Thermal Physics Experiment

PART I
Temperature Sensors

Introduction

The most familiar temperature sensor is the thermometer. A thermometer consists of a fixed-volume reservoir connected to a capillary. The reservoir and part of the capillary are filled with a liquid (usually mercury or colored alcohol). The volume of the liquid depends (approximately linearly) on the temperature, so as the temperature rises the liquid fills more and more of the capillary. Calibration marks on the side of the capillary convert the volume of the liquid to temperature in °C.

Thermistors are semiconductor devices that exhibit a temperature dependant resistance. Thermistors, like thermometers, must be calibrated, i.e., an approximate functional relationship between the resistance of the device an the temperature must be found. Unlike thermometers this relationship is nonlinear and generally exponential. For example:

$$R = Ae^{-BT} \qquad \text{or} \qquad R = ae^{-b/T(^\circ\mathrm{K})}$$

Thermocouples differ from the above temperature sensors in that they measure the temperature *difference* between *two* junctions instead of the actual temperature at one "junction". Roughly speaking the voltage produced by a thermocouple depends linearly on the difference in temperature between the thermocouple's two junctions:

$$V = C\,(T_1 - T_2)$$

(In fact the exact relationship is slightly nonlinear.)

The above three sensors are all temperature *transducers* in that each converts one physical quantity (in these cases temperature) to another physical quantity (volume, resistance, voltage). The *calibration* for each device is the relationship that gives the temperature as a function of the other physical quantity (volume, resistance, voltage). In the first part of this experiment you will calibrate a thermistor and thermocouple using the manufacturer's thermometer calibration.

Apparatus

MATERIALS:

- Temperature Sensor Apparatus
  - room temperature water
  - 500 ml Erlenmeyer flasks (2)
  - test tubes (2)
    - thermometer
    - thermistor
    - copper-constantan thermocouple
- 192 or 196 DMM (for thermocouple voltage) — requires warm-up ($\sim$ 1 hr.)
- 169 DMM (for thermistor resistance)
- hot plate

The thermometer, thermistor, and one junction of the thermocouple are placed close together in the water-filled test tube. (The idea is that the thermometer, thermistor and thermocouple junction should all be at the same temperature.) The test tube is placed in a water-filled Erlenmeyer flask, which sits on the hot plate. The remaining Erlenmeyer flask is also filled with room temperature water in which the thermocouple reference junction sits. (This reference junction must remain at a fixed temperature during the experiment, so keep it well away from possible heat sources.)

A precision voltmeter (e.g., 192 or 196) on its lowest voltage scale is needed to accurately measure the small thermocouple voltage. (Microvolt accuracy is needed.) The manual suggests a one hour warm-up period for these voltmeters, so turn them on immediately.

Thermistor resistance is easily measured with the normal 169 DMM.

Procedure

Data collection requires about 40 minutes. Attempts to rush the experiment (e.g., by trying to heat the water faster) generally result in uneven heating (the thermometer, thermistor, and thermocouple junction not at the same temperature) and hence yield poor results. Have patience! You may want to start the 30 minute heating needed in Part II simultaneously.

Record room temperature and the temperature of the reference thermocouple junction at the start of the experiment. Turn the hot plate to 500 watts. Record thermistor resistance and thermocouple voltage at 5°C intervals up to the highest temperature reached (near 100°C). Record room temperature and the temperature of the reference thermocouple junction at the end of the experiment.

Analysis

SIDPLOT thermocouple voltage vs. temperature using both linear and quadratic relationships. (The quadratic relationship should produce a smaller reduced χ^2 as the relationship is actually slightly nonlinear.) *SIDPLOT* thermistor resistance vs. temperature using the exponential relation.

PART II
Thermal Conductivity

Introduction

Heat (energy) spontaneously flows from higher temperature regions to lower temperature regions. This experiment investigates the factors that control the *rate* of energy flow (R, units: W = J/s or cal/s). Essentially the important factors are known to be: (1) geometric factors — the distance (l) that separates the hot and cold regions and the area (A) of contact, (2) temperature factors — the temperatures of the hot (T_h) and cold (T_c) regions, and (3) material factors — the nature of the material that fills the gap between the hot and cold regions, which can be described in a single number called the thermal conductivity (κ). These factors can be put together into a single equation for the rate of heat flow:

$$R = \frac{\kappa A\,(T_h - T_c)}{l}$$

This equation says we could decrease the rate of heat flow by using a material with a smaller thermal conductivity (i.e., a better thermal insulator), increasing the thickness of the material, decreasing the contact area or decreasing the temperature difference.

Apparatus

MATERIALS:

- Variac (on 40) + immersion heater
- 192 or 196 DMM (for thermocouple voltage) — requires warm-up ($\sim$ 1 hr.)
- Thermal Conductivity Apparatus
  - styrofoam top + weight
  - styrofoam bottom
  - heat source + boiling water
  - material to be tested (glass)
  - heat receiver (initially at room temperature)
  - constantan wire (red) + wires to DMM
- watch with second hand
- heat sink compound

The heat source is a slab of nickel-plated copper at the bottom of a slightly-insulated pan. The pan is filled (about 6 cm deep) with water which is continuously heated by the immersion heater. The boiling water in the pan is designed to keep the source at a constant temperature during the course of the experiment.

The heat receiver is a nickel-plated, 340 g, copper plug in the top of a slightly-insulated bottom. The receiver is heated at a rate that depends on the material between the receiver and the source. The continuous flow of energy to the receiver results in a continuously increasing temperature of the receiver.

The temperature difference between the source and the receiver is monitored by a thermocouple (with junctions in the source and the receiver) using a precision voltmeter.

A light coating of heat sink compound is spread on the receiver before the glass is placed on top of it. Another light coating of heat sink compound is placed on top of the glass before the source is placed on top of it. The heat sink compound is used to assure that the entire area of the receiver is in contact with the glass. (The heat sink compound should be removed after the experiment.)

Theory I

When the hot source is placed on top of the receiver-glass combination, heat immediately starts to flow into the receiver. You know that if a quantity of heat Q is added to the receiver (with mass m and specific heat c), the receiver's temperature rises from room temperature ($T_\circ$) to T:

$$Q = mc\,(T - T_\circ)$$

If we take the time derivative of this equation, we find:

$$\frac{dQ}{dt} = R = mc\,\frac{dT}{dt}$$

In this experiment the rate of heat flow R is determined by the factors discussed above, so

$$\frac{\kappa A\,(T_h - T)}{l} = R = mc\,\frac{dT}{dt} \tag{1}$$

Since the thermocouple measures the temperature difference ($T_h - T = \Delta T$), it will be helpful to rewrite the above equation:

$$\frac{\kappa A \Delta T}{l} = R = mc\,\frac{d}{dt}\,(T_h - \Delta T) = -\,mc\,\frac{d\Delta T}{dt}$$

since T_h is constant. The thermocouple voltage V is linearly related to ΔT ($V = C\Delta T$), so if we multiply the above equation by C, we find:

$$\frac{\kappa A V}{l} = -\,mc\,\frac{dV}{dt}$$

or

$$-\,\frac{\kappa A}{lmc}\,V = \frac{dV}{dt}$$

with solution

$$V = V_{\circ} e^{-Bt} \tag{2}$$

$$B = \frac{\kappa A}{lmc} \tag{3}$$

Thus, by finding the parameters of the exponential relationship between thermocouple voltage and time we can find the numerical value of B, from which κ can be determined, if we know A, l, m and c.

Procedure

Data collection requires about 60 minutes. Attempts to rush the experiment (e.g., by trying to heat the water faster) generally result in uneven heating of the source and hence yield poor results. Have patience! The 30 minute source-water heating may occur simultaneous with Part I.

Place the source on the styrofoam bottom, fill with about 6 cm of water, add the immersion heater, cover with the styrofoam & weight top, turn the variac to 40 and begin the slow source-water heating process. (The water should boil for 10 minutes before the source is considered ready.)

Measure the thickness of the sample with a micrometer and the diameter of the receiver with calipers. Prepare the receiver-sample by spreading a *small* amount of heat sink compound on the receiver. (Avoid getting any compound on the wood insulation.) Press on the sample. Spread a small amount of heat sink compound on the top of the sample.

Connect the thermocouple junctions in the receiver and source to each other (with the red constantan wire) and to the voltmeter with copper wires. (Note: constantan wire connects the lhs terminals, copper wire connects the rhs terminals.) Record the voltage (V_{start}) achieved when the source-water is ready.

Place the source on top of the receiver-sample. Begin recording the thermocouple voltage every minute. (The first one or two minutes may not be valid — the top of the glass needs to heat up to the source temperature before equilibrium is reached.) Continue data taking for about 30 minutes or until the thermocouple voltage is changing less than 10 μV/min.

Theory II

Frequently the data produced does not accurately follow the exponential relationship discussed above. What could be wrong? Assuming the procedure was properly followed, something must be wrong with the theory. Actually all sorts of things are not exactly taken into account in the above theory. For example, in Part I you showed that the thermocouple voltage is not exactly linearly related to the temperature difference. Similarly we assumed c, l, A, κ were all constant during the experiment; in fact they all change slightly with the temperature of the sample.

The "problem" with the data is (usually) that the measured thermocouple voltage does not seem to go all the way to zero as required by Eq. **??**, instead it looks more like:

$$V = V_\circ e^{-Bt} + V_\infty \tag{4}$$

i.e., for very long times the voltage approaches some constant V_∞. This suggests that the source and receiver never reach exactly the same temperature, which, in turn, could be the result of a heat "leak" from the receiver to the room, i.e., the receiver is not perfectly insulated.

If we include this heat loss in equation we find:

$$\frac{\kappa A\left(T_h - T\right)}{l} - K\left(T - T_\circ\right) = mc\,\frac{dT}{dt}$$

where K depends on the geometric and material factors of the heat leak. Subtracting and adding T_h we have:

$$\frac{\kappa A\left(\Delta T\right)}{l} - K\left(-\Delta T + T_h - T_\circ\right) = -\,mc\,\frac{d\Delta T}{dt}$$

Multiplying by C yields

$$-\left(\frac{\kappa A}{l} + K\right)V + KV_{\text{start}} = mc\,\frac{dV}{dt}$$

which has a solution of the form given in Eq. **??** where

$$\begin{aligned} V_\infty &= \frac{K}{\frac{\kappa A}{l} + K} V_{\text{start}} \\ B &= \frac{\kappa A}{lmc} + \frac{K}{mc} \\ V_\circ &= V_{\text{start}} - V_\infty \end{aligned}$$

which may be rearranged as

$$B = \frac{\kappa A}{lmc}\left(1 + \frac{V_\infty}{V_\circ}\right) \tag{5}$$

Analysis

PLOT thermocouple voltage vs. time using a log scale for the y-axis. Find the thermal conductivity by *FIT*ting to Eq. **??** or *SIDPLOT*ing to Eq. **??**, as appropriate. Report κ with an uncertainty.

Questions

1.) Find the value of C using the results of Part I. Use V_{start} to find the T_h.

2.) What would be the resistance of the thermistor at 10°C? at 10°K? Comment.

3.) Could the thermal conductivity of the sample be determined by filling the receiver pan with ice water instead of boiling water? Explain.

4.) Derive Equation **??**.

5.) The "R-value" of building insulation is l/κ in units of $\text{ft}^2 \cdot {}^\circ\text{F} \cdot \text{hr}/\text{Btu}$. Find the R-value of your sample.