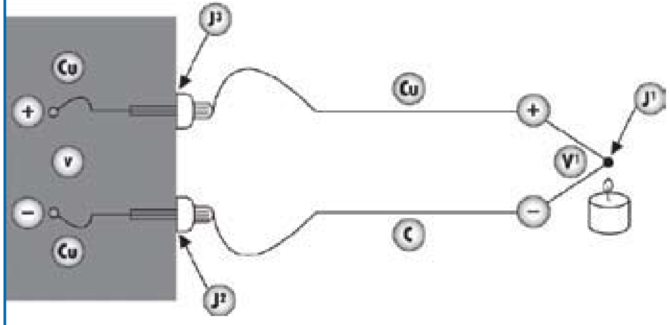
Thermal Fundamentals

Thermocouples: What They Are and How They Work

With their versatility and ease of use, thermocouples are the most common means for temperature measurement. Thermocouples date back to 1821, when Thomas Seebeck, an Estonian scientist, found that when two dissimilar metals with P/N characteristics were connected at both ends, and one end was heated, there was a resulting flow of current in this thermoelectric circuit.

Today, this voltage is known as electromotive force (emf), and is a function of the junction temperature and composition of the two metals. The repeatable nature of emf, along with standardized material types and calibration curves, have made thermocouples the devices of choice for many temperature measuring applications.

Despite the simplicity of thermocouples, their emf voltage cannot be measured directly. As shown in Figure 1, using a voltage measuring device will create two additional thermocouple junctions, designated as J2 and J3 in the thermoelectric circuit.



Figue 1. Measuring junction voltage with a DMV [1].

The voltage reading then becomes a function of three temperatures, two of which are of no interest to the experimenter. To solve this problem, another junction needs to be created in series in the circuit, as shown in Figure 2.

This added junction is kept at a known temperature, 0°C, by submerging it in an ice bath, and thus becoming the reference temperature. Most commonly, a mixture of pure water and pure ice at 1 atmosphere of pressure is used for the reference junction. Today, electronic measuring devices simulate an ice reference bath without the need for an actual ice bath. This is often referred to as cold junction compensation (CJC).

After adding the ice bath, there are still two junctions at the device terminals, but each of these consists of the same two materials. If held at the same temperature, their emf voltage will be the same and cancel each other out.

Thermocouples can be made of any two dissimilar metal wires that can create a PN junction, and their emf voltage depends on the composition of the chosen metals. However, what makes thermocouples so popular is that the materials used to construct them are restricted and their outputs emf have been standardized. Certain materials and combinations are better than the others, and some have basically become the standard for given temperature ranges. Table 1 lists some of the available thermocouples on the market.

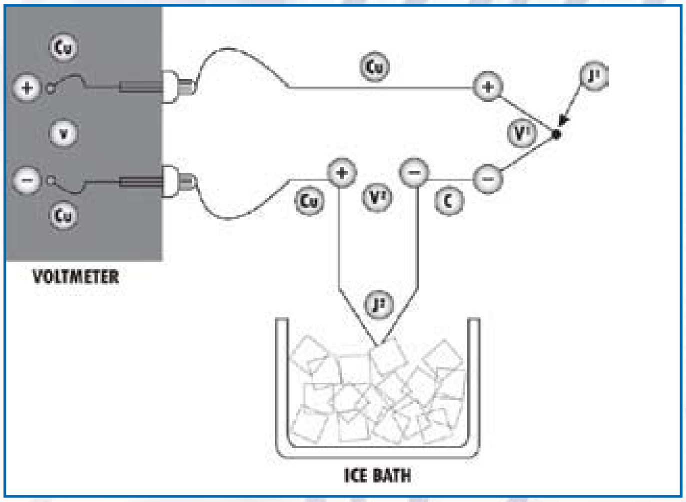


Figure 2. External reference junction [1].

Selecting the right type of thermocouple for an application depends on many factors. These include sensitivity, temperature range, corrosion resistance, linearity of output voltage, and cost. For example, types R and S are relatively expensive and are not sensitive. However, they perform well at high temperatures up to 1768°C and are resistant to a number of corrosives. Type C thermocouples are suitable for higher temperature applications, but they are relatively expensive and corrode easily in an oxidizing environment. A & T type thermocouples are inexpensive and very sensitive but will corrode at temperatures above 400°C. Type K is very popular for general use,

Thermocouple type	Material Composition	Temperature Range °C	Uncertainty	Color Code
t	Cu vs. Constantan	-250 to 350 C	Greater of 1C or 0.75%	Blue-Red
k	Chromel vs. Alumel	-250 to 1250 C	Greater of 2.2 C or 0.75%	Yellow-Red
j	Iron vs Constantan	0 ti 750 C	Greater of 2.2 C or 0.75%	White-Red
r	Platinum vs. Platinum-13% Rodium	0 to 1450 C	Greater of 1.5 C or 0.25%	None Established
s	Platinum vs. Platinum-10% Rodium	0 to 1450 C	Greater of 1.5 C or 0.25%	None Established
c	Tungsten 5% Rhenium vs. Tungsten 26% Rhenium	0 to 2320 C	Greater of 4.5 C to 425C, 1% to 2320 C	None Established
e	Chromel vs. Constantan	-200 to 900 C	Greater of 1.7 C or 0.5%	Purple-Red

Table 1. Different types of thermocouples.

relatively inexpensive, reasonably corrosion-resistant, and can be used at high temperatures, up to 1372°C. K-type thermocouples also provide relatively linear output as compared to the other types [2].

The actual magnitude of the thermocouple emf is very small, and is in the order of few millivolts. At a given temperature, Type E has the highest output emf among common types, but this voltage is still measured in millivolts. The sensitivity of thermocouples is also relatively low. For instance, the voltage change per degree Celcius from 38 to 93°C is only 36 microvolts. As a result, thermocouples require accurate and sensitive measuring devices and cannot be used for temperature changes of less than 0.1°C. Traditionally, expensive voltage balancing potentiometers were used to measure emf. Today, a high quality digital voltmeter is sufficient [3].

The National Institute of Standards and Technology (NIST) has developed standard calibration curves for determining temperature based on the measured emf voltage. These data represent the output emf of thermocouples when an ice cold junction is used, and are incorporated in the memory of most DAQ systems. Unfortunately, the temperature-voltage relationship of thermocouples is nonlinear and curve-fitted using polynomial functions. Obviously, the higher the order of the polynomial function, the higher the accuracy of temperature reading. The polynomial function should only be used inside the temperature range of the thermocouple type and should not be extrapolated. To save computational time, a lower order polynomial fit can be used for a smaller temperature range.

Thermocouple wires come in a variety of sizes. Usually, the higher the temperature, the heavier the wire should be . As the size increases, however, the time response to temperature increases. Therefore, some compromise between response and life may be required.

Thermocouples can be connected electrically in series or in parallel. When connected in series, the combination is usually called a thermopile, whereas there is no particular name for thermocouples connected in parallel. A wiring schematic of a thermopile combination is shown in Figure 3.

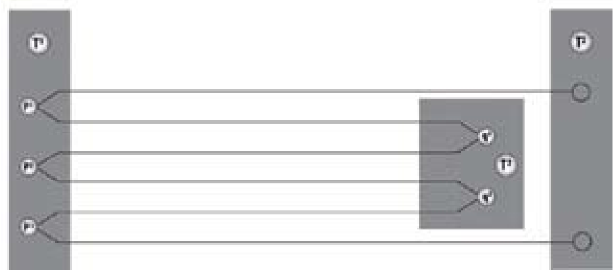


Figure 3. Series-connected thermocouples forming a thermopile.

The total output from n thermocouples will be equal to sum of the individual emf's. The main purpose of using a thermopile rather than a single thermocouple is to obtain a more sensitive element. Parallel connection of thermocouples is used for averaging.

References:
1. Omega Temperature Handbook, Omega Engineering, Inc. 2nd edition.
2. Wheeler, A. and Ganji, A., Introduction to Engineering Experimentation, Prentice Hall Inc., pp. 240-246, 1996.
3. Beckwith, T., Marangoni, R., and Lienhard, J., Mechanical Measurements, Fifth Edition, Addison Wesley Longman, pp. 676-685, 1993.