

Demonstration experiments with a Stirling engine

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NOTES ON EXPERIMENTS

'Notes on experiments' enables teachers at both school and tertiary level to share their ideas with other readers. *Physics Education* welcomes submissions from readers who know of some simple improvement to a commercially made piece of apparatus, or who have designed a new gadget or improved a standard experiment. In particular the

Editor would welcome brief descriptions of experiments devised or procedures evolved during the course of project work or investigations undertaken by students; such submissions should be made under the joint name of the teacher and the student.

Demonstration experiments with a Stirling engine

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The development of thermodynamics was greatly stimulated in the nineteenth century by studies of heat engines. In teaching thermodynamics today we still make use of heat engines, both as ideas to develop theory, and as real things to illustrate working thermodynamic principles. The Stirling engine, first developed in the early nineteenth century, combines both possibilities [1]. In recent years, interest in this engine has mainly focused on applications to refrigeration cycles [2]. In addition, there has been some interest because of its potential as a more fuel-efficient and cleaner engine [3].

The Stirling engine provides a close approximation to the Carnot engine, in that the maximum efficiency of a Stirling cycle operating between reservoirs at temperatures T_1 and T_2 is given by

$$\eta = 1 - \frac{T_2}{T_1} \quad (1)$$

just as for the Carnot cycle [4]. It operates by making use of a 'regenerator', which acts as a thermal reservoir to recycle heat back into the system. The fundamental ideas of the Stirling engine are discussed in almost all introductory thermodynamics texts. In this note we describe some experiments that may be performed using the *Leybold* Stirling engine [5].

Our interest in the Stirling engine is primarily as a tool to illustrate some basic thermodynamic

principles. We use it here to illustrate the characteristics of a heat engine and interpret a pV diagram. Secondly, we show how the Stirling engine can be used to demonstrate the principles of operation of a refrigerator and heat pump.

Operation of the Stirling engine as a heat engine

The primary purpose of this investigation is to allow students to generate and interpret a pV diagram, permitting the students to see 'work' in action. A schematic diagram of the apparatus is shown in figure 1. Two pistons move in the cylinder. The top region of the cylinder is heated by an electric heater, and the lower walls of the cylinder are cooled by flowing water. The upper piston moves air from the heated region of the cylinder to the cooler region through the regenerator, which is a central hole in the piston filled with copper wool. When the gas passes from the heated region, through the regenerator, to the cooler region, it releases heat to the copper wool and is cooled. When it passes in the other direction it retrieves this heat and is warmed.

The pressure and volume changes in the engine are observed using a pV indicator [6], which causes a beam of light from a small diode laser to be reflected from a mirror onto a distant screen. A schematic diagram of this device is shown in figure 2. A length of fishing line is connected from

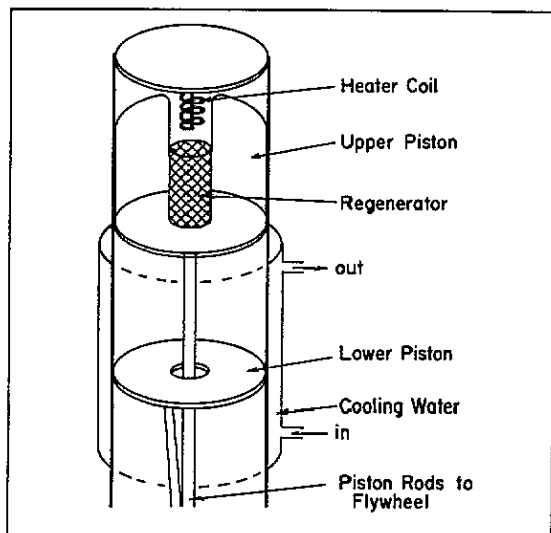
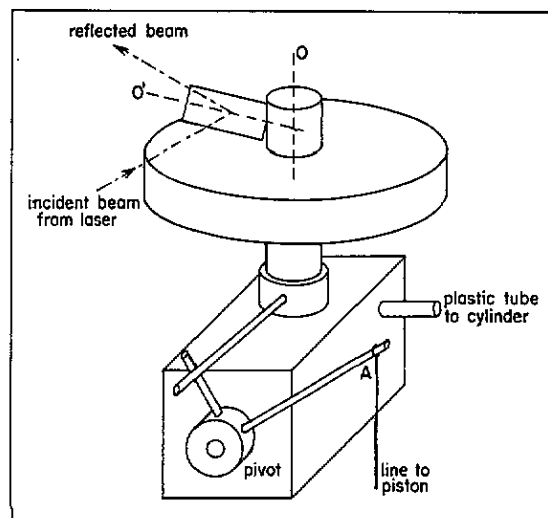


Figure 1. Schematic diagram showing the arrangement of the pistons. When the volume is at its minimum most of the gas is in the heated part of the cylinder at temperature T_2 . When heat is released the gas is at its maximum volume and is in contact with the cold region of the cylinder at temperature T_1 .

the lever at A to the piston. The vertical motion of the piston causes the mirror to oscillate about an axis at O. This causes the reflected beam to move horizontally between two points on the screen, corresponding to the volume swept out by the piston.

Figure 2. Schematic diagram of the pV indicator. Changes in volume and pressure cause the mirror to oscillate about the axes O and O' respectively.



Changes in pressure cause the mirror to oscillate about a horizontal axis (O' in the diagram), and the reflected beam moves vertically. The combined effect of the volume and pressure changes within the cylinder is to cause the reflected beam to trace out a closed path, the area of which corresponds to the work done per cycle by the engine. An independent measurement of the change in volume (150 cm^3) and the maximum pressure of the gas inside the cylinder (0.17 MPa) allows the work done per cycle to be calculated.

Figure 3 shows pressure-volume curves obtained under conditions corresponding to three different temperatures of the upper reservoir, the lowest of which corresponds to a heater current of 10 A, which was the minimum current required in order to achieve a relatively slow, but steady rotation of the flywheel (typically about three revolutions per second). The other two curves were obtained at heater currents of 11.5 A and 14 A. The temperature of the water used to cool the lower part of the cylinder was kept constant at 12°C .

We see immediately from figure 3 that the work done per cycle increases with temperature, as expected. To obtain more quantitative data, the area of each curve was measured using a planimeter. A simultaneous measurement of the rate of rotation of the flywheel allows the power output, and hence the efficiency of the engine, to be calculated at each new heater current. Typical experimental results are shown in table 1.

The efficiency of the engine is very low because

Figure 3. pV diagrams for the Stirling engine operating at three different temperature gradients. The 12°C isotherm, calculated for an ideal gas, is shown for comparison (broken curve).

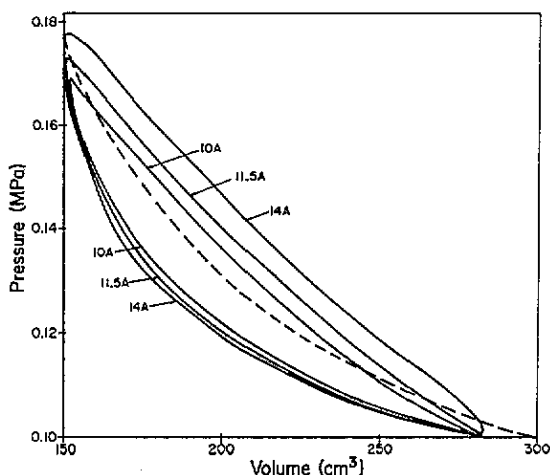


Table 1. Efficiency of the Stirling engine as a function of electrical power input.

Electrical power input (W)	Power output (W)	Efficiency (%)
97	4.4	4.5
132	8.2	6.2
183	15.3	8.4

most of the electrical heat energy is lost to the surroundings. In contrast, the efficiency of a commercial Stirling engine may approach 40% where the heater temperature is close to 800 °C [7].

The system contains 0.012 mole of gas. Assuming ideal gas behaviour, we have superimposed the 12 °C isotherm (shown by the broken curve) onto the experimental curves in figure 3. We note that although the low-temperature part of the (experimental) cycle does not follow the isotherm precisely (largely due to energy losses), the form of the curve is as would be expected. A high-temperature isotherm cannot be drawn, since, in the present experiment, we cannot determine T_2 because the temperature of the gas is not constant. There is, instead, a non-uniform temperature gradient, which extends from a local high-temperature source (i.e. the heater coil) to the surface of the moving piston.

Determining the output power using a Prony brake

In its simplest form, the Prony brake consists of a friction band passed around the axle of the flywheel. By measuring the force on a copper band placed around the shaft, we can obtain the power output P of the engine from the expression

$$P = \frac{2\pi r N (F_A - F_B)}{t} \quad (2)$$

where r is the radius of the shaft and N is the number of revolutions of the flywheel made in time t .

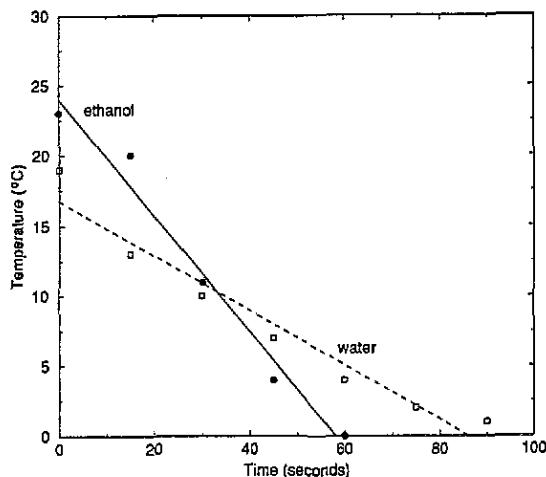
For each of the three heater currents used above, we use equation (2) to determine the power output in each case to be 3.4 W, 7.0 W and 10.2 W, respectively. These values are slightly lower than those in table 1; the difference can be accounted for by energy losses due to friction.

Operation of the engine as a refrigerator or heat pump

By now, the student should appreciate the fact that mechanical energy can be extracted, owing to the temperature difference between the two reservoirs, albeit at low efficiency. Conversely, when we put mechanical energy into the system, a temperature difference will be set up between the upper and lower regions of the cylinder, and the engine can be made to operate as either a refrigerator or a heat pump, depending on the direction of rotation of the flywheel. A classroom demonstration may be performed when we turn the flywheel using an electric motor, and use the apparatus to boil water, or freeze water as desired.

A more quantitative study can be made by measuring the rate at which various liquids cool, thus permitting a determination of the rate of heat removal from the system. We used the Stirling engine to cool water from room temperature to 0 °C, and also ethanol, which has a significantly different heat capacity. In the present work, the heater element was replaced by a test tube containing 1 cm³ of liquid. The temperature of the liquid was monitored using a thermistor, which, because of its small size and low heat capacity, was considered to be more suitable for measuring temperature than a mercury-in-glass thermometer.

Figure 4. Cooling curves for water (broken line) and ethanol (full line) when the Stirling engine operates as a refrigerator. A least-squares fit to the data shows that the rate of heat removal from the water is 0.8 W with an uncertainty of $\pm 10\%$. Assuming that the rate of heat removal is constant, we deduce that the specific heat capacity for ethanol is $2.1 \text{ J g}^{-1} \text{ K}^{-1}$, which agrees favourably with a tabulated value of $2.42 \text{ J g}^{-1} \text{ K}^{-1}$.



When a body cools from a temperature T_2 to a lower temperature T_1 , the heat lost is equal to $C(T_2 - T_1)$, where C is its heat capacity. If we arrange for the rate of heat extraction to be constant by keeping the speed of the flywheel constant, a graph of temperature against time should give a straight line of slope

$$\frac{\text{rate of loss of heat}}{\text{heat capacity of the liquid}}$$

In other words, the slope of the cooling curve is inversely proportional to the heat capacity of the liquid. If we know the heat capacity of one liquid, then we have a means of determining the heat capacity of other liquids. Data obtained for water and ethanol are shown in figure 4. We assume that the graphs are linear to a first-order approximation; this is necessary because, according to the model, heat must be removed from the system at a uniform rate. Water shows a slight deviation from linearity close to 0°C , as freezing begins. It can be shown that heat is extracted from each liquid at a rate of approximately 0.8 W. This value again illustrates the low efficiency of the apparatus and may serve as a basis for further classroom discussion.

Summary

This Stirling engine is particularly useful for physics students at the Advanced level, as well as the introductory college level, since it illustrates the thermodynamic principles of a cyclic process. Available work is measured directly by the area of

the closed cycle on a pV diagram. Both heating and cooling are observed, with quantitative measurements made to determine the relative heat capacities of different liquids. A more sophisticated apparatus would be required for more quantitative investigations.

Acknowledgments

We wish to thank M Morrow for providing assistance, as well as the students who helped in the development of this experiment. We also wish to thank R Guest for drawing the diagrams used in figures 1, 2 and 3.

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