Experiment 3

Electrical Energy

3.1   Objectives

- Calculate the electrical power dissipated in a resistor.

- Determine the heat added to the water by an immersed heater.

- Determine if the energy dissipated by an immersion resistor is completely transferred to heat added to the water.

- Measure the resistance of an immersion heater.

3.2   Introduction

The Law of Conservation of Energy states that energy cannot be created or destroyed, but it can be converted. We convert electrical energy to other kinds of energy all the time; from using electric stoves to heat our food to the neurons in our brains using action potentials to activate neurotransmitters that control and regulate our bodies. Today we will essentially be modeling the electric tea kettle.

3.3 Key Concepts

As always, you can find a summary online at HyperPhysics[1]. Look for keywords: heat and thermodynamics (heat, specific heat), electricity and magnetism (electric power, power).

3.4 Theory

When a voltage is applied across a resistor, an electric current will flow through the resistor. As an electron travels along, it occasionally collides with the ions of the resistor and causes these ions to vibrate with greater amplitude than they had before the collision. In this way, the collisions increase the vibrational amplitude and thus the vibrational energy of the ions. This increase in vibrational energy corresponds to a change in thermal energy (heat). Electrical energy has been converted into heat. This is an example of the conversion of energy from one form to another.

The electrical **power** (P) dissipated by a resistor is given by

$$P = IV, \tag{3.1}$$

where P is the power in watts (W), V is the voltage in volts (V), and I is the current in amps (A). Using Ohm's law, $V = IR$, Eq. 3.1 can also be written in the forms of $P = I^2R$ or $P = V^2/R$. Which equation you use for power often depends on which quantities you are able to measure. From the power, we can calculate the **work** done by the resistor, which is given by

$$W = P\,\Delta t, \tag{3.2}$$

where W is the work in joules (J) and Δt is the amount of time in seconds (s) that the voltage is applied to the resistor.

Heat is a form of energy. Traditionally, heat is measured in units of calories (cal) instead of joules. One calorie is defined as the amount of heat necessary to raise the temperature of 1 gram of water by one degree Celsius (℃). The conversion factor between calories and joules is

$$1 \text{ cal} = 4.18 \text{ J.} \tag{3.3}$$

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[1]http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

Last updated February 1, 2013

When a resistor is immersed in a cup of water and a current is passed through it, the electrical energy dissipated by the resistor will be converted into heat, and the heat may be absorbed by the water, the cup, the resistor, etc. The amount of heat H added to an amount of water of mass m_w by changing its temperature by ΔT can be calculated by using the following equation:

$$H = m_\text{w}\, c_\text{w}\, \Delta T + S, \tag{3.4}$$

where c_w is the specific heat of water, $c_\text{w} = 1.0$ ᶜᵃˡ/g °C. Note that to get the heat energy H in joules to compare it to the work done by the resistor, **you'll need to convert it from calories to joules** using Eq. 3.3. In Eq. 3.4, $m_\text{w}\, c_\text{w}\, \Delta T$ is the heat absorbed by the water, while S represents the total heat absorbed by all other parts of the apparatus. The calorimeter is a very good insulator. Therefore, S will be very small compared to the heat gained by the water, so we will assume $S \approx 0$.

3.5 In today's lab

In this experiment you will calculate the electrical energy dissipated by a resistor immersed in water and measure the amount of heat added to the water. You will then determine if energy has been conserved.

We will use deionized water that has been refrigerated to cool it to below room temperature. We will not start to take data until the water is about 4 ℃ below room temperature. Then, we will continue to take data until the water has reached about 4 ℃ above room temperature. This is done because our calorimeter (a cup) is not in fact a perfect insulator, and heat from the surroundings (i.e. the room) introduces a systematic error in our measurement. Heat absorbed by the water from the room while the water is below room temperature will be offset by the heat lost to the room while the water is above room temperature. Using this method balances out the systematic error and allows us to measure only the heat transferred to the water by the resistor.

We assume that energy will be conserved. If this is true, then the energy that was produced by the resistor will all be absorbed by the water. By comparing the electrical energy produced (work done) by the resistor and the heat energy gained by the water, we can verify this.

Figure 3.1: The calorimeter is a small "thermos bottle" with a screw-top lid in which a resistor is soldered (circled).

3.6   Equipment

- Calorimeter – the insulated cup and lid is a very good insulator so it is assumed that no energy is transferred out of the container. It has a resistor in it that heats up. The calorimeter is shown in Fig 3.1

- digital multimeter, to measure voltage across the heating resistor

- thermometer (actually a multimeter set to read temperature), which is shown in Fig. 3.2

- power supply(which is different from the last lab) and shown in Fig. 3.3

Figure 3.2: A thermocouple is a device that will respond to tiny changes in temperature (circled). It's attached to the multimeter.

Figure 3.3: The power supply is a high-current device. We'll use the 6V and 5A maximum scales on the bottom of each of the windows. You connect to the resistor through the sockets on the top of the calorimeter and to the + and − "0 TO 6 V" connectors on the front (circled).

3.7   Procedure

Safety tips

- **Important!** When running electricity through the resistor, it will heat up, so keep it submerged in water so it does not overheat. You can desolder the resistor by running high current through it when it's "dry."

Taking Data

You'll use the spreadsheet for the Energy lab on your computer and fill in the various fields on the left. When filling in these fields make sure to choose reasonably sized uncertainties and add units to the table. Then as you heat the water slowly, record your readings on the right.

1. **Measure the resistance of the resistor** that is attached to the lid of the calorimeter, using the multimeter set to read Ω. See Fig. 3.4.

2. **We need to know the mass of the water in the cup.** To do this measure the mass of the cup before and after adding the water using the digital scale in the back of the room. We want to start our experiment with water about 4 °C colder than room temperature. To get this, you'll mix chilled water from the refrigerator with room temperature water from the container provided. Fill your calorimeter with enough water to **completely** cover the resistor coil when the lid is on.

3. **Measure room temperature.** Instead of a liquid thermometer as shown in Fig. 3.5, we'll use a thermocouple[2] connected to a multimeter to measure temperatures. Find the yellow icon of a thermometer on one of the settings of the multimeter that the probe is plugged into. Set the dial to point to that icon and press the yellow button (to the right of the RANGE button) to start reading in degrees Celsius, see Fig. 3.4. The probe takes some time to get to room temperature, so don't play with it too much before taking a room temperature

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[2]A thermocouple works via the thermoelectric effect. It has two dissimilar metals fused together and the temperature is then determined by measuring a temperature dependent voltage across this junction.
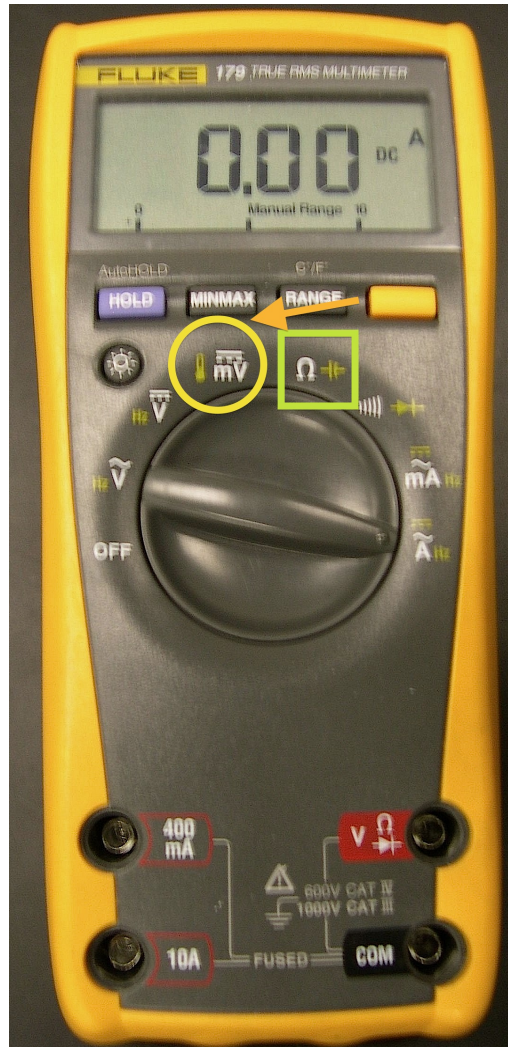
Last updated February 1, 2013

Figure 3.4: Digital multimeter with the green rectangle showing the setting for measuring resistance in ohms and the yellow circle showing the setting for measuring temperature in degrees Celsius. Notice that the latter setting will require the yellow button to be pushed (to the right of the RANGE button.)
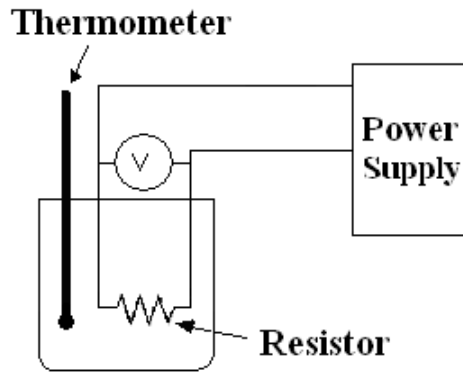
Figure 3.5: Schematic of experimental setup.
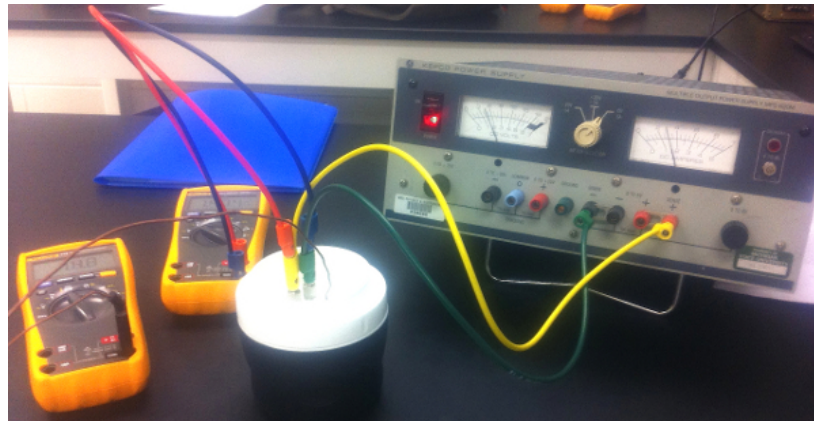
Figure 3.6: Picture of working setup.

reading. (To be sure that it's settled and makes sense, you can switch to Fahrenheit using the range setting. The room temperature should be around 70°F, but make sure to do your measurements in Celsius.)

4. **Connect the circuit as in Fig. 3.5.** One multimeter is now acting as the thermometer and another is acting as a voltmeter. See Fig. 3.6 for a picture of a working setup.

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5. **Once the resistor is covered with water and the lid is on the calorimeter, turn on the power supply and get ready to take data.** You'll record the temperature of the water every 30 seconds, so get ready to watch the clock or use a stopwatch (there are many stopwatches on the internet if you want to use one of those). Turn the current knob (which is just a limit knob) all the way up and adjust the voltage until you have a current of approximately 3 A. Read and record the current from the power supply meter, and measure the voltage with the digital multimeter at the output of the power supply (V_{PS}) and at the calorimeter (V_{cal}).[3] Use the voltage at the calorimeter V_{cal} for your calculations.

6. **Collect data.** With the power supply on, wait to take data until the temperature of the water is between 3.0 and 4.0 ℃ less than room temperature. Record your starting temperature at time $t = 0$ on your spreadsheet. **One member of the team must continuously and gently shake the cup to dissipate the heat uniformly in the water.** If this isn't done the thermometer will not be reading the average temperature in the calorimeter. Continue collecting data until you reach as far above room temperature as you started below. For example, if you started collecting data at 3.5 ℃ below room temperature then continue taking data until you reach 3.5 ℃ above room temperature.

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[3]We are asking you to measure voltage at two points that are connected by a wire, so they should be the same voltage according to what we know about ideal wires. You may find that they are different, see Question 4.

3.8 Questions

1. Calculate the temperature change (ΔT) and the time span (Δt) from start to stop. Also, calculate their uncertainties. For uncertainties, $\delta(\Delta T) = 2\,\delta T$ and $\delta(\Delta t) = 2\,\delta t$.

2. Calculate the power dissipated in the resistor, using V_{cal} and its associated error, in two ways: a) $P = IV$ with $\delta P = P\,(\delta V/V + \delta I/I)$ and b) $P = V^2/R$ with $\delta P = P\,(2\,\delta V/V + \delta R/R)$.

3. Which equation gives a more precise value for power? Justify your response. (Hint: Think about what variables were used in each equation and the size of their uncertainties.)

4. Were V_{cal} and V_{PS} different? Why? (Hint: What assumptions do we make about the effect of the wires on the circuit?) Why should you use V_{cal}?

5. Determine the work done by the resistor (in joules) and its associated error using $W = P \Delta t$ and $\delta W = W(\delta P/P + \delta(\Delta t)/\Delta t)$. Use the more precise power value when doing this calculation.

6. Which uncertainty is more important, the uncertainty in time or in power? Justify your answer.

7. Was the power constant? Justify your answer. To help answer this question construct a temperature (ΔT) versus time (Δt) graph from your data and use the fact that the slope is related to the power. (Hints regarding your plot: remember that the equation of a straight line is $y = mx + b$. To write your results in the straight line equation form you need to figure out what x, y, m (the slope) and b (the y-intercept) are. That is, write the equation of ΔT versus Δt in the "$y = mx + b$" form for your plot, with all of the right symbols, by combining the equations for work and heat from the theory section and rearranging the variables. It should include: $\Delta T, \Delta t, P, m_w$, and c_w. Notice which variables are equal to the slope. Do you have to worry about the y-intercept?)

8. Calculate the heat added to the water using Eq. 3.4 and its associated uncertainty. The specific heat of water $c_\mathrm{w} = 1.0$ cal/g°C and the uncertainty is $\delta H = H(\delta m/m + \delta(\Delta T)/\Delta T)$.

9. Compare the work done by the resistor and the heat added to the water. Is energy conserved? (You should take into account the uncertainties.) Was the heat energy found in the water less or more than the electrical energy? (Was energy lost or gained?) Discuss possible sources of apparent energy loss or gain in this experiment and its analysis.