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THE FUNCTIONAL ANALYSIS OF A GAMMA TYPE STIRLING ENGINE

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Abstract: *This study aims to investigate the function of a Gamma type Stirling engine, analyzing mainly the influence of the temperature gradient on the angular velocity and power produced by it. To determine the power generated by the engine, the collected data was processed using an algorithm based on the Schmidt theory modeled in Mathcad. The importance of the temperature gradient was also very well highlighted by the increase in maximum angular velocity with over 150 [rpm] when a cooling rib was added. In time, both the angular velocity and the power reach an approximate constant value, the fluctuations appearing due to the fact that the heat source is not an ideal one.*
Key words: *Stirling engine, Gamma type, temperature, pressure, angular velocity, working fluid, mechanical power, multifuel engine*

1. INTRODUCTION

Due to the current energy crisis a transition can be observed, from the classic thermodynamic systems which produce mechanical work by burning fossil fuels, to alternative means which do not depend on it. The most notable of them are: electrical engines, hydrogen engines, biofuel engines and multifuel engines. The Stirling engine is included in the last category, because combustion takes place outside the cylinder.

It's mode of operation, advantages, classification criteria and it's fields of reference are extensively presented by Homuţescu [1] as well as by other acknowledged authors.

A series of theories were formulated to mathematically model the processes which occur during the operation of the engine. Kontragool and Wongwises [2] wrote a detailed study on this matter, which included: the Malmo formula-which takes into account only the amount of energy received by the system and the thermal efficiency; the Schmidt formula - which works with the assumption that the processes are isothermal and the movement is sinusoidal; the West formula (a simplification of the Schmidt formula) which allows the calculation of the indicated power or the power at the crankshaft, and the Beale formula which allows the calculation of the power at a mean pressure by taking into account the mean pressure, the swept volume and the engine's angular velocity. This study concludes that the mean pressure method leads to the smallest errors when analyze a Gamma type Stirling engine.

From an experimental point of view, the study conducted by Çinar and Karabulut [3] shows that: the power increases with the pressure of the working fluid up to a maximum value if the temperature of the heat exchangers are maintained at a constant value; the power increases linearly with the temperature and is twice as high if helium is used as working fluid, instead of air; the variation of the power-angular velocity dependence reaches a maximum value and then declines; the power increases with the enlargement of the heat exchange area; the torque increases irregular once the engine slows down, and it too depends on the working fluid. Another approach on this matter was made by Gheith et.al. in their study [4] from which the following may be noted: the pressures vary periodically and are out of phase, and in the compression space, the pressure is 0.2[bar] higher; the expansion phase lasts longer; the temperatures evolve periodically and almost opposed in phase; the phases are not well defined on the pressure-Volume (pV) diagram; contradictory to the previously mentioned study is the postulate which alleges that the power doesn't reach a maximum with the increase of pressure (this might occur thanks to the different pressures of the gas used for the experiments); the increase of power with the water flow on the cooling circuit is linear; the angular velocity increases once the water flow and the working fluid's pressure increase; the power reaches a maximum when the pressure of the working fluid surpasses 5[bar]; the power-temperature dependence increases linearly; at higher pressures of the working fluid, the cooling gets harder due to the higher number of molecules thermally loaded. In another study by the same author [5] the classification of the influencing factors by importance is done by using the Pareto diagram: the most important was revealed to be the temperature difference between the heat sources followed closely by the working fluid's pressure. Ranked third by importance was the interaction between pressure and temperature. The last two factors woth mentioning were the water flow and the interaction between the pressure of the working gas and the water flow.

The purpose of this paper consists in determining the performances of a Gamma type Stirling engine with a total swept volume of 38.16 [cm^3] and the way that different factors (the temperature difference between the heat source and the way the cooling is done) influence them. In parallel, the pV diagram was drawn using an executable file developed in MATLAB based on the Schmidt theory [6].

2. EXPERIMENTAL ANALYSIS

The Gamma type Stirling engine (Fig.1) was built inside the Department of Mechanical Engineering (Faculty of Mechanics, Technical University of Cluj-Napoca, Romania).The main constructive parameters are the following: total swept volume: 38.16 [cm^3]; total dead volume: 18.78 [cm^3]; phase angle: 90 [deg]; flywheel radius: 70 [mm]; material of the expansion piston: aluminum; working piston material: graphite; material of the hot heat exchanger: aluminum; material of the cold heat exchanger: brass; working fluid: air; working fluid pressure: 1 [bar]. A longitudinal section of the 3D modeled engine (in SolidWorks) is presented in Fig. 2, where: 1 – expansion piston; 2 – the cylinder of the expansion piston/the hot heat exchanger; 3 – radiator/cold heat exchanger; 4 – the con-rod of the expansion piston; 5 – plate; 6 – cylinder of the working piston; 7 – working piston; 8 – the con-rod of the working piston; 9 - the crank of the working piston; 10 – flywheel; 11 – the crank of the expansion piston.

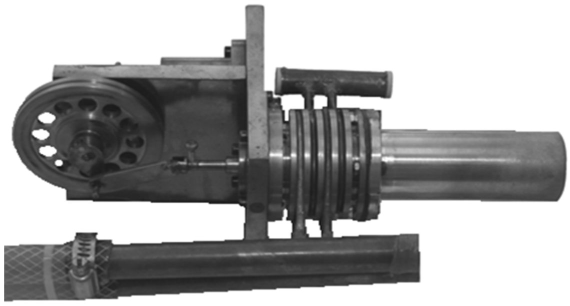

Fig.1 Gamma type Stirling engine.

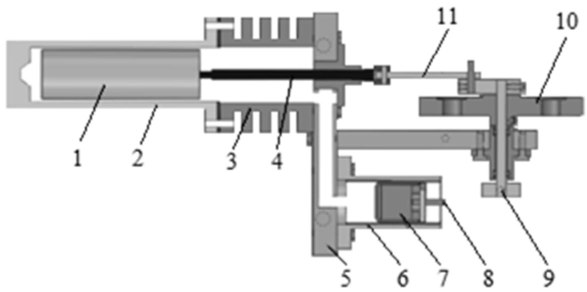

Fig.2 Longitudinal section of the Gamma type Stirling engine.

The heat source was a gas burner (propane-isobutane-butane), and two cooling ribs fed from the water network with a constant flow were mounted on the radiator. To measure the temperature field, a thermal camera was used (FLIR T400), and for the angular velocity measurements a DT-1236L digital tachometer was used (the angular velocity measurement was done without touching the engine). The experimental measurement stand is presented in Fig. 3.

The temperature and angular velocity were recorded every 30 seconds during 2 sets of measurements corresponding to the analyzed situations: in the first case the cooling is realized using one rib (3 sets of data), and in the second one the cooling is done using two ribs (4 sets of data) as shown in Fig.1. The areas of interest for temperature measuring were the two heat exchange areas (hot and cold). At the beginning and the end of each measurement the gas quantity remaining in the burner was weighted to establish the consumption during the trial time, and also to determine how much fuel does the engine need to reach it's maximum performances.

To determine the power generated by the engine, the measured data was processed using an algorithm based on the Schmidt theory [6], modeled in Mathcad. The obtained data was then charted and introduced in the Origin™ software which allows the drafting of the dependency diagrams between parameters.

Fig.3 The experimental measurement stand.

3. RESULTS

In the case of using only one cooling rib, the following diagrams were drafted: on Fig.4 the variation of the hot heat exchanger [degrees Celsius] depending on time [seconds]; in Fig.5 the variation of angular velocity [rot/min] – speed - depending on time [seconds], and in Fig.6 the dependency between power [Watts] and time [seconds]. In the case of using two cooling ribs: in Fig.7 - the variation of the temperature of the hot heat exchanger depending on time; in Fig.8 the variation of the engine's angular velocity depending on time and in Fig.9 the variation between power and time. The temperature gradient between the hot heat exchanger and the cold heat exchanger for this two configuration is shown in Figure 10 and Figure 11.

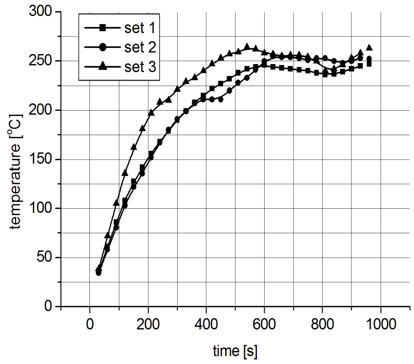

Fig.4 The variation of the hot heat exchanger depending on time using one cooling rib.

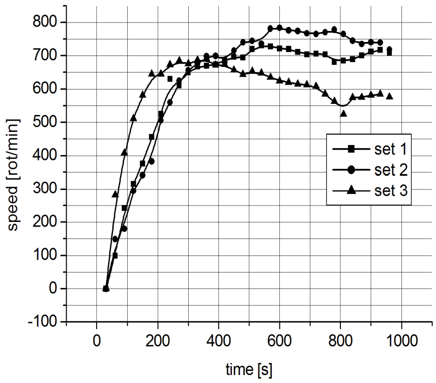

Fig.5 The variation of angular velocity depending on time using one cooling rib.

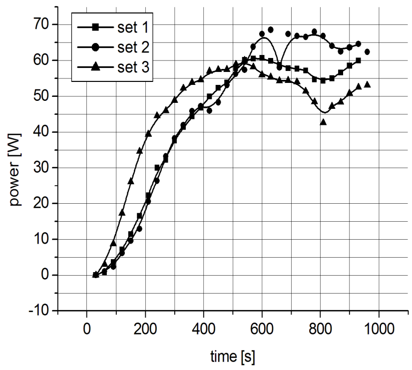

Fig.6 The variation of power depending on time using one cooling rib.

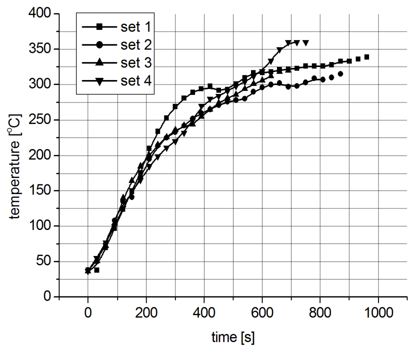

Fig.7 The variation of the hot heat exchanger depending on time using two cooling rib.

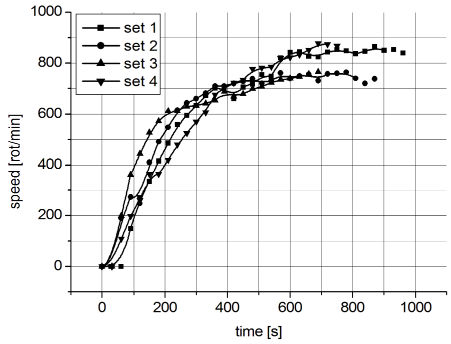

Fig.8 The variation of angular velocity depending on time using two cooling rib.

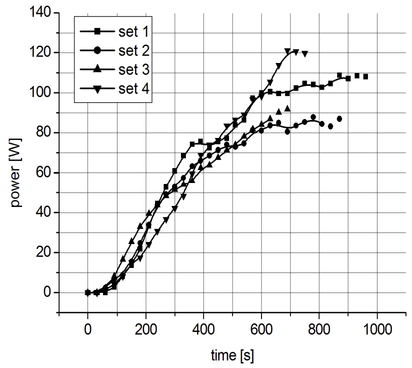

Fig.9 The variation of power depending on time using two cooling rib.

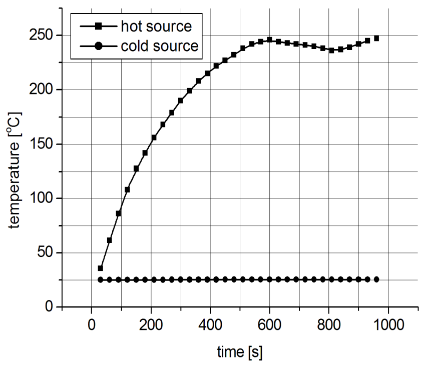

Fig.10 The temperature gradient between the hot heat exchanger and the cold heat exchanger for one cooling rib.

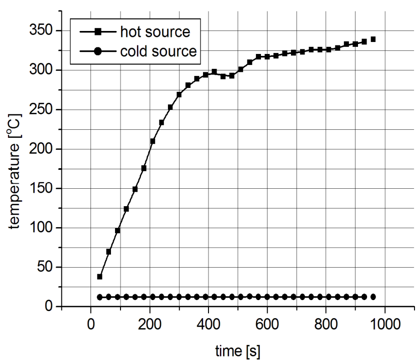

Fig.11 The temperature gradient between the hot heat exchanger and the cold heat exchanger for two cooling rib.

If the cooling is done naturally, it can be observed that in a short period of time (approximately 10 minutes) the temperature gradient between the hot area Fig. 2 - reference 2), and the cold area (Fig.2 - reference 3) becomes 0, high thermal expansion values are recorded, the engine stalls and stops working.

If a cooling rib with a ring-like transversal section made from copper through which a cooling fluid passes (in this case water) is mounted on the radiator, it can be noticed, as shown in Fig.10, that after the transitory heating, the temperature gradient remains constant (approx. 225 degrees Celsius). As shown in Fig.4, for all 3 sets of measurements, the pattern is almost identical. On the same static temperature sector, the angular velocity has values between 560 and 750 [rot/min]. Using the Schmidt theory it was calculated (plotted in fig.6) that the power has values between 45 and 65[W].

If a second cooling rib is mounted, the temperature differential on the same static temperature sector is about 310 [degrees Celsius]. Compared to the previous case, the temperature gradient is higher with about 24%. Fig. 7 shows that the pattern is almost identical. Also the necessity of better control of the usage of thermal energy becomes apparent, for example, by heating the hot heat exchanger in an enclosed chamber, in order to minimize heat loss. When using the two cooling ribs, the maximum angular velocity is about 650 – 850 [rot/min] (Fig. 8). Compared to the previous case, the angular velocity increases by 13%. The power, as shown on Fig.9 is between 80 – 120 [W]. It can be noticed an increase in power of about 43%.

The mean fuel consumption for every set of measurements was about 22.5 [g].

Figure 12 shows the relation between temperature and angular velocity in the case of using only one cooling rib. For the same configuration, Fig.13 shows the variation of power with the temperature, and in Fig.14 shows how the angular velocity influences the power.

Also, when two cooling ribs are used, the variation of angular velocity with regards to temperature (Fig.15), power in relation with temperature (Fig.16), and power with angular velocity (Fig.17) are shown.

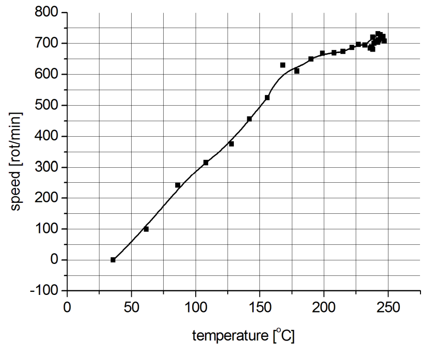

Fig.12 The variation of angular velocity depending on temperature for one cooling rib.

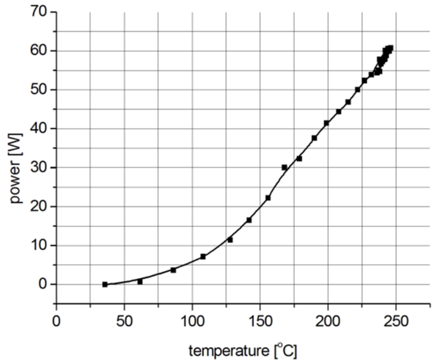

Fig.13 The variation of power depending on temperature for one cooling rib.

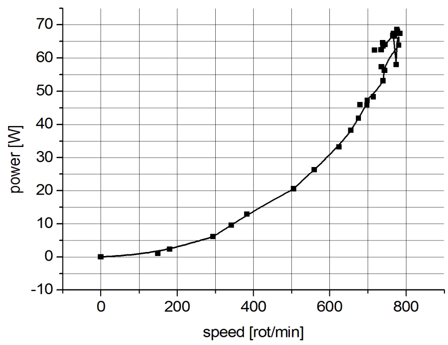

Fig.14 The variation of power depending on angular velocity for one cooling rib.

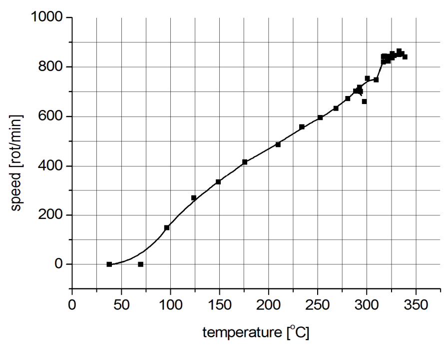

Fig.15 The variation of angular velocity depending on temperature for two cooling rib.

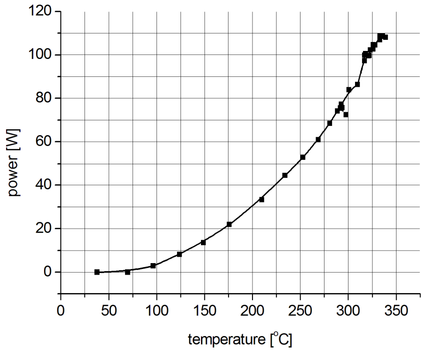

Fig.16 The variation of power depending on temperature for two cooling rib.

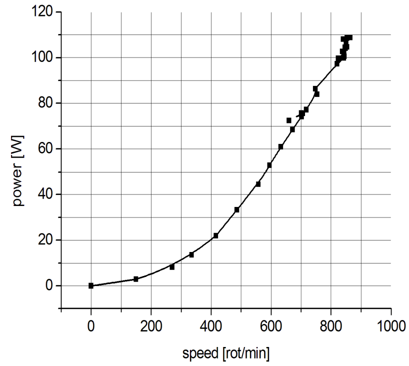

Fig.17 The variation of power depending on angular velocity for two cooling rib.

By analyzing these diagrams one can deduce that the engine's steady state is characterized by a point cloud distributed on a narrow area. For the transitory operating phase, between temperature and angular velocity here is a linear relationship, but between power and angular velocity there is no such functions.

4. CONCLUSION

It has been noticed that after a period of approximately 10 minutes both heat exchangers reach an approximately constant temperature.

From the diagrams plotted in Origin™ a linear relationship between the increase of temperature and angular velocity, and a sudden rise in power with the increase of the temperature differential may be observed. The importance of the temperature difference can be also seen, by an increase of 150 [rot/min] in angular velocity when a second cooling rib is added. In time, both the angular velocity and the power reach an approximate constant value, the fluctuations appearing due to the fact that the heat source is not an ideal one.

5. ACKNOWLEDGEMENTS

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Analiza funcţională pentru un motor Stirling de tip Gamma

Rezumat: *Prezentul studiu urmăreşte analiza funcţională pentru un motor Stirling de tip Gamma analizându-se în principal influenţa gradientului de temperatură asupra turaţiei şi puterii dezvoltate. Pentru a determina puterea generată de motor datele măsurate au fost prelucrate printr-un algoritm bazat pe teoria lui Schmidt şi introdus în programul Mathcad. Importanţa influenţei gradientului de temperatură este foarte bine evidenţiată şi de creşterea turaţiei maxime cu peste 150 [rot/min] odată cu adăugarea unei spire de răcire. Odată cu trecerea timpului, atât turaţia cât şi puterea ajung la o valoarea aproximativ constantă, oscilaţiile fiind datorate faptului că sursa caldă nu este una ideală.*

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