

HEAT OF FUSION AND MECHANICAL EQUIVALENT OF HEAT

CAUTION: Please handle thermometers gently. Broken mercury-filled thermometers should be taken to Rm. B-31 for disposal as mercury is very toxic. If a red-liquid thermometer breaks, it may be placed in the trash.

This experiment consists of two independent parts. In part A you will measure the heat of fusion of ice using a calorimeter and the method of mixtures. In part B you will show the equivalence of the transfer of energy through work and heat. This is done by doing a measured amount of work against a frictional force and measuring the resultant heat transferred to the system. Your results should show that the amount of heat produced is directly proportional to the amount of work done, and enable you to compute the conversion factor between units of work and heat.

PART A. HEAT OF FUSION

When we heat a substance, we increase its internal energy, and its temperature will normally rise. However under certain circumstances the heat added to the system goes into doing work on the system without increasing the temperature. This happens when the substance undergoes a change of phase or state, for example, a liquid to a gas or a solid to a liquid. The heat goes into the work needed to break the intermolecular bonds which characterize the state. This heat is called the *latent heat* of the phase change. When a substance melts, the latent heat is called the *heat of fusion* and when it changes from liquid to gas it is called the *heat of vaporization*.

When a substance is not undergoing a change of phase the temperature will change in proportion to the amount of heat added. The proportionality is given by the mass m of the substance and its *specific heat*, c , so that the relation of heat added ΔQ to the change in temperature ΔT is

$$\Delta Q = mc\Delta T \quad (1)$$

The specific heat generally depends on the particular phase that the substance is in. For water $c_{\text{liquid}} = 1.0 \text{ cal/g}\cdot^\circ\text{C}$, $c_{\text{ice}} = c_{\text{steam}} = 0.5 \text{ cal/g}\cdot^\circ\text{C}$.

When adding heat to ice at 0°C the temperature will not change but the ice will melt. A certain amount of heat per unit mass is needed to melt the ice. This is the heat of fusion L_f which has units of cal/g. Hence the heat needed to melt a given mass of ice is given by

$$Q_{fusion} = mL_f \quad (2)$$

Latent heats are characteristic of the substance and the phase change it is undergoing. For water the heat of fusion L_f is 80 cal/g and the heat of vaporization L_v is 540 cal/g. This means that 80 calories of heat energy are needed to melt 1 gram of ice at 0°C and 540 calories are needed to vaporize 1 gram of water at 100°C.

In this experiment you will use the method of mixtures to measure the heat of fusion of water. If several substances at different temperatures are mixed together, heat will flow from the hotter ones to the colder ones until all reach a common *equilibrium* temperature. This is true even if some of the substances undergo a phase transition in the process. If the work done on the system by outside forces is zero, and if the system is insulated so that no heat is lost to the surroundings, conservation of energy and the first law of thermodynamics, $\Delta U=Q-W$, tell us that the internal energy does not change. In particular, the heat Q lost by the hotter substances is equal to the heat gained by the cooler ones. This is expressed mathematically as $\Delta U=Q-W=0$ and $W=0$, so

$$Q_{net} = Q_{gain} - Q_{loss} = 0 \quad (3)$$

If you add a quantity of ice of mass m_i at 0°C to a sufficient amount of warm water of mass m_w in a calorimeter of mass m_{cal} , all at temperature T_h , in order to melt the ice the system must come to equilibrium at some intermediate final temperature T_f . As stated above, the heat needed to melt the ice and bring the melted ice up to the final temperature is equal to the heat lost by the warm water and the calorimeter cup, or from Eq. (3),

$$Q_{fusion} + Q_{ice\ water} - Q_{warm\ water} - Q_{cal} = 0$$

so that

$$\begin{aligned} m_i L_f + m_i c_w (T_f - 0) &= m_w c_w (T_h - T_f) + m_{cal} c_{cal} (T_h - T_f) \\ &= (m_w c_w + m_{cal} c_{cal}) (T_h - T_f) \end{aligned} \quad (4)$$

This equation can be used to determine the heat of fusion L_f if all the other quantities are known.

APPARATUS

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| o Calorimeter (2 cups, stirrer, & stopper) | o 15°C - 35°C thermometer (high precision) |
| o Balance | o -20°C - 110°C thermometer |
| o Hooked 5kg weight | o Vernier calipers |
| o Table clamp with crank | o Braided copper band |
| o Calorimeter (threaded cap and feet) | o Adjustable cord with S loops |

PROCEDURE: A

1. Weigh the dry calorimeter cup (without ring) and stirrer on the laboratory balance. Also record the types of metal and specific heats of the cup and stirrer.
2. Fill the inner calorimeter cup about half full of warm tap water at about 10-15°C above room temperature. Weigh the cup with the water to determine the mass of water added. Stir the water gently and record its temperature T_h .
3. Select a few small pieces of ice and dry them with a paper towel. (Why is it important that the ice be dry?) Without touching the ice with your bare fingers add it to the calorimeter cup bit by bit without splashing.
4. While adding the ice, gently stir the water and note the temperature. Keep adding ice until the mixture is 10-15°C below room temperature. (To better control the final temperature add the ice more slowly toward the end.) Continue stirring the mixture until all the ice has melted. Record the final temperature T_f .
5. Weigh and record the mass of the inner calorimeter cup and its contents in order to determine the mass of the ice added to the system.
6. Compute the latent heat of fusion of the ice using Eq. (4) and compare with the accepted value of 80 cal/g.

PART B. THE MECHANICAL EQUIVALENT OF HEAT

There are two ways to increase the internal energy of a system. A force can do mechanical work on the system, or heat can flow into it from outside. In this experiment, you will do work against the frictional force between two surfaces that are rubbing together; these surfaces will become hot, and the temperature difference between the rubbing surfaces and the rest of the system will cause heat to flow within the system. By measuring the temperature increase of the system as a function of the amount of work done, you can calculate the heat produced (using Eq. (1)) as a function of work done, and determine whether they are proportional to each other. Such an experiment is really quite simple in concept, and the only difficulty is in measuring the internal energy increase for all parts of the system.

The method that will be used here is to wrap a braided copper band tightly around a copper cylinder and turn the cylinder while the band is kept taut. The cylinder is filled with water, and because both the cylinder and the band are excellent conductors of heat, they both remain at nearly the same temperature and transfer heat to the water which is at a very slightly lower temperature than the cylinder and band. We will make the approximation that the water, cylinder, and band are all at the same temperature. If the rise in temperature is ΔT , the quantity of heat needed to produce this rise is

$$\Delta Q = m_b c_b \Delta T + m_c c_c \Delta T + m_w c_w \Delta T + m_t c_t \Delta T \quad (5)$$

where m_b and c_b are the mass and specific heat of the band, m_c and c_c are the mass and specific heat of the cylinder, m_w and c_w are the mass and specific heat of the water in the cylinder, and m_t and c_t are the mass and specific heat of the thermometer used to measure the temperature rise ΔT . The specific heat of the copper used in this equipment is 0.092 cal/g \cdot °C. The specific heat of aluminum is 0.215 cal/g \cdot °C, and the specific heat of water is 1.00 cal/g \cdot °C. For the thermometer furnished with the equipment the product $m_t c_t$ is 0.80 cal/°C. The masses of the copper band, the copper cylinder, and the water can all be determined by weighing. With these measurements you can determine the quantity of heat produced. Presumably this increase in internal energy is the result of mechanical work done. The copper band is wrapped several times around the cylinder and held taut by a large mass suspended from one end. We can calculate the work as (force) \times (distance), and to do this we must measure both the force and the distance moved. The ingenuity in the design of the experiment enters here. We can have the motion through a large distance produced in a compact apparatus by turning the cylinder around several hundred times; the apparatus has a hand crank for doing this. The total distance moved will be $\pi D N$ where πD is the circumference of the drum and N is the number of turns. The force applied is exactly equal and opposite to the force of friction, as long as we turn the drum at a constant speed. Because the braided copper band has much greater tension at one end than at the other, due to the friction, and because the tight end presses against the drum with greater force than does the looser end, the frictional force is different along different parts of the band. However, the design of the experiment allows us to get around this difficulty. The sum of all of the frictional forces that must be overcome is balanced by the weight of the mass hanging on the end of the band. If we turn the cylinder at a constant speed the total work done, for N turns, is

$$W = \pi D N M g \quad (6)$$

where M is the mass hanging on the end of the copper band. Now we have a plan for the experiment. We turn the cylinder several hundred times, measure the rise in temperature, and calculate both the heat Q and the work W . By taking temperature readings every fifty turns of the cylinder we can find out whether the quantity of heat produced is proportional to the amount of work done.

PROCEDURE: B

1. Examine the apparatus carefully and be sure that you understand the operation. Learn how to fasten and unfasten the cylinder from the crank, and how to seal it when it is filled with water so that there will be no leaks. It is important to have the rubber ring and the two copper rings inside the cap to maintain the seal. Wrap the copper band around the cylinder three to five times, attach the 5.0 kg mass to one end so that it rests on the ground, and attach the other end to a spring fastened to a peg on the apparatus base. Make sure the peg is secure. If it is not secure it will pop out and possibly injure somebody. Adjust the length of the S cord, using the S loops, supporting the 5.0 kg mass so that when the crank is turned at a uniform speed the mass is lifted completely off the floor and the spring holds the slack end of the copper band in a horizontal position. The band should slide over the surface of the drum smoothly when the crank is turned at a steady rate. Now that the apparatus is adjusted properly remove the calorimeter.
2. Weigh the copper band and the empty cylinder, then fill the cylinder about three-fourths full of cold water (about 50 or 60 grams) and weigh again to find the mass of cold water. Insert the thermometer and fasten the screw seal so that no water can leak out. Measure the diameter of the cylinder with a pair of calipers. (If you haven't used calipers before ask your T.F.). Attach the cylinder to the crank. Quickly go through Procedure (1) again to make sure the equipment is adjusted properly still.
3. Start the experiment immediately, and work rapidly so that the heat lost to the room will be small. If you start three or four degrees below room temperature and finish three or four degrees above room temperature, the quantity of heat gained from the room when below room temperature will be about balanced by the heat lost to the room when above room temperature. If the thermometer reads more than about three or four degrees below room temperature, turn the crank until the thermometer reaches this value.
4. For each fifty turn interval, calculate the quantity of mechanical work done and the quantity of heat produced. To compare the values for each interval and find whether they are proportional, plot a graph having quantity of heat produced as the ordinate and mechanical work as the abscissa. If these are proportional the graph should be a straight line passing through the origin, and the mean value of the constant of proportionality can be determined from the slope.
5. The term "mechanical equivalent of heat" usually refers to the conversion factor used for converting heat energy units, in calories, to mechanical energy units, in Joules. It is the constant J in the relation $W = JQ$. Determine the mean value of J from your data, and compare this with the conversion factor in your textbook.

QUESTIONS

PART A

1. Discuss the principle sources of error in the heat of fusion experiment.
2. What error in L_f would be introduced if the ice were not dry?
3. What error in L_f would be introduced if the ice were initially colder than 0°C ?
4. A piece of ice with a mass of 30 grams at 0°C is added to 100 ml of water at 20°C . Assuming that no heat is lost to the surroundings, what is the final temperature of the system? Explain. (Ignore the heat capacity of the calorimeter)

PART B

5. Discuss the principle sources of error in this experiment.
6. Explain how your work in this experiment, in particular your graph, indicates that heat is the transfer of energy.
7. A 2000-pound car is traveling at 60 miles per hour when the engine is disengaged and the brakes applied, bringing the car to a stop. How many calories of heat are produced in the stopping process?

**DATA SHEET — HEAT OF FUSION AND
MECHANICAL EQUIVALENT OF HEAT**

TA [][■]

NAME: _____ INSTRUCTOR: _____

PARTNER: _____ SECTION: _____ DATE: _____

PART A

Mass of stirrer	_____	Specific heat of stirrer	_____
Mass of calorimeter	_____	Specific heat of calorimeter	_____
Mass of calorimeter and water	_____	Mass of ice	_____
Mass of water	_____	Calculated heat of fusion	_____
Initial temperature of water	_____	Accepted value of L_f	_____
Final equilibrium temperature	_____	Percent error	_____
Mass of calorimeter, water, and ice	_____		

PART B

Mass of empty calorimeter drum and scaling ferule, m_c _____

Mass of copper band, m_b _____

Mass of calorimeter drum, sealing ferule, and water _____

Mass of water, m_w _____

Diameter of drum, D _____

Number of turns	0	50	100	150	200	250	300	350
Temperature								
Temperature rise $T - T_0$								

Mechanical equivalent of heat J , from the graph _____

Accepted value of mechanical equivalent of heat _____

Percent error _____