

### Section A: Introduction

The invention of steam engine played a very significant role in the Industrial Revolution from the late 1700s to early 1800s. The steam engine is an example of a heat engine which converts thermal energy into useful mechanical energy. The First and Second Laws of Thermodynamics, which you will study (or had just studied) in the later part of this module, came about through the effort to understand the nature of thermal energy and to improve the efficiency of heat engines.

In this experiment, you will have a chance to study how a very simple heat engine works.

### Section B: Brief Theory (condensed from Serway & Jewett)

A heat engine is a device that takes in energy by heat and operating, in a cyclic process, expels a fraction of that energy by means of work. For instance, in a typical process by which power plant produces electricity, coal or some other fuel is burned and the high-temperature gases produced are used to convert liquid water to steam. This steam is directed at the blades of a turbine, setting it into rotation. The mechanical energy associated with this rotation is used to drive an electric generator.

The heat engine carries some working substance through the process during which (1) the working substance absorbs energy by heat from a high-temperature energy reservoir, (2) work is done by the engine, and (3) energy is expelled by heat to a lower-temperature reservoir. It is useful to represent this schematically as in Figure 2.1. The engine absorbs a quantity of energy  $Q_h$  from the hot reservoir. The engine does work  $W$  and then give a quantity of energy  $Q_c$  to the cold reservoir. Because the working substance goes through a cycle, its initial and final internal energies are equal, and so the work done by the heat engine is equal to the net energy transferred to it. Therefore

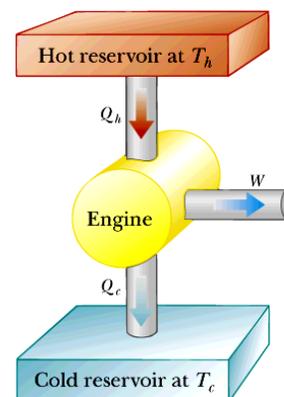
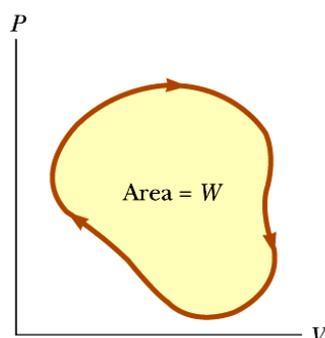


Figure 2.1

$$W_{net} = Q_h - Q_c$$



The work done by a gas in any thermodynamic process can be shown to be the area under the curve of a  $P$ - $V$  diagram. Therefore if the working substance is a gas, the net work done in a cyclic process is the area enclosed by the curve representing the process on a  $P$ - $V$  diagram. This is shown for an arbitrary cyclic process in Figure 2.2.

Figure 2.2. Work done by a gas in a cycle.

The efficiency  $e$  of a heat engine is defined as the ratio of the net work done by the engine to the energy input at the higher temperature during one cycle. Thus it is easy to see that

$$e = \frac{W_{net}}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h}.$$

### Section C: A Possible Scenario

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 g to 200 g from a processing conveyer belt to the packing conveyer belt that is a few 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. In this experiment we would like you to verify experimentally that the useful mechanical work in lifting a mass,  $m$ , through a vertical distance,  $y$ , is equal to the net thermodynamic work done during a cycle as determined by finding the enclosed area on a  $P$ - $V$  diagram. Essentially, you are comparing useful mechanical “ $m_{a}g y$ ” work (as in Figure 2.3a) with the accounting of work in an engine cycle as a function of pressure and volume changes given by the expression (as in Figure 2.3b):

$$W_{net} = \oint p dV$$

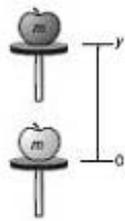


Figure 2.3a

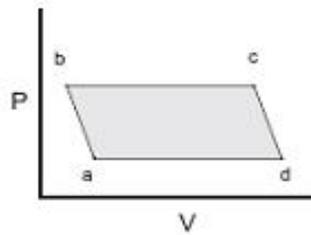
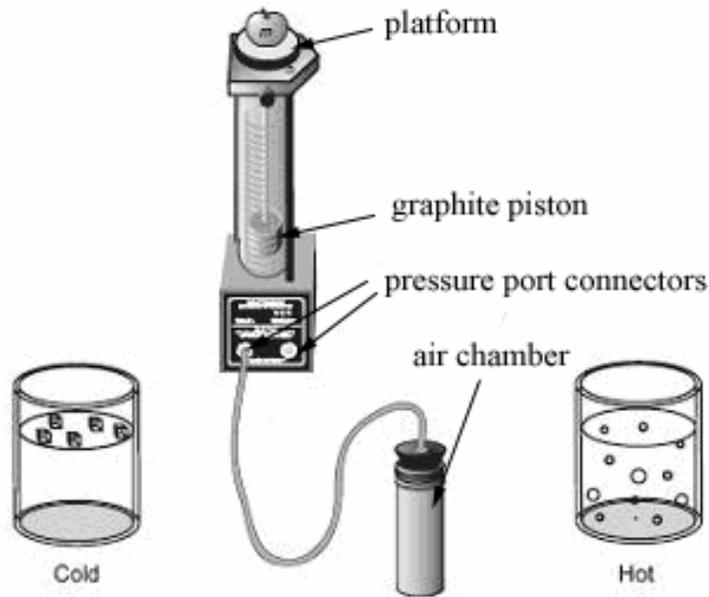


Figure 2.3b

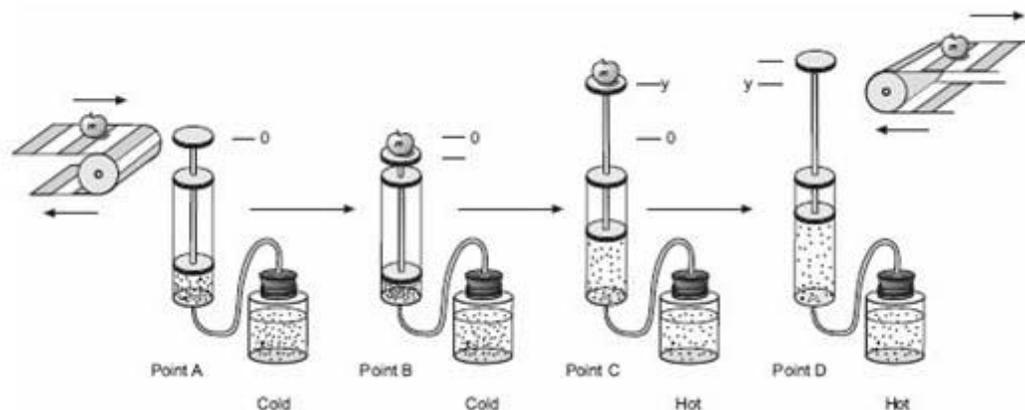
## Section D: Apparatus (The Incredible Mass Lifter Engine)

The heat engine consists of a hollow cylinder with a graphite piston that can move along the axis of the cylinder with very little friction. The piston has a platform attached to it for lifting masses. A short length of flexible tubing attaches the cylinder to an air chamber (consisting of a small can sealed with a rubber stopper that can be placed alternatively in the cold and hot reservoirs). A diagram this mass lifter is shown in Figure 2.4.



*Figure 2.4: Setup for the heat engine*

If the temperature of the air trapped inside the cylinder, hose and can is increased, then its volume will increase, causing the platform to rise. Thus, you can increase the volume of the trapped air by moving the can from the cold to the hot reservoir. Then when the apple has been raised 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 the gas decreases a bit. Finally, the volume of the gas will decrease when the air chamber is returned to the cold reservoir. This causes the piston to descend to its original position once again. The various stages of the mass lifter cycle are shown in Figure 2.5 and approximately represented through the  $P$ - $V$  diagram in Figure 2.3b.



*Figure 2.5. Simplified diagram of the heat engine at different stages of its cycle*

## **Section E: Procedure**

### ***Part I***

Before taking data on the pressure, air volume and the height of lift with the heat engine, you should set it up and run it through a few cycles to get used to its operation. A good way to start is to fill one container with room temperature water and another with preheated water at about 60-70°C. The engine cycle is much easier to describe if you begin with the piston resting above the bottom of the cylinder. Thus we suggest you raise the piston a few cm before inserting the rubber stopper firmly in the can. Also, air does leak out of the cylinder slowly. If a large mass is being lifted, the leakage rate increases. Therefore, we suggest that you limit the added mass to something between 50 g and 200 g.

Run through the cycle (without taking any data) as indicated below a few times.

- i) Transition  $a \rightarrow b$ : Add the mass to the platform;
- ii) Transition  $b \rightarrow c$ : Place the can in the hot reservoir;
- iii) Transition  $c \rightarrow d$ : Remove the mass from the platform;
- iv) Transition  $d \rightarrow a$ : Place the can in the cold reservoir.

After observing a few engine cycles, describe what happens during each of these transitions carefully in your report, indicating which of these are approximately adiabatic (where no heat enters or leaves the system) and which are isobaric. You can observe the changes in the volume of the gas directly and you can predict how the pressure exerted on the gas by the surroundings ought to change from point to point by using the definition of pressure as force per unit area.

### ***Part II***

Set up the low pressure and rotary motion sensors and start the *DataStudio* software as explained in Appendix A. With the hot and cold temperatures still at 60-70°C and room temperature respectively, run through the complete cycle as indicated above.

With the piston about 2 cm above the bottom, close the system to outside air. Make sure that the rubber stopper is firmly in place in the can. You will start the cycle at point  $a$  with the can in the cold reservoir. Start the data collection on the computer at this point. Proceed through the rest of the cycle.

You should repeat the experiment several times to obtain the best results. Print the best plots for three different masses, e.g., 50 g, 100 g and 150 g, on a single graph. Indicate also the temperatures of the hot and cold reservoir in your report.

### ***Part III***

We will next study how the work done is affected by increasing the temperature of the hot reservoir to about 80-90°C and decreasing the temperature of the cold reservoir to that of melting ice. Please use caution when handling the hot water. Stir to maintain a uniform temperature and do **NOT** heat until the water boils. Record the temperatures in your report.

Again, perform the cycle several times to obtain the best results. Repeat with the same masses you have used in Part II and print the best results.

### **Section F: Calculations and discussion**

- 1 Explain how you can calculate the work done by the engine from the  $P$ - $V$  diagram. State any approximations you will make. Similarly explain how you will calculate the mechanical work done in raising the different masses through different heights in Parts II and III.
- 2 Tabulate your results for the six plots and compare the work done obtained from the  $P$ - $V$  diagrams and the mechanical work done.
- 3 Discuss some possible reasons why the two works done calculated above could be different.
- 4 Compare the work done at the different hot and cold reservoir temperatures, i.e., between Part II and Part III. State any conclusion you can draw from the results.

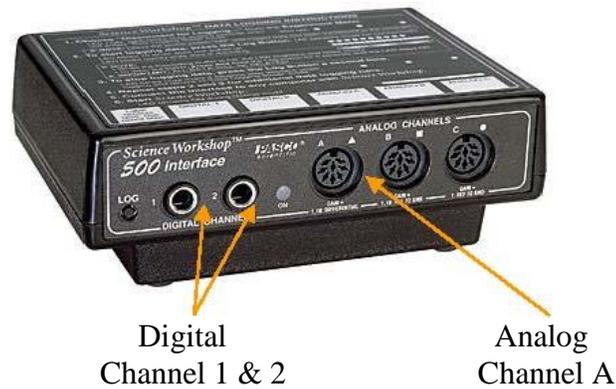
*Possible data that you may need in your calculations and discussion.*

Piston diameter =  $(32.5 \pm 0.1)$  mm Mass of piston & platform =  $(35.0 \pm 0.1)$  g

You may also request for other measuring instruments from the lab officers if you want to determine any other values.

### **Appendix A : Science Workshop Connections & Software Interface Setup**

- 1 Connect the tubing from the low pressure sensor gauge to the second pressure port of base apparatus and the low pressure sensor cable to Analog Channel A of the Science Workshop Interface (as shown in Figure 2.6).
- 2 Devise a suitable method to measure the position of the platform with the Rotary Motion Sensor. For example you could loop a string over the large pulley with one end tied to a 50-gram weight resting on the platform and the other end tied to a 5-gram weight so that the string is always taut and pulley rotates when the platform moves. Connect the Rotary Motion Sensor cable to Digital Channels 1 and 2.
- 3 Connect the *Science Workshop* interface to the computer, turn on the interface. Start *DataStudio*.



**Figure 2.6: The Science Workshop interface**

4. Start experiment by double click the “*DataStudio*” icon.
5. Left click on the mouse at Analog Channel A and select the “**Low Pressure Sensor**”.
6. Set the Low Pressure Sensor so that it measures the “**Pressure, Ch A (kPa)**”. Uncheck “**Voltage, ChA (V)**”. This is the default setting.
7. Left click on the mouse at Digital Channels 1 & 2 and select the “**Rotary Motion Sensor**”.
8. Set the Rotary Motion Sensor so that
  - the sample rate is **50 Hz** (default);
  - it measures **Position, Ch 1 & 2 (m)**;
  - it records **360 divisions per rotation** (default);
  - Linear calibration set to **Large Pulley (groove)** if you had followed the instruction in step 2, or set according to what you have done.
9. In the program, select a graph display and set it to show “**Pressure (kPa)**” on vertical axis and click on horizontal axis to replace “**Time**” to “**Position, Ch1&2 (m)**”. (Strictly speaking, this is not a P-V graph but a graph of pressure versus position. In your calculation, remember to convert position to volume.)
10. You are now ready to collect data.