MECHANICAL WORK AND ENERGY CONVERSION INTO HEAT

Purpose

a. To demonstrate the conversion of mechanical work to heat.

b. To determine the relationship between the conventional units of work and heat.

Theory

Energy is one of the fundamental quantities in physics. Energy can be found in different forms and converted from one to other forms. In this experiment, we will demonstrate mechanical energy conversion into heat and establish the relationship between the conventional units of work and heat experimentally.

According to the work-energy theorem, which follows from Newton's laws of motion, when a force does work on an object, the object's energy increases. Sometimes this energy takes the form of kinetic and potential energy of the object as a whole (such as when you throw a ball up in the air). But sometimes it can take the form of internal energy. For example, if you rub your hands you can feel your hands getting warm. When the force of friction acts on an object, the object's temperature increases, indicating an increase of internal energy. We will turn a metal cylinder against friction for mechanical work. Schematic for this experiment is shown in Figure 1. A nylon cord is wrapped around a metal cylinder and a weight is hung at the end of the cord. We rotate the cylinder inside the wrapped cord.

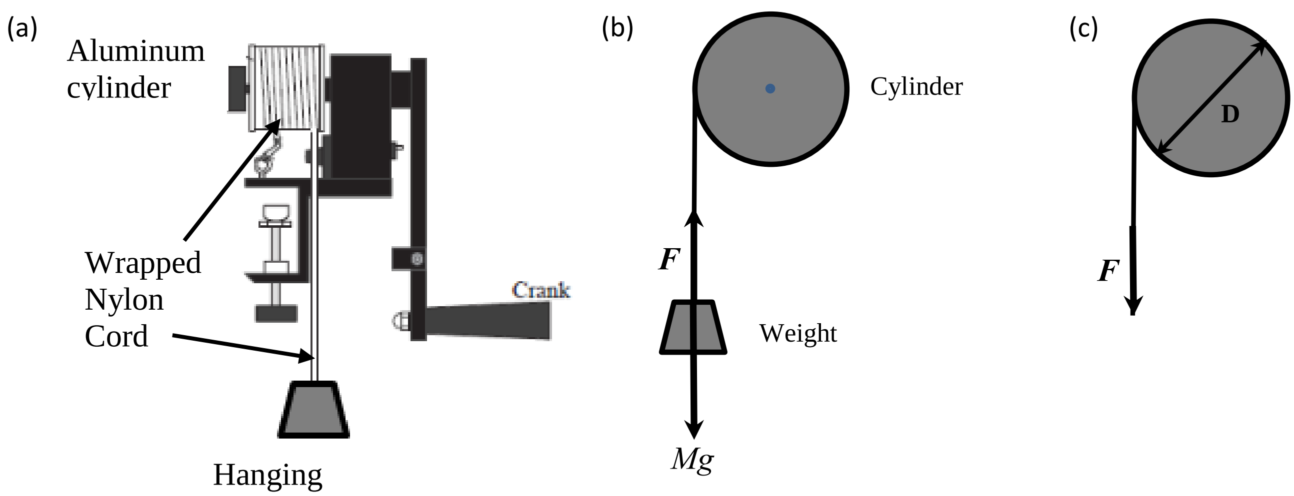


Figure 1: (a) Set up for energy conversion (b) force diagram for bucket and (c) cylinder.

Mechanical work is expended by turning a crank handle against the frictional force between the metal surface and the cord. We try to keep the cord and the bucket in equilibrium. Thus the upward frictional force felt by the cord balances the hanging weight.

$$F = M g , \qquad (1)$$

where M is the mass of the hanging object. F is also the force exerted by the cord on the cylinder. The work done by the frictional force on the cylinder, for each turn of the crank, is F times the circumference of the cylinder. If there are N turns, the work is $W = N F (\pi D) = N M g (\pi D)$, where D is the diameter of the cylinder. Thus

$$W = (\pi D M g) N . \qquad (2)$$

N is the number of turns the crack is rotated. Remember you are doing mechanical work against the friction. The work done by the friction adds the internal energy thereby increasing the temperature of the cylinder. The work-energy theorem is $W = \Delta E$. Assuming all the mechanical work is used to increase the internal energy and raised the temperature by ΔT, we can then write W in terms of temperature as

$$W = A \, \Delta T , \qquad (3)$$

where A is a constant.

The most common way of raising the temperature of an object is to add heat. Heat is the energy transferred between objects because of a temperature difference. The process of heating is really a process of adding energy. Quantitatively,

$$Q = m \, c \, \Delta T , \qquad (4)$$

where Q is the heat added, m is the object's mass, c is the specific heat, and ΔT is the change in temperature. ΔT is in ˚C, m in kg, Q in kcal, and c in kcal/(kg·˚C). The kcal unit is that of kilocalories, a non-SI unit of energy that was historically used for heat.

The quantity A can be thought of as the amount of work (in Joules) necessary to raise the temperature by 1 ˚C; it will be the slope of a graph of W vs. T. Similarly, if a system is heated, the product mc is the amount of heat (in kcal) needed to raise the temperature by 1 ˚C. Both heat and work represent energy but historically have been measured in different units. Traditionally heat has been measured in the units of calories (cal). 1 cal of heat raises the temperature of 1 g of water at around 15 ^{o}C by 1 Celsius degree. In this experiment, you will determine equivalence between these two units, calories and joules. (Note: the Calorie (Cal) used for food (note the capital C) is 1000 cal or 1 Kcal.)

James Joule, in a series of experiments in the 1840s, demonstrated the "equivalence" of heat and work in this sense. Our experiment is a modernized version of Joule's experiment. By continuously doing work on a system (an aluminum cylinder), we will be able to watch its temperature rise. We will plot a graph of W vs. T, and determine the slope, A. Then we will compare A to the quantity mc, where the mass m of the cylinder will be measured and the value of c for aluminum will be looked up in a handbook. If A is the work needed to raise the temperature by 1 ˚C, and mc is the heat needed to raise the temperature by 1 ˚C, then the ratio, A/mc, is the number of joules per kcal. This important constant establishes the quantitative relationship between heat in kcal and work in joules.

Apparatus

Mechanical equivalent apparatus with Aluminum cylinder, crank, axle and counter system, nylon cord, bucket, weights, electrical meter, two electrical leads, and pieces of paper towel.

Description of Apparatus

The experimental set up for this experiment is shown in Figure 1. Work will be done on an aluminum cylinder, which fits over an axle, and can be rotated by a crank. A counter on the apparatus records how many times the crank is turned. A nylon cord is wrapped three or four times around the cylinder, and friction between the cord and the cylinder is created as the cord slides relative to the surface of the cylinder, around its circumference. One end of the cord hangs below the lab table, where it is attached to a bucket holding heavy weights. Rather than pull the cord around the cylinder, we rotate the cylinder inside the cord. We try to keep the cord and the bucket stationary, with the bucket suspended a few centimeters above the floor. In this way we have an equilibrium of forces: the upward frictional force felt by the cord balances the weight of the bucket.

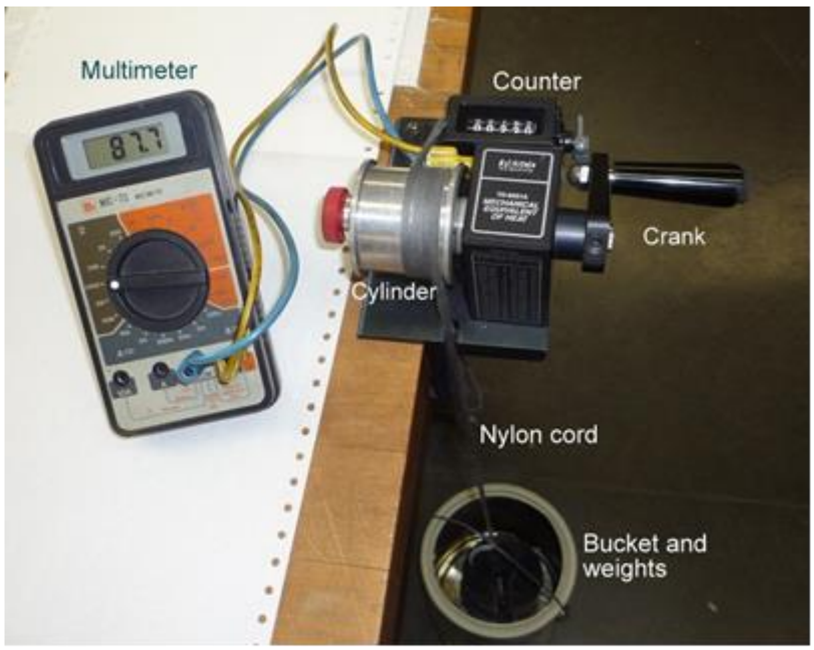


Figure 2: Picture of a real experimental set up

From equation (2), mechanical work,

$$W = (\pi D M g) N .$$

By counting the number of turn N made by the crank, we can determine the mechanical work. To measure the temperature of the cylinder while it is rotating, we use a device called a thermistor. It is based on the fact that the electrical resistance of materials varies with temperature. The thermistor is embedded in the aluminum cylinder, and electrical contacts are made to the two copper rings that can be seen at the base of the cylinder.

When the cylinder slides onto the axle, these rings press against two copper contacts. You may need to check that this electrical contact is secure. A multimeter is used to measure the resistance of the thermistor through two leads attached to the copper contacts. The relationship between resistance and temperature is given on the graph attached to this write-up. The unit of resistance is the Ohm (Ω). From the reading of the resistance of the thermistor, we can work out the temperature of the aluminum cylinder.

Procedure

1. Measure the mass (*m*) and diameter (*D*) of the cylinder.
2. We will want the cylinder to begin below room temperature. Place it in a zip-loc bag to keep it dry, and put it into an ice-water bath. It will take a few minutes to cool down. *It is critical to keep the cylinder and the nylon cord dry throughout this experiment; otherwise your result will not be accurate at all. Throughout the experiment, make sure to keep the cylinder dry by using pieces of paper towel provided.*
3. Measure the mass of the bucket and calculate *M*, the total mass of the bucket plus the weights inside.
4. The specific heat of aluminum is 0.22 kcal/(kg·˚C). Calculate the product, *mc*, for the cylinder.
5. Look at the graph of resistance vs. temperature. Make some rough notes on the values of resistance from 10 ˚C up to 30 ˚C, so that you will know about the range of temperature that your apparatus is at during the heating process. How much change in resistance corresponds to a change of 2 or 3 ˚C in temperature?
6. Attach the multimeter, and set the scale to 200 kΩ maximum.
7. Measure room temperature with a thermometer.
8. When you are ready to proceed, place the cylinder on the axle, *making sure the notch is in place so that the rings press against the contacts*, and the cylinder rotates securely. Remove the knurled knob from the handle of the crank and use it to secure the cylinder on the shaft. Wrap the cord around the cylinder about four times in such a way that it doesn't overlap itself. The bucket should be suspended a few centimeters above the floor. Do not allow the bucket to move higher. If it falls, it could damage your toes. Securely tie the loose end of the nylon cord to an appropriate fixture beneath the table, so that when the cylinder is rotating, the nylon cord remains stationary.
9. Note the initial resistance value. It should correspond to a temperature at least 5 -10˚C below room temperature. Reset the crank counter to zero.
10. Now, turn the crank smoothly while keeping the bucket suspended and stationary. Don't let the cord bunch up or overlap itself. Take simultaneous readings of the counter and the multimeter after each increase of 2 or 3 ˚C. Note that you do not have to crank at a constant rate, and it will be convenient to slow down when taking a reading. Keep going until you get up to about 30 ˚C. Hence the range of temperature you should consider is approximately 10 – 30^{o}C.

Computation

From your multimeter readings, determine each temperature of measurement, and record in the data table. Calculate the total work done at each measurement, from Equation 2. Plot Work (in Joules) vs. Temperature and mark room temperature on the graph. Look carefully at the points, and decide whether the data can be fit well by a straight line, or whether it might be better fit by a smooth curve.

Deviation from a straight line may occur because of heat transfer with the environment. If the only input of energy to the cylinder were the work done by the cord, the work would be proportional to the increase in temperature. But when the cylinder is below room temperature, some heat is gained by the cylinder from the environment. Hence the slope will be too small. When the cylinder is hotter than the air in the room, there is some loss of heat to the room. In this case, more work would be required to raise the temperature one degree than would be the case with no heat loss. Hence the slope would be too large.

If your data are fit by a smooth curve, the best value for the work-temperature relationship would be the slope drawn tangent to the curve at room temperature.

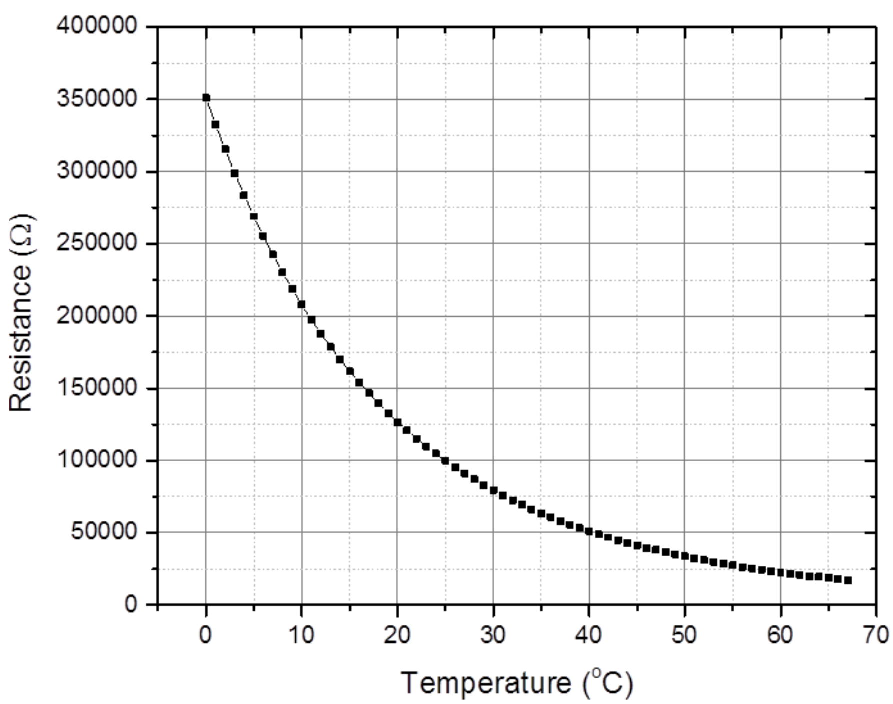
The slope you find is what we called "*A*", the work in joules needed to raise the temperature by 1 ˚C. The quantity, *mc*, calculated above, is the heat in kcal needed to raise the temperature by 1 ˚C. Calculate the ratio, *A/mc*. Compare to the accepted value, 4186 J/kcal (4.186 J/cal), and find the percent error.

Questions

1. Why is aluminum a better choice for the object than, say, steel or plastic?
2. In this experiment, we do not want a significant amount of heat to be transferred from the air to the cylinder, or from the cylinder to the air. Would it be better to have a long narrow cylinder (say, diameter = 1 cm), assuming it had the same volume, or not? Explain.
3. In this experiment, the starting temperature was about as far below room temperature as the final temperature was above room temperature. Explain why this procedure tends to minimize the effect of heat transfer between the cylinder and the environment.
4. Why is it not necessary to crank at a constant rate?
5. A small error occurs if you pull on the loose end of the cord while turning the crank. Why is this error unimportant?

Res. (Ω)	Temp. (∞C)	Res. (Ω)	Temp. (∞C)
351,020	0	66,356	34
332,640	1	63,480	35
315,320	2	60,743	36
298,990	3	58,138	37
283,600	4	55,658	38
269,080	5	53,297	39
255,380	6	51,048	40
242,460	7	48,905	41
230,260	8	46,863	42
218,730	9	44,917	43
207,850	10	43,062	44
197,560	11	41,292	45
187,840	12	39,605	46
178,650	13	37,995	47
169,950	14	36,458	48
161,730	15	34,991	49
153,950	16	33,591	50
146,580	17	32,253	51
139,610	18	30,976	52
133,000	19	29,756	53
126,740	20	28,590	54
120,810	21	27,475	55
115,190	22	26,409	56
109,850	23	25,390	57
104,800	24	24,415	58
100,000	25	23,483	59
95,447	26	22,590	60
91,126	27	21,736	61
87,022	28	20,919	62
83,124	29	20,136	63
79,422	30	19,386	64
75,903	31	18,668	65
72,560	32	17,980	66
69,380	33	17,321	67

Resistance versus temperature of the thermistor.



Data Sheet

Date experiment performed:

Name of the group members:

Mass of cylinder (*m*):

Diameter of the cylinder (*D*):

Mass of the bucket and weight (*M*):

Table 1.

Number of turns, N	Multimeter reading (Ω)	Temperature (^{o}C)	Work (J), $W = (\pi D M g) N$