Experiment B6
Thermal Properties of Materials
Procedure

Deliverables: Checked lab notebook, Brief technical memo

Overview

In this lab, you will examine the thermal properties of various materials commonly used in mechanical engineering. This is important, as high temperatures will often cause mechanical structures to fail (i.e. car engines can seize up and steel beams can buckle).

Part I: Specific Heat

Theoretical Background

In thermodynamics, the word "heat" refers to the thermal *energy* contained in a material. Thus, heat will have units of Joules, calories, or BTUs (units of energy). Substances that have a greater temperature will contain more heat. *Specific heat* is a chemical property that relates changes in thermal energy to changes in temperature. Specific heat c_p is defined by the equation

$$c_p = \frac{\Delta q}{m\Delta T}, \tag{1}$$

where Δq is the change in internal energy (heat), m is the mass of the substance, and ΔT is the change in temperature.

In aerospace and mechanical engineering, specific heat is typically expressed in units of Joules per gram per Kelvin (J/g/K). For example, the specific heat of water is 4.185 J/g/K, so adding 4.185 Joules of thermal energy to 1 gram of water will cause its temperature to increase by 1 degree Kelvin.

Experimental Procedure

There are five different materials in this lab for you to test: aluminum, copper, brass, stainless steel, and carbon fiber composite. **You must test all of them.** Table 1 lists the average mass and uncertainty for the different samples.

Table 1 – Values of the mass m of the samples for measuring specific heat.

Material	Copper	Brass	Stainless Steel	Carbon Fiber	Aluminum
mass, m (g)	17.50±0.02	16.70±0.02	15.50±0.02	2.85±0.02	5.30±0.02

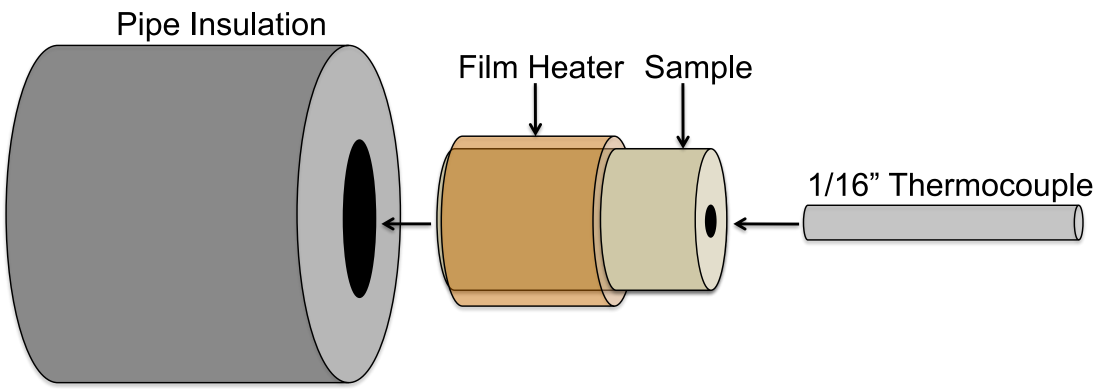

Figure 1 - A schematic of the experimental setup for measuring specific heat.

1. Pick up one of the samples with a heater wrapped around it and determine what the material is. If you are unsure, ask the TA or lab instructor for help.
2. Connect the thermocouple (TC) into the "T_1" port on top of the red Omega HH806AU digital readout. Turn on the logger, and check to make sure it is working by grabbing the TC tip with your fingers.
3. Place the sample in the pipe insulation, such that the heater wires are hanging out the other end. Insert the tip of the thermocouple into the hole on the end of the sample. Wait a few seconds and record the temperature T_i in your lab notebook.
4. Set up the Keysight U8002A DC power supply:
    a. Press the "OVER VOLTAGE" button and make sure it is set to 30V.
    b. Press the "OVER CURRENT" button and make sure it is set to 0.4 A.
    c. Plug the banana to grabber cables into the + and – outputs. Do NOT connect the heater yet.
    d. Press the Output ON/OFF button. You should see a value for voltage and current show up on the screen.
    e. Toggle the Voltage/Current button and turn up the voltage to 26V.
    f. Press the Output ON/OFF button. The screen should say "OFF".
5. Connect the cables from the power supply to the film heater wires.
6. Check to make sure the TC is still snuggly in the sample. If it is not, you will get bad data!
7. Locate the stopwatch, and reset it to zero.
8. Simultaneously press the Output ON/OFF button and start the stopwatch. When the stopwatch gets to 20 seconds, press the Output ON/OFF button and stop the stopwatch. Record the time Δt, and estimate the uncertainty in Δt.
9. While the heater is on, record the current i and voltage V. Use these to calculate the heater power $\dot{q} = iV$.

CAUTION: Do not leave the heater on for more 30 seconds. It will get very hot very quickly!

10. The temperature reading on the red HH806AU digital readout should go up and come back down after the heater is turned off. Record the maximum value it reaches T_{max}.
11. Make sure the heater is off. Carefully remove the sample from the pipe insulation.

Pro-tip: The experiment is all about timing you might consider doing a couple of practice runs to get the timing down before you go live.

12. Calculate the change in temperature $\Delta T = T_{max} - T_i$. Calculate the total heat given to the sample $\Delta q = \dot{q}\Delta T$. Using these values and the corresponding mass m from Table 1, calculate the specific heat using Eq. (1).
13. Repeat this procedure until you have gone through all 5 samples in Table 1.

Part II: Thermal Conductivity

Theoretical Background

Thermal energy always flows from hot to cold. For instance, if a metal rod is heated at one end and cooled at the other, heat will flow from the hot end to the cold end. The "flux" of thermal energy q'', or rate of heat flow per unit area in W/m^2, is governed by Fick's Law

$$q'' = -k\frac{dT}{dx} \tag{2}$$

where dT/dx is the "temperature gradient" and k is the thermal conductivity. Figure 2 illustrates the temperature profile of a metal rod that is heated at one end and cooled at the other. The heat flows from the hot end to the cold end at a rate proportional to the slope of the line dT/dx.

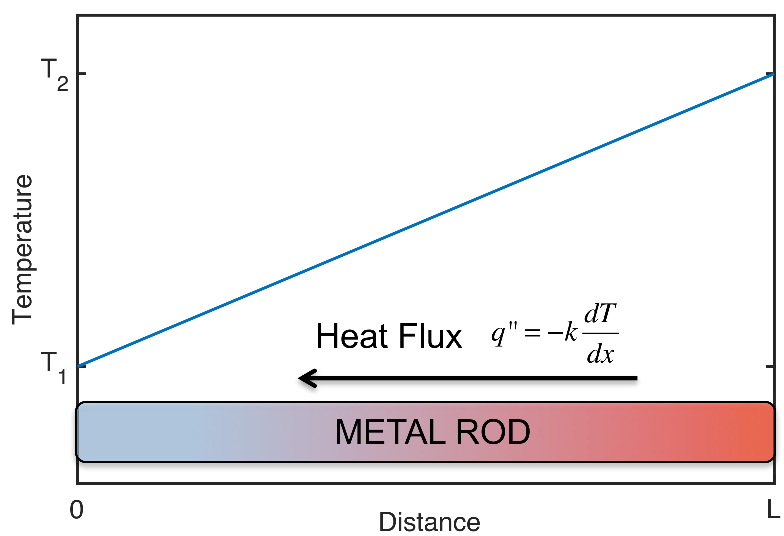

Figure 2 – The temperature profile of a metal rod heated on the right end and cooled on the left end.

Experimental Procedure
Shown in Figure 3 is a schematic of the experimental apparatus you will use in this experiment. It consists of a uniform cylindrical rod with an electric heater on one end and cooling water on the other. The entire rod will be wrapped in pipe insulation. For an insulated, uniform rod with a constant cross section under stead state conditions, Equation (2) can be written as

$$\frac{\dot{q}}{A} = -k\frac{\Delta T}{\Delta x}, \qquad (3)$$

where $\dot{q} = iV$ is the power input on the on the hot end, A is the cross sectional area of the rod, k is the thermal conductivity of the material, $\Delta T = T_2 - T_1$ is the measured temperature difference between the two points, and $\Delta x = L$ is the distance between the two points. You will measure $\dot{q} = iV$, A, ΔT, and L and use them to calculate the thermal conductivity k.

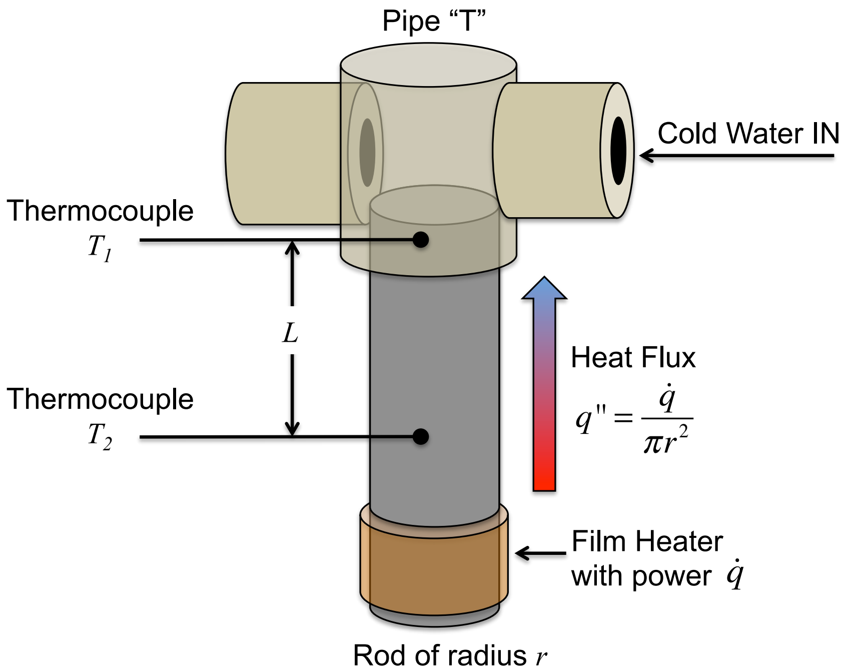

Figure 3 – A schematic of the experimental apparatus used for measuring thermal conductivity of a metallic rod.

On the counter top, you will find 3 to 5 different experimental setups connected to the cold-water valve manifold on the wall. (A photograph of the full experimental setup is shown in Appendix B.) Each of setup contains a different material. One group of 2 students will set up each of the experiments under the supervision of the lab instructor.

1. Make sure the DC power supply is turned off and disconnected.
2. Locate the downstream end of the tubing and make sure it in a sink where the water can properly drain. No water should be coming out of the end.

3. Visually trace the tube, starting from the sink, upstream through the experimental apparatus, then through the flowmeter and into the cold-water valve manifold on the wall. Sketch a schematic of all this in your lab notebook.
4. Remove the pipe insulation. (Press the plastic tab on the zip ties to remove them.)
5. Determine what material you have, and write it down in your lab notebook.
6. Use a ruler or a pair of calipers to measure the distance between the two thermocouples L. Estimate the uncertainty in L and write it down in your lab notebook along with the value of L.
7. Use the calipers to measure the diameter of the rod $D = 2r$. Estimate the uncertainty in D and write it down in your lab notebook along with the value of D.
8. Wrap the insulation around the rod with the wires hanging from the bottom. Secure it with zip ties.
9. Plug the two thermocouples into the red HH806AU digital readout. Turn it on, and you should see T_1, T_2, and ΔT displayed on the screen in units of Celsius.
10. Make sure the pipe T on the sample is securely mounted in the beaker clamp and the flowmeter is securely mounted in the other beaker clamp. The valves on the cold-water manifold should all be turned to an angle of 45°.
11. Slowly turn the knob on the flowmeter counterclockwise to start the flow of water. Keep turning it until you reach a flow rate of 30 GPH (gallons per hour).

CAUTION – If you see water start leaking anywhere onto the counter, immediately notify the lab instructor.

12. Set up the Keysight U8002A DC power supply:
    a. Press the “OVER VOLTAGE” button and make sure it is set to 30V.
    b. Press the “OVER CURRENT” button and make sure it is set to 0.4 A.
    c. Plug the banana to grabber cables into the + and – outputs. Do NOT connect the heater yet.
    d. Press the Output ON/OFF button. You should see a value for voltage and current show up on the screen.
    e. Toggle the Voltage/Current button and turn up the voltage to 26V.
    f. Press the Output ON/OFF button. The screen should say “OFF”.
13. Connect the cables from the power supply to the film heater wires.
14. Press the Output ON/OFF button. You should see the temperature gradually begin to go up.
15. While the heater is on, record the current i and voltage V. Use these to calculate the heater power $\dot{q} = iV$.
16. Wait for the temperatures to reach steady state. This may take up to 20 minutes, depending on what material you have. (The red HH806AU digital thermocouple readout will

automatically shut itself off to save battery power. When this happens, turn it back on.)

17. When it reaches steady-state, record the two temperatures in your lab notebook.
18. Examine the other setups on the counter and consult with the students who set them up. Record the material type, temperatures, and dimensions *L* and *D* of the other setups in your lab notebook
19. When everyone has their data, return the setups to their original state:
    a. Turn off and disconnect all of the heaters.
    b. Turn off the red HH806AU digital readouts and disconnect the thermocouples.
    c. Turn the flow rate back to zero.
20. Solve Eq. (3) for *k* and use your measured parameters to determine the thermal conductivity of the different setups.

Data Analysis and Deliverables

Using LaTeX or MS Word, make the following items and give them concise, intelligent captions. **Additionally, write 1 – 3 paragraphs separate from the caption describing what you did in lab and how it relates to the plot/table. Any relevant equations should go in this paragraph.**

BE SURE TO INCLUDE UNITS IN THESE:

1. For Part I, make a table with a row for each material. Along each row in the table, please include the following parameters:
    a. The sample mass and its uncertainty $m \pm U_m$.
    b. The heater power $\dot{q} = iV$.
    c. The amount of time you had the heater on for the material $\Delta t \pm U_t$.
    d. The change in temperature and its uncertainty $\Delta T \pm U_T$. (You can get the uncertainty from the data sheet for the HH806AU digital thermocouple readout for a "Type K" thermocouple.)
    e. The specific heat you calculated along with its uncertainty $c \pm U_c$.
    f. A published value for the specific heat of the material. (Be sure to include a reference.)
2. For Part II, make a table with a row for each material. Along each row in the table, please include the following parameters:
    a. The sample diameter and its uncertainty $D \pm U_D$.
    b. The sample length and its uncertainty $L \pm U_L$.
    c. The heater power $\dot{q} = iV$.
    d. The temperature difference and its uncertainty $\Delta T \pm U_T$. (You can get the uncertainty from the data sheet for the HH806AU digital thermocouple readout for a "Type K" thermocouple.)
    e. The thermal conductivity you calculated along with its uncertainty $k \pm U_k$.
    f. A published value for the thermal conductivity of the material. (Be sure to include a reference.)

Talking Points – Discuss these in your paragraphs.

- Compare measured specific heat and thermal conductivity of the various material to one another. Which has the highest specific heat? Which is the most conductive? Which has the lowest specific heat? Which is the least conductive?
- Compare your measured values of specific heat and thermal conductivity to the published values. Are you within the uncertainty in your measurement?
- What was the biggest source of uncertainty in your measured values for specific heat and thermal conductivity? How do you think you might improve this?

Appendix A

Equipment

Part I

- Keysight U8002A DC power supply
- Banana plug to minigrabber cables for DC power supply
- Stopwatch
- 1/16” thermocouple
- HH806AU digital thermocouple readout
- Copper, brass, aluminum, stainless steel, and carbon fiber samples with 5W film heaters
- Pipe insulation

Part II

- Keysight U8002A DC power supply
- Banana plug to minigrabber cables for DC power supply
- HH806AU digital thermocouple readout
- Cylindrical samples mounted in pipe T with 5W film heater and thermocouples (5SC/5LSC)
- 0 – 40 GPH flowmeter with needle valve
- Lab stand with 2 beaker clamps
- 3/8” clear tubing
- Cooling water valve manifold
- Sink with working drain
- Pipe insulation
- Removable zip ties
- Calipers and ruler

Appendix B

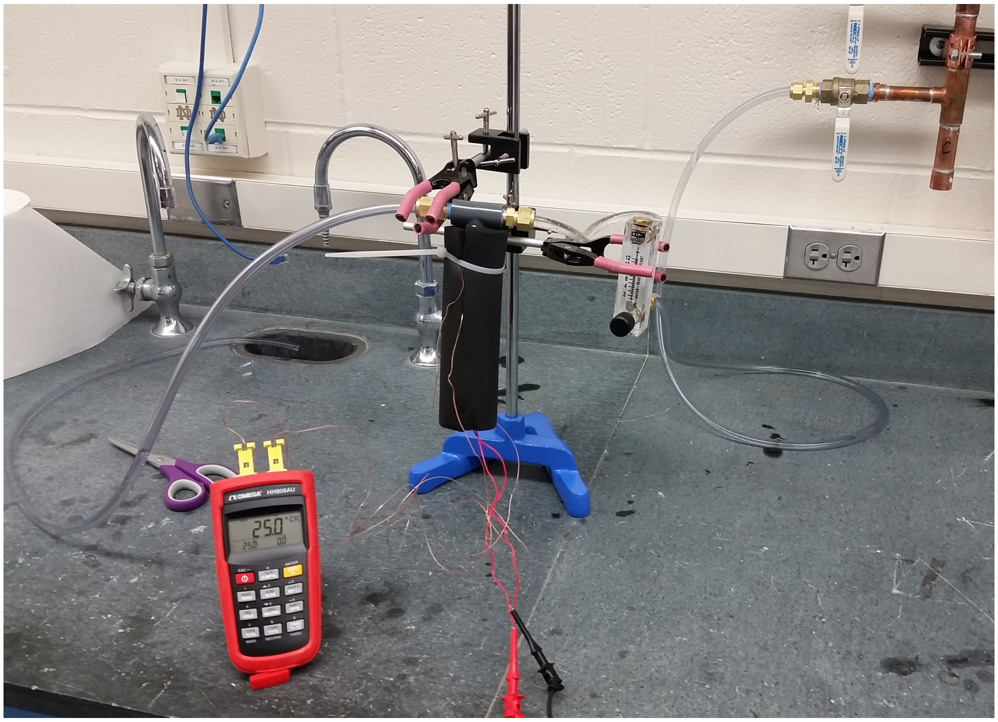

Figure 4 – A photograph of the experimental set up for measuring thermal conductivity.