**PHY 123 Lab 8 - Mechanical Equivalent of Heat**

The purpose of this lab is to measure the conversion factor between mechanical energy and heat energy.

Important! You need to print out the 1 page worksheet you find by clicking on this link [http://www.ic.sunysb.edu/Class/phy121pk/labs/pdfs/PHY123Spring2012MechEquivOfHeatWorksheet.pdf] and bring it with you to your lab session.

If you need the .pdf version of these instructions you can get them here [http://www.ic.sunysb.edu/Class/phy121pk/labs/pdfs/PHY 123 Spring 2012 Lab 8 Mechanical Equivalent of Heat.pdf].

**Video (NOTE: the embedded video title has the incorrect lab number and it is NOT the last lab of the semester)**

**Equipment (NOTE: the static photos below differ slightly from your setup, which has the crank handle facing up, not to the side. See the video.)**

- spring balance
- thermometer (**Be careful! It's glass!**)
- aluminum-wire stirring rod
- inner brass cup
- outer brass cup
- small clamp (check limitation of screw)
- large C-clamp
- pliers to tighten clamp
- crank (on vertical shaft, not horizontal shaft) with gears that turn the cylinder
- beam balance for weighting some experimental components
Introduction

It will help you to begin by reviewing the following material in *Knight, Jones and Field* (2nd ed.) (KJF2): Chap. 7.4, Chap. 10, Chap. 11.

The relationship between heat flow into a material and its resulting temperature change was deduced long before our present understanding of heat as a form of energy. An incorrect “caloric theory”, now obsolete, was invented by Antoine Lavoisier in the late 1780s. It held that heat was a self-repellent fluid – the “caloric” – that flowed from hot to cold. Lavoisier was attempting to correct an earlier, also incorrect, “phlogiston theory” (of combustion) that was introduced in the 17th century, with phlogiston the supposed substance of heat. Not until the work of Count Rumford in the late 1790s and, especially, James Joule and others in the mid 19th century, was heat understood to be a form of energy that had to be included for the conservation of energy to be maintained as a central concept in physics; see this link [http://en.wikipedia.org/wiki/Mechanical_equivalent_of_heat].

Along the way, a unit of heat (the calorie) was invented to quantify heat flow. A calorie is defined as the amount of heat necessary to raise the temperature of one gram of water by one degree Celsius. The equivalence of heat energy and mechanical energy can be deduced by measuring, for example, the amount of heat created when a frictional force does a known amount of work on an object (the “system”).

http://www.ic.sunysb.edu/class/phy121pk/labs/doku.php?id=lab_8
We will use this technique to measure the proportionality constant between the heat unit calorie and the energy unit Joule.

A simple schematic diagram of the apparatus is shown above. The inner brass cup is partly filled with water. The outer brass cup is connected to a crank handle that will be turned (by you and/or your lab partner) around an axis of rotation (shaft driving a gear set). The inner cup is stationary. Thus, with the inner cup lowered into, and kept in contact with, the outer cup, there is friction between them. During your cranking of the handle, the work done by the frictional force is converted to heat. You will measure the mechanical work done (in Joules) and the heat generated (in calories) and thus determine the conversion factor between the two units.

If you apply a constant torque $\tau$ to a disk with radius $R$ by applying a constant force $F$ tangentially to the disk, the torque is given by $\tau = FR$. The work $W$ done by turning the disk through an angle $\theta$ is given by $W = \tau \theta$. If $N$ turns are made this angle is $(N \times 2\pi)$ radians. Thus the work done in $N$ turns is

$$W = 2\pi NFR$$

(8.1)

In your experiment you don’t turn the disk holding the inner brass cup; you turn the outer cup with a crank and hold the disk stationary with a string exerting a force that is measured by a spring balance attached to the string. The frictional force between the two cups does not set the inner cup and disk in motion, but, rather, it is balanced by the tension force in the string. Thus the formula (8.1) above is valid for the way you carry out the experiment.

The amount of heat delivered to the system can be determined by measuring the change, $\delta T$, in the temperature of the system. In general, the amount of heat $Q$ absorbed or released by a single material with mass $m$ and specific heat $c$, which does not undergo a phase change, can be calculated by using the equation

$$Q = mc\delta T$$

(8.2)
In this lab, we will use the Greek letter \( \delta \) to denote ‘change’, not \( \Delta \), which will be used to denote uncertainties as we have done for the other labs.

When you begin the experiment by turning the crank to generate heat by friction, you will start with water at an initial temperature, \( T_i \), a few degrees Celsius below room temperature, \( T_{room} \), and end the experiment at a final temperature, \( T_f \), that should be about the same amount above room temperature. You should do this so that the heat gained by the system from the environment (the room) when the water temperature is below \( T_{room} \) is roughly canceled by the heat lost from the system to the environment (the room) when the water temperature is above \( T_{room} \).

**Procedure**

- Disassemble the apparatus by moving the small clamp pressing against the aluminum disk off the top of that disk.
- The stopper in the middle of the aluminum disk contains a thermometer and a stirring rod; remove the stopper from the middle. **Be careful not to stress (and break!) the glass thermometer.**
- Gently remove the thermometer and the stirring rod from the stopper. Put the thermometer on the table top (where it's safe from being broken accidentally) and after a sufficient time for it to equilibrate to a steady value, use it to measure the room temperature, \( T_{room} \). Write this temperature on your worksheet along with a reasonable estimate you make for the absolute uncertainty in reading this temperature. **NOTE:** This uncertainty corresponds to your ability to read the temperature, i.e., the resolution of your reading. Since you do not have a temperature standard, you have no idea of what the accuracy is for this reading. The lab teaching staff checked this for all 15 thermometers in the room. We found that different thermometers disagree with each other by a few degrees Celsius when they “should be” recording the same temperature, via., \( T_{room} \), which was twenty-something degrees Celsius. However, they disagreed by the same amount (to a few tenths of a degree Celsius in most cases) when we used them to measure our “standard”, a cup of water in thermal equilibrium with ice, viz., zero degrees Celsius. Therefore, we found each thermometer does a reasonably accurate job of reading temperature differences. For this reason you must use the same thermometer, “your” thermometer, to read all temperatures for your experimental apparatus.
- Unscrew the two screws on top of the aluminum disk. Pull out the inner and outer brass cups.
- Using a beam balance to measure the masses of the following components:

\[
\begin{align*}
    m_b &= \text{mass of inner brass cup and outer brass cup combined} \\
    m_s &= \text{mass of stirring rod} \\
    m_{th} &= \text{mass of thermometer}
\end{align*}
\]

- Assuming that each mass measurement has an absolute uncertainty of 0.2 grams, enter all mass values on your worksheet.

- Add cold water (roughly 6-8°C below room temperature) to the inner brass cup so that it is about 90% full. (You will have to make your sample of “cold water” by using tap water and small bits of ice that the TA will have available for you. You must figure out how to get your “thermal system” to the suggested amount of temperature below \( T_{room} \).) After you have added the water, put the inner and outer brass cup on a beam balance to determine the total mass of the cups plus water. To determine the mass of the water, \( m_w \), subtract \( m_b \) from this total mass. Assume this measurement has an absolute uncertainty of 0.2 grams and enter it on your worksheet.
- Measure the diameter $d$ of the aluminum disk with a ruler and assume that it has an absolute uncertainty of 2 mm. Make sure your measurement does not include the depth of the groove where the string sits (on both ends of the diameter). Write your values on your worksheet.

- Reassemble the device with the inner cup still filled with the water for which you determined the weight above. Make sure that there is a piece of paper between the inner and outer cup during reassembly so that the crank can be turned smoothly against friction. Make sure that the string is sitting in the grooves of the aluminum disk and of the pulley. The pulley should be aligned as shown in the figure below.

![Diagram showing the correct alignment of the pulley and string.](image)

- There should be a slight force on the spring, i.e., the arrow should be pointing to a value higher than 0 when the string is connected to the spring balance. In order to increase the force of friction, clamp down on the aluminum disk down by tightening the screws on the black clamp. You want the measured frictional force to be 2 - 3 N when you and/or your partner turn the crank. You can check the accuracy of the spring balance by using an $m = 200$ gram weight (provided by the TA: it should be out on/near your table) as a test mass. Of course its weight is $w = mg$.

- Insert the bent-aluminum-wire stirring rod into the slit of the stopper so that you can stir the water effectively. After stirring the water to have a uniform temperature, measure the initial temperature, $T_i$. **NOTE:** This $T_i$ is the temperature that should be 6 to 8 °C below $T_{room}$! Write the equilibrated, measured value for your $T_i$, along with your estimate of its absolute (reading) uncertainty, on your worksheet.

- The crank handle is attached to a counter so that the number of turns can be measured. Make sure you know what direction to turn the crank so that the turns counter counts “up”, not down. Check to see that each revolution of the cylinder (in which the outer brass cup is to sit stationary) raises the counter by 1 digit. Also note that when the crank handle is turned, the spring balance registers the force needed to keep the inner cup stationary. Adjust the “springy device” that presses down on the aluminum disk so that the force registered by the spring balance will be in the range 2 to 3 Newtons when you turn the crank smoothly and continuously. This will be (approximately) the force of friction between the rotating inner brass cup and the stationary outer brass cup. Since you cannot “zero” the mechanical counter, make sure you record the initial value of the counter on your worksheet before you start doing the cranking for the actual experiment. As you and/or your partner turn the crank, try to keep the force steady by turning smoothly and continuously.

- While one partner cranks, the other should frequently be “spot-checking” the temperature of the water and recording the values of the force, $F$, on the spring balance. Since you will notice that the arrow of the spring balance tends to jitter between two values, take the average of them as a reasonable estimate for $F$. The smallest subdivision of the spring balance scale of 0.1 N is not a good estimate for $\Delta F$, the uncertainty in $F$. Above, you should have already checked the accuracy.
of your spring balance with a 200 gram test mass. Because of the “jumpiness” of your spot-checked readings, assign a 15% (reading) relative uncertainty to your measurement of $F$. On your worksheet record the average of the force values you wrote down during the spot-checking above along with its absolute uncertainty, which you need to calculate from the suggested 15% relative uncertainty and your calculated average value for $F$.

- DO NOT stop cranking the handle during the spot-checked temperature measurements. If one person doing the cranking gets tired, the partners should switch jobs as quickly as possible.

- Continue to crank the apparatus until the final temperature $T_f$ is roughly as far above room temperature as the initial temperature $T_i$ was below it. You definitely want to keep symmetry about room temperature, i.e., if $T_i$ was 6 °C below room temperature, you should keep cranking until the temperature has risen about 6 °C above room temperature.

- Even after you have stopped cranking, continue to make frequent temperature measurements because the temperature value will continue to rise for a short time, and don’t forget to stir the water before you take each measurement. Your highest temperature value will be the final temperature value, $T_f$. Make an estimate for the (reading) uncertainty, and record both values on your worksheet. Also record the final value of the turns counter. Calculate $N$, the number of turns of the outer cup by subtracting the initial counter value from the final counter value and enter it on your worksheet.

### Analysis

Use Eq. (8.1) to calculate the work $W$ done by friction when you and/or your partner turned the crank. Calculate its uncertainty according to expressions (E.3) and (E.7) in *Uncertainty, Error and Graphs*, the Lab 1 manual, from the uncertainties of the effective diameter $d$ of the disk and the force $F$. Calculate the temperature rise $\Delta T$ of the system and its absolute uncertainty according to expression (E.6) from the Lab 1 manual.

In this experiment, the generated heat is absorbed not just by one single material; it is absorbed by four different materials: the water, the brass cups, the bent-wire stirring rod, and the thermometer. To calculate the total heat absorbed by this system, you must use Eq. (8.2) for each of the materials. Assume that the stirring rod is made of aluminum and the thermometer is made of glass. The specific heat $c$ for each material is provided in the table below; consider them to be without experimental uncertainty. **Note the units.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Heat $c$ [cal g$^{-1}$°C$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>1.000</td>
</tr>
<tr>
<td>brass</td>
<td>0.092</td>
</tr>
<tr>
<td>aluminum (stir rod)</td>
<td>0.215</td>
</tr>
<tr>
<td>glass (thermometer)</td>
<td>0.200</td>
</tr>
</tbody>
</table>

To calculate the heat, $Q_w$, absorbed by the water, use Eq. (8.2). Repeat the calculation for the brass cups, for the stirring rod, and for the thermometer. Record these values on your worksheet. Calculate the total heat $Q$ by taking the sum of the heat absorbed by each of the four materials. You should see that the main contributions to the overall absorbed heat are from the brass cups and the water. Since the relative uncertainties in the masses of both the brass cups and the water are fairly small, you can consider only the uncertainty in your change of temperature ($\Delta T$) when calculating the uncertainty in $Q$. Therefore, you can find the absolute uncertainty in $Q$ simply by multiplying it by the relative uncertainty in $\Delta T$.

Calculate your value for the experimental proportionality constant between the heat unit of the calorie and the energy unit of the Joule by calculating the ratio $\frac{W}{Q}$. Calculate the uncertainty for this ratio according to
expressions (E.3) and (E.7) from the Lab 1 manual. Compare your measured value of \( \frac{W}{Q} \) with the accepted value of 4.190 J/cal (for the so-called “mean calorie” – there are several different definitions of the calorie! This doesn’t happen for SI units such as the Joule.) and check whether your measurement is consistent with it, i.e., do they agree within experimental uncertainty.