Heat Engine

Equipment: Capstone, 2 large glass beakers (one for ice water, the other for boiling water), temperature sensor, pressure sensor, rotary motion sensor, meter stick, calipers, set of weights, ice, boiling water, large table clamp, 90 cm rod to mount and hold heat engine and rotary motion sensor to the bench, hot plate, plastic bin 13" x 8" x 4", thermometer

Reading: Appropriate sections for first, second law of thermodynamics, and PV diagrams.

1 Introduction

Mankind has had direct sources of mechanical energy such as water and wind power for a long time. But the industrial revolution added the steam engine, which is a kind of heat engine. In a heat engine, the pressure of a working substance is increased either by heat from a high temperature reservoir or by energy released in an exothermic chemical reaction. (Recall that heat is energy that flows due to a temperature difference.) The working substance, which now has an increased pressure and temperature, pushes on a piston or turbine blade and does work. The working substance is cooled while doing the work. In some kinds of heat engines, such as internal combustion gasoline engines and steam locomotives, the working substance is discarded at this point. In other heat engines, the working substance is not discarded and is recycled. Such a heat engine is called cyclic.

In a cyclic heat engine the working substance goes through a series of changes but returns to its initial state. (Internal combustion engines can be approximated by cyclic engines. For the gasoline engine, this is the Otto cycle. For diesel engines, it is the Diesel cycle.)

In this lab a cyclic heat engine utilizing air as the working substance is operated. The pressure (p) and volume (V) of the working substance is traced on a p-V plot. Assuming no loss of working substance, in one cycle the p-V curve is a closed loop. A differential amount of work dW done by the heat engine is pdV. In one cycle the work done by the engine is the areas enclosed by the p-V loop.

The experiment can be done rather quickly. Fully understanding what is going on will take a considerable amount of thought unless your thermodynamics is in very good shape.

2 Apparatus

Fig. 1 is a sketch of the apparatus. The heat engine has a precision bore Pyrex cylinder fitted with a graphite piston. There is very little friction and air leakage between the piston and cylinder. One end of a piston rod is attached to the piston and the other end to a platform for adding mass. A piece of string goes from the mass platform to a rotary motion sensor which detects the position of the piston. Two pieces of tubing emerge from the bottom of the cylinder. One goes to a pressure gauge and the other to an air chamber. There are two containers, one with ice water and the other with hot water. The temperature of the hot water is measured with a sensor. The air chamber is alternately put in the ice water and the hot water.

The working substance is air trapped inside the cylinder, tubing, and air chamber. The absolute pressure of the working substance is determined by the weight of the piston, piston rod, mass platform, and mass **M** added to the mass platform, by the pressure of the air outside the cylinder on the piston, and by the tension in the string to the rotary motion sensor.

Not shown in Fig. 1 is a thumbscrew that can lock the piston rod. This is convenient when setting up the apparatus, but be sure the piston rod is free when carrying the engine through a cycle. Also not shown is a scale on the cylinder which starts near the bottom of the cylinder and goes up toward the top.

The air chamber is sealed with a rubber stopper. **This should be inserted firmly to avoid leakage.**

3 Description of Operation

The working substance, air, is confined by the volume of the cylinder below the piston, the volume of the tubing, and the volume of the air chamber. Fig. 2 shows a pressure-volume or p-V curve of a cycle of the heat engine. When operating the heat engine, a p-V curve is traced out on a graph display. The vertical axis of the graph is the pressure as read by the pressure gauge. The horizontal axis is the position of the piston as measured by the rotary motion sensor. The piston position is proportional to volume changes of the working substance.

At point **(a)** the air chamber is immersed in the ice water. Once a steady state has been reached. A mass M is placed on the mass platform, increasing the pressure and bringing the system to point **(b)**. The system is brought to point **(c)** by putting the air chamber in the hot water bath. After the mass M is then removed from the mass platform bringing the system to point **(d)**. The system is then returned to point **(a)** by putting the air chamber in the ice water. The net work done during the cycle has been to raise the height of mass M, plus any work to overcome friction.

Question 1. From looking at a p-V diagram that you have taken, how would you know if any working substance had been lost during a cycle?

4 Theory

The theory will not be worked out in detail. That will be left to you. Many approximations need to be made, and you can use your judgment and physical insight. One approximation you can make, and is assumed below, is that the working substance, air, is an ideal diatomic gas, and satisfies the ideal gas law, $pV = nRT$, where p is the pressure, V is the volume, n is the number of moles, R is the gas constant, and T is the absolute temperature.

Refer to the p-V diagram of Fig. 2. Processes bc and da are isobaric (constant pressure). In the following, define a convenient notation such as V_a = the volume at a, V_b = the volume at b, p_{bc} = the pressure along process bc, etc.

Question 2. How much work is done *by* the working substance and how much heat is *added* to the working substance for processes bc and da? What is the change in internal energy of the working substance between b and c, and between d and a?

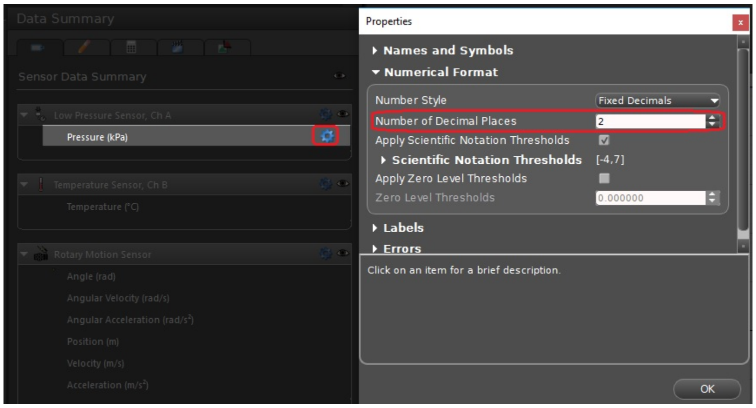
Processes **ab** and **cd** are much more difficult to approximate. The air in the air chamber is at either at T_{ab}, the temperature of the ice water, or at T_{cd}, the temperature of the hot water. But the air in the tubing and in the cylinder is not at these temperatures. You may make other approximations if you wish, but as a start, you might consider the processes **ab** and **cd** to be isothermal with the temperatures of the two baths. If you do this, when taking data keep the piston near the bottom of the cylinder so as to minimize the volume of the gas that is outside the air chamber.

Question 3. Same as question 2, except for processes ab and cd.

Question 4. For one complete cycle, what is the change in internal energy of, the net heat added to, and the the net work done by, the working substance?

5 Experimental Preliminaries

- Record the values of the piston diameter and platform mass. The values are on the apparatus.
- Make the necessary measurements that will enable you to calculate the volume of the working substance. This will include the length of the tubing. *Do not* take the tubing apart to measure the inner diameter. The value is 1/8 inch. (It is very hard to take the tubing off the couplings without damaging it!) The volume in the cylinder above zero on the cylinder scale can be obtained at any time by reading the cylinder scale. But you should measure the length of the cylinder that is below zero on the cylinder scale.
- Start Capstone.
- Plug the low pressure sensor into channel A
- Plug the temperature sensor into channel B
- Plug the rotary motion into channels 1 and 2
- Go to the Capstone Hardware setup window and left click on each input of the interface to setup each sensor. Program channel A for the Low Pressure Sensor (Gauge). Program Channel B for the temperature sensor. Then program channels 1 and 2 for the rotary motion sensor.
- Click the gear icon of the rotary motion sensor in the Hardware setup window and change the resolution to ”High” and linear scale to ”Large Pulley Groove.”
- Setup and tie a string from the bottom of the mass platform and allow it to go over the large groove of the rotary motion sensor. Then tie a 10 g mass on the other end of the string.
- You will open digits displays for both pressure and temperature. You will specify 3 decimal places for pressure display. (You will also be able to read the pressure from the graph display, but having a separate digits reading will be useful.)
- To change the number of decimal points click on **Data summary** icon. A data summary window will open up. Click on pressure and a gear icon will appear and then click on the gear icon. Illustration below will aid you.



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Apply Scientific Notation Thresholds: ☑
Scientific Notation Thresholds: [-4,7]
Apply Zero Level Thresholds: ☐
Zero Level Thresholds: 0.000000

- Open a graph display. For the vertical axis select pressure and for the horizontal axis of the graph above where it says "Time" change it to position. The graph is now set up with pressure on the vertical axis and a quantity that is proportional to the volume on the horizontal axis.

6 Experiments

Initial the entire apparatus should be at room temperature (air chamber should not be in either bath).

- Remove any mass from the mass platform. The two pieces of tubing that go to the air chamber and pressure gauge are attached to the cylinder assembly by removable couplings. Remove one of the tubes by twisting slightly counter clockwise and pulling out. This opens the trapped air to the outside.
- Move the bottom of the piston to the 20 cm mark on the cylinder scale and lock the piston with the thumbscrew. Re-connect the tubing and loosen the thumb screw.
- Determine the number of moles of air in the system by using the ideal gas law. There will be a slow leakage of air from the system over time, so you should be prepared to run the heat engine immediately after determining the parameters necessary for calculating the quantity of air. If the experiment goes on for some time, repeat these procedures.

To minimize working substance leakage, the engine should be carried through a cycle in an expeditious manner. On the other hand, you should not go through the cycle so fast that each of the points **a**, **b**, **c**, and **d** are not at steady state before going on to the next point. A good check is to look at the trace in the graph display. When the trace no longer moves, steady state has been reached.

- Remove any mass from the mass platform. Insert the temperature sensor into the hot water bath. You should record the temperature right at the beginning and end of each cycle.
- Click Record and immerse the air chamber into the ice bath. When steady state has been reached, the system is at **point a**. Put a 200 g mass *slowly* on the platform to bring the system to **point b**. (putting the mass on slowly approximates doing it quasi-statically.) Put the air chamber in the hot water bath and bring the system to **point c**. Removing the 200 g mass *slowly* brings the system to **point d**. Finally return the system to the starting **point a** by putting the air chamber in the ice water bath.

Repeat the cycle several times, waiting a few minutes between each cycle. Print out a graph with all the cycles on it for discussion, but also print out a graph with a single good cycle on it for analysis.

Question 5. Why do the p-V curves just taken look a little different from each other?

Repeat the above but use a 100 g mass.

Question 6. Why will leakage be less of a problem with the 100 g mass? Why are the p-V curves different?

7 Analysis

Analyze the data from one good cycle. Because of the closed nature of the curve, you will probably have to do pdV integrations for work graphically from your print-out, but conceivably it could be done using the integration routine of Capstone.

For the four legs of the cycle and for one complete cycle, compare the work calculated from pdV to that calculated from mgh.

8 Finishing Up

Please leave the bench as you found it. Thank you.

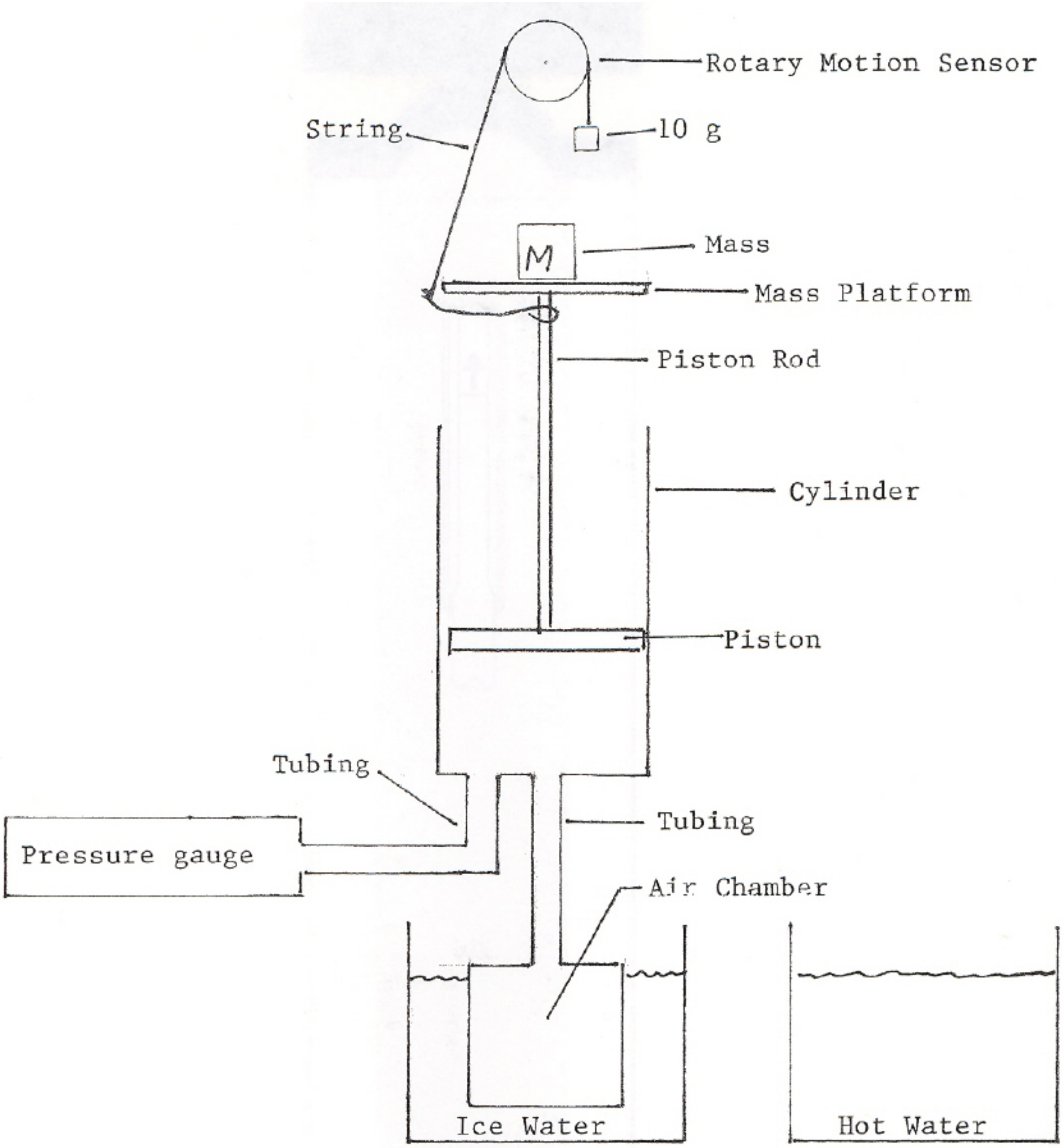
Rotary Motion Sensor
String
10 g
M
Mass
Mass Platform
Piston Rod
Cylinder
Piston
Tubing
Tubing
Pressure gauge
Air Chamber
Ice Water
Hot Water

Figure 1:

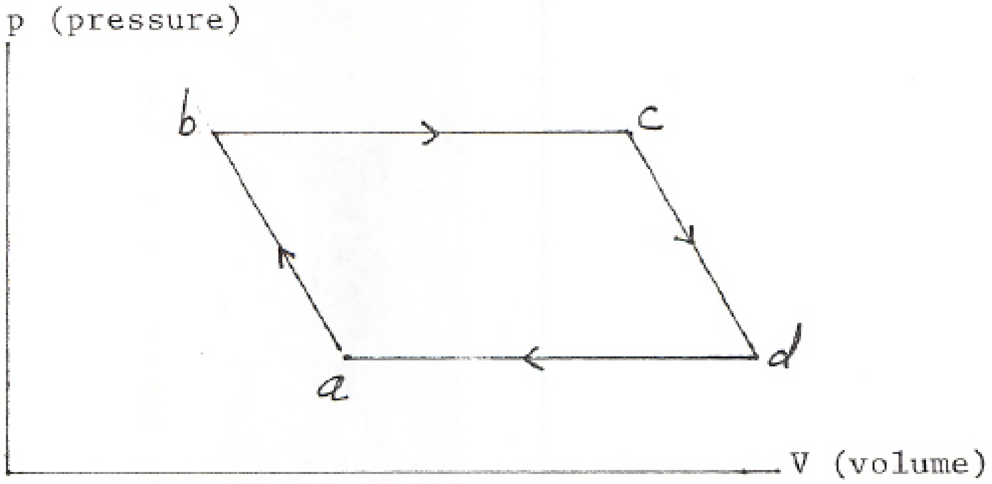

Figure 2: