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:

Calorimeter (aluminum drum and thermometer seal)
Nylon band (see Figure 1)
Thermometer
5-kg mass

THEORY

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

$$\textit{Work Done} = \Delta PE + \Delta KE + \Delta(\textit{Heat Energy}) \qquad (1)$$

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

In a previous experiment, ANALYSIS OF FREEFALL, 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:

$$\Delta KE + \Delta PE = 0, \qquad (2)$$

or in alternative form:

$$KE + PE = E_m = \textit{constant}, \qquad (2')$$

where E_m is the total mechanical energy.

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

$$\textit{Friction Work} = \Delta(\textit{Heat Energy}). \qquad (3)$$

This is the equation you are to test.

A nylon band (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 band 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 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 *Δ(Heat Energy)*, and see whether they are equal. We will now discuss how this can be done.

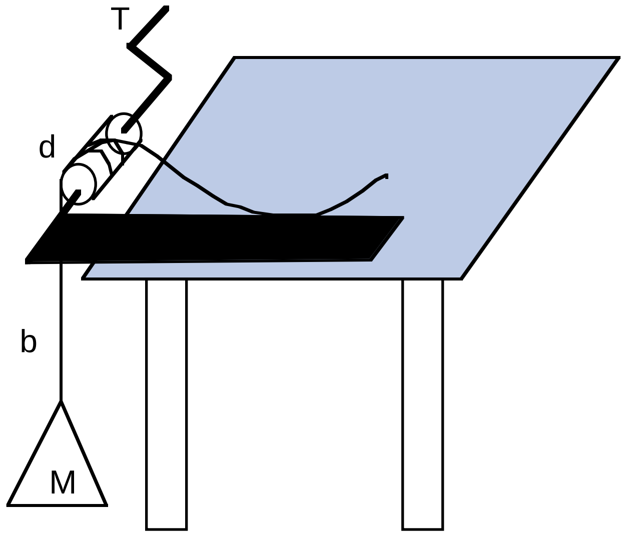

Figure 1

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

$$\text{Friction Work} = f_f\, s_{//} \qquad (4)$$

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

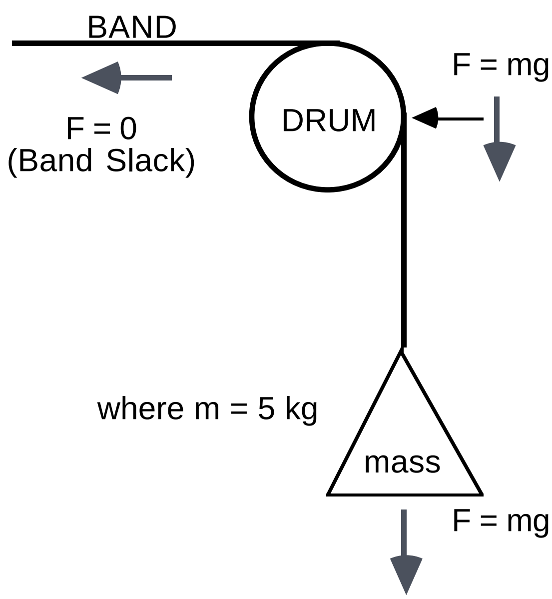

Figure 2

We see there that the weight is pulling down on the nylon band with a force *mg* (where g is the acceleration due to gravity), and, since the band doesn't move, that this force must be transmitted by the band right up to the point where the band meets the aluminum drum. At that point the force becomes the friction force, f_f, between the band 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 which passes this same point. Thus 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:

$$\Delta W = \text{Friction Work (in Joules)} = (mg)\,(nc_D) \qquad (5)$$

where

$$m = 5\ kg.$$

(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:

$$\Delta H = C\,M\ \Delta T \qquad (6)$$

where C is the specific heat capacity of the system. To calculate ΔH you need to know 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 1 gram of water by 1 degree Centigrade (Celsius) from 14.5 to 15.5˚C. The conversion factor between calories and joules is:

$$1\ \text{calorie} = 4.18\ \text{joules}. \qquad (7)$$

In the present experiment, C is made up of contributions from two different components: (1) the aluminum drum and (2) the nylon band. We will neglect the heating of the nylon band. The heat capacity is given by the product of the mass of the component times the specific heat capacity 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:

$$\Delta H\ \text{(in calories)} = [0.215\ M_D]\ \Delta T. \qquad (8)$$

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. Measure the ambient room temperature with the thermometer touching the calorimeter. Make sure the reading is stable. Remove the thermometer and place the calorimeter in the refrigerator or freezer. Leave the calorimeter in there until its temperature is at least 3˚ below room temperature. Mount the calorimeter on the plastic back plate and lock. **BE GENTLE**.

BE SURE THE DRUM SURFACE IS DRY AND CLEAN. If necessary run some steel wool over the surface to clean it. Wrap the band around the drum 4 turns. Turning the crank will lift the weight off the floor until there is no tension in the cord. 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 and counting for 300 turns of the crank. Previous tests have shown that this will cause the final temperature to be about 3˚ above room temperature. Thus heat gain from the air while below room temperature will compensate for the heat lost while above. Crank continuously at a constant speed.

When you have finished taking your data, calculate ΔW, the *Friction Work* and ΔH, the change in Heat Energy, using equations (5) and (8) and compare the ratio $\Delta W/\Delta H$ with the expected value. Calculate also the uncertainties in each of these quantities. 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:

1) Data used in the calculations of friction work and ΔH
2) Calculations of friction work and ΔH
3) Calculations of the uncertainties in friction work and ΔH
4) Discussion of whether energy is conserved, based on the results of the experiment.
5) Answers to the questions.

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 kcal?

Heat Equivalent of Mechanical Energy

Partner:

Name:

Section:

Measured

Calculated

		Value		Errors	Units
					fill in
Diameter of drum	D=		δD=		
Circumference of drum	C_d=		δC_d=		
Mass of calorimeter/drum	M=		δM=		
Suspended mass	m=		δm=		
Room temperature	T_{room}				
Starting temperature	T_1=		δT_1=		
Final temperature	T_2=		δT_2=		
Temperature difference	ΔT=		δΔT=		
Number of turns:	n=				
Friction Work	ΔW=		δΔW=		Joules
Heat energy	ΔH=		δΔH=		Calories
ΔW / ΔH =			Error:		

Answer ALL the questions.

Summary of errors:

$\delta C_d = C_d\ (\delta D / D)$

$\delta(\Delta T) = \delta T_1 + \delta T_2$

$\delta(\Delta W) = \Delta W\ \{\delta m/m + \delta Cd/Cd\}$

$\delta(\Delta H) = \Delta H\ \{\delta M/M + \delta\Delta T/\Delta T\}$

$\delta(\Delta W/\Delta H) = \Delta W/\Delta H\ \{\delta\Delta W/\Delta W + \delta\Delta H/\Delta H\}$