CENCO Physics Selective Experiments In Physics

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THE CONTINUOUS FLOW CALORIMETER

OBJECT: To make an experimental determination of the mechanical equivalent of heat using a continuous flow calorimeter.

METHOD: A stream of water flowing through a glass tube is heated by an electric current passing through a heating element contained in the tube. The temperature difference between the water entering and leaving the tube depends upon the amount of energy supplied per unit time to the heating element (power input) and upon the mass of water flowing through the tube per unit time. A uniform rate of flow of water is maintained and several determinations of the temperature difference are made for corresponding values of the power input. From the measured rate of flow and the slope of a graph of power input versus temperature difference, the value of the mechanical equivalent of heat is determined.

THEORY: One of the most fundamental discoveries in physics was the discovery that heat is a form of energy. The conversion of mechanical energy, or work, into heat is a transformation that is readily accomplished; indeed, because of friction, it is one that can never be entirely prevented in any mechanical system. The inverse transformation, that of converting heat into mechanical energy, on the other hand, can only be accomplished under very special conditions and is subject to certain rigid restrictions. Moreover, although the transformation of mechanical energy into heat may be complete under ordinary circumstances, only a limited portion of any given amount of heat can be converted into work in any practical case. The mechanical equivalent of heat is numerically the number of units of mechanical energy equivalent to one unit of heat energy. Thus, if W units of work are converted into H units of heat,

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

where the numerical value of the mechanical equivalent of heat J depends upon the units in which W and H are expressed. When W is expressed in ergs and H in calories, J is in *ergs per calorie*; when W is in joules and H in calories, J is in *joules per calorie*. In the British system J is usually expressed *in foot-pounds per Btu.*

The evaluation of J is an experimental problem involving the conversion of a known amount of work into a measured quantity of heat. Thus, J is an empirical constant and the accuracy of its evaluation is limited by experimental errors. It may be remarked that, although the value of J is approximate (as is any empirical quantity), it may be determined practically to any desired accuracy by sufficient refinement of experimental procedures.

Numerous experimental methods have been employed in the measurement of J. In the oldest and most direct method the work (which is produced by a known force acting through a known distance) is done against friction, and the heat that is produced is measured by the temperature rise of a body to which the heat is communicated, the mass and specific heat of the body being known. In the electrical method the heat is produced by an electric current flowing through a coil of wire immersed in water. Fig. 1 represents a calorimeter C containing water in which is immersed a heating element E

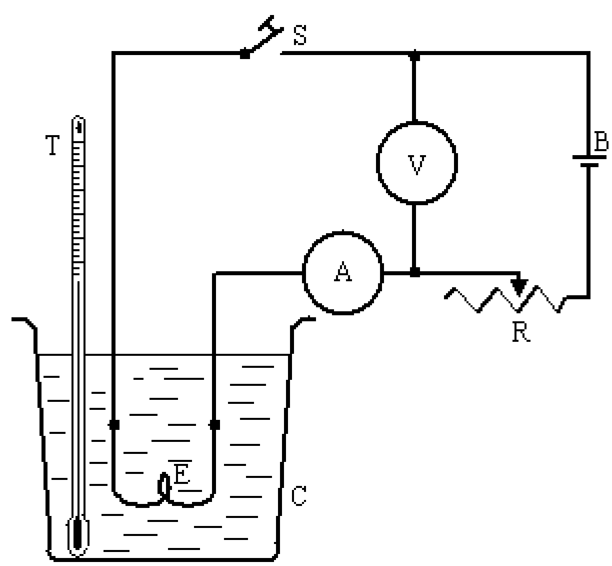

Fig. 1. Mechanical equivalent of heat - static method. C - calorimeter, E - heating element, T - thermometer, A - ammeter, V - voltmeter, B - battery, R - rheostat, S - switch

connected to a battery B. If the current in the coil is I amperes and the potential drop across the coil is V volts, the electrical energy W (in joules) supplied to the coil in t seconds is

$$W = IVt \tag{2}$$

When this energy is imparted to the water, the temperature of the water is raised. The amount of heat H required to raise the temperature of m grams of water from a temperature T_1 to a temperature T_2 is

$$H = mc(T_2 - T_1) \tag{3}$$

where the specific heat c of the water is 1 calorie per gram per degree C. Substituting the expressions for W and H from Eqs. (2) and (3) in Eq. (1)

$$IVt = Jmc\left(T_2 - T_1\right) \tag{4}$$

from which

$$J = \frac{IVt}{mc\left(T_2 - T_1\right)} \tag{5}$$

When the water equivalent of the calorimeter is taken into account, the relationships expressed by Eq. (5) afford a simple and direct method of determining J. This method may be called a static method in contrast to the dynamic, or flow, method employed in this experiment.

In the continuous flow method the calorimeter consists of a tube C through which a steady stream of water is kept flowing (Fig. 2). The heating element E consists of a coil of wire stretched the length of the tube. As the water flows through the tube its temperature is raised from T_1 at the inlet to T_2 at the outlet. The mass m of water flowing through the tube in the time t is measured. If the rate of flow of water and the power supplied to the coil are kept constant, a constant temperature difference will be established. The value of J may then be obtained with the aid of Eq. (5). One advantage of the flow calorimeter is that, since the temperatures T_1 and T_2 are kept constant, the thermal capacities of the calorimeter, heating element, and thermometers are not involved in the computations. A more reliable determination of J may be made by measuring the temperature differences produced by different values of the power input, the rate of flow m/t being kept constant. Setting $IV=P$ and $T_2 - T_1 = \Delta T$ Eq. (5) may be written

$$P = \frac{mc}{t} J \cdot \Delta T \tag{6}$$

or

$$P = k \cdot \Delta T \tag{7}$$

where the constant $k = mcJ/t$.

Eq. (7) is the equation of a straight line of slope k passing through the origin. Thus, if a curve is plotted of P versus ΔT, the value of J may be determined from the slope of the curve and the measured rate of flow m/t, the specific heat c being numerically unity.

In the foregoing treatment it is assumed that all of the energy expended in the coil is delivered to the water and, furthermore, that the water receives no heat from any other source. In other words, the assumption is that no heat transfer takes place between the calorimeter and its surroundings.

The rate of exchange of heat between the calorimeter and its surroundings depends upon the difference in temperature between the calorimeter and its surroundings, and upon a constant of the apparatus which is an index of its tendency to transfer heat. Eq. (7) may then be revised as follows

$$P = k \cdot \Delta T + k'\left(\bar{T} - T_R\right) \tag{8}$$

where $\bar{T} = \frac{T_1 + T_2}{2}$ the average water temperature, T_R is

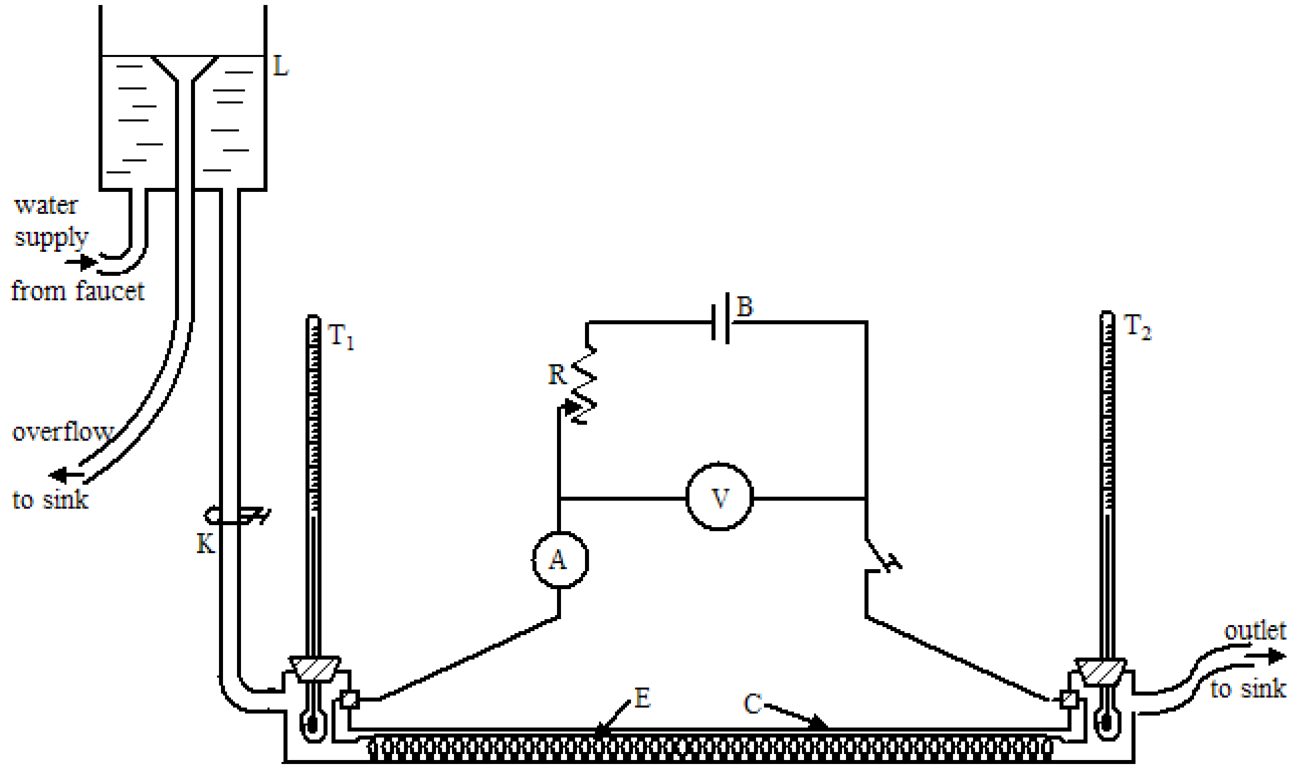

Fig. 2. Mechanical equivalent of heat - flow method.

the room temperature, and k' is a factor involving (among other things) the insulation and radiation properties of the calorimeter. If the temperatures are arranged so that the inlet temperature T_1 is as much below room temperature T_R as the outlet temperature T_2 is above room temperature, then $\overline{T} = T_R$, and the correction term is zero. If $\overline{T}$ is not equal to T_R, and if k' is very small, the correction term is negligible. If the correction term is not negligible, the curve of P versus ΔT is not a straight line passing through the origin. The factor k' might be such that the curve, although linear, does not pass through the origin; or it might be such as to cause a non-linear curve to pass through the origin. In either case the slope does not provide a reliable determination of the value of J. If the calorimeter tube C is made of glass and if the average water temperature T does not differ too greatly T_R, it will be found that the correction term is negligible. The heat losses may be reduced materially by wrapping the glass tube with cotton.

APPARATUS: The continuous flow calorimeter represented diagrammatically in Fig. 2 and illustrated in Fig. 3 consists

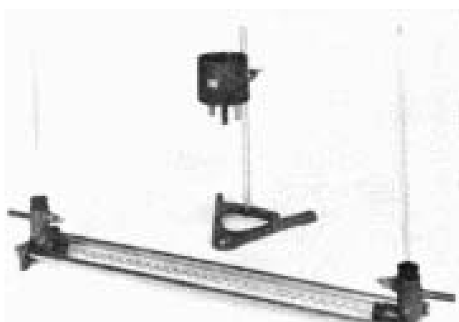

Fig. 3. Continuous Flow Calorimeter

essentially of a glass tube C mounted between two cast iron brackets which are provided with hose connections and thermometer wells. The heating element E is a coil of constantan wire of about 0.3ohm resistance running through the tube and connected to binding posts on the iron brackets. Water from the faucet is supplied to the calorimeter through the constant level tank L which maintains a constant head and assures uniform flow. A 6volt storage battery B is connected in series with the heating element E, a rheostat R, and a direct current ammeter A. The potential drop across the wire is indicated by the direct current voltmeter V across the line.

Instead of the storage battery an alternating current power supply such as that illustrated diagrammatically in Fig. 4 may be used. A constant-voltage transformer Z_1, which receives power from the a.c. line, is connected to the primary of a step-down transformer Z_2. The "series connector" X is merely a convenient unit for introducing a variable resistance R in series with the primary winding of the transformer Z_2. The secondary of the step-down transformer is connected to the terminals of the heating element E. The ammeter A and the voltmeter V are alternating current instruments. A great advantage of this type of power supply is the ease and accuracy with which the power can be regulated.

The accessory equipment required consists of two thermometers with a range of 0° to 50°C graduated in tenths (or preferably hundredths) of a degree, two single hole rubber stoppers, a support stand for the constant level tank, rubber tubing, pinchcocks, a 250cc graduate, a seconds clock or stopwatch, a 0- to 15amp ammeter, a 0- to 6volt voltmeter, a slide wire rheostat, a 6volt storage battery, and a switch.

Sometimes difficulty is encountered in obtaining a uniform temperature of the tap water. In this case a convenient and highly satisfactory modification of the procedure consists in employing a large storage tank which is kept filled at all times so that the water comes to room temperature. The tank should be located at sufficient height to provide adequate head of water and should have enough capacity to provide for several runs.

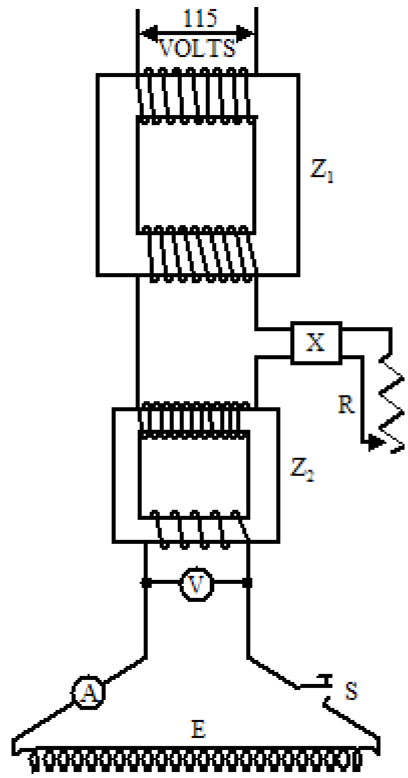

Fig. 4. Alternating current power supply for Continuous Flow Calorimeter.

PROCEDURE:

Experimental: Place the apparatus on a table near the sink. Clamp the constant level tank L on its support stand at a height of 12 to 18 inches above the table. Connect one of the outlets in the base of the tank to one end of the calorimeter with a length of rubber tubing as shown in Fig. 2. Close the tubing with the pinchcock K. Connect another length of tubing to the outlet of the calorimeter and arrange it to empty into the sink. Connect a tube to the overflow pipe in the tank so as to drain into the sink. Finally connect the tank to the water faucet with rubber tubing.

Connect the power supply as shown in Fig. 2 (or Fig. 4) but do not close the switch S until water is flowing through the calorimeter. *Have the connections inspected by the instructor before closing the switch.*

Fit the thermometers T_1 and T_2 into the rubber stoppers and insert them in the thermometer wells. Open the water faucet slightly and regulate the flow through the tank until the water level remains just even with the top of the overflow pipe. Open the pinchcock K and start a flow of water through the calorimeter. Loosen the thermometers and allow the wells to fill completely before seating the thermometers securely. Regulate the flow with the pinchcock K until between 250 and 350 cubic centimeters of water pass through the system per minute.

Measure the rate of flow by catching the water from the outlet in a graduate, inserting the graduate while observing the clock and removing it at the end of a fixed time, say I minute. It may be necessary to readjust the supply from the faucet after the pinchcock is opened in order to keep the water level in the tank even with the overflow. This level should be watched during the course of the experiment.

When a steady rate of flow has been established, observe the initial inlet and outlet temperatures. Close the switch S and adjust the rheostat R until the power is approximately 25watts. Observe the temperatures T_1 and T_2 and, when they become steady, record the values in Table I. Also record the current, voltage, mass of water caught and the measuring time.

Increase the power by approximately 25 watts and again allow the temperatures to become steady, recording all values as before. Continue in this way, increasing the power in steps of approximately 25 watts until a total of 5 determinations has been made. After each determination check the rate of flow. *It is important that the rate be kept constant*.

Interpretation of Data: Compute the values of the power P and the temperature difference ΔT. Record the data as in Table I. Plot a curve on Cartesian paper with *P* as ordinate and ΔT as abscissa. Determine the slope *k* of this curve, and from the value of *k* and the rate of flow *m/t* compute the value of *J*. Compare with the accepted value and record the percentage difference.

QUESTIONS: 1. What do the initial values of the inlet and outlet temperatures indicate about the possibility of heat exchange between the calorimeter and the room?

2. What does the curve of P versus ΔT indicate about heat losses?

3. What would be the physical significance of a negative *P*-intercept on this curve?

4. Describe a set of experimental conditions that would insure that the slope of the curve would be unaffected even though the curve failed to pass through the origin."

5. In the circuit of Fig. 2 find the percentage error caused by neglecting the potential drop across the ammeter, assuming the resistance R_A of the ammeter to be 0.004ohm, that of the voltmeter (R_v) 1000ohms, and that of the coil (R_c) 0.4ohm.

6. If the voltmeter is connected directly across the heating coil so that the ammeter reading includes both the coil current I_c and the voltmeter current I_v, what percentage error results from neglecting the voltmeter current, assuming the same circuit constants?

7. Assuming the knife switch to have a resistance of 0.01ohm due to dirty contacts, calculate the percentage error introduced by neglecting the switch resistance (a) when the circuit is that used in Problem 5; (b) when the circuit of Problem 6 is used.

TABLE I

m gm	t sec	I amp	V volts	P watts	T_1 deg C	T_2 deg C	ΔT deg C