

Efficiency of a Stirling engine

Objectives

In this experiment you will:

- Understand the basic operation of a Stirling heat engine
- Devise ways to measure the efficiency and energy flow in the engine

Introduction

The idea of a *heat engine* is important in thermodynamics. It takes some energy from a source of heat, and makes it available as mechanical work. Thermodynamics sets strict limits on how effectively this can be done, even before the perfection of the engine is considered. The model Stirling engine in this experiment is subject to both kinds of constraint. The aim of this experiment is to study quantitatively the operation of the engine, and evaluate its efficiency (which is terrible, as is typical for a small model). To make this possible, we have added a variety of instrumentation to the model. The exact way in which you use the instruments and perform the calculations is partly left to you to determine.

1 Operation of the engine

All heat engines require both a source of heat and a way of disposing of “waste” heat. In our model, the lower metal plate is heated electrically, while the upper plate is cooled by the surrounding air. Apply 12 volts to the heater on the lower plate, and wait a few minutes for it to warm up. By recording both current and voltage, you can track how much power is supplied to the hot end of the engine.

What feature of thermodynamics requires there to be waste heat? In other words, why can't we have an engine that turns all the incoming heat energy into work? **Q**

After a few minutes, a gentle rotation of the flywheel arm should cause the engine to run continuously. Clearly, the motion involves the flexible piston applying force to a crank, the piston being pushed outwards as the air sealed within the engine is heated. But how does the engine run in a cycle, alternately pushing and pulling on the crank? **Q** Observe the operation and work this out. Hint: the cork disk that looks like a piston is actually quite loose, and is called a *displacer* in the jargon of heat engines.

2 Measuring the input and output power

A direct way of measuring the mechanical output is to use it to raise a weight. Using the pulley and thread provided, with a bit of care you can hook the thread on to the engine shaft while it is running, and cause a 10 g weight to be lifted. Make measurements of the speed at which the weight is raised, and hence calculate the power. Be careful to discount the slowing down of the engine that will occur when the load is first added. There is a tachometer that can be used to keep an eye on the rotation rate of the engine. While this is going on, record also the power being put in by the electrical heater.

3 Calculations on efficiency

Using your previous measurements of input power and output work, evaluate the overall efficiency of the engine, i.e. (output/input). This result encompasses both the unavoidable thermodynamic limitations and the extra losses and inefficiencies in the model engine.

The thermodynamics of heat engines is discussed in textbooks such as Young and Freedman. One conclusion is that the maximum possible efficiency of a mechanically perfect heat engine is given by the Carnot efficiency,

$$\eta = 1 - \frac{T_C}{T_H},$$

where T_H is the absolute temperature of the hot side of the engine, and T_C that of the cold side. Use the thermocouples that are attached to the hot and cold plates of the engine to measure these temperatures, and hence calculate the Carnot efficiency. You can make the the engine look a bit better by reporting its efficiency as a fraction of the Carnot limit.

However you describe it, the efficiency of this engine is poor. Identify some of the major sources of inefficiency, and how they might be improved. Consider both thermodynamic and practical contributions. **Q**

4 The thermodynamic cycle

Figure 1 shows an idealised view of how the pressure and volume of the gas inside a Stirling engine change during a cycle.

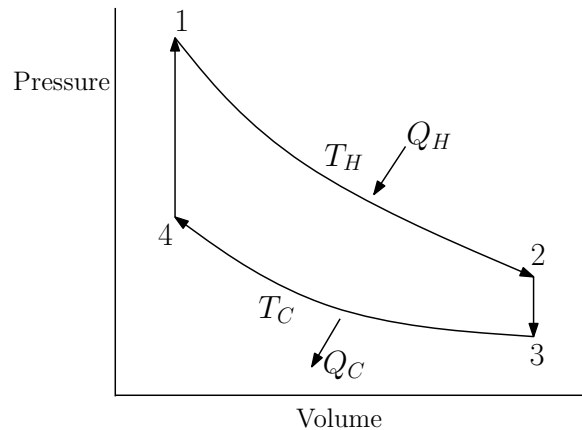


Figure 1: Idealised Stirling cycle

The curved lines are isotherms, ie. lines of constant temperature, along which pressure varies inversely with volume, according to Boyle's law.

- 1 → 2: gas is in contact with the hot end and expands at T_H , taking in heat Q_H .
- 2 → 3: gas is displaced to the cold end without changing volume.
- 3 → 4: gas is compressed in contact with the cold end at T_C , giving out heat Q_C .
- 4 → 1: gas is displaced to the hot end.

The work done *by* the gas in segment 1 → 2, when it expands against the piston, is just $\int P dV$, the area under the 1 → 2 isotherm. Likewise, the work done *on* the gas in segment 3 → 4 is the area under the lower isotherm. By subtraction, the net work done by the gas on the piston in the course of a whole cycle is thus given by the area enclosed by the cycle 1 → 2 → 3 → 4 → 1. Show that this is dimensionally correct. **Q**

The engine has attached both a position transducer which can be used to measure volume changes, and a pressure transducer. Connect these to a data acquisition system, and record the actual P-V diagram while the engine is working. Either the USB1208FS data acquisition module with the IVSMU software, or a digital oscilloscope will work. You will need to estimate the relationship between changes in the gas volume and the displacement transducer output. The diagram will be very non-ideal, but you should be able to see and measure the enclosed area. Make a calibrated plot for your lab book.

In conjunction with a measurement of the number of cycles per second from the tachometer, you should be able to work out the power being transmitted from the gas to the piston. Compare this with the thermal input power and the work output that you measured previously. Can you evaluate how much of the input is lost before it even warms the gas, and how much is lost in the mechanical system beyond the piston?

5 Further work

All engines have an optimum load at which they work most efficiently: too little load and little work will be done; too much and the engine will stall. There is no reason to suppose that the 10 g mass attached by a thread to the engine shaft is the optimum load for this engine, so try different loads to see which is the most efficient. What changes do you see in the P-V diagram as the load is changed?

MSC 2012-09-30