C1. Stirling Cycle

I. OBJECTIVE OF THE EXPERIMENT

The study of the thermodynamic Stirling cycle, and measuring the heat engine's efficiency at different speeds. Study of the efficiency of the engine working as a cooling machine, as well as a heat pump.

II. INTRODUCTION AND PHENOMENOLOGY

The interest manifested in new motors is justified by the current need for machines that pollute less, and are more efficient.

Apart from motors that use electrical energy, and those that use our muscles, all engines are thermal. Two examples are the combustion engine (designed by Beau de la Rochas in 1864, and first built in 1878 by Ott) and the heat engine (invented in 1816 by the Scottish pastor Stirling).

A thermal engine is a thermal machine that can convert part of a heat flux $\phi_2 - \phi_1$ coming from a flux ϕ_2 [J/s] of a heat source at temperature T_2, into a mechanical power P_m. The heat flux ϕ_1 is always lost, since it is released to a cold source at temperature T_1 (see fig. 1).

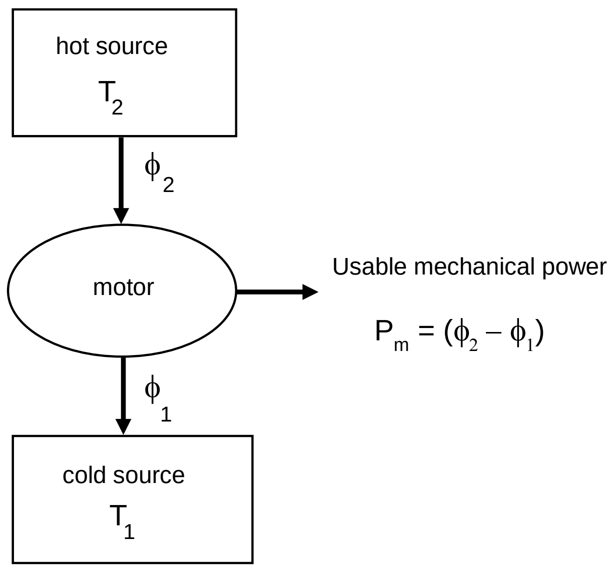

Fig. 1: Basic principle of heat engines

The thermal engine uses a thermodynamic cycle. The Carnot cycle is represented in a PV diagram by two isotherms and two adiabates. The Stirling cycle differs in that it is represented by two isotherms and two isochors.

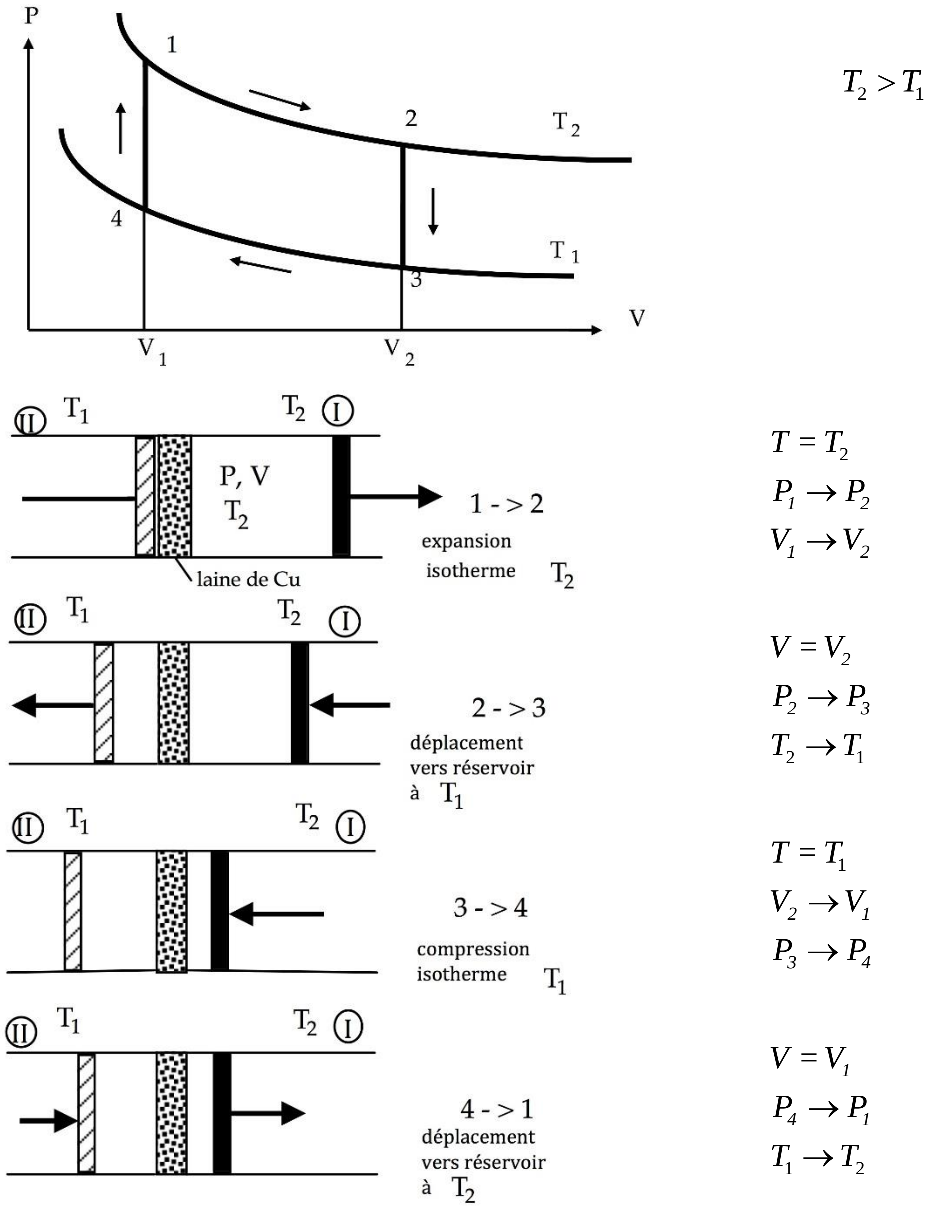

Fig. 2: Stirling cycle.

Thermodynamics tells us that the engine's efficiency ρ defined by the ratio of the mechanical power W divided by the heat flux ϕ_2 from the hot source is less than the ideal efficiency of a Carnot cycle (see thermodynamics lecture):

$$\rho = \frac{P_m}{\phi_2} < 1 - \frac{T_2}{T_1}$$

Combustion engines get rid of the lost heat ϕ_1 by releasing it directly in the atmosphere via the exhaust gases: this is called an *open cycle*. However, a closed cycle heat engine such as the Stirling cycle releases ϕ_1 via a cooling system. The released flux ϕ_1 quickly rises as ρ get smaller (fig. 3), giving us one extra reason to increase ρ as much as possible.

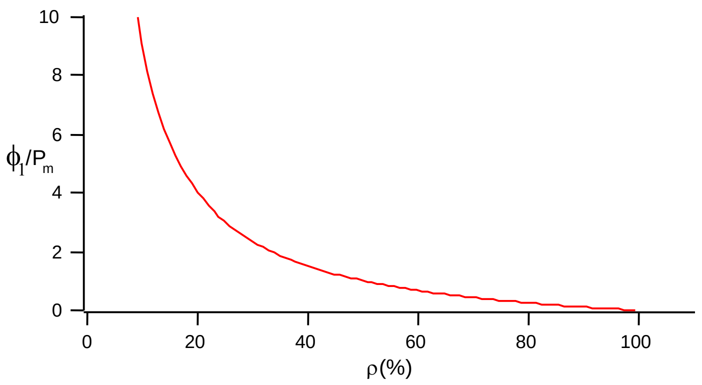

Fig. 3: Evacuated heat flux (in heat kW/mechanical kW) versus efficiency.

Albeit requiring a midsized device to evacuate heat, the Stirling cycle has three major advantages compared to the combustion engine. It is silent, requires a smaller $\frac{T_1}{T_2}$ temperature ratio, and its efficiency ρ is better with respect to the maximal thermodynamic limit.

III. EXPERIMENTAL SETUP

As a Heat Engine.

The lab version of the Stirling engine (fig. 4) uses air trapped in a cylinder containing two pistons, whose motions are out of phase by approximately a quarter of a rotation.
A motion piston fulfills the task of putting the air in thermal contact with the cold and hot source alternatively. The hot source is a heating body, and the cold source a water cooling circuit. A work piston follows the volume variations of the gas and transfers the harvested work to the shaft of the engine.
During phase 4 of the isochoric compression, (constant volume, increasing pressure), the air heats up faster once it's in contact with the copper wool, by recovering the heat it had transferred during the isothermal expansion in phase 1. Therefore, the frequency of the cycles increases. The copper wool helps extend the heat source.

An image of the setup can be found at the end of the document, figure 9.

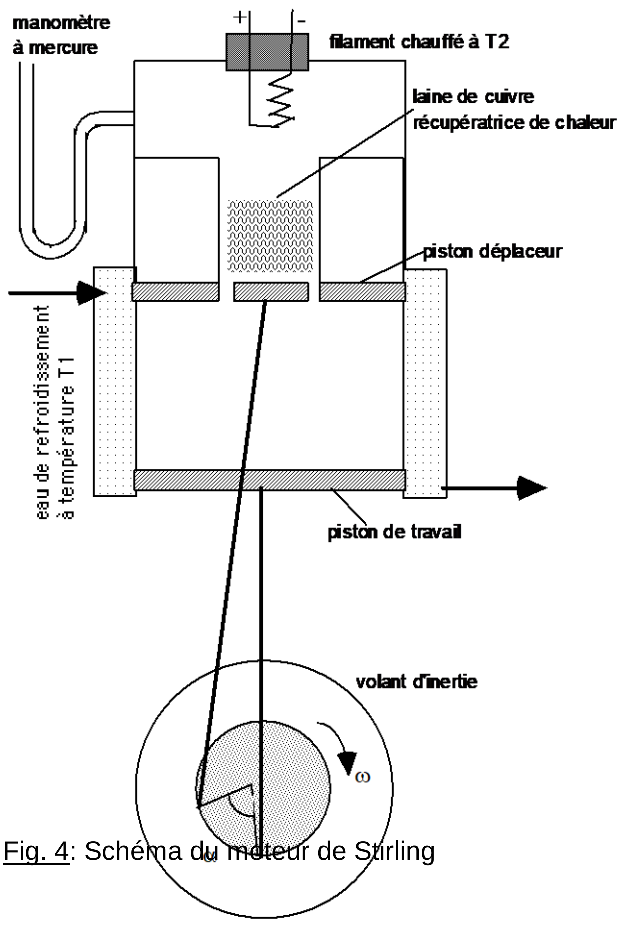

Fig. 4: Schéma du moteur de Stirling

Cooling machine and heat pump

Instead of using the machine as a heat engine, the Stirling machine can be used as a cooling machine or as a heat pump, if it is set in motion by a motor making the machine spin in the directions I and II respectively. (see fig. 5).

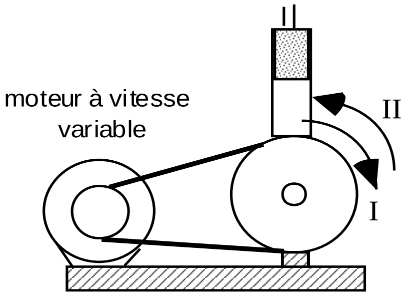

Fig. 5: Making the machine spin using an electric motor

In these cases, the top of the cylinder can either be heated or cooled. The heating body is then replaces by a smaller heating body and a thermal probe (see fig. 6).

WARNING: The removable parts closing the top of the machine are fragile. Please manipulate with care.

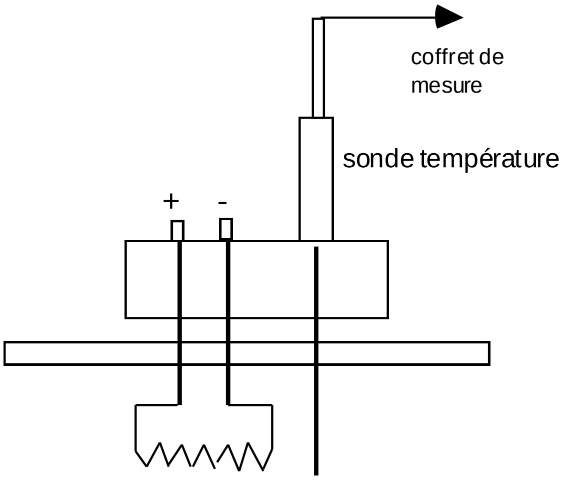

Fig. 6: Temperature probe and heating body.

Measurable values during the experiment.

A flowmeter measures the amount of water that flows through the cooling system every minute. Two temperature probes, measure the water's temperature entering and exiting the system. The height of the lower part of the ball defines the rate of flow. In order to get a value in cm^3/min, look at the conversion table that can be found in the lab. The rate of flow along with the temperature difference allows you to determine the heat flux ϕ_1.

The heat flux ϕ_2 is simply determined by calculating the electric power supplied to the heating body. When using the machine as a cooling system, set the heating body in such a way that the temperature of the system remains constant. When this is the case, the heat evacuated by the cooling machine corresponds to the electric power supplied to the heating body.

The mechanical power generated by the heat engine P_m is measured using a brake on the engine's shaft (see fig. 7). The torque exerted by the engine can be adjusted by spacing the braking device and the flywheel. The angular velocity ω is measured using a tachometer. The mechanical power is then obtained by (demonstrate):

$$P_m = \omega \cdot F \cdot R \cdot \cos\alpha .$$

Finally, a small mirror, able to rotate about its horizontal and vertical axes is mechanically linked to the pressure gauge and the work piston in such a way that by reflection of a light beam, it projects a PV diagram onto a screen. Therefore, the PV diagram can be transcribed onto a sheet of paper. The diagram can be calibrated by estimating the minimum and maximum volume contained between the two pistons, and by reading the minimal and maximal pressures on the pressure gauge. Once the proper calibration has been established, the generated work over one cycle W can be estimated by determining the surface of the PV diagram. This is made easier by discretizing the diagram (see fig. 8).

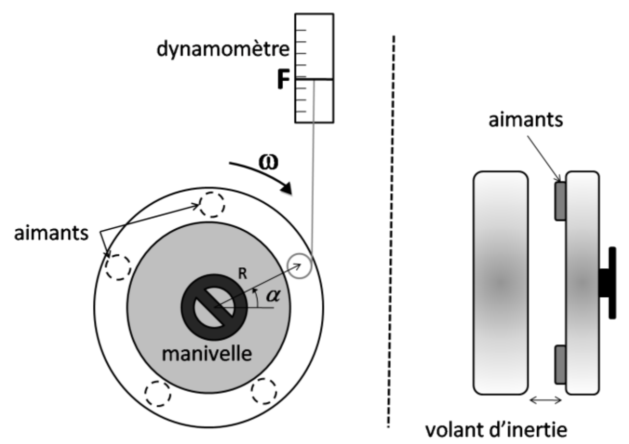

Fig. 7: Breaking mechanism, front and side view.

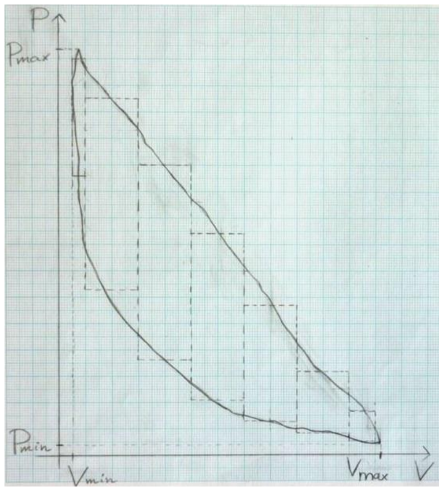

Fig. 8: Experimental PV diagram, with discretization.

IV. REQUIRED WORK

MOTOR

1) Calculate the theoretical efficiency of the Stirling cycle used as a heat engine. (see PV diagram in figure 2). Propose an evaluation of the hot source temperature.

2) Compare the values of the power and efficiency measured by:

   a) The area in the experimental PV diagram
   b) The braking method
   c) The heat differences: $\varphi_2 - \varphi_1 = P_m$ (fig. 1).

   Discuss the validity of the measurements. Work with fixed heat flow ϕ_2 .

3) Characterize the engine by a “torque-angular velocity” diagram. (Vary the distance of the breaking mechanism).

4) Study the efficiency of the heat engine as a function of the angular velocity ω of its shaft. Compare this value to the maximal thermodynamic efficiency.

COOLING MACHINE

5) Study the efficiency of the cooling machine as a function of the velocity of the electric motor. Remember that in this case, the efficiency is defined by the ratio of the evacuated heat flux ϕ by the supplied power. Discuss.

ATTENTION: Replace the heating body with the smaller one (which has a thermocouple mounted). Regulate the power supplied in order to maintain the temperature at room temperature in order to avoid heat exchange with the environment. This smaller heating filament **can't sustain high currents**!

OPTIONAL WORK

6) Study a property of your choice about the machine working as a heat pump.

The cycle is identical in refrigerating machine and heat pump. What changes is the source to consider.

Think about the modifiable parameters (temperature of the sources, power of the engine, ...), methods (flow difference, PV diagram, ...) and the interest of the measurements.

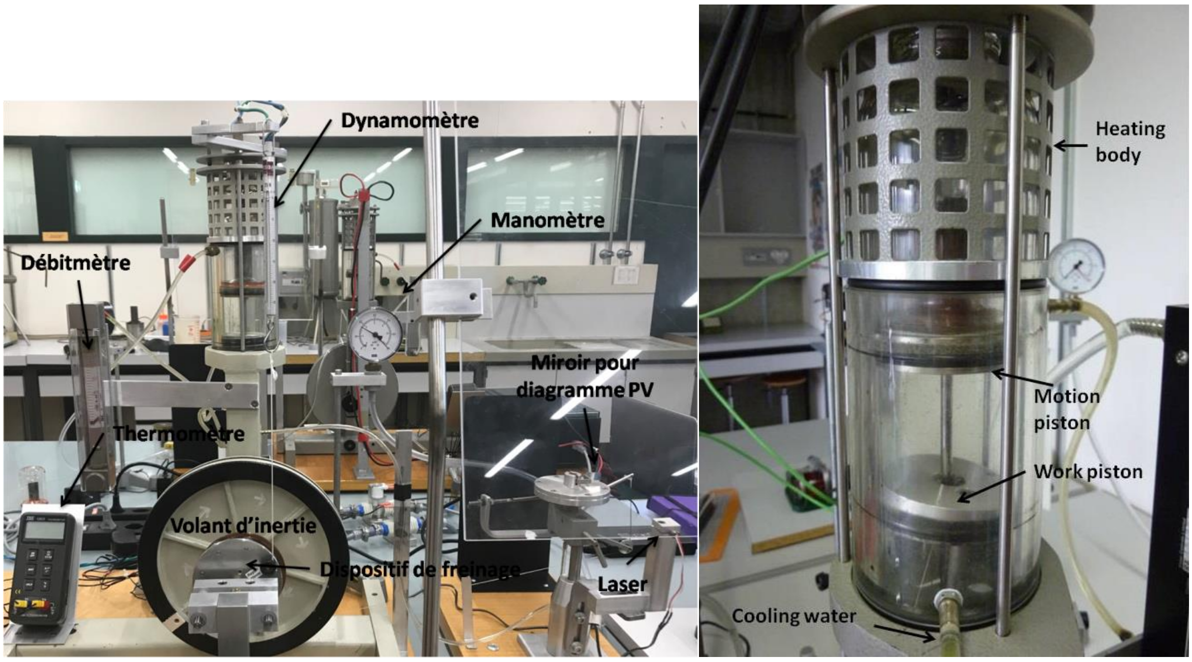

Fig. 9: Images of the used Stirling engine