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# Hot Air Engines

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## Abstract

Invented in 1816, the hot-air engines have known significant commercial success in the nineteenth century, before falling into disuse. Nowadays they enjoy a renewed interest for some specific applications. The "hot-air engines" family is made up of two groups: Stirling engines and Ericsson engines. The operating principle of Stirling and Ericsson engines, their troubled history, their advantages and their niche applications are briefly presented, especially in the field of micro-combined heat and power, solar energy conversion and biomass energy conversion. The design of an open cycle Ericsson engine for solar application is proposed. A first prototype of the hot part of the engine has been built and tested. Experimental results are presented.

**Keywords**: Hot air engine, Stirling engine, Ericsson engine, Joule cycle engine, External heat supply reciprocating engine.

## 1. Introduction

Applied thermodynamics tells that a heat engine thermodynamic cycle is obtained if the fluid state processes describe a clockwise closed loop in a thermodynamic state diagram such as the temperature – entropy state diagram (Fig. 1).

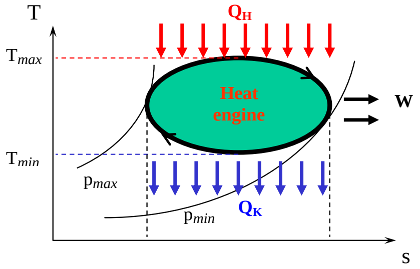


**Fig. 1**. Qualitative heat engine cycle in the temperature-entropy diagram

Figure 1 shows that the working fluid of a heat engine has to exchange heat with a hot and a cold source, but also has to undergo a pressure increase (compression) at low temperature and a pressure decrease (expansion) at a higher temperature. So the operation of a heat engine can be described as the succession of a cold fluid compression, a heat supply from a hot source, and a hot fluid expansion. The heat engines can be classified according the technology chosen for the compression device, the heat supply, the expansion device and the nature of the working fluid (Stouffs, 2002a). So in an internal combustion engine, the compression and the expansion occur in the same reciprocating machine and the heat supply is obtained by internal combustion in the cylinder. In a gas turbine, the compression and the expansion are realized in separate turbomachines and the heat is supplied in a separate combustion chamber. In a steam power plant the compression is realized in a turbopump, the expansion is realized in a steam turbine, the heat is supplied through a steam generator heat exchanger and the working fluid undergoes cyclic phase changes.

Amongst the wide diversity of thermal engines, a special family of engines can be identified from the following features: separate reciprocating compression and expansion machines, external heat supply, regenerator or recuperator, monophasic gaseous working fluid (Stouffs, 2002b). These engines are sometimes called ‘hot air engines’ (Finkelstein, 2001), even if the air used in the XIX$^{th}$ century engines has been replaced by high pressure hydrogen or helium in a lot of modern engines. Hot air engines have known commercial success during the XIX$^{th}$ century (Kolin, 1991), but, since the beginning of the XX$^{th}$ century, they have been discarded and replaced by internal combustion engines or electric motors. The family of hot air engines is divided in two subgroups: the Stirling engines, invented in 1816, have no valves (Fig. 2) whereas Ericsson engines, invented in 1833 (Fig. 3) have valves in order to isolate the cylinders.

Typical hot air engines are made up of five working spaces:

- The expansion space E
- The heater H
- The regenerator or recuperator R
- The cooler K
- The compression space C.

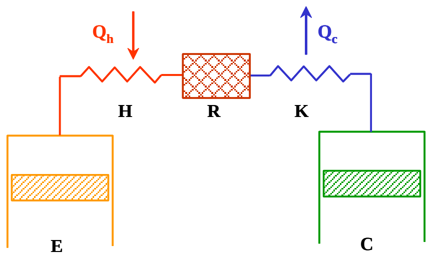


**Fig. 2.** Principle of the Stirling engine

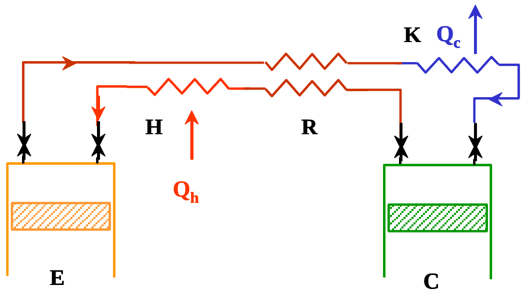


**Fig. 3.** Principle of the Ericsson engine

## 2. Hot Air Engines Operation

### 2.1 Stirling Engine

It can be deduced from the previous definition, that the range of machines which can be called 'Stirling engines' is actually very wide. This can also be inferred from the different names given to specific Stirling engines: hot air or hot gas engines, Heinrici engines, Robinson engines, Franchot engines, Rider or Siemens engines, Martini engines, Ringbom engines, free piston engines, flat plate engines, low Delta T engines, ... to name but a few. All these appellations refer to Stirling engines.

All existing Stirling engines are reciprocating machines, with periodically oscillating fluid flow from the hot to the cold part of the engine and conversely. Figure 4 illustrates the three usual configurations of Stirling engines.

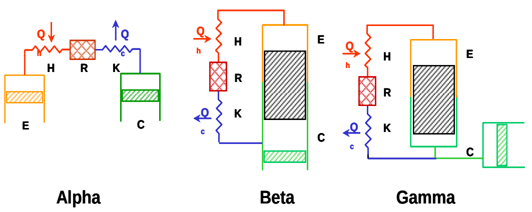


**Fig. 4.** Stirling engine basic geometrical configurations

While the alpha configuration has two pistons, one in the compressor space and one in the expansion space, the beta and gamma configurations have one power piston in the compression space, operating volume variations of the working fluid, and one displacer displacing the working fluid from the hot part to the cold part of the engine at constant volume.

In order to run properly, the two moving parts of a Stirling engine have to move in a specific way.

- When the gas is mainly located in the cold part of the engine (large volume of C, small E), the compression occurs, that is, the pistons motions are such that the compression volume C decreases, whereas the expansion volume E is kept constantly small.
- Next, the high pressure gas is transferred from the cold to the hot part of the engine, that is, the pistons motions are such that the compression volume C decreases, whereas the expansion volume E increases, the total volume of the engine being kept constant. During this process, the gas flows through the regenerator where heat transfer occurs from the regenerator solid matrix to the gas.
- When the gas is mainly located in the hot part of the engine (large volume of E, small C), the expansion occurs, that is, the pistons motions are such that the expansion volume E increases, whereas the compression volume C is kept constantly small.
- Finally, the low pressure gas is transferred from the hot to the cold part of the engine, that is, the pistons motions are such that the expansion volume E decreases, whereas the compression volume C increases, the total volume of the engine being kept constant. During this process, the gas flows through the regenerator where heat transfer occurs from the gas to the regenerator solid matrix.

As in every thermal engine, the mechanical work results from the balance between the work produced by the hot gas expansion and the lower work consumed by the cold gas compression.

It could seem surprising that this description of the Stirling engine operation does not refer to the usual 'Stirling thermodynamic cycle' made of two isothermal and two isochoric processes, as presented in most thermodynamics textbooks. This is actually due to the fact that the fluid thermodynamic state in a Stirling engine is far from being uniform. The instantaneous temperature gradients in the engine, for instance, are very important, so that there is not 'one' thermodynamic cycle for the fluid in the engine, but a lot of cycles, according to which fluid particle is considered. Therefore, the idea of the 'reference thermodynamic cycle' is not as interesting for Stirling engines as for conventional IC engines or for gas turbines, for instance (Organ, 1992). The simplest but still pertinent way to describe the thermodynamic processes of a Stirling engine is the ideal Schmidt analysis (Schmidt, 1871).

### 2.2 Ericsson Engine

The Ericsson engine can be carried out either by a closed cycle (Fig. 3) with cooler (in this case the system can run at high pressure and can use working fluids such as helium or hydrogen), or by an open cycle with or without recuperator. In this case, the working fluid is air that can be expanded down to the atmospheric pressure. In the simplest configuration, the Ericsson engine runs in an open cycle without heat recovery (Fig. 5). The atmospheric air is compressed by the compressor C: it receives heat from the hot source through the heater H. The hot air, under pressure, produces work by expansion in the expander E. In this case, the Ericsson engine is similar to a gas turbine where the turbocompressor has been replaced by a reciprocating compressor, the turbine by a piston/cylinder machine, and the combustion chamber by a heat exchanger.

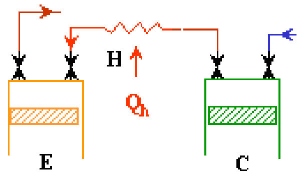


**Fig. 5**. Simplest Ericsson engine configuration

The theoretical Ericsson cycle (2 isotherms and 2 isobars) is not suited to describe an ideal Ericsson engine. Indeed, heat transfers take place at constant pressure while compression and expansion are supposed isentropic, corresponding to the Joule cycle, often used to describe the gas turbine.

## 3. Hot Air Engines Specificities and Advantages

The following specificities and advantages of Stirling engines should be reminded:

- A hot air engine accepts any kind of heat source (combustion, solar, nuclear, thermal storage, etc.); it is possible to switch from one source to another, while operating the engine (for example, from solar energy to gas combustion when night is falling).
- It is possible to design hot air engine which can run with a very low temperature difference between the hot and the cold source.
- In case of combustion, very low pollutant emissions levels can be obtained, since the combustion is external and continuous.
- High temperature hot air engines achieve energetic efficiencies similar to efficiencies of diesel engines with the same shaft power.
- There is neither explosion nor internal combustion in a hot air engine, so that the engine runs very quietly, with low mechanical stresses compared to an IC engine; the instantaneous torque is quite constant; the need for maintenance is very low and the operating life of a hot air engine is very high.
- In case of mass production, the cost of a hot air engine is potentially similar to that of a conventional IC engine.

## 4. Ericsson *vs* Stirling Engine

The Ericsson engine has several advantages compared to the Stirling engine:

- The compression and expansion enclosures are isolated from heat exchangers when working; this means that the heat exchangers volume is not to be considered as dead (unswept) volume which is detrimental to specific power and, to a lesser degree, efficiency; there is no compromise to find between (dead) heat exchangers volume to minimize and heat transfer exchangers area to maximize; this balance is very difficult to obtain in the case of the Stirling engine design.
- The fluid circuit is a loop; the flow is one-directional whereas it is oscillating in the Stirling engine*;* the thermodynamic behaviour of one-directional flow can be modelled accurately; the internal heat exchanger can be a simple counter flow heat exchanger inducing lower pressure losses than the equivalent regenerator in the Stirling configuration;
- The loop circuit of the Ericsson configuration (Fig. 3) suppresses the aberration of the Stirling configuration: in the Stirling configuration (Fig. 2) the working fluid flows through both the heater and the cooler in each fluid flow direction, whereas it would be preferable that the fluid bypasses the heater H when flowing from the expansion space E to the compression space C and conversely, it would be preferable that it bypasses the cooler K when flowing from the compression space C to the expansion space E.
- The kind of pistons motion used for the kinematic mechanism has no influence on the engine performance in the Ericsson engine, whereas it is of significant importance in Stirling engine; simple and efficient mechanism can thus be used for Ericsson engine.
- The valves of Ericsson engines could be used to control the engine, in particular for transients or load variations.

On the other hand, the disadvantages of a Ericsson engine are the following:

- The valves of Ericsson engines lead to supplementary pressure losses and mechanical energy consumption with reference to the equivalent Stirling engine.
- The valves could be noisy; however, the technology developed in the field of internal combustion engines allows the manufacturing of efficient and low noise valves.
- The valves could reduce the reliability of the Ericsson engine compared to the Stirling engine. But current technology in the field of reciprocating engines and compressors allows the manufacturing of reliable long-lasting valves.
- The valves increase the engine complexity.

## 5. Hot Air Engines: A Brief History

Hot air engines are amongst the very first heat engines to have been invented. The first hot air engine has been built by the Scottish pastor Robert Stirling in 1816 (Fig. 6), in the beta Stirling engine configuration. In 1833, Ericsson built a closed cycle Ericsson engine (Fig. 7).

Some years later, he invented an open cycle engine (Fig. 8). A Ericsson heat engine has been used to power a ship (Fig. 9). This engine had a power of 220 kW with a global efficiency of 13.5 % and a speed of rotation of 6.5

rpm. The maximum air pressure was 0.16 MPa, the piston stroke was 1.8 m and the compression cylinder bore was 3.5m, while the expansion cylinder bore was 4.3 m (Kolin, 1991).

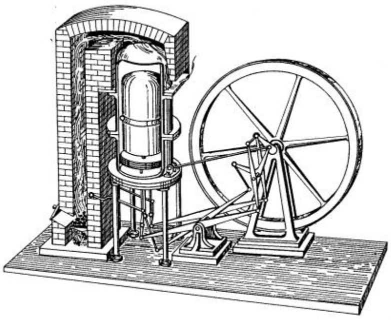

**Fig. 6.** The first Stirling engine (1816)

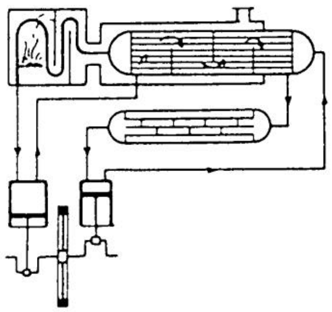

**Fig. 7.** The first Ericsson engine (1833) (Kolin, 1991)

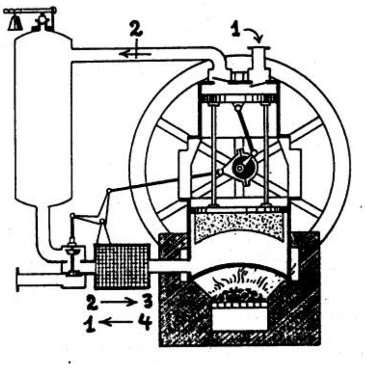


**Fig. 8.** The open cycle Ericsson engine (1853) (Kolin, 1991)

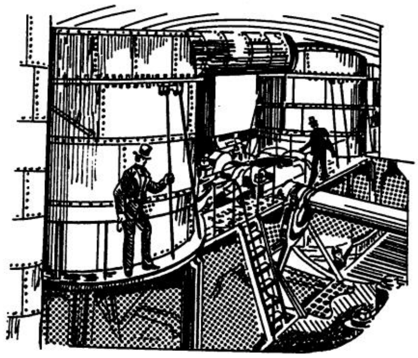

**Fig. 9.** The ship Ericsson engine (1853) (Kolin, 1991)

It is worth noting that Ericsson was also a pioneer in the field of thermodynamic solar energy conversion (Fig. 10). Hot air engines have known commercial success during the XIX$^{th}$ century, but, since the beginning of the XX$^{th}$ century, they have been discarded and replaced by internal combustion engines or electric motors.

Since the pioneer work of the Philips Company, around the Second World War, the attention has been drawn again on Stirling engines and lots of research and developments have been carried out. However, up to now, not many studies are dedicated to Ericsson engines.

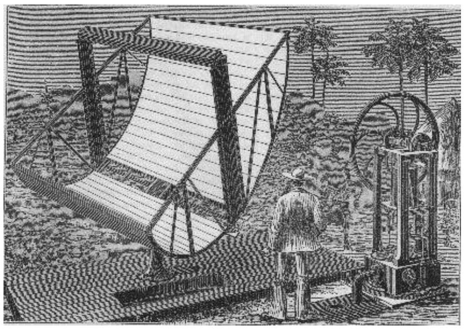

**Fig. 10.** Thermodynamic solar energy conversion by Ericsson (1883)

## 6. Stirling Engines: Some Examples

In 1950 Philips developed a very interesting electric generator in order to supply electricity to a radio (Fig. 11). The generator operated with combustion of methanol and ran very quietly. However this system had no commercial success since at that time the transistor radio was invented, which could operate with batteries.

**Fig. 11.** The Philips electric generator (1950)

**Fig. 12.** Ford's 4-215 Stirling engine in a Ford Taunus

Some developments were done by Philips and General Motor for automotive applications. Siemens configuration double-acting Stirling engines developed by United Stirling (USAB, Malmö) were successfully tested in a Ford Pinto, a Ford Taunus (Fig. 12) and a truck. However the engine was very bulky and the power control system was complicated.

The world largest civil submarine SAGA (Fig. 13) developed by the French companies COMEX and IFREMER is propelled by two 75 kW USAB Stirling engines with a thermal efficiency of 31 % (Sauzade *et al.*, 1991).

**Fig. 13.** SAGA submarine and the USAB Stirling engines

In the field of thermodynamic solar energy conversion, the so-called Dish/STIRLING technology has led to outstanding realizations (Stine and Diver, 1994; Kongtragool *et al.*, 2003). Figure 14 is a picture of such a system installed in front of the French solar furnace of Odeillo (PROMES, CNRS). Figure 15 presents another example of such a system, able to produce 25 kW of electric power. Initially developed and tested by McDonnell Douglas and Southern California Edison, it has been acquired by Stirling Energy Systems (SES) in 1996.

This system, built in the years 1984-1985, is made up of a 10.57 meter equivalent diameter concentrator. The original STIRLING engine is a kinematic 4-95 MkII engine built by United Stirling AB (USAB). This engine has a 38-42% efficiency for a maximum hydrogen working fluid temperature of 720 °C. The whole system leads to a global solar to electric energy conversion efficiency of more than 30%. Since 1984, it has held the world record for efficiency in converting solar energy into grid-quality electricity.

Unlike internal combustion engines, hot air engines generate low noise and do not need frequent maintenance. Therefore they are particularly suited for low-power combined heat and power (CHP), for residential applications for instance. Up to now, several Stirling engines have been designed for micro-cogeneration (Pehnt *et al.*, 2006, Onovwiona *et al.*, 2006). Several systems are already available or will be soon on the market. As an example, Fig. 16 presents the Whispergen CHP system installed in a kitchen, while Fig. 17 shows the Sunmachine wood pellets micro-cogenerator.

**Fig. 14.** Solar Dish/Stirling technology system (Source: CNRS-PROMES, Font-Romeu, France)

**Fig. 15.** SES Solar Dish/Stirling system (Source: www.stirlingenergy.com)

**Fig. 16.** The WhisperGen micro-cogenerator (Source: www.whispergen.com)

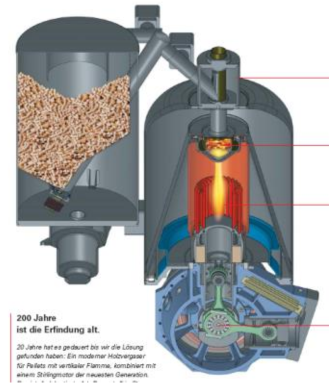


**Fig. 17.** The wood pellets Sunmachine micro-cogenerator (Source: www.sunmachine.de)

It is possible to design Stirling engine for very low temperature difference. Figure 18 presents a cheap and low tech solar pump developed by Sunmachine, without solar concentration. Figure 19 shows the so-called Sunpulse low ΔT engine designed by BSR.

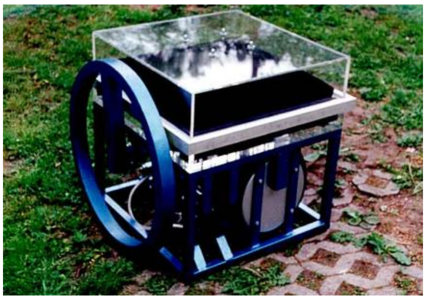

**Fig. 18.** A low ΔT solar pump (Source: www.sunmachine.de)

## 7. Ericsson Engines: Some Possible Applications

Up to now they are very few research and development effort in the field of Ericsson engines. While some works are devoted to internal combustion Joule cycle Ericsson engine from fossil fuel (Moss *et al.* , 2005, Bell and Patridge, 2003), other studies deal with external heat supply Joule cycle Ericsson engine (Bonnet *et al.*, 2005, Alaphilippe and Stouffs, 2008).

**Fig. 19.** A low ΔT solar engine (Source: www.bsrsolar.com)

As for Stirling engines, Ericsson engines are specially interesting for thermodynamic solar energy conversion and for micro-cogeneration. However, in both fields, Ericsson engines can have some specific advantages on Stirling engines.

### 7.1 Micro-Cogeneration

It has been shown that a natural gas CHP system based on an open cycle Ericsson engine could be interesting and profitable (Bonnet *et al.*, 2005).

Furthermore there is a great interest for micro-cogeneration systems based on wood energy. The only commercially available system up to now is based on a Stirling engine fuelled by wood pellets (Fig. 17) (Thiers *et al.*, 2010). Other tests have been carried out by coupling a Stirling engine in a conventional wood boiler. One of the main problems consists in the fouling of the Stirling heater and the difficulty to clean its surface due to its compactness (Kammerich, 2008, Sicre *et al.*, 2008). For this application the Ericsson engine is interesting since the heater does not need to be compact and may be designed according to heat transfer and fouling consideration only.

### 7.2 Low Power Solar Energy Conversion

The 'Dish/Stirling' technology relies on high temperature Stirling engines and requires a high solar energy concentration ratio. This technology is very efficient. However it is clear that these systems are quite heavy, leading to high costs. Especially the parabolic 'dish' concentrator, the sun tracking system and the engine fixation at the concentrator focus are quite expensive. Also the high pressure high temperature engine requires an expensive technology.

Due to the need to minimize the heater volume, solar energy conversion by means of a Stirling engine implies to focus solar beams on a point that means to use an expensive parabolic dish. Using an Ericsson engine allows large heater thus linear solar concentrator such as parabolic trough. Modeling results have shown that the coupling of a parabolic trough with an open cycle Ericsson engine could lead to a yearly global efficiency higher than 10 % while using a low tech and cheap system (Alaphilippe and Stouffs, 2008; Alaphilippe, 2007).

## 8. Ericsson Engines: A First Prototype

It has thus been decided to build and test a first Ericsson engine prototype. The prototype built up to now is not a complete engine but only the most difficult part to design that is the 'hot' part of the reciprocating Joule-cycle Ericsson engine. It comprises not only the 'hot' valves, but also the whole expansion cylinder, the double contrarotating crankshaft and the camshaft. By comparison with a complete Ericsson engine, only the compression cylinder is missing.

The prototype is designed to work with air in open cycle as the working fluid and to withstand compressed air supply at a pressure of 300 kPa and a maximum temperature of 650 °C. The prototype expansion cylinder capacity is 0.65 dm3. The expansion cylinder bore is 80 mm, the piston stroke is 129 mm and the maximum rotation speed is 950 rpm. This leads to an expected air mass flow rate of 5 $10^{-3}$ kg/s, an indicated expansion cylinder power of 1140 W and an expected mechanical power of about 1 kW. Eventually an expansion cylinder of 257 mm bore and a compression cylinder of 163 mm bore will be fitted to the prototype instead of the actual 80 mm bore expansion cylinder leading to an expected net mechanical power of 3.8 kW at 950 rpm suited for solar application (Alaphilippe, 2007). Figure 20 presents a picture of the prototype.

Extended tests have been carried out in a wide range of rotational speed and inlet temperature. As an example, Fig. 21 presents the pressure evolutions recorded upstream from the heater, in the prototype inlet pipe and in the cylinder head for an air temperature of 518 °C in the inlet pipe. It can be observed that the pressure difference between the inlet pipe and the cylinder head is very low during the admission phase, that is from about the top dead center TDC = 0 ° up to 90 ° crankshaft. This shows that the pressure loss due to the inlet valve is very weak. Figure 21 shows pressure oscillations due to acoustic phenomena in the inlet line which presents rough section variations. Finally it can be observed on Fig. 21 that in spite of two important buffer spaces upstream from the inlet pipe, the pressure in the inlet pipe decreases during the admission phase, while the pressure upstream the heater remains constant.

**Fig. 20.** The prototype of the 'hot 'part of the Ericsson engine

The three diagrams are not perfectly superimposed on one another for each rotational speed because the inlet pressure and the inlet and outlet cam adjustments have not been reproduced exactly identically in the three tests. It is however observed that the shape of the diagrams is globally independent of the rotational speed as expected. Figure 22 presents the indicated diagrams corresponding to three different rotational speeds.

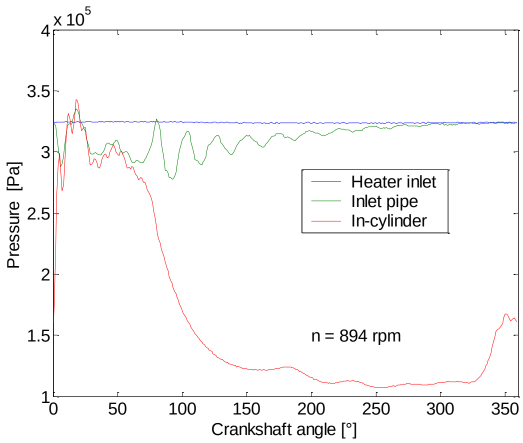


**Fig. 21.** Pressure evolution for an inlet temperature of 518 °C

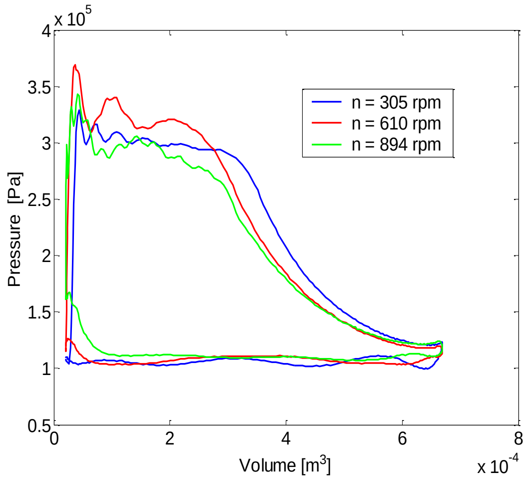


**Fig. 22.** Indicated diagrams for an inlet temperature of 518°C and for three rotational speeds.

The experimental indicated power obtained for a rotational speed of 950 rpm is 1160 W. This result perfectly fits the value of 1142 W expected from the modeling results. The averaged experimental mechanical efficiency value is 0.87, very close to the mechanical efficiency of 0.90 considered in the modeling work. For a rotational speed of 950 rpm the shaft power is 1003 W. This value is to be compared to the expected value of 1028 W.

The tests results have been very encouraging. Therefore it has been decided to dismantle the prototype in order to add the compression piston to allow the test of a complete Ericsson engine.

## 9. Conclusion

Hot air engines can play a key role in future energy conversion systems especially for renewable energy conversion (solar, biomass) and for micro- cogeneration. They present an important potential as well from the energy as from the economic point of view. They can be the subject of fundamental and applied research. If lots of research and developments have already been carried out in the field of Stirling engines, not many studies are dedicated to Ericsson engines up to now. However Ericsson engines seem to be very promising for such applications such as solar energy conversion or micro-cogeneration from conventional fossil fuels or biomass. That is why a first prototype of the 'hot' part of an Ericsson engine has been designed and built. It has been successfully tested in our Laboratory.

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