CENCO Physics
Selective Experiments In Physics

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SPECIFIC HEAT OF LIQUIDS – RADIATION METHOD

OBJECT: To determine the specific heat of a liquid by comparing its rate of cooling with the rate of cooling of water.

METHOD: A polished metal cup is filled with the liquid whose specific heat is to be determined and a similar cup is filled with water. After being heated, these liquids are allowed to cool and a cooling curve is plotted for each. The length of time required for each liquid to fall through the same temperature range is determined from the curves and these times are used to determine the specific heat of the liquid.

THEORY: In order to raise the temperature of a body, heat must be added to it and the quantity of heat *H* required is proportional to the mass *m* of the body and to the rise in temperature ΔT. Or, stated algebraically

$$H = c \cdot m \cdot \Delta T \tag{1}$$

where the constant of proportionality *c* is called the specific heat of the material. Eq. (1) may be thought of as the defining equation of specific heat. In the metric system *c* is expressed in calories per gram per degree centigrade (cal/gm˚C) and is *numerically* equal to the number of calories of heat required to raise the temperature of one gram of the material one degree centigrade. The product $c \cdot m$ is called the thermal capacity *C* of the body. Obviously *C* is expressed in calories per degree centigrade (cal/˚C) and is numerically equal to the quantity of heat required to raise the temperature of the body one-degree. Since *m* grams of any substance are thermally equivalent to $c \cdot m$ (or C) grams of water, the thermal capacity of a body is sometimes called the "water equivalent" of the body. When a body is composed of several kinds of materials, the quantity of heat required to produce a certain temperature change is most easily determined by adding the thermal capacities of the individual parts and multiplying the sum by the change in temperature.

Any body not at absolute zero of temperature radiates energy. The rate R_1 at which a body radiates energy depends upon the temperature of the body as well as the nature and area of the radiating surface. It may be shown that the heat energy radiated per second per unit area of surface is proportional to the fourth power of the absolute temperature; or

$$R_1 = kAT_1^4 \tag{2}$$

where T_1 is the temperature of the body measured in degrees absolute, *A* is the area of the radiating surface, and *k* is a constant which depends upon the character of the surface. The law stated algebraically in Eq. (2) was first proposed by Stefan in 1879 on the basis of the meager data then available and was later derived from theoretical considerations by Boltzmann. It is known as the Stefan-Boltzmann law. The value of *k* in Eq. (2) depends upon the units in which R_1 and *A* are expressed. In the discussion that follows it is assumed that R_1 is expressed in calories per second and *A* in square centimeters.

If the body is completely surrounded by walls and other

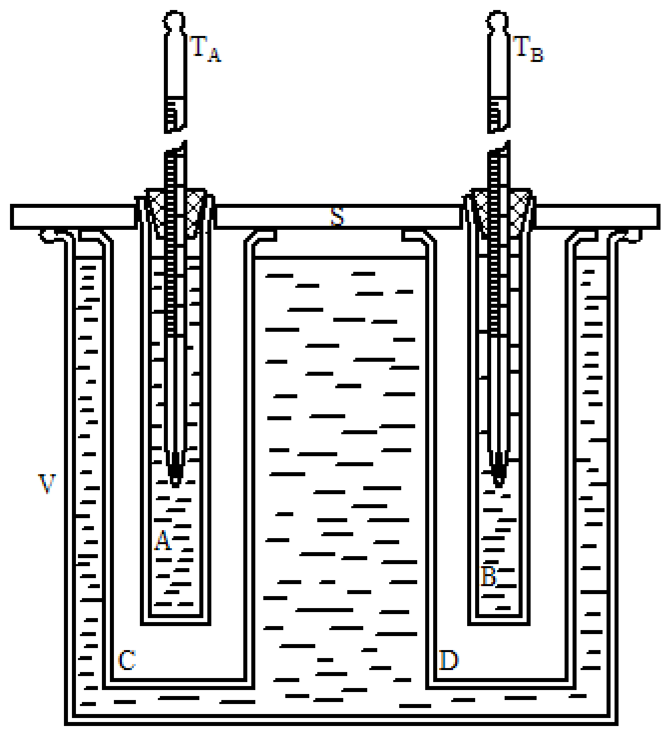

Fig. 1. Radiation method of comparing thermal capacities.

bodies at a temperature T_o, the rate R_o at which it absorbs energy from the surroundings is given by the equation

$$R_o = kAT_o^4 \tag{3}$$

and the net rate *R* of loss of heat by radiation is given by

$$R = R_1 - R_o = kA\left(T_1^4 - T_o^4\right) \tag{4}$$

Factoring Eq. (4) yields

$$R = kA\left(T_1^2 + T_o^2\right)\left(T_1 + T_o\right)\left(T_1 - T_o\right) \tag{5}$$

and if T_1 is only slightly larger than T_o Eq. (5) leads to the approximate relationship

$$R = 4kAT_0^3\left(T_1 - T_o\right) = K\left(T_1 - T_o\right) \tag{6}$$

where $K = 4kAT_o^3$. Since k and A are constants, Eq. (6) shows that, if T_o remains constant, R is proportional to (T_1 - T_o). Since under ordinary circumstances the rate at which a body radiates heat is proportional to the rate at which the temperature decreases (rate of cooling), Eq. (6) indicates that the rate of cooling of a body is proportional to the difference in temperature between the body and its surroundings. This law is known as Newton's law of cooling. Although this law is only an approximation to the truth and is not applicable when the temperature difference is large, it is sufficiently accurate in many practical situations and is widely used.

In the discussion above only the heat lost by radiation was considered. Usually, in practice, heat is lost by convection and by conduction as well as by radiation. Experiment has shown, however, that when the temperature difference is small the net rate R' at which heat is lost by all three methods is proportional to the difference in temperature between a body and its surroundings. Assume that two vessels A and B having the same size, shape, and surface characteristics are surrounded by a water jacket as shown in Fig.1 and that the temperature of this water jacket does not vary. When A and B are at the same temperature, the rate at which heat is lost from the two vessels is the same, but this does not indicate that they have the same rate of cooling. If the thermal capacity of vessel A and its contents is greater than the thermal capacity of vessel B and its contents, the temperature of vessel A will fall less rapidly than vessel B. In fact, the difference in the rates of cooling may be used to compare the thermal capacities.

Typical cooling curves for cups containing approximately equal volumes of different liquids are shown in Fig. 2. It is evident from these curves that the time Δt_A required for cup A and its contents to cool through the temperature range ΔT is greater than the time required for cup Band its contents to cool through the same temperature range. The average rate R'_A at which cup A loses heat in this range is given by the equation

$$R'_A = \left(C_A + c_A m_A\right)\Delta T / \Delta t_A \tag{7}$$

where C_A is the thermal capacity of the cup and thermometer, m_A is the mass of the liquid in the cup, and C_A the specific heat of the liquid. The corresponding equation for cup B is

$$R'_B = \left(C_B + c_B m_B\right)\Delta T / \Delta t_B \tag{8}$$

Since the surfaces of the two cups are alike and since they have fallen through the same temperature range ΔT, it follows that $R'_A = R'_B$ and

$$\frac{C_A + c_A m_A}{\Delta t_A} = \frac{C_B + c_B m_B}{\Delta t_B} \tag{9}$$

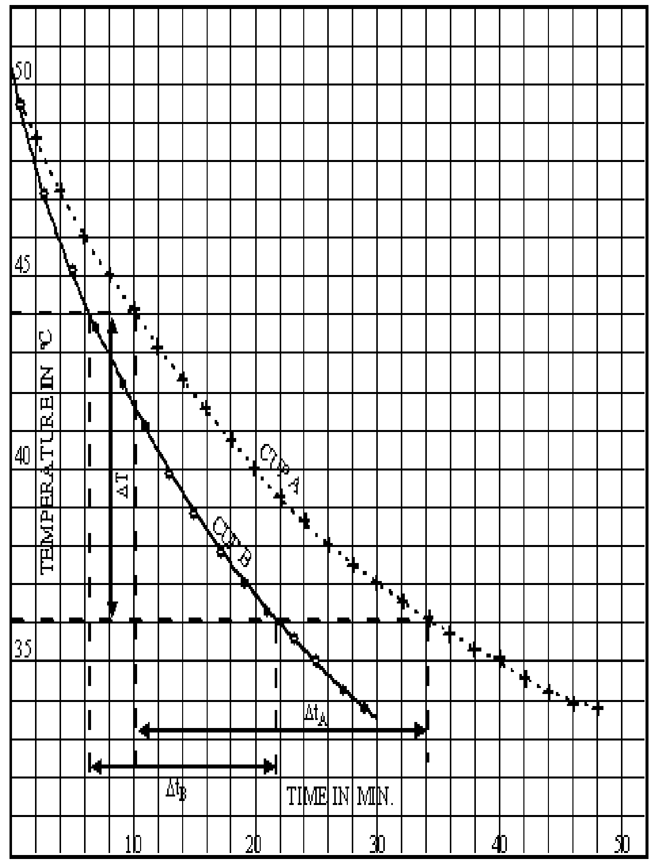

Fig. 2. Cooling curves of the two liquids.

If one of the cups contains water, or any other liquid for which the specific heat is known, Eq. (9) may be used to determine the specific heat of the other liquid.

In the derivation of Eq. (9) it was assumed only that in this fixed temperature range the rate at which heat is lost from cup A is equal to the rate at which heat is lost from cup B. This should be true whether heat is lost only by radiation or whether it is lost by radiation, convection and conduction. It should also be noted that in the derivation of this equation Newton's law of cooling was not used and the validity of the equation is not affected by the approximations in this law.

APPARATUS: A radiation calorimeter, two thermometers graduated to 50°C in one tenth degree divisions, one thermometer graduated in degrees, a beaker, a Bunsen burner, a stop watch and a balance are required.

The radiation calorimeter is illustrated in Fig. 3 and the arrangement of the various parts of this apparatus is shown in Fig. 1. Two brass vessels C and D supported by a strip of asbestos board S are suspended in the large outer copper vessel V which contains water at room temperature. A pair of nickel-plated and highly polished brass tubes A and b (called

Fig. 3. The Radiation Calorimeter

radiation tubes), extending into the brass vessels through holes in the asbestos board, contain the liquids under investigation. The temperatures of these liquids are read by means of the thermometers T_A and T_B.

PROCEDURE: With the supporting strip S and the brass vessels C and D in position as shown in Fig. 1, fill the outer vessel V with water at room temperature. Weigh the tube A when empty and again when almost full of water. In a similar manner determine the weight of tube B when empty and when almost full of the liquid whose specific heat is to be determined. With the thermometers T_A and T_B supported by cork stoppers in the radiation tubes, place these tubes in a beaker of hot water until each tube and its contents reaches a temperature of approximately 50°C. When the proper temperature has been reached, remove the tubes from the hot water, dry the outside surfaces, and place them in the calorimeter as indicated in Fig. 1. Read each thermometer every two minutes until the temperature pas fallen at least 15°C. Starting the stop watch when the first thermometer reading is taken, read one thermometer on the even minutes and the other thermometer on the odd minutes. Since one cup cools more slowly than the other, the temperature readings of the slow-cooling cup must be continued for a longer period of time. Note the temperature of the water in the large copper vessel V.

Determine the thermal capacity of each radiation cup and each thermometer. The specific heat of the red brass from which the cups are made is 0.090cal/gm/˚C. Since glass is a poor conductor of heat, only that portion of the thermometer which was immersed in the liquid need be considered in calculating its thermal capacity. Although the specific heats of glass and mercury are quite different, fortunately equal volumes of these two materials have approximately the same thermal capacities (0.46cal/cm^3˚C). The volume of the submerged portion of the thermometer may be determined in the following manner. Place one of the radiation tubes on the balance and weigh. Then, holding one of the thermometers in the hand, immerse it in the water to the same depth as in the experiment and observe the apparent increase in weight. The increase in weight in grams is numerically equal to the volume in cubic centimeters of the submerged portion of the thermometer. Repeat with the other thermometer. Compute the combined water equivalent of each cup and the corresponding thermometer.

Plot the cooling curves for both cups in the manner indicated in Fig. 2. Choose some convenient temperature range ΔT and determine from the graph the time required for each cup to fall through this temperature range. Use Eq. (9) to compute the specific heat of the liquid. Repeat for at least two other temperature ranges.

The data plotted in Fig. 2 may be used to check the validity of Newton's law of cooling. From this graph it is seen that 11.6 minutes are required for the temperature of cup A to fall from 42°C to 38°C. The rate of cooling at an average temperature of approximately (why approximately?) 40°C is therefore 0.345 degree per minute. Apply this method to the curves previously constructed to determine the rate of cooling for at least four different temperatures for each cup. Plot a graph showing the relationship between rate of cooling and temperature for each cup. Interpret these curves.

Optional: 1. For an ideal black body, one that absorbs all the radiation that falls on it and reflects none, *k* in Eqs. (2) to (6) is 1.36×10^{-12} cal $cm^{-2} sec^{-1} deg^{-4}$. Compare the rate of loss of heat from the polished metal cup used in this experiment with the radiation from an ideal black body at the same temperature.

2. Replace one of the polished metal cups with a similar cup finished in dead black, fill both cups with hot water, and plot a cooling curve for each. Interpret these curves.

QUESTIONS: 1. Using Eq. (I) as a basis, define specific heat.

2. Why was the outer vessel in this experiment made to hold such a large quantity of water?

3. If the two thermometers used in this experiment have equal thermal capacities, may these thermal capacities be neglected? Explain.

4. The specific heat of a substance is numerically the same in the British system as in the metric system. Explain why.

5. A man is served coffee with his meal but does not wish to drink it until afterward. To keep the coffee from getting cold should he pour in the cream immediately or just before drinking? Give reasons.

6. Eq. (6) is used to compute R. What is the percentage error in this computation which is due to approximations in Eq. (6)? Assume that the temperature of the body is 47°C and that the temperature of the surroundings is 27°C.

7. What effects do the thermal conductivity and the viscosity of the liquids have on the results?

8. Justify Eq. (7).