THE INCREDIBLE MASS-LIFTING HEAT ENGINE (10/30/09)

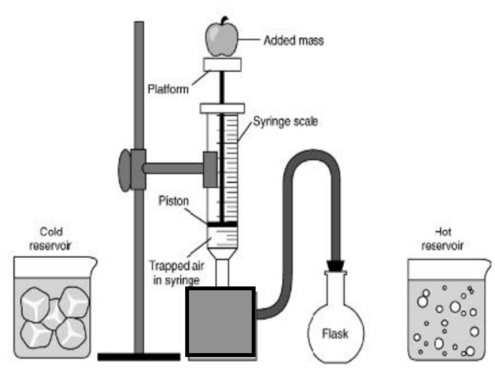
Equipment:

- 1 glass syringe, 10cc
- 1 Erlenmeyer flask, 25 ml
- 1 #0 1-hole rubber stopper with Tygon® tubing & connector
- 1 vertical rod
- 1 rod clamp
- 1 test tube clamp
- 250 ml beaker
- 8 oz Styrofoam cup (for ice/water mix)
- 1 50 g mass
- crushed ice, approx 50 ml
- small tray (to contain spillage)
- ruler
- pitcher (for water)
- thermometer (2)
- level
- hot plate
- paper towels
- electronic balance (optional – one for class)

Your working group has been approached by the Newton Apple Company about testing a heat engine that lifts apples that vary in mass from 50 to 100 g from a processing conveyor belt to the packing conveyor belt, which is 5 cm higher. The engine you are to experiment with is a "real" thermal engine that can be taken through a four-stage expansion and compression cycle and that can do useful mechanical work by lifting small masses from one height to another.

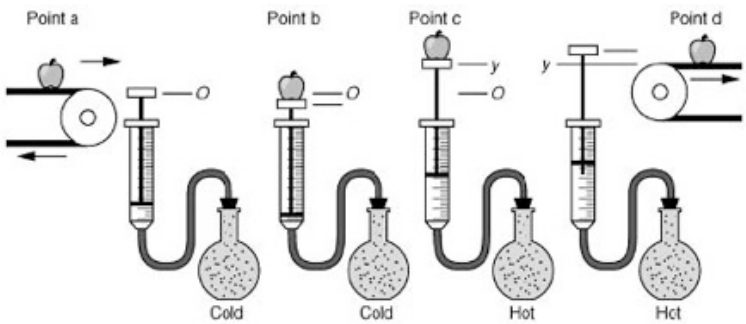
We would like you to verify experimentally that the useful mechanical work done in lifting a mass m through a vertical distance y is equal to the net thermodynamic work done during a cycle as determined from the enclosed area on a p −V diagram. Essentially you are comparing useful mechanical lifting work, calculated using mgy, with the thermodynamic work performed during one cycle of the heat engine obtained by calculating the area enclosed by one cycle on a p –V diagram.

The cylinder of the incredible mass-lifter engine is a low-friction glass syringe. The flat top of the handle of the piston serves as a platform for lifting masses. The flask can be connected to the syringe with a short length of flexible tubing, and placed alternately in a cold reservoir and a hot reservoir. A schematic diagram of this mass lifter follows.



If the temperature of the air trapped inside the cylinder, hose, and flask is increased, then its pressure will increase, causing the platform to rise. Thus, you can increase the volume of the trapped air by moving the flask from the cold to the hot reservoir. Then when the mass has been raised through a distance y, it can be removed from the platform. The platform should then rise a bit more as the pressure on the cylinder of gas decreases a bit. Finally, the volume of the gas will decrease when the flask is returned to the cold reservoir. This causes the piston to descend to its original position (ideally) once again. The various stages of the mass lifter cycle are shown in the diagram that follows.

The lifting and lowering parts of the cycle should be approximately isobaric, since the pressure in the air trapped in the syringe is determined by the weight of the piston (and the mass on top of the handle) pushing down on the gas. The other two parts of the cycle, when the mass is added and removed from the piston handle, should be approximately adiabatic, because, as they occur very quickly, there is not enough time for an appreciable amount of heat to flow into or out of the system.



A good way to start is to fetch about a pint of water in a pitcher, pour 150 ml into your beaker and preheat it to about **50-55 °C**. Then put some ice in a Styrofoam cup and fill it about half full with an ice/water mix. Before taking data you should set it up and run it through a few cycles to get used to its operation.

<u>CAUTION:</u> NEVER HOLD THE SYRINGE UPSIDE DOWN. THE GLASS PISTON COULD FALL OUT AND BREAK.

To avoid having the piston hit bottom during the cycle, you will need to begin with the piston resting above the bottom of the syringe when the contained air is cold. Thus, we suggest first inserting the rubber stopper (with the tubing) into your flask and immersing the flask in the ice/water mix. Allow ample time for the air in the flask to reach thermal equilibrium with the ice/water mix. Raise the piston so that the volume of air in the syringe is about 2 cc then connect the tubing to the syringe (with a push & twist). Since more mass on the piston will mean greater pressure and more air leakage, we suggest that you limit the added mass to 50 g (instead of an apple). When taking measurements, be efficient – don't let the syringe sit for too long or your experiment may be compromised by leakage. **Note: The tubing is sealed in the stopper hole. Do not pull on it!**

IMPORTANT: As you take the engine though its cycle, observe whether the piston is moving freely in the syringe. Use a level to make sure the syringe is vertical. (If you still suspect sticking, try tapping the test tube clamp <u>lightly</u> with a pencil.) Make sure the rubber stopper is firmly in place and the tubing connector is screwed tightly to the bottom of the syringe.

After observing a few engine cycles, you should be able to describe each of the points a, b, c, and d of the cycle, carefully indicating which of the transitions between points are approximately adiabatic and which are isobaric.

You should reflect on your observations by answering the questions in the next activity. You can observe changes in the volume of the gas directly and you can predict how the pressure exerted on the gas by its surroundings ought to change from point to point by using the definition of pressure as force per unit area.

Part A: DESCRIPTION OF THE ENGINE CYCLE

(Suggestion: Fill in all your predictions first then go thru the cycle and record observations.)

1. Predicted transition a → b: With the system closed to outside air and the flask in equilibrium with the cold reservoir, what should happen to the height of the platform when you add a mass? Explain the basis of your prediction.

Observed transition a → b: Make sure that you start with about 2 mL of gas in the cylinder. Carefully add the 50 g mass to the platform.
<u>Describe</u> what happened. Is this what you predicted? Why might this process be approximately adiabatic?

2. Predicted transition b → c: What do you expect to happen during transition b→ c, when you place the flask in the hot reservoir?

Observed b → c: Place the flask in the hot reservoir. (This is the engine power stroke!) Describe what happens. Is this what you predicted? Why should this process be isobaric?

3. **Predicted transition c → d:** Continue to hold the flask in the hot reservoir and predict what will happen if the added mass that is now lifted is removed from the platform onto an upper conveyor belt. Explain the reasons for your prediction.

Observed c → d: Remove the added mass.
Describe what actually happens. Is this what you predicted? Why might this process be approximately adiabatic?

4. **Predicted transition d → a**: What do you predict will happen if you now place the flask back in the cold reservoir? Explain the reasons for your prediction.

Observed d → a: Cool the system back down to its original temperature for a minute or two before placing a new mass on it. Place the flask in the cold reservoir and describe what actually happens to the volume of the trapped air.

How does the volume of the gas actually compare to the original volume of the trapped air at point **a,** at the beginning of the cycle? Is it the same or has some of the air leaked out? Theoretically, the pressure of the gas should be the same once you cool the system back to its original temperature. Why?

Part B: Determining Volume and Pressure for a Cycle

The total volume of contained gas is the volume of the Erlenmeyer flask + volume of the tubing + volume in the syringe. But the volume of the Erlenmeyer flask and the tubing is a constant of the experiment, V_o, that will not be needed in your calculations. (You will not need to determine V_o in this lab). The absolute pressure of the gas is $P_{atm} + \frac{Mg}{A_{piston}}$ where M is ($m_{added} + m_{piston}$).

You may assume that m_{piston} is 16.77 grams. You can use the fact that the syringe is graduated to determine the effective cross-sectional area of the piston: Use your ruler to verify that the length of the syringe scale from 0 cc to 10 cc is 5.70 cm. The product of this length times the cross-sectional area (A_{piston}) should equal 10 cc. So A_{piston} is this volume divided by this length.

Calculate A_{piston} = ______________

To calculate the thermodynamic work done during a cycle of this engine you will need to plot a P vs. V diagram for the engine based on determinations of the volumes and pressures of air trapped in the syringe at points a, b, c, and d in the cycle.

Write down the expression for the total (i.e. absolute) pressure in the syringe, without any added mass, and calculate the pressure added by the weight of the syringe. (Don't forget to add in the atmospheric pressure P_{atm}.)

P = ______________________________ = _____________________________.

Part C: WORK DONE BY THE HEAT ENGINE

a. Take any measurements needed to determine the volume and pressure of air in the system, as well as the elevation, y, of the piston, at all four points in the engine cycle. (You should do this **rapidly enough to avoid significant air leakage** around the piston.) Summarize your measurements, with units, in the space below.

b. Next, use your measurements to calculate the pressure and volume of the system at point **a**. Show your equations and calculations in the space below and summarize your results with units. (Denote the fixed volume of air in the tubing and flask by "V_o" and atmospheric pressure by "P_{atm}".)

P_a =________________ V_a =____________________

c. Use the measurements at point **b** to calculate the pressure and total volume of the air in the system at that point in the cycle. Show your equations and calculations in the space below and summarize your results with units.

P_b=________________ V_b=____________________

d. What is the height y, through which the added mass is lifted in the transition from b → c?

y = _________

e. Use the measurements at point **c** to calculate the total volume and pressure of the air in the system at that point in the cycle. Show your equations and calculations in the following space and summarize your results with units.

P_c=________________ V_c=___________________

f. Remove the added mass and make any measurements needed to calculate the volume and pressure of air in the system at point **d** in the cycle. Show your equations and calculations in the following space and summarize your results with units.

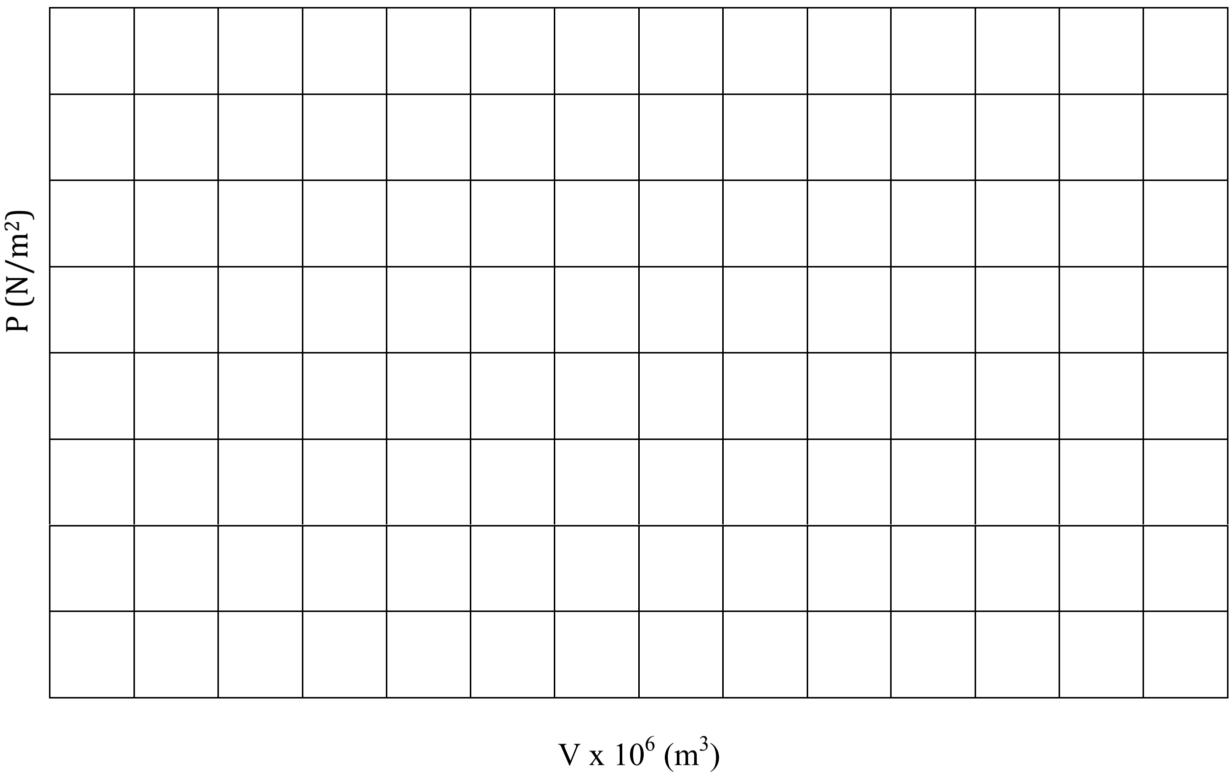
P_d =________________ V_d =____________________

Reflection: We expect that transitions from a → b and from c → d are approximately adiabatic. Explain why.

You should have found that the transitions from b → c, and from d → a, are isobaric. Explain why this is the case.

Part D: Finding Thermodynamic Work from the P-V Diagram

a. Fill in the appropriate numbers on the scale on the graph frame that follows and plot the P-V diagram for your engine cycle. (Suggestion: Consider using V_o and P_{atm} as reference labels.)



b. On the graph above label each of the points on the cycle (a, b, c, and d). Indicate on the graph which of the transitions (a → b, b → c, etc.) are adiabatic and which are isobaric.

c. Using your graph, figure out a way to determine the net work done in a cycle. (hint: You can use the computer if you wish to determine the equation of the lines connecting points a → b and c → d, and/or you can assume the shape is a shape with a known formula for its area, such as a parallelogram or a trapazoid).

Thermodynamic Work: Compute the thermodynamic work in joules, and describe your method below showing any necessary calculations.

Mechanical Work: Use the result for the height that the mass is lifted in the power stroke of the engine to calculate the useful mechanical work performed by the heat engine.

Comparison: How does the thermodynamic work compare to the useful mechanical work? Please use the correct number of significant figures in your comparison. Calculate the percent difference. Discuss your results.

% Difference = __________________

Error: Calculate the error in your measurement for your thermodynamic work and your mechanical work.
Here are some typical uncertainties of various laboratory instruments:

- Meter stick: ± 0.02cm
- Vernier caliper: ± 0.01cm
- Triple-beam balance: ± 0.02g
- Graduated cylinder: 20% of the least count

Process	Value	Uncertainty
Average	$\bar{x} = \frac{x_1 + x_2 + x_3 + \ldots + x_N}{N}$	$\sigma_x = \sqrt{\frac{(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + \ldots + (x_N - \bar{x})^2}{N-1}}$
Addition	$\bar{z} = \bar{x} + \bar{y}$	$\sigma_z = \sqrt{(\sigma_x)^2 + (\sigma_y)^2}$
Subtraction	$\bar{z} = \bar{x} - \bar{y}$	$\sigma_z = \sqrt{(\sigma_x)^2 + (\sigma_y)^2}$
Multiplication	$\bar{z} = \bar{x} * \bar{y}$	$\sigma_z = \bar{z} * \sqrt{\left(\frac{\sigma_x}{\bar{x}}\right)^2 + \left(\frac{\sigma_y}{\bar{y}}\right)^2}$
Division	$\bar{z} = \bar{x} \div \bar{y}$	$\sigma_z = \bar{z} * \sqrt{\left(\frac{\sigma_x}{\bar{x}}\right)^2 + \left(\frac{\sigma_y}{\bar{y}}\right)^2}$

Thermodynamic Work = W ± ΔW

Mechanical Work = W ± ΔW

Thermodynamic Work = _______________

Mechanical Work = ______________

The agreement between the two calculations should be quite good. Considering your calculated error, are you surprised? Why? *(Discuss why you get and expect to get good results)*