

### Lab #3: Temperature and Thermal Equilibrium

#### Temperature and Temperature Scales

Temperature is one of the most familiar and fundamental thermodynamic quantities. We have an intuitive feel for temperature, e.g. hot versus cold objects. However, a precise measurements depends on the establishment of a relative temperature scale, based on the change in some physical property of a material as it is heated or cooled over some temperature range. Thus a *thermometer* may be based on a length of a metal rod, the height of a column of mercury, or the volume of a gas under pressure. In addition, the electrical current carried by certain materials can change with temperature, and thus it is possible to use electronic devices to measure temperature. The familiar Fahrenheit and Celsius scales are just two of many temperature scales set up by early investigators of heat and thermodynamics. Both of these scales were set up by taking two fixed points of reliable, easily reproducible temperatures. The Celsius scale was originally based on the freezing point and the boiling point of water, 0°C and 100°C, respectively. You will measure temperatures in terms of the Celsius scale.

#### Thermometers

In these exercises you will experiment with two types of thermometers, investigating how the temperature of a substance is affected when it interacts with an environment or another substance at a different temperature. You will use the familiar glass bulb thermometer and a *thermistor*. In a glass bulb thermometer, the liquid expands when heated and contracts when cooled, so the length of the column of liquid can be used to measure changes in temperature. A thermistor is a semiconductor device with a temperature-dependant electrical resistance over a limited temperature range. Two types of thermistor probes are provided to you. One can be plugged into an ohmmeter. The resistance measured by the ohmmeter can then be converted to a temperature using the conversion table provided with the probe. The other thermistor probe is plugged into the computer and uses *DataStudio* software to directly convert the measured resistance into a temperature. *Be careful with the tips of the probes – they are expensive and easily damaged.*

#### Thermal Equilibrium and Heat Transfer

When the temperature of a system remains constant, we refer to it as being in thermal equilibrium. Since we cannot see what really goes on when something changes temperature, we have to develop some new concepts to try to explain what is happening. One of these new concepts is that of *heat transfer*.

#### Activity 1: Measuring Temperatures and Temperature Changes

(a) You will first measure room temperature using the thermometers, which have been in the room long enough to come to thermal equilibrium.

Glass Bulb Room Temperature \_\_\_\_\_

(b) For the thermistor probe connected to the ohmmeter, turn on the ohmmeter and note the resistance registered. Use the conversion card to convert to a temperature, interpolating to the nearest tenth of a degree.

Thermistor (ohmmeter) Room Temperature \_\_\_\_\_

(c) Measure room temperature using the thermistor connected to the computer interface and the *DataStudio* software.

Thermistor (DataStudio) Room Temperature: \_\_\_\_\_

(d) How do the temperatures measured using the three different thermometers compare?

### **Activity 2: Predicting Relative Temperatures**

(a) Use your sense of touch to try to predict the relative temperatures of a piece of wood, a Styrofoam cup, and a metal can. Rank them highest to lowest in terms of relative temperature.

(b) Now measure the temperatures of the objects in part a using the thermistor probe connected to the ohmmeter.

Wood: \_\_\_\_\_

Styrofoam: \_\_\_\_\_

Metal: \_\_\_\_\_

(c) Did the measured temperatures of these objects agree with your predictions? Is your sense of touch an accurate predictor of relative temperatures?

(d) Can you explain why some objects feel cooler than others? Hint: Is the temperature of your hand different from the room temperature? If so, what is happening when you touch a room temperature object?

### Activity 3: Investigating Temperature Changes and Thermal Interactions

In this part, you will examine how the temperature of your thermometer changes when immersed and then removed from a canister of hot water. Hot water can be obtained from the steam generator canisters at your lab tables.

(a) Fill one of your Styrofoam cups with hot water using a baster. (*Please use caution and don't spill it on yourself.*)

Start acquiring data on a temperature versus time graph using *DataStudio*. Place the thermistor connected to the computer interface in the hot water. Watch the graph of temperature versus time. Does the temperature of the hot water immediately register? Draw a qualitative graph of the temperature versus time graph in the space below and write a sentence explaining how the temperature of the thermistor changes with time.

(b) Now remove the thermistor from the hot water. What happens to the thermistor's temperature? Draw a qualitative graph, predicting the approximate dependence of the temperature on time.

(c) We say that we measure the temperature of a substance using a thermometer. Of what are we *actually* measuring the temperature?

(d) The thermistor probe undergoes a *thermal interaction* when it is placed in the hot water, or removed from the hot water. We say that the temperature is caused by a *transfer of thermal energy or heat* from one body to another. To what is heat being transferred when you place the probe in the water? When you remove the probe from the water?

(e) The measurement of temperature therefore depends on allowing the probe to reach *thermal equilibrium* with the substance being measured. Another way to say this is that the probe and the substance reach an *equilibrium temperature*. Say you filled two containers, a thimble and a mug, with hot water from your canister and then inserted probes initially at room temperature in each. How would the equilibrium temperature of the water in the thimble compare to the equilibrium temperature of the water in the mug?

#### Activity 4: Measuring Cooling Curves

In Activity 3, you saw that the measurement of temperature by a thermometer depends on allowing enough time for the thermometer to reach thermal equilibrium with a substance. You will now investigate quantitatively how the temperature varies with time as a body cools.

(a) Fill one of your Styrofoam cups with room temperature water and the other half full with hot water from your steam generator. Measure the temperature of the room temperature water with the thermistor connected to the computer interface and record the result:

Temperature of room temperature water  $T_r \pm \Delta T_r =$  \_\_\_\_\_

(b) Place the thermistor probe in the hot water and allow it to come to thermal equilibrium with the water. Record the temperature of the hot water and the probe:

Temperature of hot water and probe  $T_0 \pm \Delta T_0 =$  \_\_\_\_\_

(c) Stop recording data with *DataStudio* and clear all data. Quickly move the thermistor from the hot water to the room temperature water and start collecting data with *DataStudio*. Stop recording data when the probe reaches approximately the original temperature of the room temperature water. Copy the data from the data table in *DataStudio* into an *Excel* spreadsheet and save the spreadsheet.

(d) Place the thermistor probe back in the hot water and allow it to come to thermal equilibrium with the water. Record the temperature of the hot water (and probe) below. Is it the same as it was earlier?

New temperature of hot water (and probe)  $\pm \Delta T =$  \_\_\_\_\_

(e) Stop recording data with *DataStudio* and clear all data. Remove the thermistor from the water, quickly and carefully dry the tip, and start collecting data. Stop recording data when the temperature of the probe is within a few degrees of room temperature. Copy the data from the data table in *DataStudio* into another *Excel* spreadsheet and save the spreadsheet.

### Activity 5: Applying Newton's Law of Cooling

Newton's Law of cooling states: "For a body cooling in a draft (i.e. by forced convection), the rate of heat loss is proportional to the difference in temperature between the body and its surroundings." That is

$$\frac{dT}{dt} = -k(T - T_r)$$

where,  $T$  is the temperature at time  $t$ ,  $T_r$  is the temperature of the surroundings, and  $k$  is the proportionality constant. This equation can be directly integrated, setting  $T(t = 0) = T_0$  to give

$$\int_{T_0}^T \frac{dT}{T - T_r} = -k dt \rightarrow T(t) = T_r + (T_0 - T_r)e^{-kt}.$$

Here,  $k$  will have units of inverse time. Thus we typically set  $k = \tau^{-1}$  and the temperature as a function of time becomes

$$T(t) = T_r + (T_0 - T_r)e^{-\frac{t}{\tau}}.$$

Also, you should note that  $T_0 - T_r$  is the total temperature drop in degrees to equilibrium temperature and  $T(t) - T_r$  is the temperature difference between  $T(t)$  and  $T_r$  at time  $t$ .

(a) In a time  $t = \tau$ , the exponential term has a value of 0.368. Thus in one time constant  $T(t) - T_r = 36.8\%$  of the original quantity ( $T_0 - T_r$ ). For  $2\tau$ , what percentage of the original temperature difference will the probe have?

(b) How many  $t$  would you have to wait until  $T(t) - T_r$  is 1% of ( $T_0 - T_r$ )?

(c) We can fit our cooling curve data from Activity 4 with the above equation and determine the time constants. Show that the above equation may be written in  $y = mx + b$  form by taking natural logarithms.

Using *Excel*, create a graph for each of your cooling curves. Do you see a linear relation between  $\ln(T - T_r)$  and  $t$  for all  $t$ ? If not, is there a region of the curve that is linear? Fit a line to the data using the linear regression tool. Report the results for the equations, time constants and uncertainties below.

(d) What is the initial temperature of the thermistor,  $T_0$ ? Include uncertainties. Compare this to the actual initial temperature recorded by *DataStudio*. Compute a percent difference if the two temperatures do not agree within the uncertainty.

Newton made use of this type of cooling curve to establish a temperature scale above 200°C. (Below 200°C, he made measurements of temperatures using glass bulb thermometers.) He applied the law by measuring the time required for an object to reach room temperature from some high, unknown temperature. By assuming that the cooling law held at the high temperature, he was able to deduce the initial temperature. He did not know that this approach is not applicable above about 200°C because it does not include all types of heat transfer mechanisms.

For your report, attach all graphs to this lab exercise packet. Also, ***write a one-page summary of your main results and findings.*** What do the results reveal about the differences in the way thermal energy is transferred during cooling of the probe in air and cooling of the probe in water?