Joule Equivalent of Electrical Energy

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Objectives

The objectives of this experiment are: (1) to understand the equivalence of electrical energy and heat energy, (2) to learn techniques of calorimetry, (3) to learn how to measure electrical energy, and (4) to measure the Joule equivalent of electrical energy.

Theory

The theory for electrical energy and power was developed using the principles of mechanical energy, and the units of energy are the same for both electrical and mechanical energy. However, heat energy is typically measured in quantities that are separately defined from the laws of mechanics and electricity and magnetism. Sir James Joule first studied the equivalence of these two forms of energy and found that there was a constant of proportionality between them and this constant is therefore referred to as the Joule equivalent of heat and given the symbol J. The Joule equivalent of heat is the amount of mechanical or electrical energy contained in a unit of heat energy. The factor is to be determined in this experiment.

Power is defined as the rate of doing work, and electrical power is defined as the amount of electrical energy being expended per unit time. The work ΔW (mechanical energy) required to move an electrical charge ΔQ through a potential difference V is given by

$$\Delta W = \Delta Q \times V \tag{1}$$

and power is P is given by

$$P = \frac{\Delta W}{\Delta t} = V \times \frac{\Delta Q}{\Delta t} \tag{2}$$

so that

$$P = V \times I\ . \tag{3}$$

In an electrical circuit the energy ΔW expended in a increment of time, Δt, in a resistance is given by

$$\Delta W = P \times \Delta t \tag{4}$$

which can be written as

$$\Delta W = V \times I \times \Delta t \tag{5}$$

when Equation (3) is substituted for P.

Electrical and mechanical energy is measured in units of joules in the SI system of units, but heat energy is measured in units of kilocalories.

The change in heat energy of a material, ΔQ, is directly proportional to the change in temperature of the material and depends on the type of material and its mass. The change is heat energy, ΔQ, for a given change of temperature, ΔT, is given by

$$\Delta Q = mc\Delta T \tag{6}$$

where m is the mass of the material and c the specific heat of the material. If electrical energy is transformed into heat energy then the equivalence of the electrical energy and heat energy is given by

$$\Delta W = J \times \Delta Q \tag{7}$$

where J is the Joule equivalent of heat or the mechanical energy equivalent of heat energy. In SI units, $J = 4186\ \text{Joules/kilocalorie}$.

In this experiment a constant current I will be used to flow through a resistive heating element and a constant potential drop V across the element will be maintained. The electrical energy expended in the heating element will be transformed into heat energy that is will increase the temperature of a quantity of water and the container in which it is kept. The change in heat energy of the container and water will be the sum of the heat energies of each and will be given by

$$\Delta Q = m_c c_c \Delta T + m_w c_w \Delta T \tag{8}$$

where m_c and m_w are the masses of the container and water respectively, and c_c and c_w are the specific heats of the material of the container and water. The values for c_c and c_w are given in Table 1. Combining Equations (5) and (8) into Equation (7)

$$VI \times \Delta t = J\left(m_c c_c \Delta T + m_w c_w \Delta T\right). \tag{9}$$

Then solving for J

$$J = \frac{VI}{\left(m_c c_c + m_w c_w\right)} \frac{1}{\frac{\Delta T}{\Delta t}}. \tag{10}$$

Equation (10) is written in that way with $\frac{\Delta T}{\Delta t}$ in the denominator because in this experiment temperature will be measured as a function of time. Temperature should be a linear function of time if constant power is applied to the heating coil and $\frac{\Delta T}{\Delta t}$ should be a constant and be equal to the slope of the linear fit to the data.

Table 1.

Specific Heat Values for Water and Aluminum	
Water	c_w = 1.0 kcal/kg/ºC
Aluminum	c_c = 0.21 kcal/kg/ºC

Apparatus

The apparatus is shown in Figures 1 and 2 and consists of (1) an assembly with resistive heating coil, stirrer, and electrical connector posts, (2) a double-wall aluminum calorimeter, (3)a low voltage, high current power supply with a digital voltmeter and ammeter, (4) electrical leads, (5) a digital multimeter, and (6) a Pasco 750 Science Workshop data acquisition system with temperature sensor.

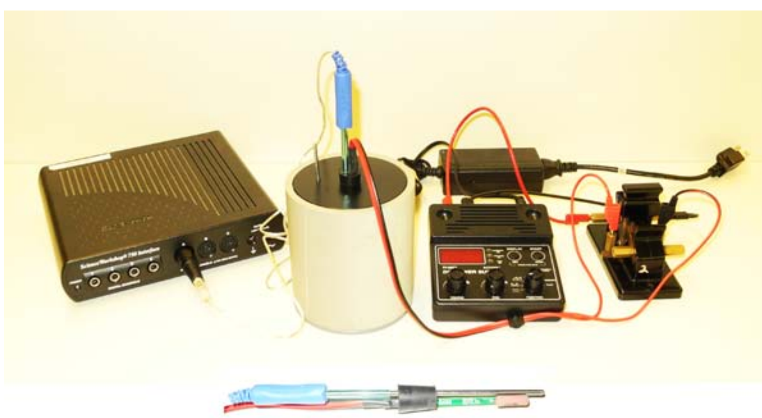
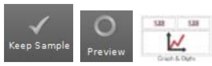
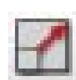


Figure 1. Apparatus and setup for performing the Joule equivalent of electrical energy experiment..

Procedure

1. 

1. Turn on the Science Workshop 750 Interface.
2. Open the Pasco Capstone data acquisition program.
3. Open the hardware setup tab on the left side of the window and add Temperature Sensor, Stainless Steel to the 750 Interface. It is under Analog Sensors.
4. Then, add a graph and a table to the page.
5. Use time (seconds) for the first column of the table and the x axis of the graph. Use temperature (Celsius) for the second column and the y axis.
6. <u>At the bottom of the window, set the program to take a reading every two seconds</u>.
7. Set up the rest of the experimental devices, including the calorimeter and the power supply and circuit.
8. Record the mass of the calorimeter before adding water and again after the water is added.
9. Adjust the current to be close to 1 amp but not over with the knife switch closed, then open the switch to cancel the flow of current before your measurements have started. . Record the voltage and resistor value on your data sheet.
10. You will want to record temperature data until 620 seconds have passed. You can set a stop point by clicking on the “Recording Conditions” button.
11. When you are ready to begin, place the probe and heater in the water, making sure that the switch on the circuit is in the off position.
12. Hit the record button and flip the switch at the same time.
13. Stir continually. To make the graph to automatically scale to fit the data that has been recorded, click on the Scale to Fit  icon at the far left on the graph’s toolbar.
14. Capstone will automatically stop recording data at 620 seconds. You should then use the button on the graph toolbar to select ranges of data for analysis to highlight everything in between 10 and 610 seconds. This will eliminate any outliers from the beginning and the end. Then, run a linear regression on this data by clicking the appropriate button on the graph toolbar and choosing “Linear: y = mx + b”.

15. Calculations for the Joule equivalent of heat and the percent error of your calculation can either be done by hand or in Excel.

Questions

1. A styrofoam coffee cup is so light and it is such a good insulator, that its mass and heat capacity may often be neglected in measurements like this one, thus making the analysis much simplier. If 150 grams of water at room temperature, 20°C is placed in a Styrofoam cup, how long will it take to raise the temperature of the water to 30°C? Assume the the power supply supplies a current of 2 amperes at a voltage of 10 volts.

2. In question 1 above, if the water is replaced by 150 grams of ethylene glycol whose specific heat is 0.57 kcal/kg/ºC, what will the time be?

Data Sheet

Data Set #1

Mass of Container and Water	m_{cw}=
Mass of Container	m_c=
Mass of Water	m_w=
Specific Heat of Water	c_w= 1.0 kcal/kg/ºC
Specific Heat of Aluminum	c_c= 0.21 kcal/kg/ºC
Voltage Drop Across Heater Coil	V=
Current Flowing in Heater Coil	I=
Slope of temperature versus time	$\frac{\Delta T}{\Delta t}$ =
Joule Equivalent of Heat	J=
% Error	

Data Set #2

Mass of Container and Water	m_{cw}=
Mass of Container	m_c=
Mass of Water	m_w=
Specific Heat of Water	c_w= 1 kcal/kg/ºC
Specific Heat of Aluminum	c_c= 0.21 kcal/kg/ºC
Voltage Drop Across Heater Coil	V=
Current Flowing in Heater Coil	I=
Slope of temperature versus time	$\frac{\Delta T}{\Delta t}$ =
Joule Equivalent of Heat	J=
% Error	