Chapter 2

Mechanical Equivalence of Heat

2.1 Purpose

The purpose of this lab is to demonstrate the equivalence between mechanical work and heat.

2.2 Introduction

Note: For this experiment, you will write a complete (formal) lab report and hand it in at the next meeting of your lab section. This lab can not be your dropped grade for the semester.

Until the 1830's it was thought that heat was an invisible fluid that flowed from high to low temperature. There was ample evidence supporting this model: as heat 'flows', hotter areas become cooler and cooler areas become hotter. Most metals expand when heated; i.e. a 'fluid' heat 'flows' into the metal, swelling it and raising its temperature.

However by the 1830's the 'fluid' heat model had to be extensively patched up to explain observations. Only with the advent of precise instrumentation and careful measurements was it generally realized that heat resulted from microscopic motion. In the 1830's James Joule, by experimenting with friction, demonstrated that heat was another form of energy. This was incompatible with the fluid model. However, as late as 1850 there were defenders of the heat-as-a-fluid model.

The major advances in physics over the last two centuries have been in the findings that two apparently dissimilar phenomena, in this case heat and mechanical work, are really two different manifestations of one underlying process.

2.2.1 Units for Heat and Mechanical Energies

Although heat and mechanical energy can be expressed in the same units, historically heat has been measured in its own units: the calorie (cal) or the British thermal unit (Btu). Mechanical and electrical energy, on the other hand, are measured in joules (J = N·m). Conversion factors are:

Figure 2.1: Mechanical equivalence of heat apparatus

1 cal	=	energy to increase the temperature of 1 g of water from 14.5 to 15.5^{o}C	=	4.1840 J
1 Btu	=	energy to increase the temperature of 1 lb of water of water by 1^{o}F	=	252 cal

2.3 Procedure

In the experiment we will determine the numerical values of the left and right sides of equation 2.1 . Then, by graphing work vs. heat, we obtain the calories-to-Joules conversion constant from the slope, which we predict to be 4.18 Joule = 1 calorie

$$4.18\ Joule = 1\ calorie \tag{2.1}$$

Special Cautions:

- Do not put your foot under the hanging weight. It could fall.
- Be sure the string is wound in the proper direction. (It should come off the drum on the side away from the table.)

2.3.1 Details of the Experimental Setup

In his friction experiments, Joule used a calorimeter, a thermally insulated container of water. The friction arose from stirring the water with a rotating paddle driven by a falling weight. The mechanical work done by the falling weight was converted into heat by the friction of the paddle with the water. A thermometer measured the rise in water temperature.

Shown in Figure 2.1 is the mechanical equivalence of heat apparatus. The apparatus consists of a drum calorimeter (aluminum drum with thermistor and turning apparatus with counter), a digital voltmeter, and a 5 kg weight with thick string. In our experiment the

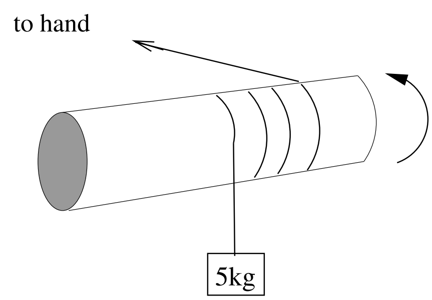

Figure 2.2: The drum is heated by friction as the string slips

friction arises from the rubbing of a string wound around an aluminum drum against the drum. The drum corresponds to Joule's water calorimeter. Temperature will be determined from the resistance of a thermistor measured by a digital multimeter (DMM). The resistance-temperature table is used to convert the thermistor values to temperature.

A mass, m = 5 kg, is suspended from one end of a string creating tension in the string (see Figure 2.2). The other end of the string is held by hand. The drum is cranked, winching up the mass. The string tension causes the string to rub against the drum surface producing friction and hence heat.

The winch setup produces constant string tension and hence constant friction. If the rubbing happens to cause an increase in tension, the mass rises and slack develops in the section of the string between the drum and the point at which the string is held. The string tension in this section then lessens, causing the drum to lose its grip on the string, dropping the mass. The lowered mass restores the tension. The drum re-grips the string and the mass again rises. Thus, the mass is kept at an approximately constant height and constant tension and friction results.

Mechanical work is supplied by cranking the drum. It is easily calculated. During cranking, work is done on the cylinder by the friction of the string. The work is W = $\tau \cdot \theta$ where τ is the torque and θ is the angle the cylinder turns. The torque is $mg\frac{d}{2}$ since the force is mg and the lever arm is $\frac{d}{2}$. For n turns the cylinder turns through an angle of n2π radians.

The mechanical work is then:

$$W_{mech} = \tau\theta = (mg\frac{d}{2})(n2\pi) = mgn\pi d \tag{2.2}$$

The units are Joules. This work is converted into heat, causing a rise in the temperature of the drum, ΔT. Using the specific heat, C_{drum} in cal/g^{o}C, and mass, M_{drum}, of the drum we can calculate the heat energy put into the drum:

$$Q = M_{drum}C_{drum}\Delta T \tag{2.3}$$

where the units are calories. Combining these we have:

$$W_{mech}[Joules] = mgn\pi d \rightarrow M_{drum}C_{drum}\Delta T[cal] \quad (2.4)$$

It is assumed that no energy is lost outside the drum. Note the left side of the above expression has units of Joules and the right side has units of calories.

2.3.2 Experimental Setup

Wind the string around the surface of the drum three to four turns and attach the mass m resting on the floor to the end of the string. Fasten the other end of the string to a tie-down point on the body of the setup, leaving a short loop at the tie-down point to be held in your fingers. Before performing the steps below read ALL the following instructions. This experiment must be done relatively quickly to minimize heat lost from the drum.

Hold the loose end of the string and begin to turn the crank. The mass should be lifted off the floor and stay at a constant height. If the mass is lifted too far, reduce the number of turns of string around the drum; if it is not lifted sufficiently, increase the number of turns. When the correct number of turns is used, the mass will remain at an constant height above the floor. Do **NOT** place your feet under the mass.

The drum's temperature, T, is determined from the resistance, R, of a thermistor mounted inside the drum. Connect a digital multimeter (DMM) across the thermistor leads to read R. The DMM must be set to the resistance (Ω) mode. A resistance-to-temperature conversion table for the thermistor is provided at the end of this chapter.

2.3.3 Data Collection

Practice cranking before beginning the actual experiment.

- To determine the initial temperature $T_{initial}$ of the drum, record $R_{initial}$ using the digital multimeter. Reset the drum rotation counter to zero.

- Start cranking the drum and start the timer. The rotation counter indicates the number of drum rotations, n. Turn the crank in increments of 50 turns up to 400 turns.

- After each set of 50 turns, stop cranking momentarily and rapidly read R. After completion of the 400 turns, stop the timer, and record the time, t_{400}.

- Let the drum cool off for a time equal to the cranking time, t_{400}. Then make a resistance reading, $R_{cooldown}$. This will be used to determine the calorimeter's heat loss to the environment during cranking.

- The diameter of the drum is 4.78 cm (.0478 m).

- T is obtained from R by linear interpolation of the thermistor resistance-temperature conversion table provided. If a measured R lies between two values R1 and R2 listed in the table, T is given by:

$$T = T2 + \frac{(T1 - T2)(R - R2)}{(R1 - R2)} \tag{2.5}$$

where T1 and T2 correspond to the temperatures for entries R1 and R2 in the table respectively.

- Calculate, for each set of 50 cranking turns, the cumulative mechanical work:

$$W_{mech} = mgn\pi d \tag{2.6}$$

where n is the number of turns from the beginning of the measurement.

- Similarly, calculate, for each 50 turn set, the heat of the drum:

$$Q = M_{drum}C_{drum}(T - T_{initial}) \tag{2.7}$$

where C_{drum} is the specific heat of the aluminum calorimeter, 215.0 cal/(kg ^{o}C). T and $T_{initial}$ are determined from R and $R_{initial}$ respectively.

- Determine the heat loss from the drum to the surrounding environment during a 50 turn cranking set as follows. The heat loss for the entire set of 400 turns is:

$$Q_{loss} = M_{drum}C_{drum}(T_{400} - T_{cooldown}) \tag{2.8}$$

- The drum heat loss for a 50 turn set is therefore approximately $\frac{1}{8}$ of the total loss. Add $\frac{1}{8}$ of the heat loss from equation 2.8 for the first data point (after 50 turns). For the second data point (after 100 turns) add $\frac{1}{4}$ of the total heat loss (equation 2.8). Add $\frac{3}{8}$ of the heat loss to the data point for 150 turns and so on for the remaining data points.

- Plot W_{mech} (y-axis) versus Q (x-axis). Determine the slope of a straight line fit to the eight data points. The slope should be the conversion factor between calories and Joules given in equation 2.1.

2.3.4 Questions to be Addressed in Your Lab Report

- How close is your measurement to the standard value of 4.18 Joule = 1 calorie?
- Where did the lost heat go? How negligible is the heat loss? What percentage of the total heat transferred was lost?

Conversion between resistance in ohms (Ω) and temperature in °C.

$R(\Omega)$	$T(°C)$	$R(\Omega)$	$T(°C)$	$R(\Omega)$	$T(°C)$	$R(\Omega)$	$T(°C)$
207000	10.1	163000	14.8	119000	21.3	76000	31.0
206000	10.2	162000	15.0	118000	21.5	75000	31.3
205000	10.3	161000	15.1	117000	21.7	74000	31.6
204000	10.4	160000	15.2	116000	21.9	73000	31.9
203000	10.5	159000	15.4	115000	22.0	72000	32.2
202000	10.6	158000	15.5	114000	22.2	71000	32.5
201000	10.7	157000	15.6	113000	22.4	70000	32.8
200000	10.8	156000	15.7	112000	22.6	69000	33.1
199000	10.9	155000	15.9	111000	22.8	68000	33.5
198000	11.0	154000	16.0	110000	23.0	67000	33.8
197000	11.1	153000	16.1	109000	23.2	66000	34.1
196000	11.2	152000	16.3	108000	23.4	65000	34.5
195000	11.3	151000	16.4	107000	23.6	64000	34.8
194000	11.4	150000	16.5	106000	23.8	63000	35.2
193000	11.5	149000	16.7	105000	24.0	62000	35.5
192000	11.6	148000	16.8	104000	24.2	61000	35.9
191000	11.7	147000	16.9	103000	24.4	60000	36.3
190000	11.8	146000	17.1	102000	24.6	59000	36.7
189000	11.9	145000	17.2	101000	24.8	58000	37.1
188000	12.0	144000	17.4	100000	25.0	57000	37.5
187000	12.1	143000	17.5	99000	25.2	56000	37.9
186000	12.2	142000	17.7	98000	25.4	55000	38.3
185000	12.3	141000	17.8	97000	25.7	54000	38.7
184000	12.4	140000	17.9	96000	25.9	53000	39.1
183000	12.5	139000	18.1	95000	26.1	52000	39.6
182000	12.6	138000	18.2	94000	26.3	51000	40.0
181000	12.7	137000	18.4	93000	26.6	50000	40.5
180000	12.9	136000	18.5	92000	26.8	49000	41.0
179000	13.0	135000	18.7	91000	27.0	48000	41.4
178000	13.1	134000	18.8	90000	27.3	47000	41.9
177000	13.2	133000	19.0	89000	27.5	46000	42.4
176000	13.3	132000	19.2	88000	27.8	45000	43.0
175000	13.4	131000	19.3	87000	28.0	44000	43.5
174000	13.5	130000	19.5	86000	28.3	43000	44.0
173000	13.6	129000	19.6	85000	28.5	42000	44.6
172000	13.8	128000	19.8	84000	28.8	41000	45.2
171000	13.9	127000	20.0	83000	29.0	40000	45.8
170000	14.0	126000	20.1	82000	29.3	39000	46.4
169000	14.1	125000	20.3	81000	29.6	38000	47.0
168000	14.2	124000	20.5	80000	29.8	37000	47.6
167000	14.4	123000	20.6	79000	30.1	36000	48.3
166000	14.5	122000	20.8	78000	30.4	35000	49.0
165000	14.6	121000	21.0	77000	30.7	34000	49.7
164000	14.7	120000	21.1				