# **Mechanical Energy and Heat**

### **Purpose:**

Students will observe the conversion of mechanical energy to thermal energy.

## **Introduction:**

The principle of conservation of energy is surprisingly new. No one person can take the credit for discovering it. Instead, the discovery of Conservation of Energy was made bit by bit, piece by piece, until the evidence finally became overwhelming sometime in the late 19<sup>th</sup> century.

One of these pieces is the idea that a specific amount of mechanical energy can be converted to a specific amount of thermal energy and back again. We are being very careful about our terminology. "Work" and "heat" represent energy that is in motion. When we do work on a system, we increase its mechanical energy. A pot of hot water has thermal energy. When it cools off, it transfers "heat" to its surroundings. These are subtle distinctions, but important ones.

There are many energy units because energy is used to explain such a variety of phenomena. Historically, various units were invented to make it easy to do calculations in various contexts. Electrical engineers use the kilowatt-hr. Chemists like the calorie, which is the amount of energy needed to warm up 1 cm<sup>3</sup> of water by 1°C. Food chemists like the kilocalorie, also called the big-C Calorie. The foot-pound, erg, Joule, electron Volt, BTU, and therm are all useful energy units. If you wish to work with energy, get used to unit conversions.

In this lab, you will observe and measure the conversion of mechanical energy into thermal energy. You'll measure the mechanical energy in Joules and the thermal energy in calories. With careful work and a little luck, you may be able to determine the correct conversion factor between these two units within the limits of error (measurement uncertainty) of your experiment.

#### A "blind" study:

Because the "textbook" result of this experiment is so well known, we will eliminate experimenter bias by doing a "blind analysis." Blind studies are standard practice in medical research. They are used in other branches of science, including physics. Human beings have a remarkable capacity to fool themselves into seeing what they expect or wish to see. To eliminate this effect, scientists deliberately hide the result of the experiment from themselves as long as possible. This makes sure that all data collection and error analysis is performed without bias. Once the analysis is finished, a single simple calculation will reveal the true experimentally determined result.

You will do your blind analysis by deliberately NOT measuring the mass of the copper drum until the very end of the experiment.

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## The Experiment:

Your apparatus is shown below.



Fig. 1a (left) shows a photograph of the apparatus. Fig. 1b (right) shows a schematic diagram of the apparatus and two force diagrams for the ends of the vertical part of the rope.

In this apparatus, a rope is wrapped around a copper drum. When the drum is turned, the rope tightens and lifts the large mass. Because the rope slips on the drum, the large mass never rises more than a few inches above the floor. The rope is not accelerating, so according to Newton's First Law the net force on the rope is zero.

To find the work done by turning the crank, consider a point on the rope that is in contact with the drum. As the drum turns, this point is continuously sliding past the drum. The drum travels a distance  $\pi$ DN against the rope, where  $\pi$ D is the circumference of the drum and N is the number of turns of the crank. From the force diagrams, it is apparent that the frictional force opposing the cranking motion is simply the weight of the large mass, or F = Mg. Therefore, the mechanical work done is given by the equation

$$W = \text{force} \times \text{distance} = Mg\pi DN \tag{1}$$

where all quantities are defined as above. You will find the value of M written on the mass.

Next, we need to determine how much heat is flowing into the copper drum as a result of the rope rubbing on the drum. The heat Q can be found from the equation for specific heat capacity:

$$Q = m_{drum} c_{copper} \Delta T$$
(2)

where  $c_{copper} = 0.0923$  cal/gram/K. The temperature change is obtained by measuring the temperature before and after turning the crank a number of times.

The quantities that you seek are not W or Q, but the ratio W/Q and the experimental error in W/Q.

$$\frac{W}{Q} = \frac{Mg\pi DN}{m_{drum}c_{copper}\Delta T}$$
(3)

Remember, we will "blind" our study by NOT measuring  $m_{drum}$  until all other parts of our measurements and analysis are complete. Until then, you may use a value of 100 g for  $m_{drum}$ . After making your measurements and performing your error analysis, you will "unblind" your experiment and compare your value of W/Q to the "textbook" value of 4.186 J/cal.

#### **Error Analysis:**

Although you're probably itching to start taking data, you will only be wasting your time unless you take a few moments to understand your sources of error. You have several measured quantities in this experiment and some given quantities. Technically, except for  $\pi$ , *every* quantity in equation (3) has an error associated with it. This includes g and c<sub>copper</sub>. We mention these errors only to let you know that you cannot always take such things for granted.

Since we're not doing a precision measurement, we need only consider sources of error that are likely to affect the result by more than 5%. The errors in g and  $c_{copper}$  can be safely ignored because they are at the 0.1% level. N is obtained by counting approximately 100 turns of the crank. Being "off" by a turn or two will not affect the result much. The mass M has been determined for you with a precision of about 1%. Your experience with the balances probably tells you that the error in m<sub>drum</sub> is likely to be 1 gram or less, which is small enough to be ignored. The only two errors that could contribute significantly to this experiment are  $\delta D$  and  $\delta(\Delta T)$ .

You will measure D with a vernier caliper. If you are unsure about how to use this device, please refer to the manual that is located on the lab table. Alternatively, you can find many instructions for reading vernier calipers online. <u>http://www.phy.ntnu.edu.tw/ntnujava/index.php?topic=52</u> You may estimate  $\delta D$  from your ability to read the caliper. Using the rules of propagation of error, the error in the work done is

$$\delta W = Mg\pi N \,\delta D \tag{4}$$

The error in  $\Delta T$  is the largest source of error in this experiment for two reasons. First, your thermometer is not very precise. You can estimate its error  $\delta(\Delta T)$  from your ability to read the dial. Secondly, the drum is not thermally insulated from the room. We will get around this in a rather clever way. Start by holding a piece of dry ice against the copper drum. Cool the drum to a few degrees (4°C, for example) below room temperature. Turn the crank approximately 100 times until the temperature of the drum is the same number of degrees above room temperature. When the drum is cool, heat flows from the room into the drum. When the drum warms up, heat flows out of it into the room. If you turn the crank quickly and steadily, the two heat flows

should approximately cancel each other. Assuming that the errors in the initial, final, and room temperature are equal, we have

$$\delta(\Delta T) = \sqrt{(\delta T_{\rm f})^2 + (\delta T_{\rm i})^2} \cong \sqrt{2}(\delta T_{\rm room})$$
<sup>(5)</sup>

and

$$\delta Q = m_{drum} c_{copper} \delta(\Delta T) \tag{6}$$

The last thing we need to do is to figure out how to determine the error in the quantity W/Q by combining  $\delta W$  and  $\delta Q$ . This requires the use of propagation of error, as described in the Measurement and Error handout. The relative errors in W and Q add in quadrature, as follows:

$$\delta\left(\frac{W}{Q}\right) = \frac{W}{Q}\sqrt{\left(\frac{\delta W}{W}\right)^2 + \left(\frac{\delta Q}{Q}\right)^2} \tag{7}$$

You now know almost everything you need to know to do this experiment, except the Experiment Questions:

#### **The Experiment Questions:**

- 1. What is YOUR experimentally determined value for W/Q?
- 2. What happens to the measured value of W/Q if we don't cool the drum first?

Note that a full answer to these questions requires a quantitative discussion of the data and a thorough discussion of measurement uncertainties.

#### **Procedure:**

If you've read everything so far, you have a pretty good idea of how this experiment should work.

- 1. Start by assuming that  $m_{drum} = 100$  grams. This is not the true number, but it will let you move forward with your calculations. Do as much as you can, down to measuring and calculating W/Q and  $\delta(W/Q)$ . Get a preliminary value for W/Q and its error. Remember to cool the drum with dry ice as described earlier in the handout.
- 2. Next, devise your own experiment to answer Experiment Question 2. This answer does not hinge on knowing the correct value of W/Q. Your discussion should include a description of what you did, your calculations of W/Q and its error, and a quantitative (talk about your numbers) comparison with your first measurement.
- 3. AFTER you have done all this, remove the thermometer, unscrew the copper drum from the apparatus and weigh the drum. Repeat your calcluations for Experiment Question 1, using the proper m<sub>drum</sub>. Obtain a "true" value of W/Q and its error, and compare it to the "textbook" value.

Keep careful notes as you work. Your notes should include:

- Brief descriptions of what you did
- Your data
- Your calculations, written out.
- Your observations

Write so that someone else (your TA) can understand what happened at your lab station, and in enough detail so that you can write a detailed lab report. Professional scientists learn (usually the hard way) not to rely on memory. IF IT WASN'T WRITTEN DOWN, IT DIDN'T HAPPEN.

Turn in your notes with your data sheets.

#### **SAFETY NOTES:**

- Handle the dry ice pellets with the polycarbonate tongs that are provided. Dry ice is extremely cold. Do not let it come in contact with your bare skin. Return leftover dry ice to the containers when you are finished with it.
- Watch your toes, especially if you are wearing sandals, flip-flops, etc. That hanging mass is very heavy.

## **Apparatus Tips:**

- You might want to turn the crank a couple of times to see whether you can turn the crank briskly and whether it lifts the big mass off the floor. If not, you can adjust the length of the rope by using the black "buckle". The mass should lift no more than an inch or two off the floor.
- The end of the thermometer is covered with silicone grease to provide a good thermal contact between the thermometer and the drum. You need the grease. Don't clean it off. Add more if you need it. The grease is not toxic. Use soap and water (available at the lab sinks) if you need to get it off your hands.
- Measure T<sub>room</sub> using the dial thermometer in your apparatus, NOT the thermometer on the lab wall.
- 100 turns of the crank is generally a good number for taking data. You may vary this number as needed. Crank quickly and steadily until the drum reaches the desired final temperature. Don't stop in the middle of a data run. (Can you guess why?)
- When you measure the diameter of the drum, measure the part that is in contact with the rope.
- If the crank handle keeps falling off, ask your T.A. for a screwdriver.

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	1.A. 5
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# Mechanical Equivalent of Heat Data Sheet

#### **Basic measurements:**

M =	δM =
D =	δD =
m <sub>drum</sub> = NOT YET!!!	δm <sub>drum</sub> =
room temperature T <sub>room =</sub>	$\delta T_{room} =$

Measure the  $T_{room}$  with the same thermometer that's in your apparatus.

**Data and calculations:** Please write these down on your own. Remember that you are writing to your TA, not yourself. Make your explanations and calculations neat and clear. Use the back of this sheet, or attach pages as necessary. Write the units with the numbers at all times.

Numbers and data tables without explanations are NOT acceptable. You must indicate what you were doing when you generated them.

#### **Final Results:**

	ΔT °C	W (Joules)	δW (Joules)	Q (calories)	δQ (calories)	W/Q (J/cal)	δ(W/Q) (J/cal)
Exp. Question 1 (blind)							
Exp. Question 2 (blind)							
Exp. Question 1 (unblind)							

m<sub>drum</sub> = \_\_\_\_\_

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Lab Section:	1.A. S	
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## **Analysis Questions:**

1. What is the answer to Experiment Question 1? Does your measurement of W/Q agree with the "textbook" value? Please discuss this in some detail, using your measured numbers in your explanation.

2. What is the answer to Experiment Question 2? Please discuss this in some detail, using your measured numbers in your explanation.

3. When the drum starts at room temperature and ends above room temperature, do your results indicate that heat leaks from the drum into the room? How can you tell?

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4. In this lab, we know what the "textbook" answer was. The challenge for you was to try to measure it for yourself. Would you characterize your efforts as being successful, partially successful, or unsuccessful? Why do you think this?

If your experiment was not successful or only partially successful, how would you like to change or improve what you did?

5. Why shouldn't you use the thermometers on the wall to measure  $T_{room}$ ?

6. Derive a propagation of error equation for  $\delta(W/Q)$  containing  $\delta D$  and  $\delta(\Delta T)$ . Use the back or attach another page if you need more room.

7. What are your final thoughts and impressions about this lab?