CALORIMETRY AND THE ELECTRICAL EQUIVALENT OF HEAT

You will have read and understood Chapter 15 of Hecht, and formally answered Questions **Q3**, **Q4** and the theoretical part of **Q5**, **Q6** and **Q7** coming to the lab.

I. BACKGROUND

In this lab we will continue to learn the principles and practice of making physical measurements. The physical measurements to be made in this lab exercise have to do with heat and electricity, the two themes of Physics 1B. This experiment is one hands-on occasion for us to reflect on the notion of heat as a form of energy. Here we will demonstrate *quantitatively* that electricity, another form of energy, can be transformed into heat.

Electricity is routinely transformed into heat in electric heaters, ovens, toasters. Suppose we can somehow trap all the heat generated by an electric heater, and measure it, we can then compare this quantity of heat to the amount of electrical energy that has been converted to it. Conservation of energy says that the two quantities are equal. Are they?

We want to measure two quantities:
1. the electrical energy E_{elec} consumed by the heater;
2. the amount of heat Q generated by the heater;

and then compare them: is $E_{elec} = Q$?

Number 1 is easy. The electrical energy burned by a heater carrying a current I under an applied voltage V in a time t is simply:

$$E_{elec} = VIt \qquad (1)$$

All we have to do is measure the current, the voltage, and time how long we run the heater[1].

Number 2 is somewhat harder. We first have to trap the heat generated by the heater, then measure it. The device that allows us to do both is called a calorimeter. It is basically a container very well insulated thermally (so the heat generated inside cannot escape) with a thermometer inside (so the rise in temperature upon heating can be measured). We can convert this rise in temperature ΔT to the quantity of heat Q responsible for it if we know the **heat capacity** C of the calorimeter:

$$Q = C\,\Delta T \qquad (2)$$

[1] Equation (1) simply states that the total energy E_{elec} expended is the power P = VI consumed times the time t over which the power is on. [In other words, there are two ways to ensure your food is burned: one, crank up the oven (P); two, leave it in the oven longer (t).] That the electric power P is equal to the voltage V times the current I stems from the very definition of the voltage (also called the electric potential): V is the electric potential energy per unit charge. Multiply the energy per unit charge V by the amount of charge flowing in unit time, i.e. the current I, you get the total energy per unit time, i.e. the power P. More on electric potentials in Experiment # 2.

Calorimeters are used, for example, by the food industry to measure the "(kilo)calorie content" of various food items. The results of these measurements figure on the packages as a guide to consumers mindful of their diet.

II. EXPERIMENT

II.A. EQUIPMENT

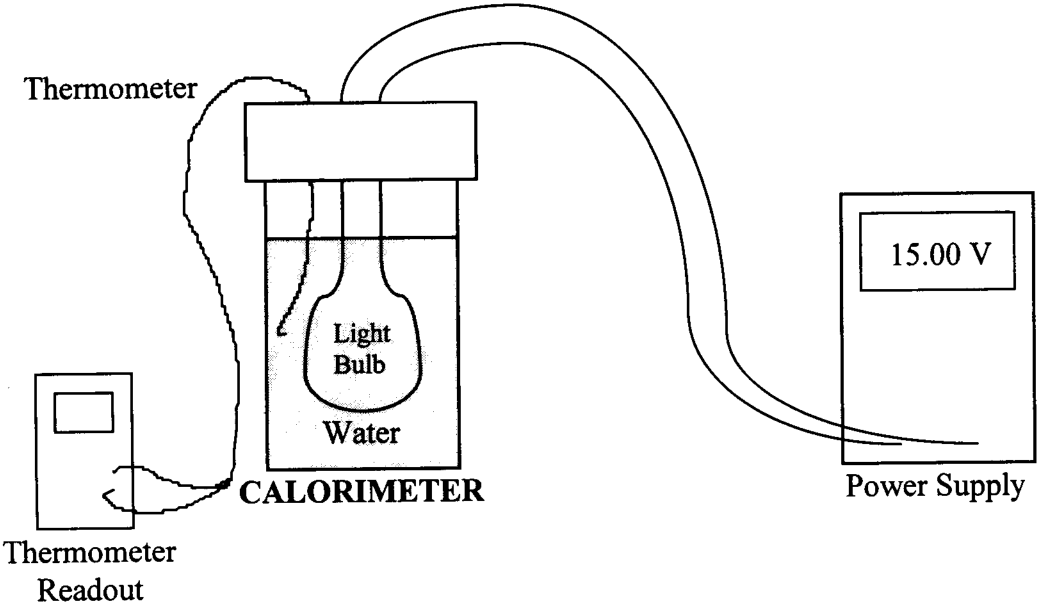

Figure 1. The Experimental Apparatus

The calorimeter consists of a lidded jar of water inside a Styrofoam cup. Styrofoam is a very good thermal insulator, McDonald's uses it to keep your burger hot. Water is a very good absorber of heat (but not of light), it is used here to absorb the heat generated by the heater[2].

The specific heat capacity of water is well known, it is

$$c = 1 \text{ cal/g.C}° = 4.186 \text{ J/g.C}°$$

The total heat capacity C of the calorimeter is then the heat capacity cM_w of the mass M_w of water in it, plus the heat capacity of the lidded jar and Styrofoam cup, which has been measured to be "equivalent to 35 g of water". That is,

$$C = c(M_w + 35 \text{ g}) \qquad (3)$$

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[2] The use of (liquid) water as heat absorber in calorimetry is a natural one, and dates back to the first calorimeter ever built, by Adam Crawford in 1778. Two years later no lesser characters than Lavoisier and Laplace collaborated to build a calorimeter to measure the rate of heat loss from live animals. They surrounded the animal chamber with ice and measured how fast the ice melted. Modern animal calorimeters have been flown on the Space Shuttle, and employed in the pharmaceutical industry to research physiological effects of drugs.

The heater is an incandescent light bulb. Light bulbs generate not only light, but also heat. (Try to change a light bulb that has been on for a while, you'll see.) In fact, one bonus piece of knowledge to be learned in this lab is the fact that light bulbs are more efficient heaters than sources of light.

II.B. PROCEDURES

1. Weigh the jar of the calorimeter before and after having filled it with tap water to the water line indicated. Deduce M_w, check that the value is consistent with the density of water.

2. Connect the power supply to the light bulb as shown in Fig. 1. The voltage (V) and current (I) furnished by the power supply can be read off the dual digital readout on its front panel, as shown in Fig. 1. Simply switch between voltage reading and current reading with the switch so labeled on the front panel.

3. Turn the power supply on and quickly adjust its voltage V to about 15 Volts. Leave the voltage alone for the rest of the experiment. Record both the starting temperature T_i and the time.
   *Hint: Do not exceed at any moment **16 Volts**. Do not fill the jar beyond the line indicated. Do not operate the light bulb out of the water, this would shorten the life of the bulb.*

   WARNING: ALWAYS KEEP YOUR HANDS DRY WHEN WORKING WITH ELECTRICITY.

4. Record the current I and voltage V. Keep an eye on these two quantities throughout the experiment. If they fluctuate, use an average value. Occasionally stir the water gently with the thermometer, to help spread the heat evenly out from the light bulb.

5. When the temperature of the water is about ten degrees C above T_i, turn the power supply off and record the end time.

6. Continue to stir the water gently with the thermometer. Watch the temperature peak then drop. Record the peak temperature T_f.

7. Pour out the warm water, refill the jar with tap water, to the same level marked. Add ten drops of India ink, and repeat the experiment (Steps 4 to 7).

8. Devise, describe and perform your own experiments to verify your theoretical answers to Questions **Q5**, **Q6** and **Q7**. You need to think carefully about what quantities you need to know, how to measure them, what precautions to take. Good luck.

III. QUESTIONS

Q1. Calculate from your data the electrical energy input E_{elec} and the quantity of heat Q generated, with and without the ink. Is energy balanced in either of the two cases? Explain exhaustively.

Q2. Calculate from your data the efficiency of the light bulb as a source of light: what percent of its total energy consumption ends up as visible radiation?

Q3. In spite of being more efficient as a heater than a light source, light bulbs are not ordinarily used as heaters. Why?

Q4. List all the reasons you can think of as to why a light bulb is used as heater in this experiment.

Q5. Had we, like Lavoisier and Laplace, surrounded our heater with ice instead of water, how much ice would have been melted in our experiment? Verify experimentally. Compare the results, theoretical and experimental, to those of Questions Q1 and Q2. Do these numbers reflect how pristine the ice is?
Hint: Do not pour ice onto a hot light bulb. A few ice cubes are all you need, do not pack the jar with ice.

WARNING: ALWAYS KEEP YOUR HANDS DRY WHEN WORKING WITH ELECTRICITY. WIPE YOUR HANDS DRY AFTER HANDLING THE ICE.

Q6. You have 100 g of water at 30 C°. How much tap water at temperature T_i would you have to pour in so that the mixture ends up at 27 C°? Verify experimentally.

Q7. You have 150 g of tap water at temperature T_i. You put in it one of the ice cubes available. What would the final temperature of the water be once the ice has all melted in it? Verify experimentally. At least how many of these ice cubes would you put in 150 g of tap water to ensure an ice-cold drink at 0 C°? Verify experimentally. (This does not mean drinking the water. Do *not* drink this water!)

Q8. Compare in your own words Fig. 1 with Fig. 15.3 of Hecht, Joule's apparatus for determining the mechanical equivalent of heat. How would *you* measure the mechanical equivalent of electricity? List all the forms of energy you can think of, and outline briefly how you would measure the equivalent between each pair.

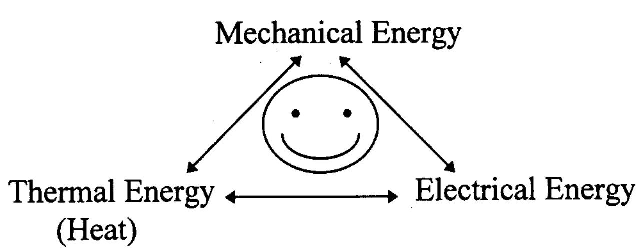

Figure 2. The Anti-Bermuda Triangle of Energy
(where nothing disappears into oblivion)