CENCO Physics

Selective Experiments In Physics

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MECHANICAL EQUIVALENT OF HEAT – ELECTRICAL METHOD

OBJECT: To determine the mechanical equivalent of heat by measuring the heat generated in an electrical resistance.

METHOD: An electric heater is immersed in a calorimeter cup filled with water. From the resistance of the heater, the potential (commonly called "voltage") applied to it and the length of time the heater is connected to the electric source, the electric energy (in joules) delivered to the heater is determined. From the rise in temperature and the thermal capacity of the cup and its contents, the heat energy (in calories) delivered by the heater is computed. The ratio of the energy delivered to heat generated is the mechanical equivalent of heat. A correction is made for the heat lost to the surroundings.

THEORY: One of the outstanding achievements of the 19th Century physics was the development of the *principle of the conservation of energy*. A necessary corollary to this principle is the *first law of thermodynamics*. This law states that when work is done in overcoming frictional resistance the quantity of heat H generated is proportional to the work $W; W \propto H$ or

$$W = JH \tag{1}$$

The constant of proportionality J is called the *mechanical equivalent of heat* and its value depends upon the units in which W and H are expressed.

Heat is one form of energy. When work is done in overcoming frictional or electrical resistance, the energy is sometimes said to be "lost." Actually it is not lost but is transformed into heat energy. Since heat is a form of energy, a quantity of heat might be measured in mechanical energy units-ergs, joules or foot-pounds. Usually, however, it is measured in heat units-calories or British thermal units (Btu). The mechanical equivalent of heat, the constant J which expresses the relation between the units of energy in these two systems (mechanical and thermal), is one of the important physical constants. It was first determined by Joule in a series of experiments beginning in 1843 and is sometimes called "Joule's equivalent." Precise experiments by many research workers since that time have served to increase the accuracy with which it is known.

The power P delivered by an electric circuit to any device is equal to the product of the current I and the applied potential E. Algebraically

$$P = EI \tag{2}$$

Since the energy W which is delivered to the device in time T is equal to PT it follows that

$$W = EIT \tag{3}$$

According to Ohm's law the current flowing in a circuit is proportional to the applied potential and the constant ratio E/I is called the resistance R of the circuit. The algebraic statement of Ohm's law is

$$R = E/I \tag{4}$$

If a voltmeter V, an ammeter A and a resistance R are connected to an electric line in the manner shown in Fig. 1,

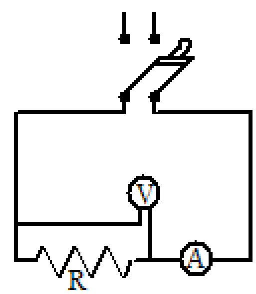

Fig. 1. Using Ohm's law to measure resistance.

the ratio of the voltmeter reading E to the ammeter reading I is the resistance R.

Substituting E/R for I in Eq. (3) yields

$$W = \frac{E^2}{R} T \tag{5}$$

Since in this experiment R is known (or measurable), E is read from a voltmeter and T is measured with a stopwatch, Eq. (5) may be used to compute the energy delivered to the system.

The above equations are valid in any system of units. In the practical system (the one used in this experiment) *E, I, R, P, W* and *T* are measured in volts, amperes, ohms, watts, joules and seconds, respectively.

The quantity of heat generated is determined from the rise in temperature and the thermal capacity of the calorimeter cup and its contents. It follows directly from the definition of specific heat c that the amount of heat H required to raise the temperature of a body (mass m) from t_o to t_F is given by the equation

$$H = mc(t_F - t_o) \tag{6}$$

The product mc is called the thermal capacity C of the body.

Since, in the metric system, c is expressed in calories per gram per degree centigrade, thermal capacity is expressed in calories per degree. The thermal capacity of a body is numerically equal to the quantity of heat required to raise the temperature of the body one-degree. Obviously, m grams of any material having specific heat c are thermally equivalent to mc grams of water. For this reason mc is often called the "water equivalent" of the body. When a body is composed of several kinds of materials, H is most easily determined by adding the thermal capacities of the individual parts and: multiplying the sum by the change in temperature, or

$$H = C(t_F - t_o) \tag{7}$$

where C is the combined thermal capacity of all parts of the system which is raised in temperature from t_o to t_F.

In this experiment part of the heat generated is used to raise the temperature of the cup and its contents, and part of the heat is radiated to the surroundings. It is necessary, therefore, to determine what the change in temperature would have been had no heat been radiated. Suppose heat is added at a uniform rate to a body which is originally at the temperature to of the surroundings. The temperature of the body is read at regular intervals and the temperature t plotted against the time T as indicated in Fig. 2. It is evident

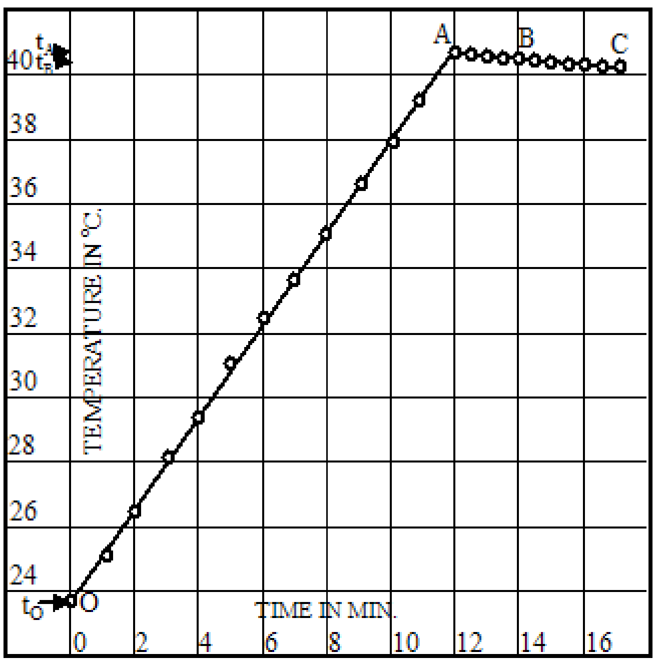

Fig. 2. Body is heated and then cools by radiation to the surroundings.

that heat was being added to the body during the interval OA and in the interval AC the body was cooling owing to radiation to the surroundings. Of course heat was also being radiated during the interval OA and it is for this loss that correction must be made.

There are several methods of correcting for the heat lost by a body to its surroundings, and the choice of method depends upon the conditions of the experiment. For the case where the temperature rises at a uniform rate, particularly if a vacuum jacketed calorimeter is used, the method outlined below is recommended. To study the cooling of the body it is advisable to construct the portion ABC of the curve on a much larger scale as indicated in Fig. 3. Newton's law of cooling states that, provided the difference in temperature is not large, the rate of cooling of a body is proportional to the difference in temperature between the body and its surroundings.

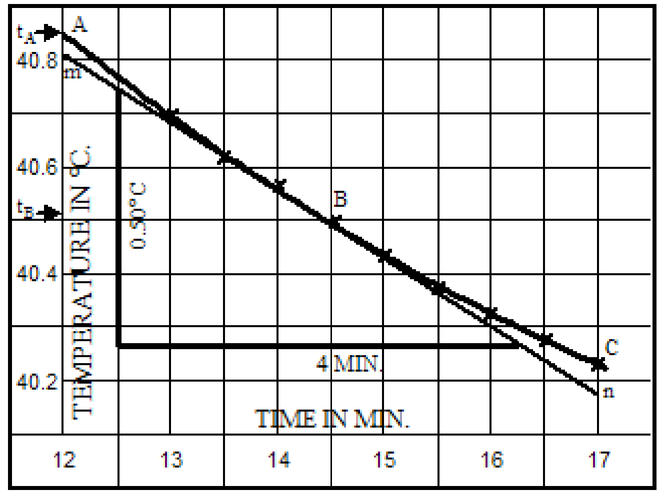

Fig. 3. The rate of cooling is determined from the slope of the curve.

The rate of cooling r_B at the temperature t_B is found from the slope of the tangent (mn) drawn to the curve at the point B. The point B is any convenient point near the middle of the section ABC of the curve. It follows from Newton's law that the graph obtained by plotting rate of cooling against temperature (Fig: 4) is a straight line and that the rate of cooling r_A at temperature t_A may be obtained by proportion. Since, while the temperature was rising, the rate of cooling increased uniformly from zero to r_A, the average rate of cooling $\bar{r}$ during the interval OA is $\frac{1}{2}r_A$. From this it follows that

$$\bar{r} = \frac{1}{2} r_B \frac{t_A - t_o}{t_B - t_o} \tag{8}$$

and that if no heat had been radiated during the experiment the temperature rise (t_F - t_o) would have been

$$t_F - t_o = (t_A - t_o) + \bar{r}(T_A - T_o) \tag{9}$$

where (T_A - T_o) is the time interval between O and A.

Referring to Fig. 3 it is seen that, neglecting the slight rounding of the curve at A, due to a small lag in the thermometer reading, the temperature t_A is 40.85°C. It is also seen that, for the experimental results plotted here, the rate of cooling r_B is 0.50°C + 4 min or 0.125°C/min. Since t_o = 23.77°C, t_A= 40.85°C and t_B = 40.50°C, Eq. (8) yields

$$\bar{r} = \frac{1}{2} \times 0.125°C/\min \times \frac{17.08°C}{16.73°C} = 0.0638°C/\min \tag{10}$$

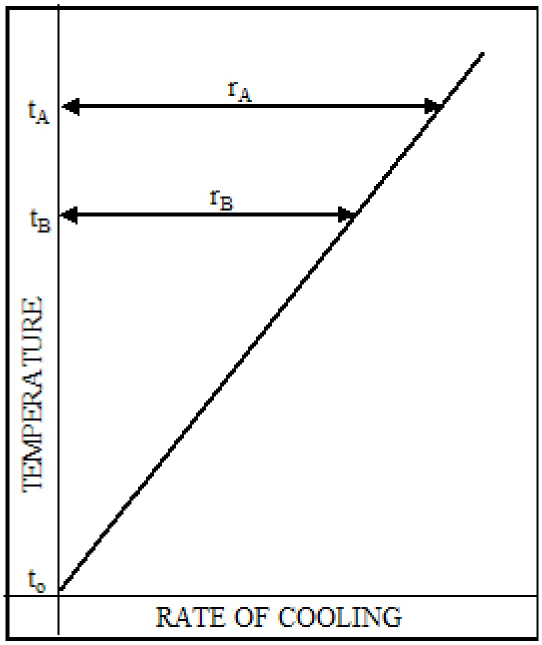

Fig. 4. The rate of cooling is proportional to the difference in temperature between the body and its surroundings.

Fig. 5. The Electric Heater

Since, as is shown in Fig. 2, T_A - T_o = 12 min, Eq. (9) gives

$$t_F - t_o = (40.85°C - 23.77°C) + 0.0638°C/\min \times 12\min = 17.08°C + 0.77°C = 17.85°C \quad (11)$$

In other words, whereas the rise in temperature was 17.08°C, if no heat had been lost to the surroundings, the rise in temperature would have been 17.85°C.

APPARATUS: A vacuum jacketed calorimeter, stirrer, electric heater, voltmeter, two centigrade thermometers graduated in one tenth degree divisions, Bunsen burner, ring stand and watch are required. An ammeter and some form of Wheatstone bridge are optional. Unless a 50-60volt electric outlet is available, a rheostat is also required. The electric heater is shown in Fig. 5. The heater is equipped with a pair of heavy leads for connecting to the power supply and a pair of lighter leads for connecting to the voltmeter. **Caution**: *Never close the switch connecting the heater to the power supply unless the metal part on the lower end of the heater is completely immersed in water or some other liquid*. To do so will ruin the heater.
The vacuum-jacketed calorimeter is shown in Fig. 6. The details of the calorimeter and the arrangement of the apparatus are shown in Fig. 7. The aluminum cup C is

Fig. 6. The Vacuum Jacketed Calorimeter

suspended inside the vacuum flask F from an insulating ring R. The cover L is lined with a thick layer of cork insulation. The cork stopper K has been bored and split to receive the heater H and holds it firmly in position. The heavy leads are connected to the power supply through the switch S and the light leads connect to the voltmeter V. To minimize heat conduction, the handle of the stirrer A and the stem of the heater H are made of glass. Temperatures are read by means of the precision thermometer T.

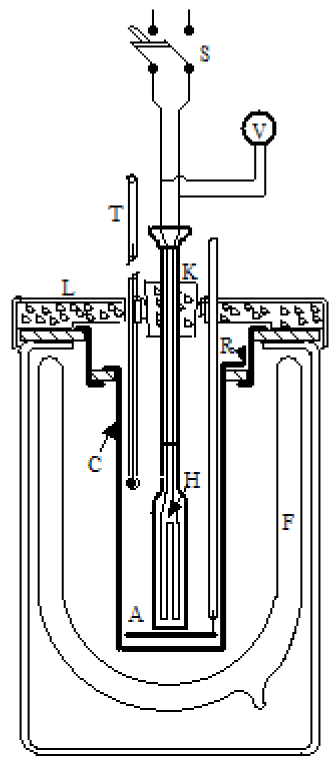

Fig. 7. Arrangement of the apparatus.

PROCEDURE: First determine the combined thermal capacity of the calorimeter cup, heater, stirrer and thermometer, using the following method. Weigh the calorimeter cup, fill it to a depth of about 3cm with water at room temperature and weigh again. Place the heater, stirrer and thermometer in the cup. Note the thermometer reading and make sure that the reading is constant. Place a quantity of water (roughly equal in volume to the water in the calorimeter cup) in the beaker, heat to about 50°C and weigh. Note the temperature of the hot water and immediately pour the water into the calorimeter cup. The stems of the thermometer, heater and stirrer (up to the level of the top of the cup) should be brought to the temperature of the mixture. Having brought the stems to the final temperature by tilting the calorimeter cup, note the final temperature of the mixture. Weigh the empty beaker and determine the mass of hot water added. Using Eq. (7) and the law of mixtures, which says that the heat gained by the cup and its original contents is equal to the heat lost by the hot water, determine the combined thermal capacity of the cup, heater, stirrer and thermometer. Since this thermal capacity is small compared to the thermal capacity of the cup full of water, the thermal capacity need not be determined to a high degree of accuracy, and it is not necessary, therefore, to consider the heat lost by radiation in this part of the experiment.

Fill the cup almost full of water at room temperature and weigh. Assemble the apparatus as shown in Fig. 7. The heater is built to be used on a 115volt line. If, however, the full 115volts is used, the temperature rise is too rapid for accurate measurement. Satisfactory results may be obtained with 50 or 60volts. If a 50-60volt outlet is not available, a rheostat should be placed in series with the heater and so adjusted that the voltmeter indicates that the desired potential is being applied. Although the heater may be used with either direct or alternating current, direct current is recommended. This recommendation is based on the fact that direct current meters are more accurate. The switch S must not be closed except when the heater is immersed in water and until the electrical connections have been checked by the instructor. Read the temperature of the water to hundredths of a degree and, when the watch reads on the minute, close the switch. After the temperature has risen about 15°C, open the switch. The switch should likewise be opened when the watch reads on the minute. While the heater is turned on, both the thermometer and the voltmeter should be read every minute. After the heater is turned off, the thermometer readings should be continued, at half-minute intervals, for at least 5 min. While the water is being heated the thermometer should be read to tenths of a degree only, but while cooling the thermometer should be read to hundredths of a degree. The water should be stirred throughout the experiment, but care should be taken that no water is splashed from the cup.

Construct curves similar to the ones shown in Figs. 2 and 3. Use the second curve and Eq. (9) to compute the rise in temperature (t_F - t_o).

The resistance of the heater may be obtained in any one of the following ways: (a) The heater, the voltmeter and an ammeter may be connected to an electric line as shown in Fig. 1, the voltmeter reading E and ammeter reading I observed, and these readings used in Eq. (4) to compute R; (b) The resistance may be measured with some form of Wheatstone bridge; (c) If time is limited the instructor may supply the value. Ask the instructor which procedure is to be followed. Since the resistance varies somewhat with temperature, the resistance should be determined at the average temperature $\frac{1}{2}(t_o + t_A)$.

Use Eq. (7) to determine H, Eq. (5) to determine W and Eq. (1) to determine J. In Eq. (5) E is the average of the several voltmeter readings and T is the time the heater is turned on. Determine the percentage difference between the value of J determined in this experiment and the standard value.

QUESTIONS: 1. What percentage error in the determination of J would be caused by each of the following: (a) an error of 5% in the combined thermal capacity of the cup, stirrer, heater and thermometer? (b) an error of 1gm in the mass of water? (c) an error of 10% in the: value of r_B? (d) an error of 1/2% in the value of E? (e) an error of 0.1˚C in t_A?

2. In this experiment does the temperature of the surroundings remain constant? Explain.

3. The curve ABC (Fig. 3) is slightly concave upward. Explain why.

4. Suppose the glass wall of the thermometer bulb were quite thick. How would this affect the curve shown in Fig. 2?

5. How fast must a bullet travel if its temperature is raised t˚C when it is stopped? Call the specific heat of the bullet c and assume that three fourths of the heat generated is in the bullet.

6. How much is the temperature of the water raised as it passes over Niagara Falls, 167ft high? Assume that all of the heat generated remains in the water.