

5. Thermocouple

In this experiment, you are introduced to the concept of thermoelectricity and to the insulated calorimeter, which is used for thermal measurements. In many physical measurements, temperature is an important variable. Most of the properties of matter depend on temperature: physical size and resistivity are two examples. The thermocouple, studied in this experiment, relies on the temperature dependence of the electrostatic potential across junctions between different metals. This thermoelectric property makes it ideal for temperature measurements over a broad range of temperatures. When making measurements in which temperature is a variable, thermal gradients in the apparatus must be kept as small as possible. For this reason, such measurements must be made in an insulated container and care must be taken that thermal equilibrium is maintained. The Thermocouple experiment has two parts: a determination of the calibration curve and a determination of the temperature of a dry ice-alcohol slurry. This is essentially the sublimation temperature of solid CO_2 .

Theory: Thermocouple

In metals, huge numbers of free electrons are available to carry current. At temperatures above 0 K, the fixed atoms vibrate about their equilibrium positions, and the free electrons undergo random motion. The average kinetic energy of the atoms and electrons increases as temperature increases – in fact, temperature is just a measure of this energy.



Figure 1:(a) Potential barrier at the surface of a metal. (b) Potential difference due to the electron distribution at the junction between two different metals.

Figure 1 (a) shows a metal surface. Inside the metal, electrons move with random velocities, and some of them are near the surface with enough kinetic energy to escape, leaving the metal positively charged. The positive metal strongly attracts the negative electron, and, at room temperature, virtually all the electrons fall back into the metal. This attraction can be understood as a potential barrier that only the most energetic electrons can cross. Suppose that the potential barrier of metal-1 is higher than that of metal-2 like in Figure 1 (b). It is, then, easier for electrons from metal-2 to cross into metal-1. Consequently, there will

be an excess of electrons in metal-1 causing a potential difference (V), across the junction. Now, the average speed of the electrons is a function of the temperature, and consequently, its kinetic energy is also. Then it follows that V is also a function of temperature. This allows us to use the temperature dependence of $V(T)$ as a measure of temperature.

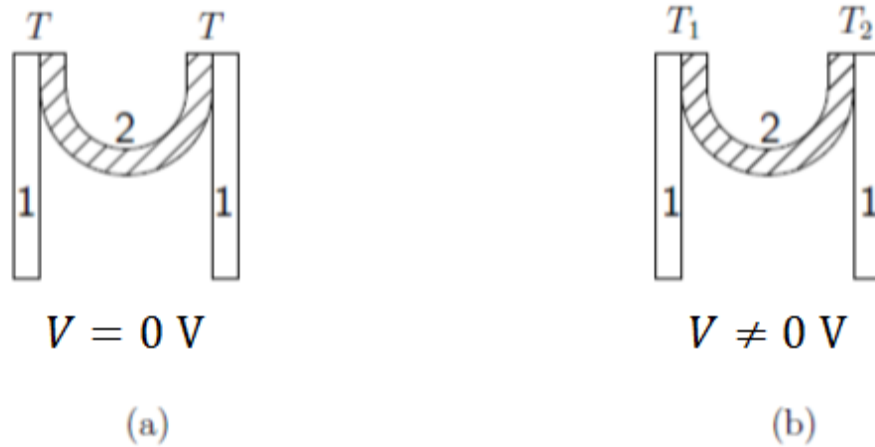


Figure 2: (a) Thermocouple with both junctions at the same temperature. (b) Thermocouple with junctions at different temperatures.

We can form a thermocouple by connecting wires made of two different metals such that a length of one metal is sandwiched between two lengths of the other. If the two junctions are at the same temperature, as in Figure 2 (a), the voltage across the open ends is $V = 0 \text{ V}$. On the other hand, if there is a difference of temperature $\Delta T = T_2 - T_1$ between the two junctions, there is a potential difference, $V \neq 0 \text{ V}$, between them. Over a wide range of temperatures and to a good approximation, this emf is given by the equation:

$$V = \alpha + \beta\Delta T + \gamma\Delta T^2 \quad (5.1)$$

where α , β , and γ are constants which depend on the two metals forming the junction of the thermocouple. The constant, γ , is usually very small so that the square term can be neglected if ΔT is not too large. Then, if the cold junction is kept at a constant temperature, for example that of melting ice (0°C), the change of voltage, ΔV , is a linear function of the hot junction temperature. Thus,

$$\Delta V = aT \quad (5.2)$$

where a is a proportionality constant characteristic of a given thermocouple over a range of temperatures. Once a is known (from a calibration process,) the measured potential difference may be used as a measure of T . Note that a in Equation 5.2 is **not** α from Equation 5.1, they are different quantities: $a \neq \alpha$!

The meter used to measure the potential difference across the thermocouple must have a very high internal resistance so as to keep the current small. (Why? Explain in Discussion.)

Theory: Calorimeter


The calorimeter is used to make measurements involving temperature and quantity of heat. It is designed to minimize heat transfers to or from the environment. It consists of an inner can suspended within a large


can by means of an insulating ring. The dead air space between the two cans is an excellent insulator. Thus, for a moderate temperature difference between room and the content of the inner can, heat transfer to or from the calorimeter is minimal. In this experiment, the calorimeter is used to reduce thermal gradients to negligible levels. When heating, it is essential to stir continuously to minimize the temperature difference between the heater and the surrounding liquid, thus, keeping the temperature uniform throughout the volume of the container.

Part 1: Calibration of the Thermocouple

The thermocouple used for this experiment is a copper-constantan thermocouple. The two outer wires are copper and the center one is constantan (a special alloy.) You must be careful not to bend the wires too sharply because the constantan is very brittle and breaks easily. Do not attempt to undo the connections. They are welded; the wires are twisted to give the welded joints some strain relief. If you notice that a weld is broken, do not proceed – your readings will not be valid. Call a demonstrator to have the thermocouple replaced.

Procedure (Part 1)

1. Pack the inner can of the *cold* calorimeter (without heater) with ice and fill with water. Much of the ice will melt immediately so repack with more ice, allowing the excess water to overflow.
2. Fill the inner can of the heater calorimeter with water as cold as you can obtain.
3. Return both cans into their respective shields and keep covered as much as possible.
4. Connect the temperature probe and the instrumentation amplifier to the LabQuest MINI. Connect the LabQuest MINI to the computer. Make sure that the amplifier has $\pm 20\text{ mV}$ range selected.
5. Open the appropriate Logger Pro file. Page 1 contains the data table that you will fill out as you're collecting data.
6. Use two wires with alligator clips to connect the two free ends of the thermocouple to the input terminals.
7. Immerse both junctions of the thermocouple well into the ice bath. Ensure that the junctions don't touch the walls of the can. Zero the amplifier: in the top menu select `Experiment/Zero...`
8. Gently attach one of the thermocouple junction to the temperature probe. The other junction remains in the ice bath.
9. Insert the thermocouple - temperature probe assembly into the hole in the stopper ensuring that it will not touch the heating element or the bottom of the can.
10. Carefully insert the stopper into the hole in the cover with the two wires passing between the stopper and the edge of the cover. Ensure that the temperature probe-thermocouple assembly does not come into contact with the heater or the stirrer. Replace the cover on the calorimeter.
11. Use two patch cords to connect the heater to the bench DC 1–12 V power supply.
12. Ground your setup: connect the little grounding wire on the heater assembly to the NEGATIVE (black) terminal of FREE LINES of the power supply.
13. Set the variac CONTROL to the appropriate setting.
14. **Have a demonstrator check your setup!**
15. Turn ON the power supply. Click COLLECT ( Collect).
16. Slowly and continually stir the calorimeter throughout the readings, occasionally shake the cold calorimeter.

17. Collect the voltage, ΔV , and temperature, T , values at every 0.2 mV by clicking Keep ( Keep).
- Stop once the temperature reaches $\sim 60^\circ\text{C}$.
18. Turn OFF the power supply.

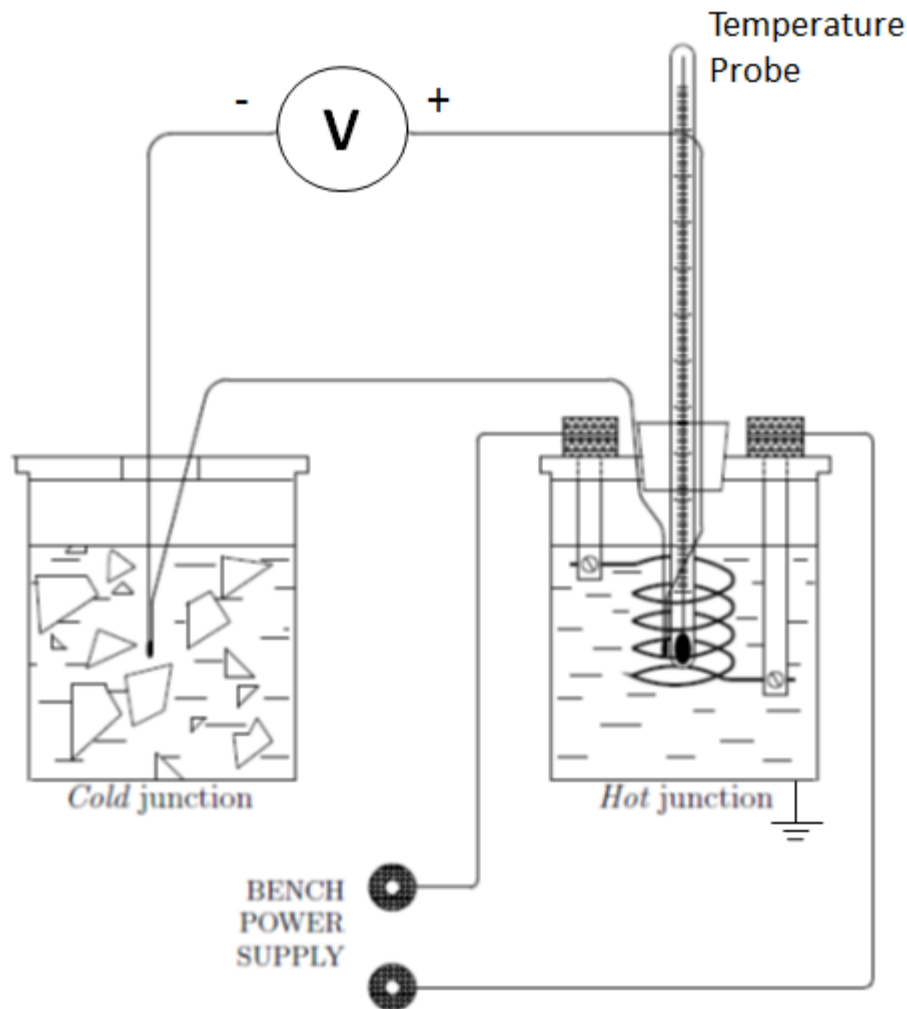



Figure 3: Experimental set-up for calibration of the thermocouple. The *cold* junction is in a water-ice mixture. An electric heating coil controls the temperature of the *hot* junction. The outer heat shield cans are not shown.

Analysis (Part 1)

19. The plot of the calibration curve, V vs T , should be automatically generated for you. Perform a Linear Fit on this graph: click Curve Fit (), under General Equations select $mx + b$ (Linear), click on Try Fit, then on OK.
20. From the slope of the line, obtain the coefficient $a \pm \sigma_a$ for the thermocouple.
21. Use Equation 5.2 to calculate the expected ΔV for $T = 100^\circ\text{C}$. This will be your calculated value: ΔV_c . Derive the error propagation expression to determine the value of $\sigma_{\Delta V_c}$ (note that $T = 100^\circ\text{C}$ has no error associated with it).

Part 2: Dry-ice bath temperature

The dry-ice-alcohol slurry is extremely cold. Be very careful – serious frost bite is a hazard.
Only allow a demonstrator to manipulate the container.

Procedure (Part 2)

22. Obtain a calorimeter filled with dry-ice-alcohol slurry from a demonstrator. Handle it only by the outer heat shield. **Do not discard after use**; return to the demonstrator.
23. Insert the *hot* junction into the slurry and wait for the voltage reading to stabilize.
24. Record your ΔV_{CO_2} reading with an appropriate reading error.

Analysis (Part 2)

25. Rearrange Equation 5.2 to calculate for the sublimation temperature of CO₂ using the ΔV_{CO_2} value you obtained. This will be your calculated temperature value: T_c . Derive the error propagation expression to calculate σ_{T_c} .
26. Data from a detailed copper-constantan thermocouple calibration from $T = 0$ to $-190^\circ C$ is plotted on Page 2 of the Logger Pro file. Fit an appropriate curve to this data based on Equation 5.1. **Check with a demonstrator.**
27. Use the graph to extrapolate the graphical value for the sublimation temperature, T_g . In the top menu click Analyze/Interpolation calculator. Enter the voltage value and record the corresponding temperature value. Assume your T_g value has $\sigma_{T_g} = 0.5^\circ C$. Make sure the Interpolation Calculator window is displayed on your graph.
28. Use the Interpolation Calculator to obtain the value of ΔV at $T = 100^\circ C$. You will need to adjust the scale on your graph so that the point you're looking for is visible. This is your graphically extrapolated value: ΔV_g . Assume $\sigma_{\Delta V_g} = 0.005 mV$. Make sure the Interpolation Calculator window is displayed on your graph. Autoscale the graph to return it to its original size.
29. Print the data tables and the graphs: select File/Print... Remember to include your name, student number and workstation number in the footer. Both Pages of the file should be printed automatically. For the Page 1 data table, write the readings errors for Voltage and Temperature into their respective column headings.
30. Perform a consistency test to compare the graphically obtained voltage ($\Delta V_g \pm \sigma_{\Delta V_g}$) and the calculated voltage ($\Delta V_c \pm \sigma_{\Delta V_c}$) at $T = 100^\circ C$.
31. Perform a consistency test between the calculated ($T_c \pm \sigma_{T_c}$) and the graphical ($T_g \pm \sigma_{T_g}$) value.
32. Perform a consistency test for each of these values compared with the accepted value for the sublimation temperature of CO₂: $T_{sub} = -(78 \pm 0)^\circ C$.

Use Table 1 to organize your consistency tests calculations. You can also refer to this table as part of your results section.

Table 1: Summary of results for consistency tests

Values being compared		Δ	σ_{Δ}	Δ/σ_{Δ}	Consistent? (Yes or NO)
$\Delta V_g \pm \sigma_{\Delta V_g}$ (... \pm ...) units	$\Delta V_c \pm \sigma_{\Delta V_c}$ (... \pm ...) units				
$T_c \pm \sigma_{T_c}$ (... \pm ...) units	$T_g \pm \sigma_{T_g}$ (... \pm ...) units				
$T_c \pm \sigma_{T_c}$ (... \pm ...) units	$T_{sub} \pm \sigma_{T_{sub}}$ (... \pm ...) units				
$T_g \pm \sigma_{T_g}$ (... \pm ...) units	$T_{sub} \pm \sigma_{T_{sub}}$ (... \pm ...) units				

Notes:

Here are the points that you need to cover in the Discussion:

- Do you expect Equation 5.2 to provide accurate extrapolation of ΔV at $T = 100^{\circ}C$? Which is better: using Equation 5.2 or using the graphical extrapolation?
- Do you expect Equation 5.2 to be accurate when finding sublimation temperature of dry ice? Why or why not?
- What results were you expecting for each of your consistency tests? Why? Did you obtain what you expected?
- What type of thermocouple are you using? Is Equation 5.1 an adequate representation of the temperature and voltage dependence for this type of thermocouple?
- What is the purpose of putting ice into the cold junction? Can the experiment be done without it?
- Why did you need to stir the water in the hot junction and occasionally shake the cold junction can?
- Why was the alcohol slurry necessary?
- Why is solid CO_2 referred to as ‘dry ice’? Is there such a thing as ‘wet ice’? Is it possible to skate on dry ice? Why or why not?