

Simple Demonstration of the Seebeck Effect

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Abstract

In this article we propose a simple and low-cost experimental set-up through which science educators can demonstrate the Seebeck effect using a thermocouple and an instrumentation amplifier. The experiment can be set up and conducted during a 1-hour laboratory session.

When a temperature gradient is introduced along the length of a metal wire, electrons start to diffuse from one end to the other end of the wire (Chambers, 1977). The direction of electron diffusion depends on the electrical properties of the metal wire. By convention, if electrons diffuse from the hot end towards the cool end of the wire, a negative thermoelectric emf is generated in the wire with respect to the hot end. Similarly, if electrons diffuse from the cool end towards the hot end of the wire, a positive thermoelectric emf is generated in the wire with respect to the hot end. This phenomenon in metals, known as the Seebeck effect, was first observed by physicist Thomas Johann Seebeck (1770-1831). Seebeck observed that when two dissimilar metal wires are formed into a closed loop and its two junctions are held at different temperatures, it has the ability to deflect a galvanometer needle. The phenomenon was later attributed to electrical current through the wires.

Metals have different thermoelectric sensitivities, or Seebeck coefficients. For example, iron has a Seebeck coefficient of $19 \mu\text{V}/^\circ\text{C}$ at 0°C , which means that for every 1°C difference in temperature, a positive thermoelectric emf (or Seebeck voltage) of $19 \mu\text{V}$ is induced in iron at temperatures around 0°C . As mentioned in the previous paragraph, a negative thermoelectric emf can also be induced in a metal, so Seebeck coefficients can also have negative values. For example, constantan (a copper-nickel alloy) has a Seebeck coefficient of $-35 \mu\text{V}/^\circ\text{C}$ at 0°C . It should be noted that the relationship between Seebeck voltage and temperature is linear only for small changes in temperature. For larger temperature ranges, the relationship becomes non-linear. It is therefore important to state the temperature at which the Seebeck coefficient is being specified.

A thermocouple is made from two dissimilar metals that are co-joined at one end (Figure 1) and can be used as a temperature sensor. As shown in Figure 1, a thermocouple consisting of metal A with Seebeck coefficient α_A and metal B with Seebeck coefficient α_B produces a thermoelectric emf (E) which is a function of the temperature of its tip (T_1), the temperature of the measuring point (T_2), and the thermocouple's Seebeck coefficient ($\alpha = \alpha_A - \alpha_B$). The relationship is mathematically expressed in Equation 1.

$$E = \alpha(T_1 - T_2) \quad (1)$$

The operation of a thermocouple is based on the different Seebeck coefficients of the dissimilar metals. If the two metals of the thermocouple were alike, or had the same Seebeck coefficient, the net emf produced at its measuring point would be zero. To measure the Seebeck voltage generated by a thermocouple, one can either use commercially available thermocouple readers or establish one's own thermocouple circuit. The reader may find it useful to review existing literature and become familiar with the different types of thermocouple circuits (Omega, n.d.). Since

thermocouples are relative temperature sensors, a thermocouple circuit requires a known reference temperature, such as an ice bath, for proper operation.

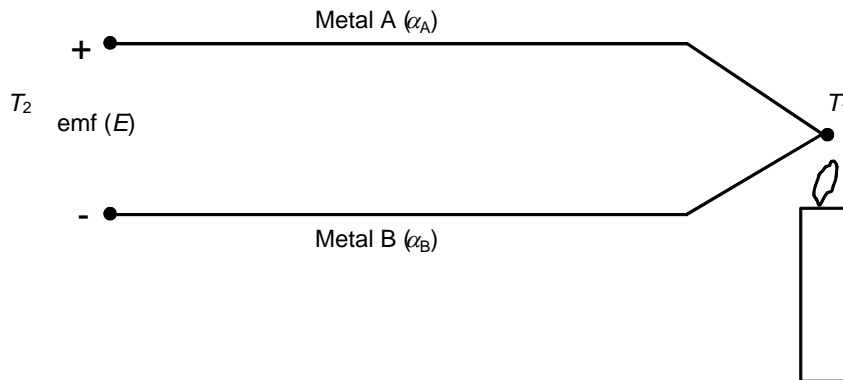


Figure 1. Schematic of a thermocouple made of metal A, with Seebeck coefficient α_A , and metal B with Seebeck coefficient α_B .

The Experiment

For our demonstration, we set up the thermocouple circuit shown in Figure 2. Table 1 provides a list of the major components used in the set-up. Our set-up includes two J-type thermocouples, each consisting of a pair of iron and constantan wires that are welded at one end. One of the thermocouples is used for measuring the reference temperature (T_{Ref}), while the other thermocouple is used for measuring the ambient temperature (T). To make the connection between the constantan wires of each thermocouple, we simply twisted them together. Since the magnitude of the Seebeck voltage generated in the setup is of the order of a few μV , an instrumentation amplifier was used to amplify the magnitude of the voltage. Analog Digital instrumentation amplifier AD620 (Analog Devices, 2004) was employed for this purpose. The AD620 chip provides a low-cost and accurate amplification mechanism to amplify the generated thermo-electric emf such that it can be easily measured with a digital multi-meter or data logger. The AD620 chip requires only one external resistor to set gains of 1 to 10,000. Furthermore, the AD620 chip requires lower power (only 1.3 mA maximum supply current), making it a suitable selection for battery-powered or portable applications.

We powered our AD620 chip using a ± 15 -V DC power supply. The gain (G) of the AD620 chip was set using a single resistor (resistance R_G) and calculated using Equation 2. In our circuit, we used a 220- Ω resistor, thereby obtaining a gain of 225.

$$G = \frac{49,400\Omega}{R_G} + 1 \tag{2}$$

Our temperature reference point consisted of crushed ice and distilled water mixed inside an insulated flask. It is important to keep the reference thermocouple inside the ice bath during the entire demonstration. To increase the accuracy of our measurements, the connections from the thermocouple ends to the AD620 chip were made through an isothermal block. The isothermal block helps in keeping the connections at the same temperature and thus minimizing errors due to unwanted parasitic thermocouples created at the connections between the thermocouple ends and the AD620 input. We established an isothermal block using a barrier strip attached to a flat copper

bar. Copper was chosen due to its high thermal mass. Thermal paste was applied between the barrier strip and the copper bar to enhance heat transfer. However, for the sake of simplicity, demonstrators may exclude the isothermal block and connect the thermocouple ends directly to the AD620 chip.

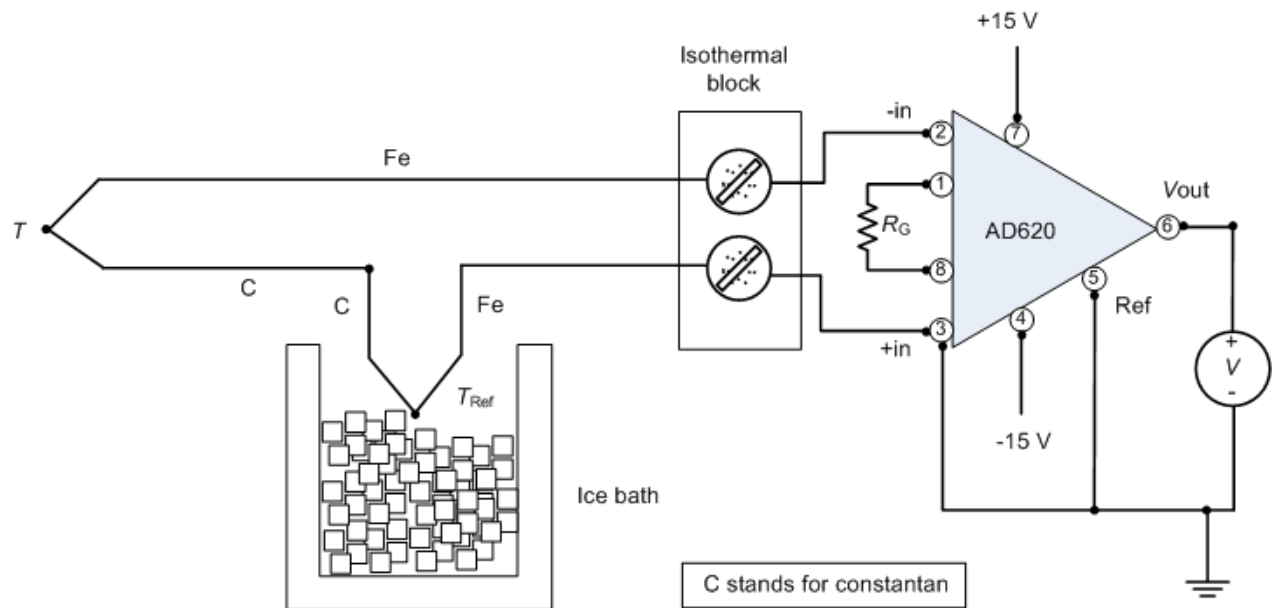


Figure 2. The thermocouple circuit.

Table 1
List of Major Equipment and Suggested Suppliers

Item	Qty	Supplier	Part Number	Unit Price (USD)
J-type thermocouple	2	RS Components	621-2186	10
AD620 instrumentation amplifier	1	Futurlec	AD620AN	5
220-Ω resistor	1	-	-	-
Digital multimeter	1	-	-	-
Insulated flask	1	-	-	-
Electric kettle	1	-	-	-
+/-15-V DC power supply	1	-	-	-
Breadboard	1	-	-	-
Copper bar (optional)	1	-	-	-
Barrier strip (optional)	1	RS Components	423-330	7
Thermal paste (optional)	1	RS Components	217-3835	20

Once all the connections are made (see Figure 3), the operation of the circuit can be quickly verified by turning on the power supply and holding the thermocouple bead (temperature T , as shown in Figure 2) between two fingers. If the digital multi-meter registers a sudden increase in the output voltage of the AD620 chip, then the circuit is most likely configured correctly. If not, the connections need to be re-examined.

The Seebeck effect can be demonstrated by subjecting the measuring thermocouple to various temperatures and recording the generated Seebeck voltage. For example, when we subjected the

thermocouple to room temperature we registered an amplified Seebeck voltage of 257 mV. In order to obtain the actual (pre-amplified) Seebeck voltage (E), one must divide the amplified voltage by the circuit gain (G). In this case, we divided 257 mV by our gain of $= 225$ to obtain an actual Seebeck voltage of $E = 1.14$ mV. To further demonstrate the Seebeck effect, we submerged the measuring thermocouple in both an ice bath and then a kettle containing boiling water. Based on our measurements, we calculated actual (pre-amplified) Seebeck voltages of 0 mV and 5.23 mV respectively. The recorded Seebeck voltages can be easily converted to temperature using either reference tables or inverse polynomials as defined by the International Temperature Scale of 1990, ITS-90 (U.S. Secretary of Commerce, 1995). Table 2 summarizes our measurements and their corresponding calculated temperatures using the ITS-90 J-type thermocouple reference table.



Figure 3. The experimental set-up.

Table 2
Measurements Using a J-Type Thermocouple With Gain of 225 and Ice/Water as Reference Temperature

Ambient condition	Amplified voltage (mV)	Pre-amplified voltage (mV)	Calculated temperature (°C)
Ice bath	0	0	0.0
Room temperature	257	1.14	22.5
Boiling water	1,177	5.23	99.5

The circuit can be used with other thermocouple types. Table 3 summarizes our voltage measurements and their corresponding calculated temperatures using the ITS-90 K-type thermocouple reference table. From the obtained results, it is easy to see that the J-type thermocouple has a higher sensitivity than the K-type thermocouple.

If class time permits, the instructor and students may find it rewarding to use the circuit to measure other known temperatures (e.g., the melting points of different solids or the boiling points of different liquids) and compare the results with published data.

Table 3
Measurements Using a K-type Thermocouple With Gain of 225 and Ice/Water as Reference Temperature

Ambient condition	Amplified voltage (mV)	Pre-amplified voltage (mV)	Calculated temperature (°C)
Ice bath	0	0	0.0
Room temperature	200	0.89	22.5
Boiling water	917	4.08	99.5

To ensure that students have understood the concepts and applications related to the Seebeck effect, it is recommended that a discussion session be conducted following the lab. During the discussion, a series of questions such as the following might be presented to the class:

- Describe the phenomenon observed by Seebeck.
- Why do metals have different Seebeck coefficients?
- Explain why some metals have positive Seebeck coefficients while others have negative coefficients.
- How does a thermocouple work? Why are thermocouples made from two dissimilar metals?
- What is the purpose of using an instrumentation amplifier?
- Why is an ice bath used as the reference temperature? Can other fixed temperatures be used?
- What is the purpose of using an isothermal block? What is a suitable material for the block and why?
- What is the ITS-90 reference table?
- Describe the thermocouple's voltage-temperature relationship. Is the relationship linear?

In Conclusion

We have described a simple and low-cost experimental setup through which science educators can demonstrate the Seebeck effect using a commercial thermocouple and an instrumentation amplifier. The experiment can be set up and conducted during a 1-hour lab session and followed by an in-class discussion. Science educators may find it particularly rewarding to expand the experiment by utilizing a computer-based data acquisition system to record the generated Seebeck voltage in real time and convert the recorded data to temperatures.

References

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