Mechanical Equivalent of Heat

Sreela Das

Lab Partner: Isaac Melendez

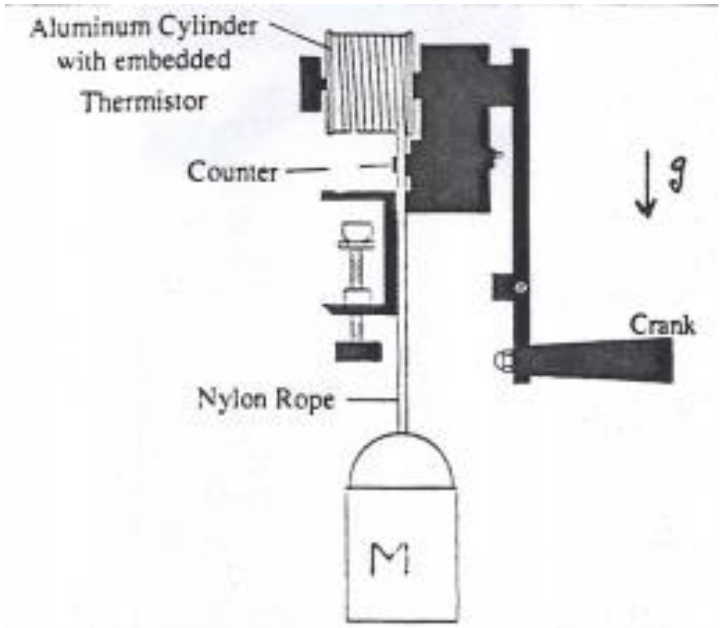
Performed: September 24, 2014

Due: October 08, 2014

Objective:

To demonstrate the mechanical equivalent of heat and observe the conversion of mechanical energy into heat and consequently into electrical resistance.

Description:



An aluminum cylinder with an embedded thermistor is attached to the crank and the resistance across it is measured by a Fluke multimeter. As the crank is rotated, the friction between the cylinder and the crank cause the cylinder (and thereby the thermistor) to heat up. The resistance of the thermistor depends negatively on the temperature so as the crank is rotated and the temperature rises, the resistance across it decreases and this decrease can be seen on the multimeter.

Theory:

The work done by the crank on the thermistor is measured in terms of the equivalent change in potential energy if the work were being done against gravity. As the crank rotates, the aluminum cylinder rotates and the cord wrapped around it raises the bucket above the ground. When the cord slips, instead of being converted into potential energy, the work is done only against the friction between the cord and the cylinder and the friction between the slip rings of the thermistor and the crank brushes. This friction generates heat and raises the temperature of the thermistor and aluminum cylinder thereby reducing the resistance across it. This work is equivalent to the work that would be required to lift the bucket off the ground by a distance of $2\pi rN$ where r is the radius of the aluminum cylinder and N the number of turns of the crank, which would be equivalent to $\int_0^{2\pi rN}(Mg)dh = (2\pi rN)Mg$

This work is converted into heat from friction which can be calculated using $Q = mc\Delta T = mc(T_2 - T_1)$ so from this we have:

$$2\pi rNMg = mc(T_2 - T_1)$$

From this, using $0.220\ cal/g \cdot \text{degC} = 220\ cal/kg \cdot \deg C$ for 'c' and SI units for all other quantities, we get that:

$$\frac{2\pi rNMg}{mc(T_2 - T_1)} = \frac{\text{Joules}}{\text{calories}}$$

Procedure:

- The aluminum cylinder was removed from the crank and cooled in an ice bath until the resistance corresponding to the desired temperature was attained. The cylinder was cooled to a lower temperature but monitored until the temperature reached a desirable value.
- The crank was then turned to do work on the cylinder thereby increasing the temperature until the higher temperature desired was reached. This too was measured by arriving at the corresponding Resistance.
- Care was taken to ensure that the bucket was raised above the ground but did not hit the table or the crank stand.

- On multiple occasions the cord would begin to overlap causing too much friction to allow for slipping. In this case the bucket would be raised until it hit the table or the crank stand and the experiment would need to be restarted.
- Multiple runs of this experiment were recorded to check for random errors.

Data:

The number of turns of the crank, the changes in Resistance and the temperature changes corresponding to these changes in Resistance were all recorded as follows:

	Mass (M, in grams)	Number of turns (N)	Initial Resistance (in kΩ)	Corresponding Initial Temperature (°C)	Final Resistance (in kΩ)	Corresponding Final Temperature (°C)
1	9958	208	169.9	14.0	78.9	30.1
2	9958	212	169.9	14.0	79.2	30.0
3	9958	204	169.9	14.0	78.8	30.1
4	9958+147.1 = 10105.1	199	169.9	14.0	81.5	29.4
5	9958+2000 = 11958	179	169.0	14.1	78.9	30.1

Assuming an uncertainty of 0.5 kΩ in the multimeter readings, we get an uncertainty of 0.25°C in the temperature measurements (within our temperature range of room temperature ±8°C).

Analysis:

We collected 3 sets of data for the regular lab which resulted in consistent readings with an experimental value of 208±2 turns for a net change of 16.06±0.04°C

From our data, we find that:

$$\frac{2\pi rNMg}{mc(T_2 - T_1)} = \frac{2\pi \times (0.024\text{m}) \times 208 \times 9.958\text{kg} \times 9.8\text{m/s}^2}{0.201\text{kg} \times 220\,\frac{\text{cal}}{\text{kg. degC}} \times 16.6} \cong 4.38\ \text{J/cal}$$

This value, as expected is slightly higher than the theoretical value of the mechanical equivalent of heat.

Assuming a 1% uncertainty in all value that were given, the uncertainty can be calculated using:

$$\left(\frac{\delta_{J/cal}}{\text{J/cal}}\right)^2 = \left(\frac{\delta_r}{r}\right)^2 + \left(\frac{\delta_N}{N}\right)^2 + \left(\frac{\delta_M}{M}\right)^2 + \left(\frac{\delta_m}{m}\right)^2 + \left(\frac{\delta_{\Delta T}}{\Delta \text{T}}\right)^2 + \left(\frac{\delta_c}{C}\right)^2$$

$$= (.01)^2 + \left(\frac{2}{208}\right)^2 + \left(\frac{0.05}{9.958}\right)^2 + \left(\frac{.05}{201.55}\right)^2 + \left(\frac{0.04}{16.06}\right)^2 + (.01)^2 \cong 3 \times 10^{-4}$$

The relative uncertainties in mass and change in temperature are in fact small enough to be negligible for this calculation

From here we can see that:

$$\frac{\delta_{\frac{J}{cal}}}{\frac{\text{J}}{\text{cal}}} = 1.79 \times 10^{-2}$$

Which gives us an absolute uncertainty of: 0.08J/cal and a range of 4.30J/cal to 4.46J/cal

Although this range does not include the theoretically expected value of mechanical equivalent, a large part of this is due to the fact that our calculations assume a thermally isolated system which is not the case with the actual experiment.

Questions:

1. If the crank is turned too slowly, the turning of the cylinder is not fast enough to cause slipping and the friction causes the bucket to rise till it hits the table/crank stand. In this case work is converted into potential energy instead of heat.
2. The cord has a non-zero thermal conductivity and therefore some heat from the aluminum cylinder is lost due to conduction through the cord but this thermal conductivity is very small in comparison with that of the aluminum cylinder and since the surface area of contact is fairly small, the heat that leaves the cylinder through conduction is negligible.

   The heat capacity of the cord is comparable with and in fact slightly larger than that of aluminum so to be at the same temperature as the aluminum, the cord absorbs a significant part of the heat from the aluminum. Since for the sake of this experiment we assume there is no heat flow out of the system, this creates an un-accounted for error in our values (giving a higher value of the mechanical equivalent of heat)
3. Making the temperature difference larger will reduce the relative error in the final calculation i.e, an uncertainty of 2°C in a 8°C temperature difference will result in a larger overall uncertainty than a 2°C uncertainty over a 20°C temperature difference. On the other hand, a smaller temperature difference (while keeping room temperature at the mean) will slow down heat flow out of the system, thereby reducing uncertainty due to heat changes and making it closer to the thermally-isolated-system approximation.
4. The lower and higher temperatures are chosen to be symmetrically above and below room temperature so that the heat flow out of the system is symmetric i.e the amount of heat flowing into the system when the cylinder is below room temperature is roughly the

same as the heat flowing out of the system when the cylinder is heated to above room temperature. This again brings us closer to a thermally-isolated-system.

5. The heat flow error is minimized by using temperatures symmetrically above and below room temperature and a cord with greater tensile strength that allows for a smaller surface area without compromising on force exerted.
6. If there is moisture on the outside of the cylinder, this will cause adhesion with the cord and will not allow slipping so the work done will be converted to potential energy instead of heat. If the moisture is on the inside of the cylinder, this will come in contact with the brushes and the cylinder will rotate more smoothly while heating up to a lesser degree. In both these cases, the result will be a higher Joule per calorie value.

Original Experiment:

Initially, we tried to increase the mass marginally by adding the mass of the Vernier calipers, but this did not make a significant difference since the additional mass (~ 147 g) was a little over 1% of the mass of the bucket, which falls close enough to make the difference negligible. Even with this small change in mass, the number of turns required to cause the same temperature change was found to be 199, slightly less than the number required without the additional mass. This verifies the inverse proportionality of the number of turns and the mass of the bucket.

To make a stronger argument for this case (one that was not within the scope of error for te regular experiment) we added a mass of 2kg to the bucket. This led to a much sharper decrease in the number of turns required – the same rise in temperature was obtained with 179 turns.

Using the equations from the work-heat equation, we can find that the mechanical equivalent of the work in this case comes out to be: 4.53J/cal which is greater than the value calculated earlier in the experiment.

Conclusion:

The work done is assumed to be going entirely into raising the temperature of the cylinder whereas this is not the case. Part of the work done goes into the change in potential energy of the bucket when it is raised and this is part of the reason why the work done is significantly larger when the additional mass is added to the bucket. Part of the uncertainty in the original part of the experiment can also be attributed to the placement of the additional mass on the bucket – if not placed exactly above the centre-of-mass, the force exerted due to the additional mass will be greater than just $m \times g$. All of this will result in a larger calculated value of work (Joules) per unit heat (calories) resulting in the kind of errors we saw.