International Journal of Control, Energy and Electrical Engineering (CEEE)
Vol.9 pp.26-29

Performance evaluation of Gamma type Stirling engine

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Abstract— **Present paper is performed to investigate the effect of working parameters on Gamma type Stirling engine performances. An experimental evaluation of an engine with a maximum power of 500 W has been done. The impact of four operating parameters (load pressure, rotational speed, hot source temperature and cooling water flow rate) on the power produced by the Stirling engine was discussed. Particular care is subsequently given to the effect of each parameter on the produced power. Results show that an optimum value of the rotation speed must always be respected to ensure the proper functioning of the Stirling machine. It is also shown that the brake power is more sensitive to a change in rotation speed and hot temperature for high charge pressure values than for lower values.**

Keywords— **Initial charge ressure, hot temperature, speed, cooling water flow rate and power**

I. Introduction

The need of reducing the fossil fuels use; the need of reducing energy bills, the need of searching alternative ways to produce cleaner energy and the possibility of waste heat recovery encourages us to gain from Stirling engine benefits[1]. Nowadays, Stirling installations are patterned and commercialized such as Microgen installation, Whispergen unit, Stirling Dish, etc. The Stirling technology provides a good solution, since it can work with any external heat source such as solar, combustion of any fuel, nuclear and even warmth. The Stirling engine is characterized by a silent mode of operation, easy maintenance, lower NOx, HC, and CO emission and a good efficiency [2].
The Stirling engine is mainly composed by five compartments: 2 working spaces and three heat exchangers (Heater, cooler and regenerator). The regenerator (porous medium) characteristics are determinant for the whole engine performances [3]. Compared to the Ericsson engine, at nearly the same working conditions, the Stirling engine presents higher global performances (specific indicated work, thermodynamic and exergetic efficiencies), due to the presence of a regenerator [4].

Many researches focus numerically and experimentally on working parameters effect on the output power of the Stirling engine (SE). Walker experiments [5] show that the SE mechanical output power depends on the expansion hot temperature. The dimensionless output power increases gradually with the expansion hot chamber temperature. Gheith et al. [6] proved that the SE power and torque increase with hot source temperature. Shuttle loss rises with temperature difference between the two ends of the displacer which is related to temperature gradient between the two heat sources. Sowale et al. [7] concluded that the performance of the Stirling engine is very sensitive to the heat transfer by conduction and the temperature of the working gas. Previous numerical investigation of 500 W Gamma type Stirling engine [3] showed that the evolution of output brake power versus rotation speed reaches an optimal value. In fact, the rotation speed increase reduces heat loss by external conduction through engine's walls, reduces heat exchange time and increases friction loss inside each heat exchanger [3]. This result is approved by Karabulut [8] when investigating the performances of a Beta type Stirling engine driving mechanism by means of a lever. Cheng et al. [9-10] developed a dynamic model incorporated with thermodynamic model to study the thermal-lag Stirling engine start process. They found that the optimal engine speed leading to maximum shaft power is significantly influenced by the geometrical parameters (bore size, stroke, and volume of working spaces). According to Chen et al. [9-10] engine speed pose strong positive effects on power but exert weak effects on efficiency. Optimal frequency depends on the Stirling engine geometric parameters. Gheith et al. [11] has shown that the heat exchanged in the heater increases with the initial charge pressure until an optimum value. The regenerator thermal irreversibility decreases with the initial charge pressure. However, the Stirling engine output power and efficiency are enhanced until an optimum value.

The aim of this experimental work is focused on the dependence of four operating parameters (load pressure, rotational speed, hot source temperature and cooling water flow rate) on the power produced by the Gamma type Stirling engine.

II. Description of the Gamma type Stirling engine (GSE)

The Gamma type Stirling engine is a motor sized by the German company Viebach ST05 G. This engine is kinematic type having a rod-crank drive system. Like all Stirling engines, this engine is composed of three heat exchangers (the heater, the regenerator and the cooler) and two work spaces. A section of this engine, on which appear the five elementary spaces of the engine, is provided in Fig. 1. The

ISSN 2356-5608

initial charging pressure Stirling Gamma engine is imposed by an external compressor. The latter makes it possible to keep a constant pressure inside the engine during the experimental measurements. The GSE uses air as a compressed working fluid at a maximum load pressure of 10 bar. Its maximum rotational speed is about 600 rpm and it can provide a maximum mechanical power of 500 W. The compression and expansion spaces are arranged at an angle of 90 °. They are animated by a classic system of crank-rod. Table 1 summarizes the different geometric characteristics of this prototype.

TABLE I
GEOMETRIC PARAMETER VALUES OF THE VIEBACH STIRLING setup

Parameters	*Values*	*Parameters*	*Values*
Working gas	air	***External diameter***	134 mm
Crank radius	66 mm	***Internal diameter***	98 mm
Length of the connecting rod	130 mm	***Height***	50 mm
Compression space		***Porous media***	Cooper
Diameter	80 mm	***Porosity***	85%
Height	145 mm	***Cooler***	
Course	75 mm	***Diameter***	12mm
Expansion space		***Length***	650 mm
Diameter	95 mm	***Heater***	
Height	120 mm	***Tube number***	20
Compression ratio	3.5	***Tube length***	349mm
Regenerator		***Tube inside diameter***	6mm

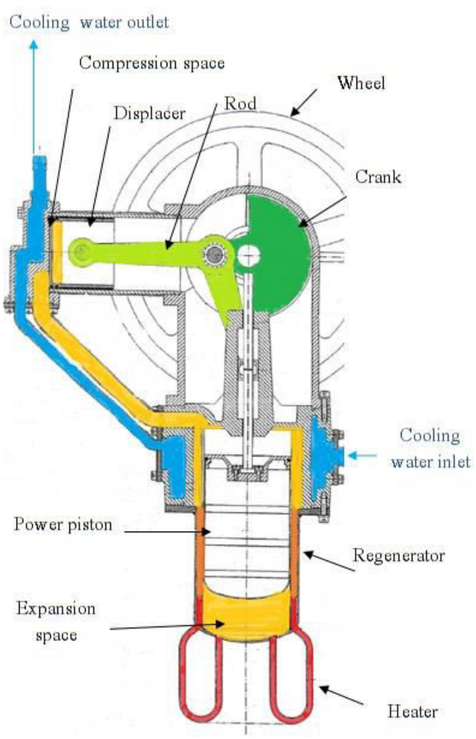


Fig. 1 Gamma type Stirling engine Geometry

III. STIRLING ENGINE PERFORMANCES

The Stirling's ideal thermodynamic cycle is composed of two isochoric and two isotherms. It is similar to the Carnot cycle; the only difference between them is that the two isothermal processes in the Carnot cycle are replaced by two isochoric processes in the Stirling cycle. As shown in fig.2, the working gas trapped in the engine undergoes the following transformation: During the first transformation (3→4), the volume of the gas decreases and the pressure increases as it gives up heat Q_k to the cold source. During the second transformation (4→1), the volume of the gas remains constant as it passes back through the regenerator and regains some of its previous heat. During the third transformation (1→2), the gas absorbs energy Q_h from the hot source, its volume increases and its pressure decreases, while the temperature remains constant. Finally, during the fourth and last transformation (2→3), the volume of the gas remains constant as it transfers through the regenerator and cools.

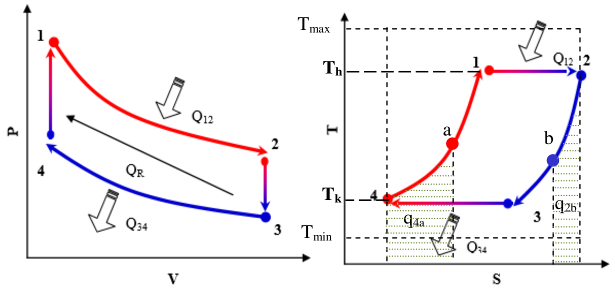


Fig.2. Theoretical cycle in the P-V and T-S diagrams of a Stirling engine

The actual efficiency of Stirling engines is obviously lower than the theoretical efficiency. The first reason is that heat transfer requires keeping a temperature difference between the sources and the working fluid. Thus, in particular, the internal transfer only partially supports heating 4-1 and cooling 2-3. We denote by α the fraction of heat exchanged:

$$q_{4a} = \alpha q_{41} = -q_{2b} = -\alpha q_{23} \quad (1)$$

The rest heat exchanged quantities qa1 and qb3, must be performed with the sources and significant thermal differences, which consumes extra energy at the hot source (qa1), increases irreversibilities, and therefore decreases the efficiency.

The second reason is that, despite the technological efforts made, transfers 1-2 and 3-4 with sources are never isothermal and transformations 4-1 and 2-3 do not strictly correspond to polytropes. All transformations have a certain level of irreversibility.

In the Stirling cycle (Fig.2) the thermal exchanges with sources also correspond to transformations with mechanical energy exchange, since, being isochoric, the two other transformations take place without work: $W_{41} = W_{23} = 0$. We can therefore write, considering the law of perfect gases P V = r T:

$$W_{12} = -rT_{max}\ln\varepsilon \quad \text{et} \quad W_{34} = rT_{min}\ln\varepsilon \quad (2)$$

$$W = W_{12} + W_{34} = r\ln\varepsilon\,(T_m - T_M) \quad (3)$$

With ε is the volumetric compression ratio:

$$\varepsilon = \frac{V_2}{V_1} = \frac{V_3}{V_4} \quad (4)$$

The temperature and the internal energy being constant, the amount of heat received from the hot source is:

$$q_{max} = q_{12} = -W_{12} = rT_{max}\ln\varepsilon \quad (5)$$

Let us examine the influence of thermal gradients in exchanges (Fig.2) on the yield and, firstly, that of the coefficient α. In this case, the expression of the job does not

ISSN 2356-5608

change. On the other hand, the heat that hot source must supply is increased by the quantity (1-α) .q41. As:

$$q_{41} = \Delta u_{41} = c_v(T_{max} - T_{min}) = \frac{r}{\gamma-1}(T_{max} - T_{min}) \quad (6)$$

Thermal efficiency of the Stirling cycle is expressed as:

$$\eta_{th} = -\frac{W}{q_M+(1-\alpha)q_{41}} = \eta_c \frac{1}{1+\frac{1-\alpha\,\eta_c}{\gamma-1\ln\varepsilon}} \quad (7)$$

With η_{th} is the Carnot yield calculated with the extreme temperatures of the cycle.

IV. RESULTS AND DISCUSSIONS

A. *Hot temperature and pressure dependence*

Fig.3 shows the contour of the power produced by the GSE as a function of the temperature of the hot source and the load pressure of the GSE. The range of temperature varies from 300°C to 500°C and that of the charging pressure varies from 3 to 8 bars. It should be noted that the same power can be obtained with different conditions. For example a power of 300 W can be obtained when P_i = 8 bar and T_h = 390°C or when P_i = 7 bar and T_h = 410 ° C. The engine power increases with the temperature of the hot source. Raising the hot end temperature provides additional heat to the working fluid inside the heater. As a result, the temperature difference between the two workspaces also increases; which improves the power produced by the Stirling engine. However, the increase in temperature of the hot end is limited by the heat capacity of the working fluid.

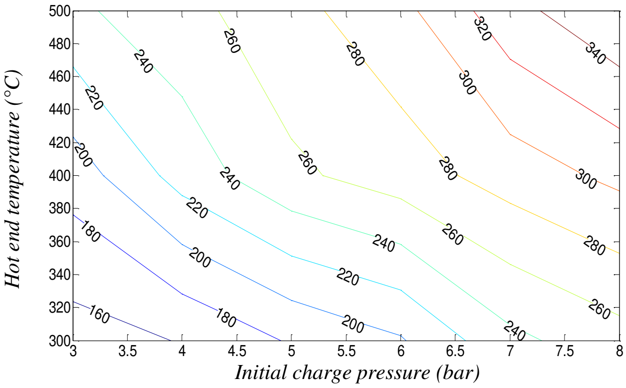


Fig. 3. Contour of power versus hot temperature and pressure

B. *Initial charge pressure and cooling flow dependences*

The initial charge pressure is imposed to the engine before it start-up. It represents the amount of working gas flowing within the engine. This mass is proportional to the initial charge pressure increase. The amount of thermal energy exchanged in the engine is closely related to the working gas mass. Fig.4 shows the power contour as a function of the charge pressure and the cooling water flow rate for two different hot temperatures (T_h = 300 °C and T_h = 500 °C). The range of flow varies from 0 to 8 l/min and that of the pressure varies from 3 to 8 bar. It is clear that increasing the cooling rate slightly improves the power produced. For T_h = 300 °C and P_i= 3.5bar, the power increases from 80 W to 160 W when the flow rate varies from 1 l/min to 7.5 l/min. Increasing the cooling rate decreases the temperature of the compression space and therefore improves the temperature difference between hot and cold source; which improves the power of the Stirling engine.

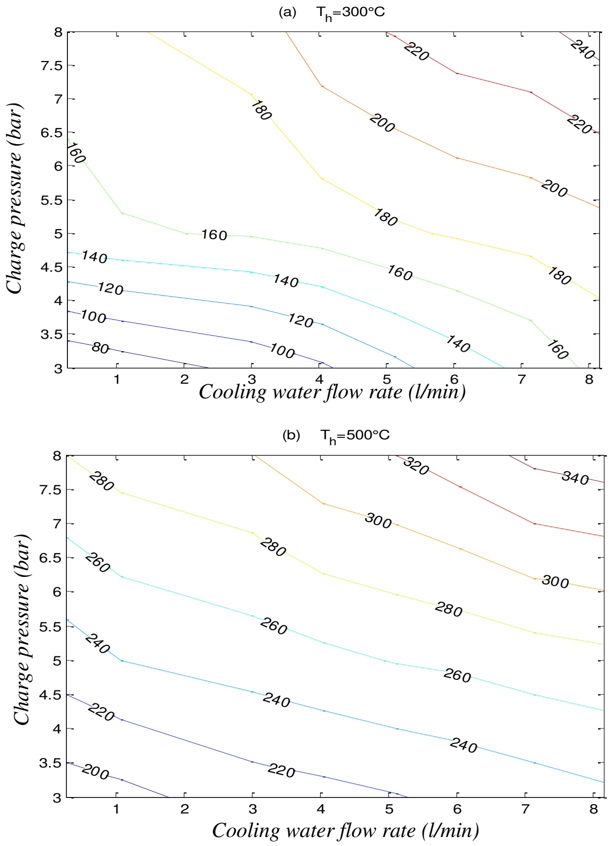
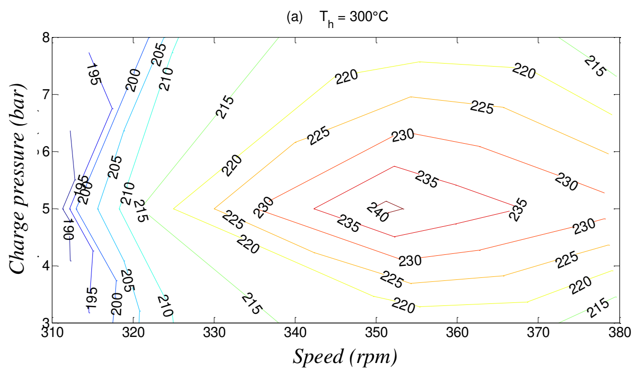


Fig. 4. Contour of power as a function of pressure and flow rate of cooling water (a)T_h=300°C (b)T_h=500°C

C. *Initial charge pressure and speed dependences*

Fig.5 shows the power contour for two different hot temperatures (T_h = 300 ° C and 500 ° C) depending on the rotation speed and the load pressure. The evolution of the power with respect to the speed of rotation reaches an optimal value. Increasing the speed reduces external conduction loss through the motor walls, reduces the heat exchange time and increases the frictional loss within each heat exchanger. If N> $N_{critical}$, the heat exchange process occurs very rapidly, the residence time of the working fluid in the three heat exchangers will become very short. The working fluid does not have time to absorb all the amount of energy delivered by the hot source. Work fluid leaks also increase; which causes the reduction of the power of the engine SG. The critical value of the rotational speed ($N_{critical}$) depends on both the charging pressure and the hot source temperature. When P_i = 5 bar and T_h = 500°C, the optimal power of 260 W is obtained for $N_{critique}$ = 360 rpm. However, when P_i = 7.3 bar and T_h = 500 °C, the optimal power of 340 W is obtained for $N_{critique}$ = 380 rpm.



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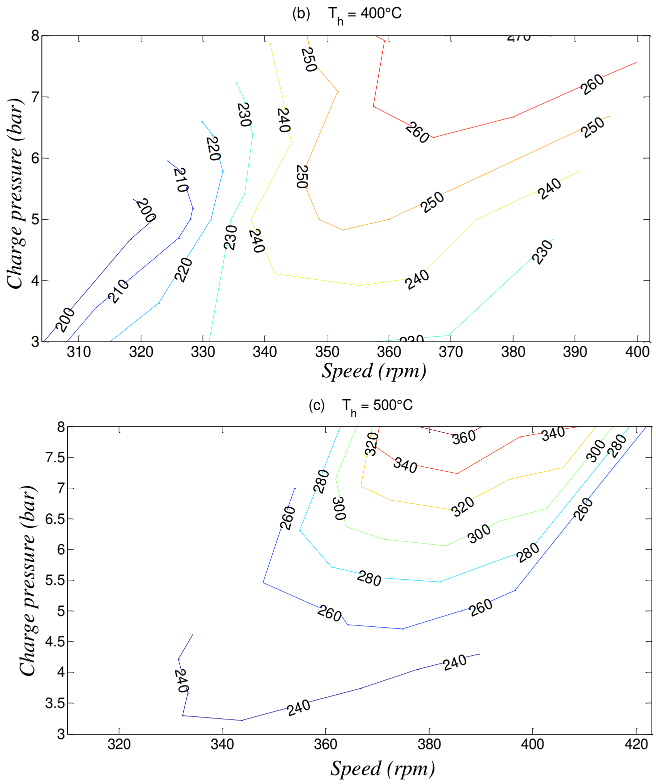

Fig. 5. Contour of power versus pressure and velocity (a)T_h=300°C (b)T_h=400°C et (c) T_h=500°C

V. Conclusions

The experimental study of the Stirling Engine leads us to conclude that:

- The parameters (speed of rotation, initial charge pressure, cooling water flow rate and hot temperature) are dependent and their interactions significantly affect the power of the Stirling engine.
- The optimal rotation speed of the Stirling engine depends on the temperature of the hot end and the pressure of the load.
- An optimum value of the rotation speed must always be respected to ensure the proper functioning of the Stirling machine (The increase of the rotation speed has double effects. On the one hand, it favors the exchanges of heat by convection and on the other hand, it increases the losses by viscous friction through the singularities of the machine).

-The increase of initial charge pressure leads to an increase of working fluid mass, which increases the Stirling engine brake power. However, the load pressure is limited on the one hand by the capacity of the motor to withstand the high pressure (resistance of the materials) and on the other by the realization of a perfect seal (to reduce the leaks of working gas)

-The increase of hot end temperature leads to an increase of the thermal exchanged energy. Thus, the increase of Stirling engine brake power. However, the temperature of the hot end should be moderate. It is limited by the melting temperature of the material of the hot heat exchanger

Acknowledgment

This work was supported by the laboratory LAMIH CNRS UMR 8201 (University of Valenciennes), the laboratory LESTE (ENIM, Monastir, Tunisia) and the European Commission within the International Research Staff Exchange Scheme (IRSES) in the 7th Framework Programme FP7/2014-2017/ under REA grant agreement n°612230. These supports are gratefully acknowledged.

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ISSN 2356-5608