Laboratory 16: Stirling Engine

In this lab you will measure a number of different process efficiencies associated with the 3b Scientific Stirling engine (see Fig. 1).

Figure 1 Stirling engine with alcohol lamp heat source and coupled to an electric dynamo. The two small brass circles in the glass tube are in thermal contact with the hot (right) and cold (left) thermal reservoirs [1].

Theory

When calculating the efficiency of a process the key is to consider the energy that goes in, E_{in}, compared to the energy that is successfully converted into the desired form, E_{des}:

$$\eta = \frac{E_{des}}{E_{in}}$$

or equivalently

$$\eta = \frac{P_{des}}{P_{in}}$$

where P_{des} is the power shifted into the desired form and P_{in} is the power input to the process.

There are a number of different process that happen on the way from chemical energy (ethanol) sitting in the lamp to current flowing through the resistor. One way to do the slicing and dicing is as follows:

1. The ethanol and oxygen react releasing energy, some of which is turned into heat that warms the air.

2. The heated air passes over the glass heat exchanger warming the hot end of the engine.

3. The air passes back and forth between the high temperature heat exchanger and the low temperature heat exchanger. This causes work to be done by the gas on the piston through
$$dW = PdV.$$

4. The piston turns the electric dynamo which drives an electric current through the resistor.

5. The resistor turns the electric current into heat that warms the water in the calorimeter.

We will lump some of these process together. In particular we will lump conversions 1, 2 and 3 into a single process which we will call 1-2-3 (it is interesting to think about how you might tease each of them apart and interested parties could extend this lab by comparing the efficiency of the heat exchanger to the theoretical prediction). The energy in comes from the lower heating value of ethanol 26,810kJ/kg [2]. (The higher heating value of ethanol 29,670kJ/kg [2] would be relevant if the water vapor in the smoke condensed giving its energy to the process.) The desired energy output comes from the integral of the PV graph. Note that if $W_1$is the work done over one cycle and f is the frequency of the engine then
$$< P >= W_1 f$$
is the mean power.

The raw value you get for the efficiency of the combined 1-2-3 process is of practical importance. This includes the energy used to both prepare the engine for use (preheating) and the energy used to sustain the running of the engine. With care you can extract the steady-state efficiency (using experimental design and curve fitting to remove the warm-up period from the analysis). Since the Stirling cycle is a reversible process (and feeding electricity into the electric motor does turn the Stirling engine into a refrigerator) its theoretical efficiency is the Carnot efficiency

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H},$$

where T_L is the temperature of the low temperature reservoir and T_H is the temperature of the high temperature reservoir (see Fig. 1).

Regarding the other efficiencies, the efficiency of the dynamo, η_4, can be found by comparing the work done on the piston to the RMS current that passes through and voltage that appears across the resistor. The efficiency of the resistor for turning electrical power into heat, η_5, can be found by using the current calorimeter.

Procedure sketch

Use the precision scale to determine fuel consumed.

Devise an experimental method that allows you to determine the steady-state efficiency of process η_{1-2-3}. You will need both energy in and desired energy out. The lab is stocked with electronic pressure gauges and electronic temperature probes (use care selecting which type to use where) to directly measure those quantities. There are a number of choices for inferring the volume including rotory-motion sensor, the sonic ranger motion sensor and video capture.

Draw a schematic for your circuit showing the voltmeter and ammeter. Double check your voltmeter and ammeter are properly connected to your circuit and that you have chosen the proper settings.

Be careful when choosing the amount of water to add to your calorimeter.

Analysis

Compare the efficiencies η_{1-2-3}, η_4, and η_5 you found to a 100% efficient processes and, where possible, to theoretical predictions.

If time and interest permit compare the observed net efficiency for the entire process $\eta_{1-2-3-4-5}$ to the efficiency of heating the calorimeter directly with the lamp.

Question:

You likely found substantial differences between the carnot efficiency and the actual efficiency. Suggest one or more reasons for the difference and how you might go about testing your hypothosis.

References

[1] "Transparent Stirling Engine," 3B Scientific, [Online]. Available: https://www.a3bs.com/stirling-engine-g-u10050,p_868_657.html. [Accessed 5 April 2016].

[2] Y. A. C. a. M. A. Boles, Thermodynamics, an Engineering Approach, New York: McGraw Hill, 2011.