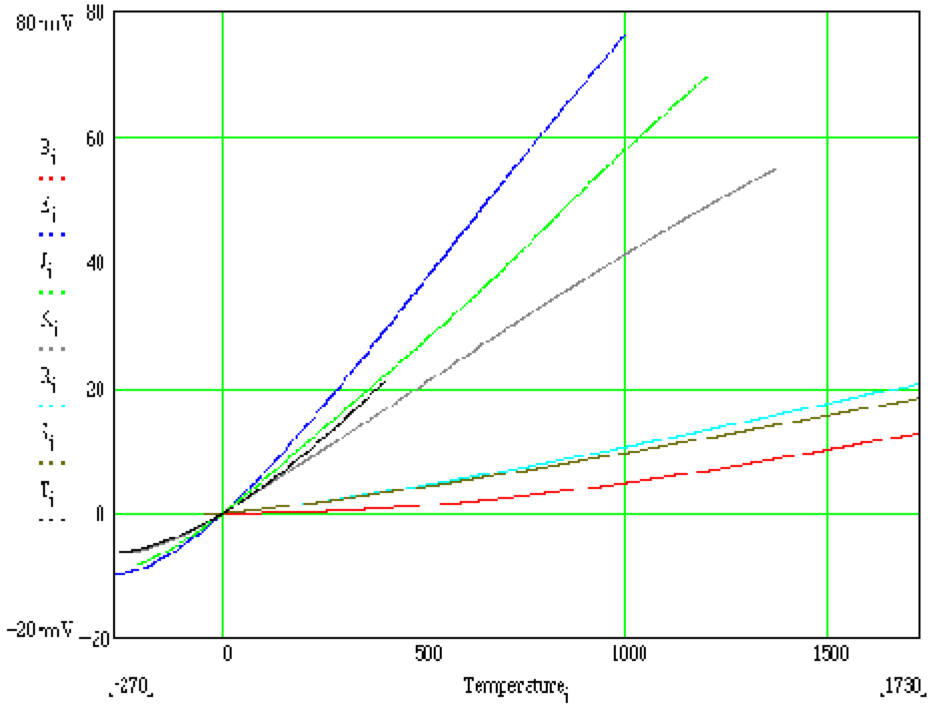

Figure 7-5: Voltage versus temperature for various types of thermocouples

Usually, errors from thermocouple to thermocouple of the same type are at least 0.5°C and are typically 1.5°C.

7.4 Design considerations

To reduce any noise pickup and to make it common mode, thermocouple wires should be shielded and twisted. A current return path for bias currents from the instrumentation amplifier must be provided as shown in the following figure.

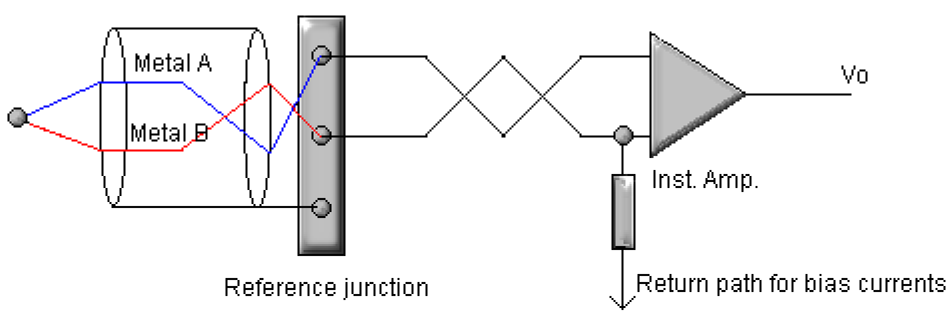

Figure 7-6: Twisting and shielding and return paths for amplifier bias currents

The return resistor should be large to reduce resistor divider effects; current loops when the thermocouple probe is not isolated. If it is too large, the bias currents (approx. 20 nA) cause a common mode voltage and the wires present a high impedance, making them susceptible to noise pickup.

NOTE: In the KAD/TDC/002, a 10 kW return resistor is provided for each channel.

7.5 Conclusion

In this paper, temperature measurement using thermocouples was introduced.

Thermocouples are self-powered, rugged, inexpensive, come in various shapes and can be used for a wide range of temperatures.

However they are non-linear, have a low voltage output and require a reference junction (and the measurement of the junction temperature).

7.6 References

The Temperature Handbook

Omega Engineering, Inc.

P.O. Box 2669

Stamford

CT 06907-0047

USA

Omega.com

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