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Heat Engines Lab 12

Equipment SWS, 600 mL pyrex beaker with handle for ice water, 350 mL pyrex beaker with handle for boiling water, 11x14x3 in tray, pressure sensor, rotary motion sensor fitted with 3-step pulley secured with a thumbscrew, 6 in C-Thru ruler, calipers, set of weights, ice, hot plate, water, thermometer, heavy duty bench clamp, 2 foot rod clamped (not screwed) to bench clamp, heat engine clamped to bottom of rod, rotary motion sensor clamped to top of rod, small plastic container to hold Al can and shield it from hot and cold sources

Reading Appropriate sections of your text books.

SAFETY

This experiment utilizes water that is close to boiling. Do not touch the surface of the hot plate. The 350 mL beaker is for the hot water. Do not fill this beaker with more than 250 mL of hot water to avoid hot watew spills. When taking the hot water beaker off the hot plate, check that the handle is not too hot. When the hot water beaker is off the hot plate it should be in a plastic tray which is there to contain any spills. Hold the Al can by the thermally insulating tubing that is above the rubber stopper of the can. Do not immerse the Al can more than 3/4 of the way into the water baths.

1 Introduction

Civilizations have 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 change of piston position is traced on a p-V plot. (The change of the piston position is proportional to the change of volume of the working substance.) 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 area enclosed by the p-V loop.

In addition to operating the apparatus as a heat engine, the apparatus can also be used to get a feel for quasi-equilibrium processes.

2 Apparatus

Fig. 1 is a sketch of the apparatus. The heat engine is a precision bore Pyrex cylinder fitted with a graphite piston. There is very little friction between the graphite piston and the cylinder, and air leakage between the piston and cylinder is small but not negligible. 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

3 Experimental Preliminaries

1. The pressure sensor should be plugged into analog channel A. The default sensitivity of Low(1X) is good. Open a digits display for the pressure sensor with 3 decimal places.

2. The rotary motion sensor should be plugged into digital channels 1 and 2. In the rotary motion display, set for 1440 divisions/rotation and Large pulley(groove). A string should go around the large grooved pulley with one end attached to a 10 g mass. The other end of the string should be tied to the piston rod and go around the end of the mass platform. See Fig. 1. Open a digits display for the rotary motion sensor with two decimal places. For this sensor select "Position, linpos (cm)."

3. The leakage past the piston is small enough that moving the piston with the system closed is not feasible. To move the piston easily, disconnect one of the hoses to the base of the cylinder. Part of the plastic coupling has two grooves. Grasp the coupling at these grooves, push slightly in and twist CCW to disconnect the hose. The piston will now move freely if the thumbscrew is loose. For the moment, let the piston rest at the bottom of the cylinder with the hose disconnected.

4. Click MON and observe the pressure reading. The pressure gauge is a differential gauge and reads the pressure difference between room pressure and the pressure in the sensor. (In common vernacular, it gives gauge pressure.) It should read zero but will be a little off. Note the zero offset.

5. Click MON and observe the read out for the rotary motion sensor as you raise the piston. The sensor should be set up so that as the piston is raised, the numbers go positive. Note that when REC or MON is clicked, this sensor starts out at zero regardless of previous readings. There is a thumbscrew that locks the piston rod. Experiment with this. It should take less than a quarter turn of the screw to lock the rod. Avoid excessive force. When you are taking data, the piston should usually be unlocked.

6. Check the calibration of the rotary motion sensor by moving the piston up and measuring the change of position of the piston platform both with the ruler and the rotary motion sensor.

7. The pressure gauge is quite sensitive. With the piston resting at the bottom of the cylinder and locked, click MON, look at the pressure gauge, and reconnect the hose you had previously unhooked. What does the pressure do and why does it do it? How long does it take for leakage past the piston to return the pressure to the room value?

8. With the piston clamped and hoses hooked up, click MON and observe the pressure gauge. Hold the can in your hand to warm it. What do you observe the pressure do?

9. The apparatus is quite sensitive to stray heat and cold sources. Keep the hot plate away from the can and heat engine. When the can is not in a hot or cold beaker, keep it in a plastic container to shield it.

10. Get a feel for the leakage around the piston as follows. Set the piston at 2 cm above its lowest position and lock the piston. IMPORTANT. Whenever these instructions say to "set the piston" (position), it assumes that you do the following:

- Disconnect a hose.
- Unlock the piston.
- Set the piston at the bottom of the cylinder.
- Click Mon.
- Rise the piston until the rotary motion sensor indicates that the piston has been raised 2.00 cm. If the display number is negative, reverse the direction of the string over the pulley. Compare to the scale on the side of the cylinder.
- Lock the piston.
- Reconnect the hose.
- The default position of the piston will be taken as 2 cm above the bottom. If the instruction "set the piston" is given, adjust the piston height to be 2 cm above the botton. If another piston height is wanted, such as 100 cm, the instruction will be "set the piston at 100 cm."

Set the piston. Open the graph display by dragging the graph display icon to the rotary motion sensor icon. Leave the horizontal axis of the graph display as time. With no weight on the platform, unlock the piston and click REC. Observe the piston position for a few minutes. Is there appreciable leakage? Repeat this procedure with a 200 g mass on the platform. In the above and in what follows, it is assumed that you will adjust the axes scales of the graph display so that your curves fill most of the graph.. You will probably find that with the 200 g mass the leakage is small but completely observable. It can not be completely neglected in the results. In particular, when when the heat engine is put through one cycle, it should be done quickly, but not so quickly that quasi-equilibrium is not maintained.

11. A trapped quantity of a gas is "springy." Set the piston at 1.0 cm, unlock the piston, and move the platform up and down a bit with a hand to see how "stiff" the trapped air is. Click MON, add 200 g to the platform, and measure how far the piston goes down. Calculate the spring constant in N/m. Set the piston at 9.0 cm and repeat the above. Compare the two spring constants and discuss.

12. On the base of the apparatus that holds the cylinder are inscribed the piston diameter and the mass of the piston-platform assembly. Record these values. Calculate the the differential pressure that that the piston and platform will exert on the working substance both with no mass on top of the platform and with 200 g on the platform. Remember the 10 g mass on the end of the string. By differential pressure is meant the pressure above one atmosphere (101 kPa). Compare the calculated pressure to the reading of the pressure gauge as follows. Set the piston. With no mass on the platform unlock the piston, click MON, and read the pressure gauge. Compare your calculated value to the reading of the pressure gauge. Don't forget the zero offset of the pressure gauge. Repeat the above procedures with 200 g on the platform.

13. For the rest of this lab, the graph display should have pressure on the vertical axis and piston position on the horizontal axis. Make these changes now. Set the sampling rate at 100 Hz.

4 Quasi-Equilibrium or Not?

Later on in this lab the heat engine will be carried through one complete cycle which will involve two isothermal (constant temperature) and two isobaric (constant pressure) processes. Ideally these processes should be carried out slowly enough so that the working substance is never far from thermal equilibrium. How slow is slow enough, and could deviations from quasi-equilibrium be observed in this apparatus? We might expect that a lower limit for the thermal relaxation time constant for the apparatus might be something like the time for a sound wave to travel the length of the apparatus. This would be of the order of 1 ms. The actual time constant will certainly be longer than this.

The following procedures are carried out with the entire apparatus at room temperature. Set the piston and put a 200 g mass on the platform. Unlock the piston and wait 3-4 s so that the apparatus will be in thermal equilibrium. Click REC, and slowly, over a period of 3-4 s, lift the mass off of the platform. Wait a few more seconds and click STOP. The p-V curve should be a straight line from beginning to end. Use SWS to obtain the slope of this line. The process is isothermal. Now repeat the above, except remove the 200 g mass quickly. The p-V curve should be a straight line with negative slope until the lower pressure limit is reached, but then should become a horizontal line that shows an increasing volume. This indicates that the volume is increasing at constant pressure. Use SWS to obtain the slope of the first part of the line. Is the magnitude of this slope more or less than that of the previous line?

When the mass is removed slowly, the process is isothermal. During the entire process the gas is near room temperature. When the mass is removed quickly, the process is not isothermal. It is at least partially adiabatic. The gas cools somewhat. Right after the mass has been removed, the gas warms up due to heat flow from the cylinder walls and increases the volume of the gas a bit. With this in mind, can you explain the difference in the slope of the lines?

Repeat the above two procedures, except put the 200 g mass on the platform instead of taking it off. If the 200 g mass is put on quickly the gas is heated up, and at the point in time that the mass is entirely on the platform, the gas will start to cool due to heat flow to the walls. This will move the p-V trace horizontal to the left. The piston leakage with the 200 g mass will obscure this. You should be able to see a difference in the slopes depending on whether the mass is put on slowly or quickly.

At this point, you should have a pretty good feel as to how slowly you need to add or remove mass to be near thermal equilibrium.

5 Description of Operation As Cyclic Heat Engine

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 can. 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 the 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.

The cycle begins at point a with the air chamber immersed in the ice water and no added mass on the platform. Assume steady state has been reached. A mass M is then placed on the mass platform, increasing the pressure and bringing the system to point b. The system is brought to point c by taking the can out of the ice water beaker and putting the can in the hot water beaker. The mass M is then removed from the mass platform at point c bringing the system to point d. The system is returned to point a by taking the can out of the hot water and putting the can in the ice water. The net pdV work done during the cycle is the area enclosed by curve abcd. (In this experiment the horizontal axis is the piston position, not the volume. The piston position is proportional to the volume.) During legs da and ab the can is in the ice water. During legs bc and cd the can is in the hot water.

Question 1. Fig. 2 is drawn assuming none of the working substance has been lost during the cycle. What would the curve look like if working substance had been lost?

6 Experiment

Set the hot plate at 3. Put 250 mL of water in the 500 mL beaker and set the beaker on the edge of the hot plate so that the handle sticks out over the edge. This will keep the handle not too hot. Put 250 mL of water in the 600 mL beaker and add some ice. Put this beaker at one end of the plastic tray.

Set the piston. Start with the can at room temperature. Monitor the temperature of the water in the two beakers. The ice water will reach 0 degrees C quickly. When the hot water reaches 95 degrees C, the experiment can begin. It is not necessary or desirable to have a rolling boil. Leave the hot water beaker on the hot plate until actually needed. When moving the can, grasp the tubing just above the rubber stopper. Due to leakage, carry out the following steps just slowly enough to maintain quasi-equilibrium. Al is a good conductor, so that it is only necessary to insert the can about 3/4 of the way into the water baths. Once the can touches the water, it will very quickly attain the temperature of the water. To keep legs bc and da quasi-static, bring the can to the surface of the water slowly.

Unlock the piston. Click REC and bring the system to point a by putting the can in the ice water. Bring the system to point b by a putting 200 g mass on the platform. Take the hot water beaker off the hot plate and place it in the plastic tray. Bring the system to point c by putting the can in the hot water. Bring the system to point d by removing the mass from the platform. Bring the system back to point a by putting the can in the ice water. Click STOP. Use the graph cross hairs to find the pressures and temperatures of points a, b, c, and d. Print out your graph.

Questions

1. How much pdV work is done by the working substance during each leg of the cycle? Assume each leg is a straight line. What is the net pdV work for the cycle? Discuss whether you should use gauge pressure or absolute pressure in these calculations and whether it makes any difference.
2. How much heat is added or removed from the system during legs ab and cd? You may assume the working substance is an ideal gas and that the internal energy does not depend on the temperature.
3. What would you need to know to calculate the heat added or removed from the system for legs bc and da?
4. Is any net work done on the piston-platform assembly?

7 Finishing Up

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

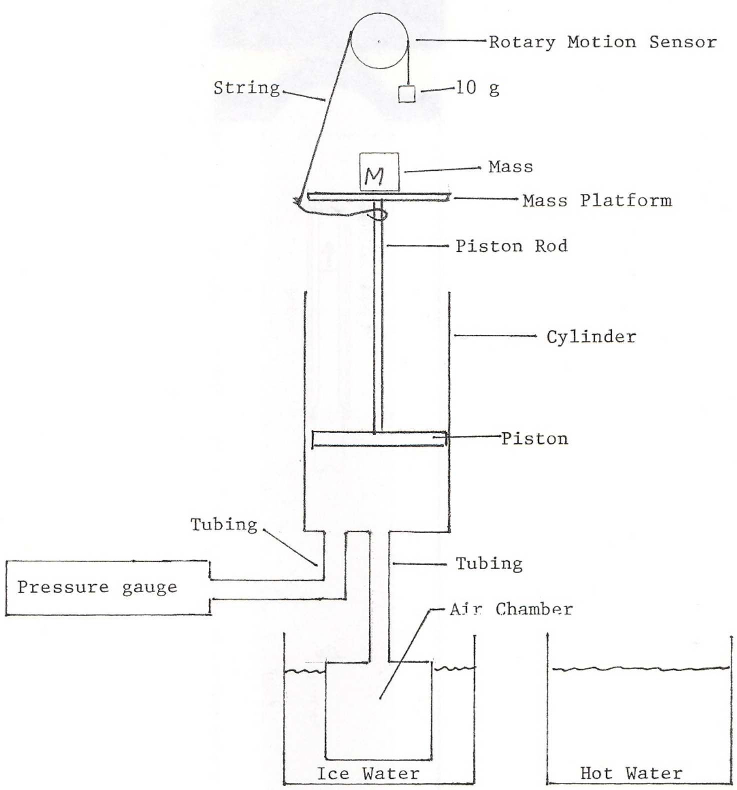

Figure 1: Apparatus Setup

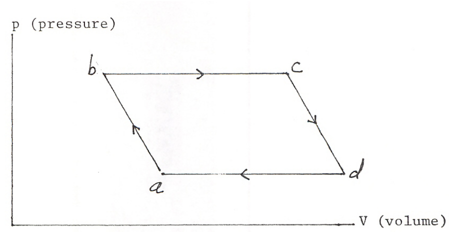

Figure 2: p-V loop