Renewable Energy

Lab 3 – Gas Laws and Heat Engines
Fall 2010

Name_____

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Introduction/Purpose:

In this exercise you will test some of the aspects of the ideal gas law under conditions of constant pressure, constant temperature, and constant volume. Then you will build a heat engine to lift apples. Okay, only small ones.

Apparatus: Pasco Gas Law Apparatus, rod stand, water baths at various temperatures, stainless-steel temperature probe, gas-pressure sensor, rotary-motion sensor, PC and Lab Pro interface, 2×50 gm and 1×100 gm masses, 35 grams attached to light thread, plastic syringes and tube couplings, constant-volume brass gas vessels.

Theory:

The Ideal Gas Law

The equation of state for an ideal gas is written:

$$PV = nRT \tag{1}$$

where: P = gas pressure [in Pa or N/m^2];

V = gas volume [in m^3];

n = number of moles of gas;

R = a constant [8.31 J/mol-K]; and

T = the absolute temperature [Kelvin]

When applied to a <u>closed system</u> (i.e. one in which the amount of gas is constant) this generates three famous relationships between the three state variables P, V and T:

1. The Law of Charles and Gay-Lussac states that when a gas is kept at a **constant pressure**, its volume is directly proportional to its temperature.
2. Boyle's Law states that when a gas is kept at a **fixed temperature**, its pressure is inversely proportional to its volume.
3. Finally, if the **volume of a gas is held constant**, its pressure is directly proportional to its temperature.

Pasco Heat Engine/Gas Law Apparatus

The closed system you are given consists of a nearly friction-free piston inside a cylinder. There are two air tubes leading from the cylinder: one goes to a pressure sensor (which is measured using the Lab Pro) and the other leads to an air reservoir (aluminum can) that can be immersed in water to change the temperature of the air in the system.

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For this apparatus the piston diameter is 32.5 ± 0.1 mm.

When positioned vertically on a rod stand, additional masses may be placed on top of the piston platform to change the pressure in the cylinder. The pressure sensor measures the absolute pressure in the cylinder, P, in kPa.

As the piston moves, the volume of the cylinder changes, although it can be held fixed by using the setscrew at the top of the cylinder. The volume of the system consists of the volume of the cylinder plus the volume of the aluminum can and the air hoses. There is a millimeter scale on the cylinder that allows one to directly measure the cylinder height, $h_{cyl.}$ (This height will be measured using the rotary motion sensor.) From this height, the volume of air under the piston, V_{cyl}, may be determined from:

$$V_{cyl} = \pi r_{cyl}^2 h_{cyl} \tag{2}$$

This measurement will NOT, however, be the same as the total system volume, V. Rather:

$$V = V_{cyl} + V_0 \tag{3}$$

Where V_0 is the volume of the aluminum can and air hoses.

V_0 can be determined if the pressure in the system is kept constant (by allowing the piston to move freely with one side always at atmospheric pressure), and vary the temperature by immersing the aluminum can in water at several different temperatures. By measuring V_{cyl} each temperature (since the ideal gas law is $P(V_{cyl} + V_0) = nRT$) you have:

$$V_{cyl} = \frac{nR}{P}T - V_0 \tag{4}$$

Thus, a plot of V_{cyl} vs. T should be a straight line with y intercept at $-V_0$.

Work Done by an Ideal Gas

One example of a system in which work is done is a piston in an air-filled cylinder. If the piston undergoes transitions in which one or more of its properties change, these transitions may be plotted on a *P-V* diagram, with pressure on the vertical axis and volume on the horizontal axis. Any work done by the system during a transition can be found from the equation:

$$W = \int_{V_i}^{V_f} PdV \tag{2}$$

Where V_i and V_f are the initial and final system volumes respectively. But, not to worry, this is also just the area under the curve on a *P-V* diagram, as seen below.

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But for reference, there are several special types of transitions that the system may undergo:

- If the volume is unchanged during the transition, the change is referred to as *isovolumetric*. In such a case, since $dV = 0$, it is obvious from equation 2 that no work is done.

- If the pressure remains constant, the transition is *isobaric*. In this case, equation 2 simplifies to:

$$W = P\Delta V \tag{3}$$

where ΔV is the change in system volume.

- If the temperature remains constant during the transition, the transition is *isothermal*. In such a case, using equation 1, $P = \dfrac{nRT}{V}$, so that equation 2 reduces to:

$$W = \int_{V_i}^{V_f} PdV = \int_{V_i}^{V_f} \frac{nrT}{V} dV = nrT \ln\left[\frac{V_f}{V_i}\right] \tag{4}$$

- If no heat enters or leaves the system during the process, it is called *adiabatic*. In this case, we can use the fact that PV^γ is constant (where $\gamma = \dfrac{5}{3}$ for monatomic gases and $\gamma = \dfrac{7}{5}$ for diatomic gases), to integrate equation 2 above.

Here's the Important Part:
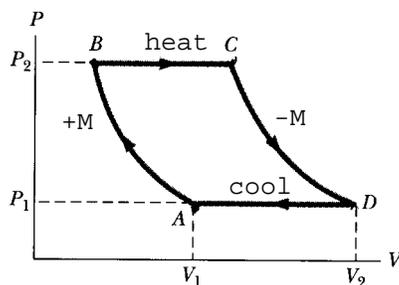
In a heat engine, a system undergoes cyclic transitions that, eventually, return it to its initial state. In this case, the work done during one complete cycle may be found simply from the area enclosed in the *P-V* diagram of the cycle.

The Incredible Mass Lifter Engine

Your lab group has been approached by the Newton Apple Company about testing a heat engine that lifts apples from a lower processing conveyer belt to a higher one. 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. A schematic diagram of the process is shown below:

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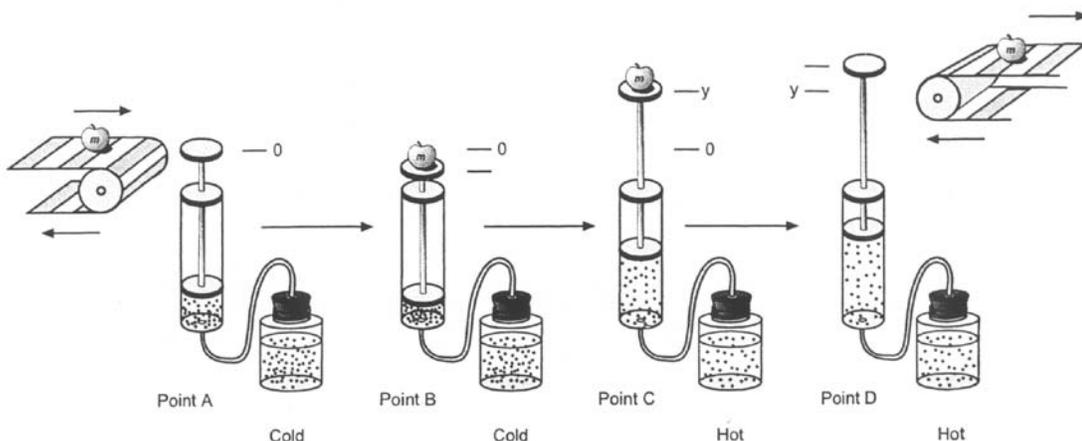
The useful work performed by the engine, calculable from the area enclosed in the *P-V* diagram, should equal *mgy*, the work done on the apple.

Procedure:

A. Law of Charles and Gay-Lussac (Constant Pressure)

1. Mount the gas law apparatus on the table. Mount the rotary motion sensor on the rod stand. To counteract the inherent weight of the piston, and to allow you to measure the piston height, $h_{cyl.,}$ tie 35 grams to one end of a light string and tie the other end of the string through the small hole in the top of the piston. Pass the string up and over the pulley on the rotary motion sensor with the 35 g mass hanging down the other side.

2. Turn on the PC and load the "Charles' Law" LoggerPro template. Record the value of *P,* which is displayed in the meter window at the lower left of the computer screen.

   The Logger Pro template automatically uses the rotary motion sensor and Eq. 2 to find the volume of air in the cylinder. However, it is good technique to also record the cylinder volumes by hand (for equilibrium in each temperature bath). This can be done by recording piston positions directly from the scale on the cylinder wall. The template also records temperature and pressure. Make sure to use the absolute temperature (Kelvin) in your analysis.

   The template will make a time series record of your data. Your goal is to observe this record and determine times where the system is in equilibrium with the temperature bath. You will be extracting values for the three sensors (T, V, and P) for a point in time that you think represents equilibrium. You'll do this for each temperature bath.

3. Carefully twist and detach the connecting hose that leads to the pressure sensor. This brings the inside of the cylinder to atmospheric pressure. Lower the piston to the bottom of the cylinder. (This mechanical zeroing is important because the encoder zeroes itself at the beginning of each data-collection run!!)

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4. Start collecting data now by pushing the "Collect" button in Logger Pro. This serves to document the mechanical zeroing operation in your dataset; but you haven't sealed the system (reattached the hose) yet, so this point won't be used in your V vs. T plot.

5. Next, seal up the system and establish the amount of air that will be subject to the ideal gas law. Raise the piston until it is near the middle of the cylinder, and then reattach the connecting hose. **Record the position of the piston here and the value from your digital thermometer (air temperature).** Alternatively, you may use a room-temperature water bath for this initialization step. You may need to repeat this initialization step later if you suspect your system has leaked any air during the Boyle's law experiment in part B.

6. **Immerse** your water can in the ice/water bath, and wait (keep it under water) until the temperature stabilizes. Now, immerse your aluminum can in water baths at different temperatures, always increasing T as you go. Verify from the pressure sensor that all transitions are isobaric.

7. Using Logger Pro to fit your equilibrium data to a straight line. Do the fit results support the Law of Charles and Gay-Lussac? That is, are the data linear?

8. From the intercept of the linear fit line, determine V_0, the volume of the aluminum can and air hoses. Discuss the physical significance of the intercept (volume at T=0). Is the intercept negative? How does it compare to a simple estimate of the volume of the can? Is there some non-linear behavior in the data? Is the whole system in equilibrium with the water bath? Discuss how that could explain the non-linear behavior you might see.

B: The Heat Engine

Design and carry out an experiment to measure the work done by the heat engine described in the theory section. This will mean taking the system through a full cycle:

       Starting at point A and compressing to point B (by adding mass)
       Heating the air to lift the mass from point B to C
       Removing the mass, so expanding from point C to D
       Cooling the air to return the "lifter" from D to A

In your analysis, be sure to compare the thermodynamic work done (i.e. the area enclosed by the *P-V* cycle) to the mechanical work done (*mgy*).

Note: you should use the effective volume for the can and tubes determined in part A of the procedure. Be sure to account for the can/tube volume in the template that you choose.