



Selective Experiments In Physics

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SPECIFIC HEAT OF A SOLID

OBJECT: To measure accurately the specific heat of various solid specimens, using the method of mixtures.

METHOD: A hot solid specimen of known mass is lowered from a steam jacket into a calorimeter containing a measured quantity of cold water. The initial temperature of the hot solid is assumed to be the temperature of boiling water under existing atmospheric pressure, and this temperature is determined by reference to steam tables. The change in temperature of the water is read from a thermometer. The heat given up by the solid is set equal to the heat absorbed by the water and calorimeter, and this equation is solved for the specific heat of the solid specimen. A correction is made for the heat lost by radiation.

THEORY: Temperature is a measure of the relative hotness or coldness of a body, and any instrument designed to measure temperature is called a thermometer. 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 . Stated algebraically

$$H = c \cdot m \cdot \Delta t \quad (1)$$

where the constant of proportionality c is called the specific heat of the material. Since heat is a form of energy, the quantity of heat H might be expressed in ordinary energy units, for example, joules or foot-pounds. It is customary, however, to measure heat in special heat-energy units. It has been found convenient to adopt as the unit of heat energy the amount of heat required to raise the temperature of a unit mass of water one degree.

In the metric system this unit is called the *calorie*. The calorie is defined as the heat required to raise the temperature of one gram of water one degree centigrade. If, in Eq. (1), H is expressed in calories, m in grams and Δt in degrees centigrade, the specific heat c is given in calories per gram per degree centigrade ($\text{cal}/\text{gm}^\circ\text{C}$). Obviously, the specific heat of a substance is numerically equal to the number of calories of heat required to raise the temperature of one gram of the substance one degree centigrade. In the British system the unit of heat energy is the *British thermal unit* (Btu) which is defined as the heat necessary to raise the temperature of one pound of water one degree Fahrenheit. In this system the specific heat of a substance is measured in British thermal units per pound per degree Fahrenheit and is numerically equal to the quantity of heat required to raise the temperature of one pound of the substance one degree Fahrenheit.

The product $c - m$ is called the *thermal capacity* C of the

body. It should be obvious that the thermal capacity of a body is numerically equal to the quantity of heat required to raise the temperature of the body one degree. Since a mass m of any substance is thermally equivalent to a mass of water equal to $c \cdot m$ (or C), 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. In the metric system C is expressed in calories per degree centigrade ($\text{cal}/^\circ\text{C}$). It should be noted that specific heat is a property of a substance and is, therefore, an important physical constant; whereas thermal capacity is a property of a particular body.

In the discussion above it was assumed that the quantity of heat required to raise the temperature of water one degree is independent of the initial temperature; that is, it requires the same amount of heat to raise the temperature from 0°C to 1°C as to raise the temperature from 50°C to 51°C , say. This is true to a fairly high degree of accuracy, but for very precise work the exact temperature range must be specified. For example, the 15 degree calorie is defined as the amount of heat required to raise the temperature of one gram of water from 14.5°C to 15.5°C ; whereas the mean calorie is defined as one hundredth of the heat required to raise the temperature of one gram of water from 0°C to 100°C . Since the difference between these two calories is only 0.024 of one per cent, it is obvious that it is almost never necessary in practice to specify the kind of calorie. In this experiment the slight variation in the thermal capacity of water with temperature is negligible. The specific heat of the specimen, however, changes considerably with temperature and this fact should not be ignored when comparing the results in this experiment with values given in tables.

Method of Mixtures: The simplest way of measuring specific heat is the method of mixtures. In this method, as the experiment is usually performed, a sample of the material under investigation is heated and then lowered into a vessel of cold water. The heat lost by the specimen is set equal to the heat gained by the rest of the system. If the only unknown quantity in this equation is the specific heat c_x of the specimen, the equation may be solved for c_x .

If, for example, a specimen at the temperature of steam t_s is lowered into a cup, filled with water and equipped with thermometer and stirrer, the temperature of the cup and its contents rises from an initial temperature t_i to a final temperature t_f . Setting the heat lost by the specimen equal

to the heat gained by the cup and its contents yields the equation

$$C_x(t_s - t_F) = (C_w + C_c + C_r + C_s)(t_F - t_I) \quad (2)$$

in which C symbolizes thermal capacity and the subscripts X , W , C , T and S refer to the specimen, water, cup, thermometer and stirrer, respectively. If the specimen and cup (masses m_x and m_c , respectively) are both made of aluminum (specific heat c_A), $m_x c_A$ may be substituted for C_x and $m_c c_A$ for C_c . Making these substitutions in Eq. (2) and solving for c_A yields

$$c_A = \frac{(C_w + C_T + C_s)(t_F - t_I)}{m_x(t_s - t_F) - m_c(t_F - t_I)} \quad (3)$$

Correction for Heat Losses: Assume that a cup and its contents are initially at the temperature t_R of the surroundings and that, when a hot solid is lowered into the cup, the relation between the temperature of the cup and elapsed time is represented by the solid-line curve of Fig. 1. The maximum temperature read by the thermometer is t_M .

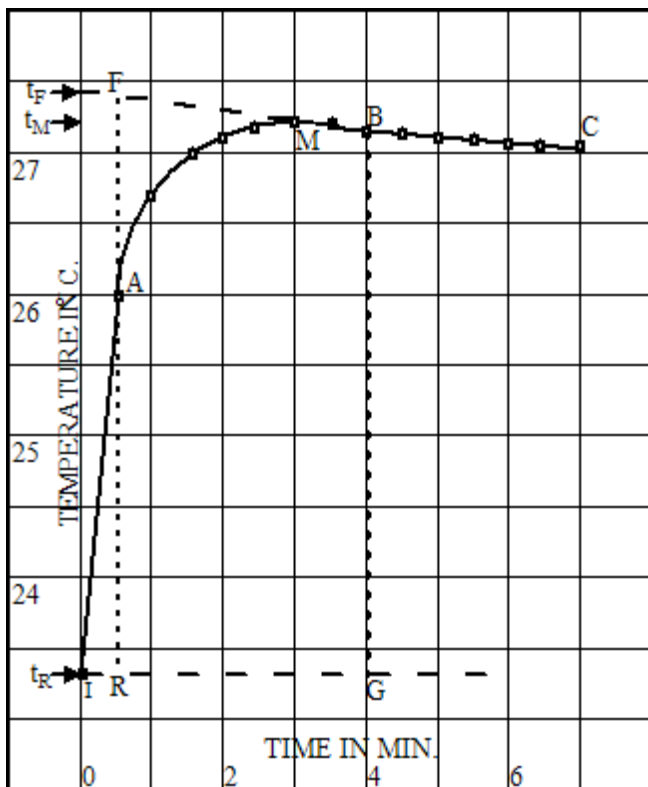


Fig. 1. Illustration of the method of correcting for heat lost to the surroundings. A glass specimen was used in taking these data.

When the temperature of the cup is above the surrounding temperature, heat is being lost to the surroundings and the problem is to determine what the final temperature would have been had no heat been lost.

There are several methods of correcting for heat losses and

the choice of method depends upon the condition of the experiment. For the general case, represented in Fig. 1, one method of correcting may be best; whereas in special cases simpler and more accurate methods may be found. For example, it is seen in Fig. 1 that the rise in temperature from I to M has not taken place at a uniform rate. It is a reasonable assumption that, in the special case where the temperature rise is uniform, correcting for heat losses is more simple. It is also seen (Fig. 1) that it takes considerable time for the temperature of the water to reach its maximum value. From this it may be concluded that the specimen is a poor thermal conductor. The case where the specimen is a good thermal conductor and the temperature rise is very rapid is a special case. In the discussion that follows the general case will first be discussed and then a method of simplifying the procedure when the specimen is a good conductor will be suggested.

The final temperature for the general case illustrated in Fig. 1 is determined in the following manner. Extrapolate the portion CB of the curve back until it intersects the ordinate axis, and construct the vertical line FR so that the areas IAR and $AFBM$ are equal. The ordinate of the point F is the final temperature t_F .

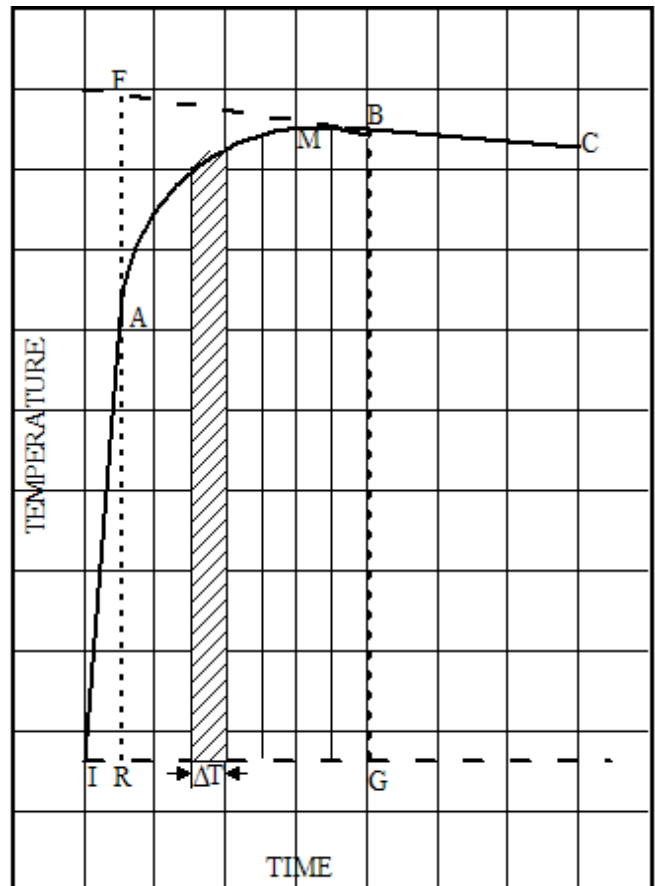


Fig. 2. The temperature loss is proportional to the area under the curve.

The justification of this procedure is based upon Newton's law of cooling which states that, if 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 Vacuum Jacketed Calorimeter.

The height of each point on the graph above the horizontal line at t_R is, therefore, proportional to the rate of cooling. Multiplication of any given time interval by the corresponding rate of cooling gives the temperature loss during this interval. Referring to Fig. 2, where the area between the curve and the horizontal line at t_R is divided into thin slices, the height of a slice (for example, the shaded one) is proportional to the rate of cooling at that particular time and the width of the slice is equal to the time interval ΔT . From this it follows that the area of the slice is proportional to the temperature loss during the interval ΔT . Upon summing the areas of all the slices, it is evident that the temperature deficiency due to loss of heat in the time interval IG is proportional to the area IAMBG. This temperature deficiency is the same as if the body had started at the temperature represented by the point R, risen instantly to temperature t_F and then cooled as indicated by the line FBC. The temperature loss in one case is proportional to the area IAMBG and in the other case to the area RFBG. These two areas are equal since FR was drawn to make area IAR equal to area AFBM. It may be concluded, therefore, that if no heat had been lost the thermometer reading would have risen from t_i to t_f and then have remained constant.

Although the student should understand the underlying principles of the above method of correcting for heat losses, in practice the actual procedure may usually be simplified considerably. The solid specimens ordinarily measured are good thermal conductors in which case the temperature of the cup rises almost immediately to its maximum value. In fact, the rise is so rapid that the line FR practically coincides with the ordinate axis and the intercept of the curve FBC with the ordinate axis may be taken as the final temperature t_f . This is the procedure that will be followed in the present experiment.

APPARATUS: A vacuum jacketed calorimeter, stirrer, centigrade thermometer graduated in one tenth degree divisions, steam jacket, steam generator, two Bunsen burners, two beakers, ring stand, balance, various solid specimens, watch and access to a barometer are required. The vacuum jacketed calorimeter is illustrated in Fig. 3 and shown in cross section in Fig. 4. The aluminum cup C is suspended inside the vacuum flask V from an insulating ring R. The cover L is lined with a thick layer of cork insulation and is provided with a cork stopper K. To minimize heat conduction the handle of the stirrer S is made of glass. Temperatures are read by means of the precision thermometer T. The steam generator is shown in Fig. 5 and the steam jacket in Fig. 6. The arrangement of the apparatus used for holding the specimen at the temperature of boiling water is illustrated schematically in Fig. 7.

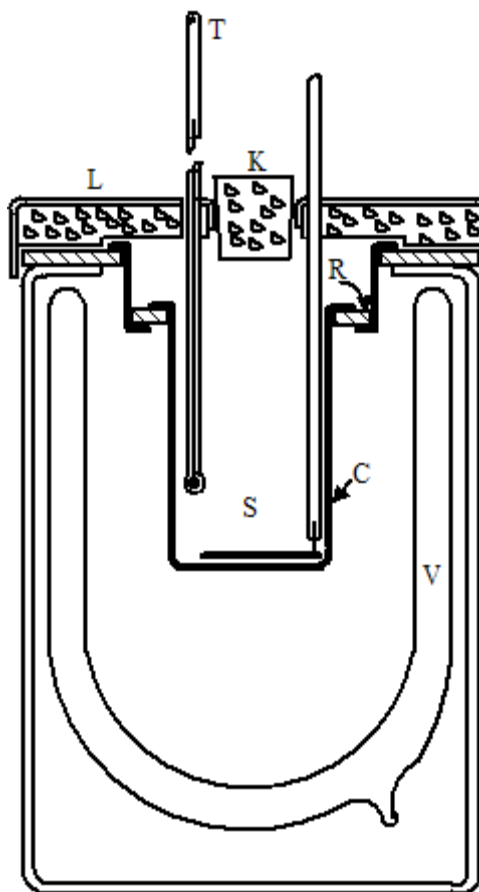


Fig. 4. Diagram of the Vacuum Jacketed Calorimeter.

The water in the steam generator G is boiled by means of the Bunsen burner B and the resulting from condensation.



Fig. 5. The Steam Generator

The specimen X is suspended inside the steam jacket by means of a string and a small clamp on the cover C of the chamber. The lower end of the heating chamber is closed with a cork stopper.

PROCEDURE: Light both Bunsen burners, placing one under the steam generator, which should be at least half full of water, and the other under the beaker of water. While waiting for the water to boil, weigh the aluminum specimen. Place the specimen in the beaker of boiling water. When the specimen has come to the temperature of boiling water remove it and, by means of the attached string, suspend it in the steam jacket.

This dries the specimen and maintains it at the temperature

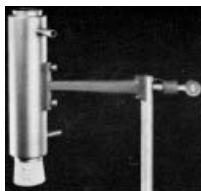


Fig. 6. The Steam Jacket

of boiling water until time to transfer it to the calorimeter. Weigh the aluminum cup, fill it with water at room temperature and weigh again. Assemble the apparatus as shown in Fig. 4 with the thermometer and stirrer in position. Stir the water and observe the thermometer reading for several minutes to make sure that the temperature is constant. To provide a supply of water at room temperature it is suggested that a tank of water be kept standing in the laboratory for this purpose.

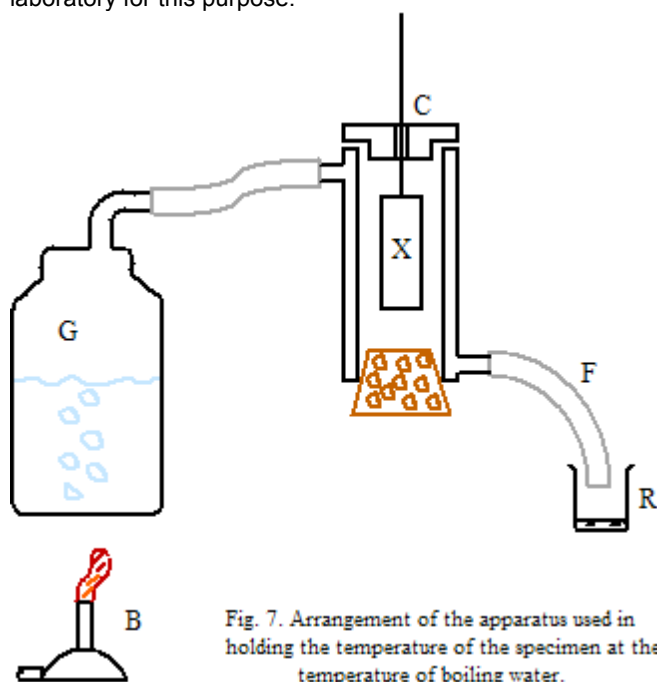


Fig. 7. Arrangement of the apparatus used in holding the temperature of the specimen at the temperature of boiling water.

Read the barometer. Use the observed barometric height and steam tables to compute the temperature of saturated water vapor under the existing atmospheric pressure. This is assumed to be the temperature within the steam jacket and, therefore, the initial temperature t_s of the specimen. Place the calorimeter directly under the steam jacket, read carefully and record the temperature t_1 of the water, remove the cork stoppers and, when the watch reads on the minute, lower the specimen into the cup of water and replace the cork stopper in the calorimeter. Read the temperature after one minute and for each half minute thereafter until at least eight temperature readings have been taken. The water should be gently stirred during this period and the thermometer readings should be estimated to hundredths of a degree centigrade. Plot a curve which shows the relationship between these temperature readings (ordinates) and elapsed time (abscissas). Extrapolate this curve to the axis of ordinates. The intercept of this curve on the ordinate axis is taken as the final temperature t_f as explained above.

Determine the thermal capacity of the thermometer and of the stirrer. Since glass is a poor conductor of heat, only that portion of the thermometer which is immersed in the water 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 capacity ($0.46 \text{ cal/cm}^3 \text{ } ^\circ\text{C}$). The volume of the submerged portion of the thermometer may be determined in the following manner. Place a vessel of water on the balance and weigh. Then, holding the thermometer 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. The thermal capacity of the stirrer may be computed from the mass and specific heat of the metal part and the volume of the submerged portion of the glass stem. If the metal part can not be weighed separately (or estimated with sufficient accuracy) the value of the thermal capacity will be supplied by the instructor.

Using Eq. (3), compute the value of the specific heat of aluminum. It should be remembered that Eq. (3) represents a special case and may be used only when the specimen and cup are made of the same material, in this case aluminum. When the cup and specimen are made of different materials, the more general equation, Eq. (2), should be used.

Repeat the experiment, using a specimen of a different material. It should be obvious how Eq. (2) may be used in this case to compute the value of the specific heat.

Optional: Repeat the experiment using a specimen that is a poor thermal conductor. The temperature of the water should be read every half minute until the temperature falls for 4 or 5 minutes after reaching a maximum. A curve similar to the one shown in Fig. 1 should be constructed and t_f determined from the intercept of the curve FBC with the line FR.

QUESTIONS: 1. Give three reasons why it is advisable to place the specimen in the steam jacket rather than transfer it directly from the boiling water to the calorimeter.

2. Compare the errors introduced into this experiment by a one-degree error in t_s and a one-tenth-degree error in t_f .

3. What percentage error in the determination of the thermal capacity of the thermometer would cause a one tenth percent error in the specific heat of the specimen?

4. The glass wall of the thermometer bulb is very thin. What are the advantages and disadvantages of this?

5. If the burner under the steam generator is turned too high, the steam is ejected with considerable velocity. Discuss the nature of the error caused by this.

6. The calorimeter cup is highly polished. Explain why.

7. It is frequently suggested that loss of heat from the calorimeter cup may be minimized by so choosing the initial temperature that it is as far below the temperature of the surroundings as the final temperature is above. Criticize this method as it applies to this experiment.

8. Show that the specific heat of a substance is numerically the same whether measured in $\text{cal/gm } ^\circ\text{C}$ or in $\text{Btu/lb } ^\circ\text{F}$.