EXPERIMENT: HEAT EQUIVALENT OF MECHANICAL ENERGY

PRIMARY OBJECTIVE:

- to observe the conversion of mechanical energy into heat, and to verify quantitatively that:

Friction Work = Change in Heat Energy

SECONDARY OBJECTIVE:

- to learn how to convert the units traditionally used to measure heat (calories) into the units appropriate to mechanical energy (joules)

APPARATUS

A calorimeter, nylon rope, thermocouple, 5-kg hanging mass, and an analytical balance will be used.

THEORY

For a mechanical system the law of conservation of energy takes the form:

$$\text{Work Done} = DPE + DKE + D(\text{Heat Energy}) \tag{1}$$

where KE is kinetic energy, and PE is potential energy.

In the experiment Analysis of a Freely-Falling Body, the work done by air friction as the weight fell through the air was sufficiently small that it could be neglected, and you found that equation (1) reduced to:

$$DKE + DPE = 0, \tag{2}$$

or in alternative form:

$$KE + PE = E_m \tag{2'}$$

where E_m is the total mechanical energy, which is a constant.

In the present experiment the changes in KE and PE are zero, so equation (1) reduces to:

$$\text{Friction Work} = D(\text{Heat Energy}). \tag{3}$$

This is the equation you that we would like to test.

A nylon rope (b) is wrapped around an aluminum drum (a) and is held by hand at one end. At the other end of the band dangles a 5-kg mass (m). The aluminum drum is turned beneath the rope by means of a crank turned by a student, and the 5-kg mass remains stationary. As the drum turns it rubs against the band, and the resulting friction generates heat, which causes the temperature of the band and of the drum to rise. The rise in temperature is a measure of the heat energy generated. To test equation (3) we must calculate the **friction work**, measure the **change in heat energy**, and see whether they are equal. We will now discuss how this can be done.

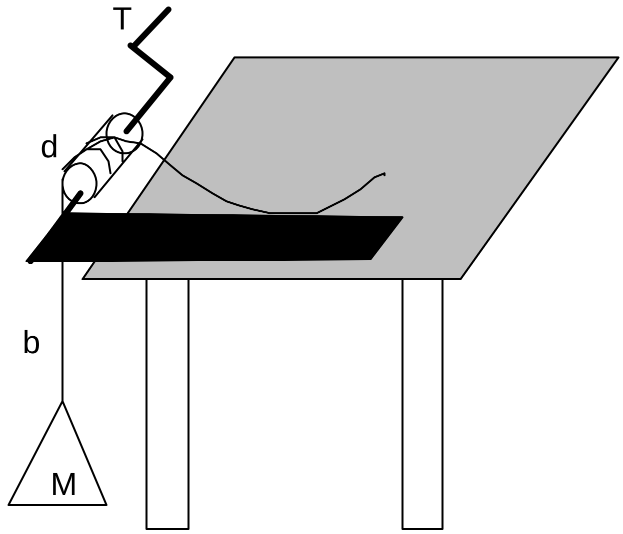

Figure 1

(a) **Friction Work:** Friction work is given by the equation

$$Friction\ Work = f_f s_{||} \tag{4}$$

where f_f is the force of friction, and $s_{||}$ is the distance <u>parallel to f_f</u> over which the force of friction acts. To see what f_f and $s_{||}$ are, we refer to figure 2.

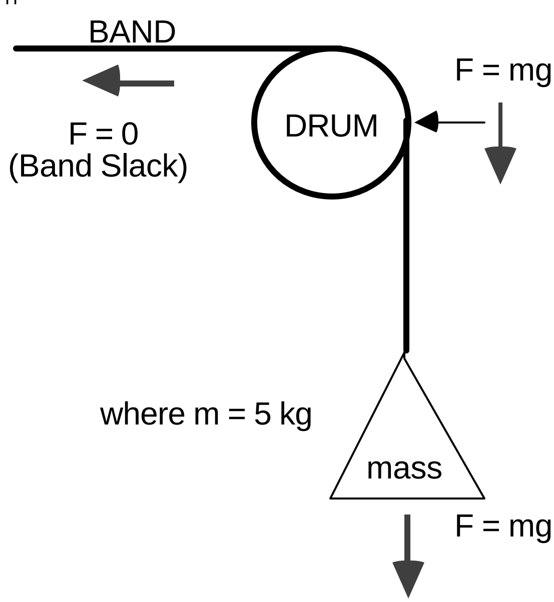

Figure 2

We see in Figure 2 that the 5-kg mass is pulling down on the nylon rope or band with a force mg, where g is the acceleration due to gravity. Since the band doesn't move, that this force must be transmitted by the rope right up to the point where it meets the aluminum drum. At that point the force becomes the friction force, f_f, between the rope and the drum. This force acts tangentially to the drum at this point. As the drum turns, the friction force is applied over that portion of the drum that passes this same point. Therefore, if the drum makes one full turn, the distance over which the force is applied is just the circumference of the drum, c_D. If the drum makes n full turns, the distance $s_{||}$ is nc_D. The Friction Work is thus given by:

$$D\,W = \textit{Friction Work} = (mg)\,(nc_D). \tag{5}$$

Remember that in the above equation m is the 5-kg hanging mass. Also note that the values used in calculating the equation should be in terms of meters, kilograms, and seconds, which will yield a friction work in units of Joules.

(b) **Change in Heat Energy:** When heat is added to a system, it causes the temperature of the system to rise. The heat energy added, ΔH, is related to the temperature rise, ΔT, by the equation:

$$DH = C\,M(DT) \tag{6}$$

where C is the specific heat capacity of the system and M is the mass of the system. To calculate ΔH you need to know C and you need to measure M and ΔT.

Although heat is just another form of energy, and can therefore be measured in Joules, for historical reasons it is measured in terms of different units, called calories. One calorie is defined as the amount of heat needed to raise the temperature of one gram of water by one degree Celsius. The conversion factor between calories and joules is:

$$1 \textit{ calorie} = 4.18 \textit{ joules}. \tag{7}$$

In the present experiment, C is made up of contributions from two different components, the aluminum drum and the nylon rope. We will neglect the heating of the rope. The heat capacity is given by the product of the mass of the component times the <u>specific heat capacity</u> of the material of which the component is composed. Water has a specific heat capacity of 1 cal/gm^o C and aluminum has a specific heat capacity of 0.215 cal/gm ^{o}C. The contribution of the drum is (0.215 cal/gm^o C) M_D where M_D is the mass of the drum. The nylon band has negligible heat capacity. With these values, equation (6) takes the form:

$$DH\ (\textit{in calories}) = [0.215\ M_D]\ DT. \tag{8}$$

If all the mechanical work goes into heat, then the ratio ΔW (in Joules) / ΔH(in calories) should be the conversion factor in equation (7).

PROCEDURE

Measure the mass of the calorimeter. Determine the circumference of the drum, c_D, by measuring its diameter with a vernier caliper. Set the thermocouple to 300mV and °C and measure the ambient room temperature with the thermocouple touching the calorimeter. Make sure the reading is stable. Remove the calorimeter from the apparatus and place it in the refrigerator or freezer. Leave the calorimeter in there until its temperature is at least 3°C below room temperature. Mount the calorimeter back on the plastic back plate and lock. **BE GENTLE** with the calorimeter, especially when removing in from and replacing it on the apparatus.

BE SURE THE DRUM SURFACE IS DRY AND CLEAN. If necessary run some steel wool over the surface to clean it. Wrap the rope around the drum four turns. Turn the crank to keep the weight lifted off the floor such that there is no tension in the part of the cord being held by the student, and so that the 5-kg mass stays hanging at one height. The part of the band on the calorimeter must be slack. If the band does not slip smoothly on the drum the drum is still dirty or wet. Correct this situation.

To compensate for heat loss by the calorimeter to the air, it is necessary to start the experiment below room temperature. Cool the calorimeter to 3° below room temperature. Begin counting turns at exactly 3° below room temperature and continue cranking until you reach a final temperature of 3° above room temperature. This way the heat **gained** from the air while the calorimeter is below room temperature will compensate for the heat **lost** to the air while it is above room temperature, as long as you crank continuously at a constant speed. Count the total number of cranks it takes you to get to your final temperature in this manner.

When you have finished taking your data calculate ΔW, the Friction Work, and ΔH, the change in Heat Energy. Compare the ratio $\Delta W/\Delta H$ with the expected value. Calculate also the uncertainties in each of these quantities (the formulae for the uncertainties are on the spreadsheet for this lab). Was energy conserved through the conversion? Would it make any difference whether you turned the crank rapidly or slowly? Why or why not?

CHECKLIST

Your lab report should include the following five items:

1) data used in the calculations of friction work and ΔH
2) sample calculations of friction work, ΔH, and the uncertainties of these values
3) discussion of whether energy is conserved based on the results of the experiment
4) answers to the questions (one above and one in Appendix)

APPENDIX

The available energy contents of various kinds of food are often listed in "calorie" charts. One of these "calories" is actually 1000 calories of the type defined in this experiment, i.e., 1 food calorie = 1 kcal or kilocalorie. Assuming the human body to be roughly 50% efficient in the conversion of food calories into mechanical work, how many turns of the crank would have been necessary to work off an average breakfast of about 600 cal?