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CONSTRUCTION AND ANALYSIS OF A PROTOTYPE STIRLING ENGINE FOR ENERGY RECOVERY FROM THE EXHAUST GASES OF AN INTERNAL COMBUSTION ENGINE

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Abstract. *The Stirling cycle provides greater efficiency than conventional gas cycles because its thermal efficiency is equal to carnot efficiency. The Stirling engine, inspired in the stirling cycle, has the peculiarity of having externally added heat, which makes it possible to generate work from various heat sources (solar, biomass, exhaust gases, among others). In the current global energy scenario there is a need to develop technologies that allow obtaining useful energy through alternative sources, and the Stirling engine appears as a viable option. The objective of this work is the development of a prototype Stirling engine Gamma that provides mechanical energy from the exhaust gases of a stationary motor and its conversion to electricity through a direct current generator coupled to the shaft Stirling engine. The prototype manufacturing process includes machining, CAD modeling and 3D printing parts, beyond the reuse of components of electrical and electronic devices. Tests conducted after the construction of the prototype showed some design failures especially in relation to seal and friction between the parts. Some important data such as engine rotation range, minimum working temperature and thermal efficiency were obtained. The tests for the validation of converting mechanical energy into electrical energy showed that improvements in the prototype design and appropriate selection of the generator can make the project viable for applications in low-power loads.*

Keywords: *Stirling Engine, Alternative energy, 3D printing, Energy recovery, Energy efficiency*.

1. INTRODUCTION

After years of studies dedicated to develop a safer engine than the steam engine, Robert Stirling created an engine that used only confined gas.

The type of engine designed works primarily heating the air confined inside by an external heat source. The expansion and contraction of the confined air provides the production of work in mechanical energy form that can be used for many different applications, among them the conversion into electricity. The engine is basically a shell and two pistons (power piston and diffuser piston). Stirling also developed the regenerator equipment which provides a significant increase in the engine thermal efficiency.

Companies, such as Philips®, have built prototypes, between the years 1950 and 1960, with thermal efficiency around 40%. NASA currently invests in research for energy in space centers. Many laboratories apply a lot of money in the area for power generation by capturing solar energy.

The Stirling cycle is commonly known to provide higher efficiency than conventional motors. This is due to the the fact that the cycle is based on two isothermal processes and a heat recovery mechanism between two isochoric processes. According Campos (2004) "The thermodynamic cycle of the Stirling engine has a theoretical efficiency equal to the Carnot cycle, but the energy transfer in ideal cycle must occur isothermal and reversibly". The better the heat exchangers works, the greater the thermal energy conversion into mechanical power is; if the regenerator losses are minimized, the amount of heat supplied to the cycle is greater.

Stirling engines are currently considered a good alternative in energy generation because the fuel combustion control is made more easily than in external combustion engines. The fuel used can be even more complex types of products and byproducts of the biodigestion process as. Given also the environmental appeal, these engines are more economical and less polluting than diesel engines, or even those gas turbines (Paula, 2007).

This paper had the goal to use the thermal energy of the exhausting gases of a stationary engine to generate electrical energy for a telemetry display for information panels. For this, a prototype was built, according models found in Internet, adapting for our application.

1.1. The Stirling Cycle

The Stirling cycle is defined at four points in a P-V graph. Considering the device as an ideal we can say that the cycle can be described as: initially, at the point 1 of P-V graph, the gas is confined and is in the cold engine's region, while the piston is in the lower position (Figure 1). In a second time an isothermal compression process of the confined air happens, what transfers the cold source a certain amount of heat, thus defining the point 2 on the chart.

The process between points 2 and 3 of the graph occurs while maintaining the fixed piston to move only the diffuser piston (Figure 1). The air passes mostly to the engine hot zone where the regenerator absorbs an amount of heat. This process is isochoric, which increases the air pressure but not the volume.

Among the points 3 and 4 on the chart occurs an isothermal expansion, which causes the air to absorb an amount of heat from the hot source (Figure 1). To complete the cycle, there is another isochoric process between points 4 and 1 of cycle, where part of the heat is stored in the regenerator at constant volume that provides a decrease in the confined air's temperature. In the latter case the diffuser will return to the original position (Figure 1).

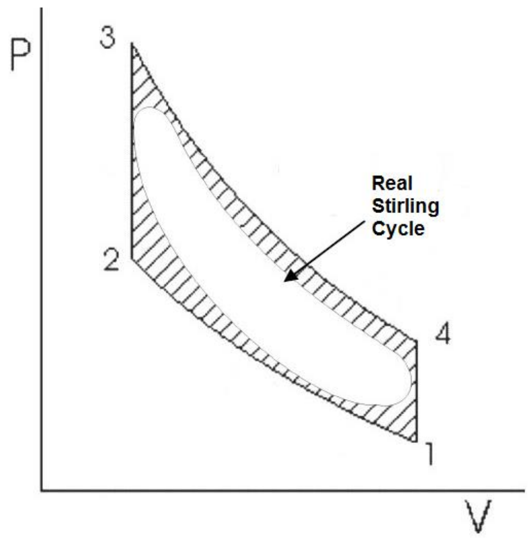

Figure 1. Real and Ideal Stirling cycle represented in P-V diagram (Paula, 2007).

According to Campos (2004), "the difficulty to make the ideal variation of the Stirling cycle volume, departs the real cycle of the theoretical cycle". The maximum power efficiency of a Carnot machine in a finite heat transfer will depend only on the hot and cold temperatures in the system, according to Equation (1).

$$\eta_{max} = \frac{(T_H - T_C)}{T_H} = 1 - \frac{T_C}{T_H} \tag{1}$$

1.2. The Engine

According to Cruz (2012) "The Stirling engine is a piston engine running on external heat source." This type of engine has many settings, however, the more noticeable are the types Alpha, Beta, and Gamma. There are fundamental differences between the three types, being the Alpha engine comprises two cylinders in a system; while one drum acts as a heat receiver, the other is responsible for heat exchange with the cold source. Within these cylinders is a piston, both of which are connected to the motor shaft for producing work (Figure 2 - a). Unlike the Alpha engine, the Beta type range engines have two pistons mounted on a same cylinder, with concentric axis (Figure 2 - b).

Similiar to the Beta-type, Gamma-type Stirling engine has two pistons, in contrast presents with two cylinders, similar to Alpha engine. Thus, the motor Gamma its entirety as a combination of two characteristics derived from the other two most common types (Figure 3). The setting has for convenience separate the hot part and the heat exchanger (Mello, 2001). Compared with the Beta-type engines its configuration also provides a more easy fit about the compression was wearing a gas confined in the motor chamber (Hirata, 1995). The main disadvantage of this type of motor is that the volume death is higher in relation to other types, which provides a lower power output (Mello, 2001), however, the engine provides a larger number of revolutions per minute, might provide best generation of energy for the required application.

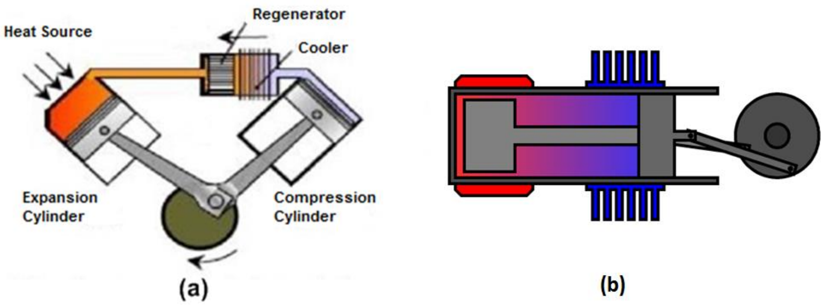

Figure 2. (a) Stirling Engine – Alpha Type; (b) Stirling Engine – Beta Type (Paula, 2007).

Once the Gamma engine has a wide area for the heat transfer from hot source for gas confined in the motor chamber, this type was chosen as the prototype for the recovery of thermal energy from the exhaust gases of stationary engine combustion.

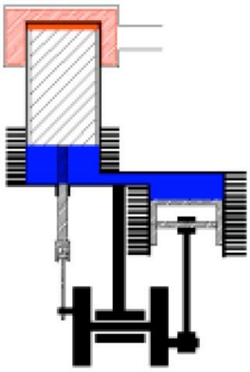

Figure 3. Stirling Engine – Gamma Type (Paula, 2007).

2. METHODOLOGY

The manufacture of the first prototypes was made in IFES - São Mateus, using the laboratories of Metrology, Manufacturing and the room of the Extension Program SamaBaja. The first prototype wasn't built in 3D software, but just using as reference some informations obtained through researches (Figure 4-a). The materials used are described in the section below.

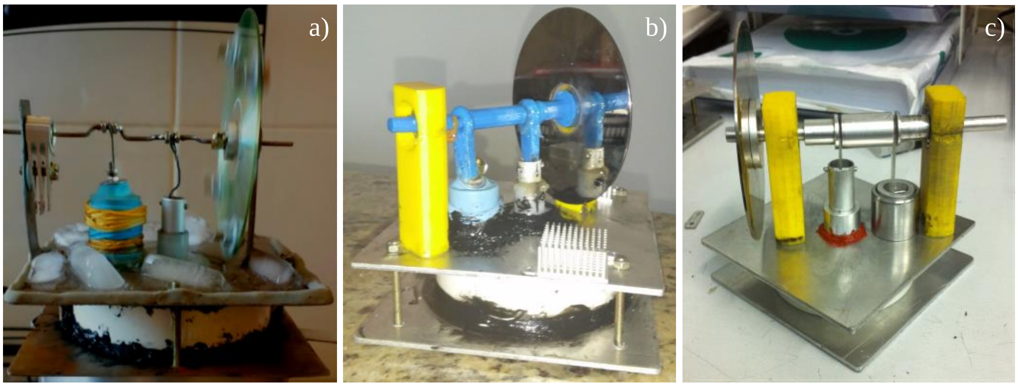

Figure 4. a) First prototype; b) Second prototype; c) Third prototype

The first prototype was made with a limited form. Searching for better results on the tests, the second prototype (Figure 4-b) was built on software SOLID EDGE ST7. The parts were modeled separately and after that, were made the assembly (Figure 5). After the computational modeling the group started the manufacturing. The steel plates were changed for aluminum plates because of the higher thermic conductivity (247 W/m·K). The crank shaft, its bases and the connecting rods were printed with ABS polymer by a 3D printer UP Plus 2 (Figure 6) aiming a better alignment of the crank shaft and reducing the friction between the components.

The prototype scaling considered the dimensions of the stationary engine to which the work applies, as example, the prototype's contact area with the exhausted gases. Still was constructed a third prototype (Figure 4-c) with heat-resistant materials in order to perform the tests at higher temperatures. The approximated dimensions of other projects and information found in the literature was considered for this work. In general, it was made searching for the less expensive manufacturing, that could grant an alternative way among as to different forms of energy generation and recovery. In Paula (2007), we can observe that objective, when was used biomass for the energy generation through the Stirling engine, as an alternative for isolated places.

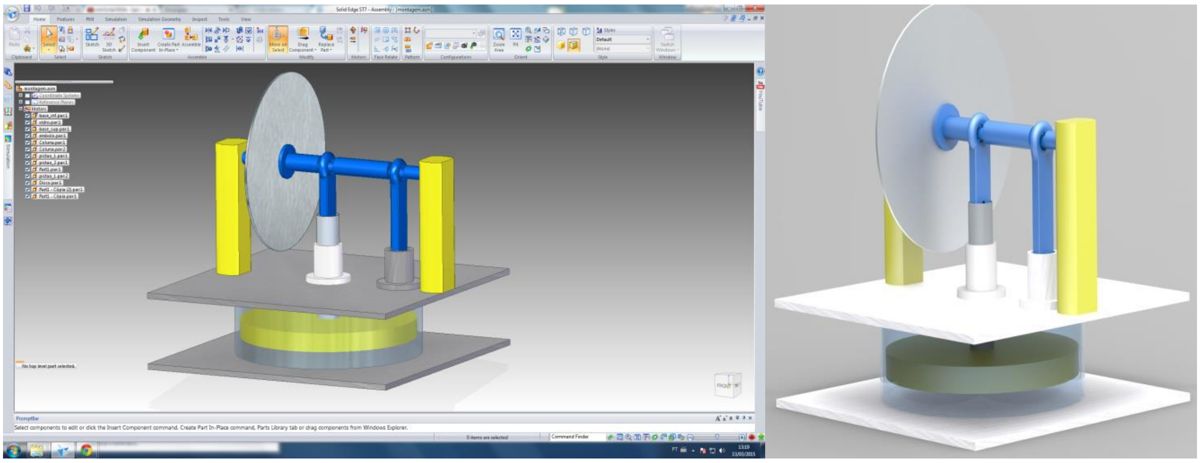

Figure 5. Prototype in the software Solid Edge ST7.

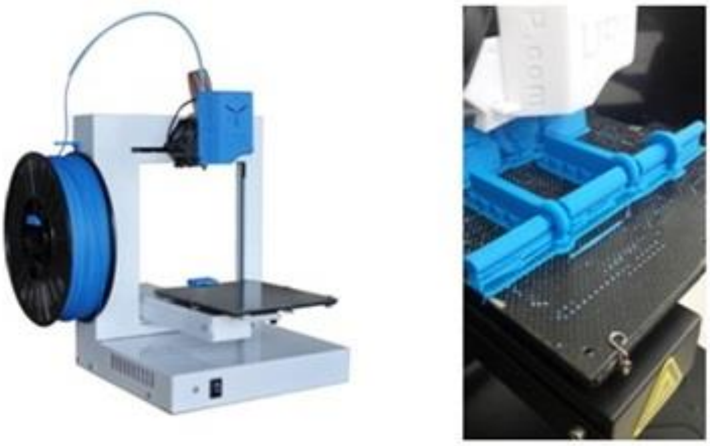

Figura 6. (a) Printer used in the build; (b) Printing the crank shaft.

2.1. Materials

To build the prototypes the group used the materials listed in the Tables 1 and 2:

Table 1- List of used materials to build the first prototype.

1 mm Steel sheets	2 expanded polystyrene sheets (EPS) with diameter of 95 mm and thickness of 15 mm
100 mm (diameter) PVC tube	4 screws (40) mm length
1 used CD (replaced)	2 ball bearings (SOL 607Z)
Galvanized wire	1 rubber balloon
BNC connector with a screw	Machined technyl like an cylinder block from diffuser piston
1" (external diameter) SAE 1020 steel tube	Silicon glue

Table 2 – List of used materials to build the second prototype.

3 mm square aluminum sheets	2 expanded polystyrene sheets (EPS) with diameter of 95 mm and thickness of 15 mm
100 mm (diameter) PVC tube	4 screws of (40) mm length
1 used CD (replaced)	2 ball bearings (SOL 607Z)
ABS (acrylonitrile butadiene styrene) to 3D printed parts	1 rubber balloon
BNC connector with a screw	Machined technyl like an cylinder block from diffuser piston
1” (external diameter) SAE 1020 steel tube	Silicon glue

2.2. Manufacture

To manufacture the first prototype parts were used simple process, like using a guillotine for cut the plates, a folding to the resignation of the bases, pliers to build the crank shaft and a drill bench.

For the second prototype, some parts (crank shaft and bases) were printed (Figure 7) while the others followed the same process than the first one. Because of the necessity of a big precision in crank shaft built and a short path for the piston, the 3D printing was used with equipments from Metrology Laboratory of IFES – São Mateus. It was necessary a set of parts with low mass, what justify the using of the ABS polimery for the printing because of the low specific mass.

After the printing, the parts were assembled with the ball bearing in which axis tip and posteriorly it was fixed in the bases. To grant more Moment of inertia for the axis and maintain the rotation movement of the pistons we putted a reused high disc, concentrically to the crank shaft. The con-rods of the axis were jointed in which component of the air-tight pistons and power piston.

To the manufacturing of the diffuser piston’s parts, we used a machined Technyl available at IFES - São Mateus, according to the project. The working piston was manufactured with a rubber balloon because of its functionality, easy fit in a steel tube and low cost. For assemble the parts we used some tools that were disponibilized by the campus and SamaBaja team, among them drills, rasp, grinder, pliers and screwdriver.

To validate the possibility of converting mechanical energy into electrical energy, an electric generator was used to analyze the feasibility of application of the device in the Stirling engine built. For the tests were used a DC Generator (Figure 8), two multimeters, jumper wires, a resistor of 500Ω, electric drill, a protoboard and a tachometer.

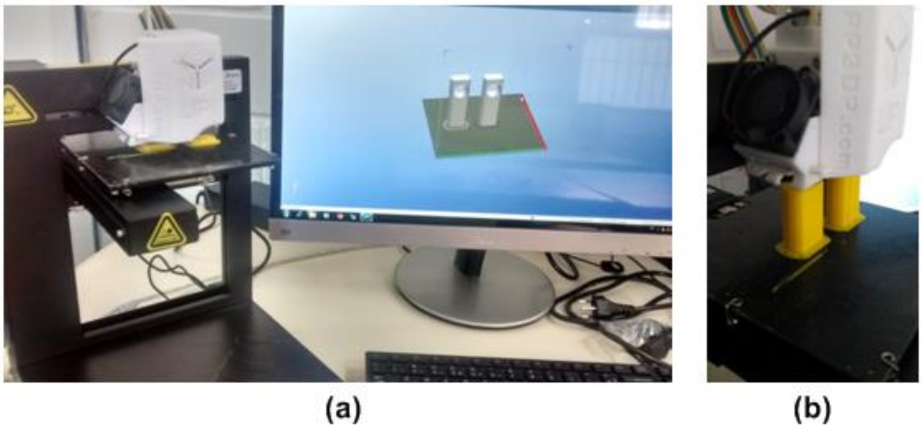

Figure 7. (a) Equipment used in the printing process; (b) Printer working.

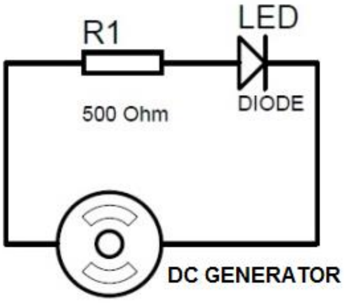

Figure 8. DC Generator Circuit

DC generators are used when is necessary a continuous current from mechanical strength. A DC generator has three main components: the stator winding, armor and switch. The stator winding is supplied with direct voltage (excitation voltage), producing a fixed magnetic field that cuts the windings of the armor when the latter rotates into the field by mechanical action.

Magnetic field along with moving coil result in electromagnetic induction and, consequently, potential difference, carried by the set of brushes and switch to the external means (Nascimento Junior, 2011). In this work we used a small motor taken from a hair dryer.

The shaft generator was attached to an electric drill in order to verify the mechanical energy conversion into electricity. In the generator output terminals one LED was connected in series with a 500Ω resistor used as current limiter, and an ammeter for measuring electric current. A voltmeter was connected to the generator output terminal for measuring voltage generated.

For assemble, the parts were pierced, screwed and fixed in the steel and aluminum plates. The other components were fixed with silicon glue for high temperatures.

3. RESULTS AND DISCUSSIONS

The prototype worked with a minimum temperature variation of approximately 100°C, because was used water vapor as hot source and ice as cold source and the engine ran. Through the tests there was obtained 108 rpm. The tests performed pointed build failures and project execution. Among the main problems found in the built of the engine, and after of the operation, was the sealing between the components. For the correct operation, it is necessary to seal the parts so that the air won't escape.

On the other hand, ensuring the seal, this turn the friction problem worse between the engine parts, as if the diffuser piston. In this case, the piston needs a little liberty in relation to the cylinder. That liberty resulted in air escape. So that was the main challenge for the build.

The friction between de components was a critic factor in the build. That aspect was difficult to have a solution, and even the movements were short, the friction prevented the system's efficiency.

From the experiments with the power generator we obtained the minimum speed required for the device to provide its output terminals the minimum voltage for the LED could show some visible glow. It was observed that the required axis rotation is greater than provided by the prototype.

Table 3 contains the results of the experiment. In it, V_{min} is the minimum voltage generated by the rotation of 2080 rpm to cause perceptible brightness in LED. V_{max} is the voltage from the maximum rotation speed of the electric drill.

Table 3 - Rotation and voltage values provided by the DC generator.

Shaft rotation speed	Voltage Generated	Electric Current
2080 rpm	V_{min} = 1,8 V	0,13 mA
2800 rpm	V_{max} = 2,45 V	1,09 mA

The results suggest the necessity for improvements in the construction of the prototype in order to increase the shaft's angular velocity and also choosing a suitable generator to the acquired rotation, thus making the design viable in low power applications.

According the Equation 1, presented previously, was calculated the thermal efficiency of engine at minimum temperature difference.

$$\eta_{max} = 1 - \frac{273}{373} = 1 - \ 0{,}732 = 0{,}268 \tag{2}$$

However, the exhausting gases of the stationary internal combustion engine analyzed to use our prototype (BRIGGS&STRATTON INTEK 10HP@3600RPM) presented a temperature of 400°C, and considering the ambient temperature of 27°C, we calculated an estimated thermal efficiency for the third prototype, that would be:

$$\eta_{max} = 1 - \frac{300}{673} = 1 - 0{,}446 = 0{,}554 \tag{3}$$

This efficiency is quite high, considering that the efficiency of most existing thermal equipment (motors, turbines, etc.) does not exceed the value of 45%. Furthermore, it is observed that a larger temperature difference between the hot source and the cold source results in higher thermal efficiency. Thus, to a cold source temperature equal to ambient temperature, the higher hot source temperature results in a higher motor efficiency as shown in Figure 9. Therefore, for the stirling engine to work under high temperature conditions, it was necessary to fabricate the engine with more heat-resistant materials, as shown earlier in Figure 4-c.

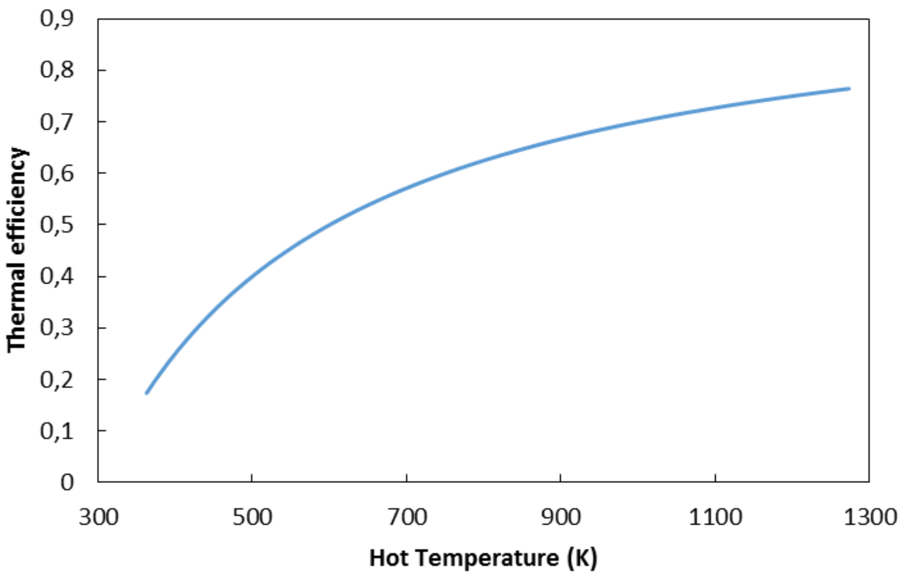

Figure 9. Thermal efficiency of stirling engine regarding the temperature of the hot source.

4. CONCLUSIONS

We reached some proposed results with the prototypes. The stirling engine can be used at commercial and industrial applications, because it bring an alternative to lost energy, recovering it in a lot of process , whereas this miss is natural.

It was observed that a larger temperature difference between the hot source and the cold source results in higher thermal efficiency. The efficiency of the engine in their working conditions (55,4%) was quite high, considering that the efficiency of most existing thermal equipment does not exceed the value of 45%.

Based on researches we propose some improvements for futures label:

- Reducing weight of moving parts;
- Reducing friction between the con-rods and the crankshaft ;
- Ensure effective sealing;
- Analyzing the highest temperature supported by the engine;
- Using the thermography camera to take accurate results.

Another application could be using the stirling engine to recovery lost heat by electronic components, specially notebooks, with the goal to generating energy to turn on some LED’s or help to charge the battery, increasing the efficiency of this equipment.

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