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CONSTRUCTION AND INSTRUMENTATION OF A THERMOACOUSTIC STIRLING ENGINE

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ABSTRACT

In this research the construction of a Thermoacoustic Stirling machine was carried out, with the aim of determining which are the constructive parameters that allow it to operate in a stable way, as well as to calculate experimentally its thermal efficiency; to achieve this, its electronic instrumentation was implemented to monitor the temporal evolution of the temperature differential, the pressure and the revolutions of the flywheel. During the experimentation, a sustained operation was obtained and the constructive parameters that allow a stable acoustic oscillation were determined. The calculation of the thermal to mechanical energy conversion efficiency, with the data collected by the instrumentation, was determined to be 17.5%.

[1] Introduction

A Stirling engine is an engine that uses the expansion of a fluid (air), which from a critical temperature difference between the hot and cold sources can perform usable mechanical work [1]. The Stirling engine, as it does not use internal combustion, does not emit pollutant gases as a waste product of the process of doing work.

The severe environmental crisis affecting mankind, coupled with the growing demand for energy in an increasingly industrialised world and the rising costs of fossil fuels, mean that alternative and diverse sources of energy have to be found. Stirling engines play an important role in this respect.

Traditional Stirling engines consist of a primary cylinder, inside which a piston is located, a secondary cylinder containing another piston (displacer piston) inside it and a flywheel, which is connected to the configuration by means of the crank-crank mechanism.

The Thermoacoustic Stirling engine minimises the complexity of the construction of these machines. It does not require a displacer piston and thus avoids the mechanical coupling between two pistons. The effect in this type of Stirling engine is caused by the movement of acoustic waves generated in the cylinder and operates thanks to the temperature gradient of the hot and cold sources respectively. [2]. As this machine is of simple construction, it is a very convenient and novel option because the manufacturing time and costs are minimised. Recently, there has been a growing interest in the study of this type of machine. A clear example is that in 2018 a review of the work carried out with the aim of optimising a Stirling engine was published [3]. A thermoacoustic engine was made with a flywheel and a reciprocating piston. The device has a loop tube with a regenerator and heat exchangers at the ends. It was concluded that when the temperature difference between the ends of the regenerator increases above a certain critical point, the flywheel undergoes a constant rotation. Simultaneous measurements of the pressure and velocity of the working gas were also carried out. [4]

Dhuchakallaya and Saechan propose a thermoacoustic Stirling engine with a phase regulator. This phase regulator was placed at the end of the resonator tube. The designed configuration makes it possible to maintain a high level of conversion efficiency. The working gas was kept compressed at 10 bar and the operating frequency was 44 Hz. Different shapes of the resonator were also investigated. As a result, higher efficiency was achieved with the engine that had the larger resonator size. The maximum thermal efficiency was up to 17.2%, which corresponds to 33.5% of the Carnot efficiency. [5]

In the year 2021, Zare and Tavakolpour-Saleh [6], addressed the modelling, construction and testing of a diaphragm thermoacoustic Stirling engine. To verify the mathematical model presented in the work, an experimental thermoacoustic engine was developed, corroborating the model, as it was determined that the practical results agree with the simulation results. The operating frequency of the motor oscillates at 13.8 Hz.

Penelet, Watanabe, and Biwa, also in 2021, carried out the theoretical description of the self-sustained oscillations resulting from the coupling of a piston-crank-flywheel assembly with a thermoacoustic-Stirling prime mover. The equations governing the piston-flywheel motion are obtained. The complete device was described by means of a fourth-order nonlinear dynamic system and solved by numerical methods. In addition, experiments were carried out to corroborate the simulation. [7]

In 2022, a paper was published in which a TASHE-type motor was studied, in which a phase adjuster is used. This configuration provides an acoustic power of up to 40 W and an energy conversion efficiency of 12.03%. There is a good theoretical-experimental agreement when comparing measurements and simulation by DeltaEC. [8]

H. Hsu and Y. T. Li, in 2023, experimentally study a thermoacoustic engine to see how the acoustic pressure fluctuates in the time-time domain. To describe this, they analysed the nonlinear effects of the flux resistance of the coupled regenerators. [9]

Among the most recent works of interest is the modelling of subcritical Hopf bifurcation in thermoacoustic Stirling engines using the Stuart-Landau model. By inducing self-sustained oscillations and measuring pressure fluctuations across different temperature gradients imposed on the regenerator, the engine transitions to a non-linear domain, characterised by high oscillation amplitudes and unique periodic patterns. [10]

Despite the wealth of literature on the study and application of the Stirling cycle, there are still not many works that study thermoacoustic Stirling machines, which shows that the current work is an area of opportunity to delve deeper into the subject.

The fundamental study problem of the present work is to construct and establish the operating conditions for the operation of a thermoacoustic Stirling machine.

It must be found which are the critical temperature and pressure values for the Stirling effect to occur in the engine. It must also be found what conditions must be established for an increase in the conversion efficiency of the machine.

Once our problem and its scope have been established, we start from the hypothesis that a system for converting thermal energy into mechanical or electrical energy can be developed by means of a thermoacoustic Stirling machine. Tests are carried out with the prototype, in order to establish the operating conditions of the machine.

[2] Procedure

A. Basic principles of thermodynamics

One of the most important and applied branches of physics is thermodynamics. In general terms, this science studies heat and how it is transferred from one body to another. One of the basic principles of Thermodynamics states that, if two bodies at different temperatures are placed in thermal contact, a flow of energy (heat) will be established from the body with a higher temperature to the body with a lower temperature. In this way, the body at a higher temperature cools down (its temperature value decreases), while the body at a lower temperature warms up (its temperature increases).

The heat that flows from the hotter to the colder body, when two objects 1 and 2 are in thermal contact, can be quantified with the following formula: [11]

$$\dot{Q}_{12} = h_{12}A_{12}(T_1 - T_2) \qquad (1)$$

Where:

h_{12}: heat transfer coefficient between bodies 1 and 2

A_{12}: area of heat transfer (thermal contact) between bodies 1 and 2

T_1hot body temperature

T_2cold body temperature

The internal energy of a substance is the energy due to all molecular, ionic or atomic interactions, depending on the nature of the substance. In general, it is directly dependent on the temperature of the substance. In this sense a positive variation of the internal energy corresponds to an increase in temperature, while a negative variation of the internal energy implies that the temperature of the object decreased. [11]

Another important thermodynamic concept is specific heat. This is defined as the amount of heat required to raise the temperature of an object or substance by one degree Celsius. [11]

It is common to measure heat in units of calories. It is known that a calorie, that one calorie equals 4.186 joules (1 cal = 4.186 J). [11]

The formula for calculating the work done by the expansion of a gas is presented below. For mathematical simplicity, a cylinder-shaped vessel is considered, with a movable piston that slides without friction with the cylinder walls, as shown in figure 1. The gas contained in the piston is assumed to be in thermal equilibrium occupying a volume V and causes a pressure P (constant) on the vessel walls and on the piston of area A. The force exerted by the gas on the piston can be calculated as: [11].

$$F = PA \qquad (2)$$

Suppose that the gas evolves by an expansion from volume V to volume V + dV "slowly", so that the system does not lose its thermodynamic equilibrium. Let us consider that the piston moves vertically a distance of dy. Then the work done by the gas on the plunger can be calculated as:

$$dW = Fdy = PAdy \qquad (3)$$

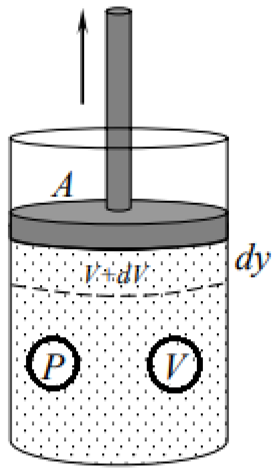

Fig. 1 Isobaric expansion of a gas [12].

Taking into account that Ady corresponds to the volume change of the gas dVthe equation above can be written as: [12]

$$dW = PdV \qquad (4)$$

From the above reasoning we can conclude the following three points:

When the gas expands dV is a positive quantity and consequently the work done by the gas is positive.

When the gas is compressed dV is a negative quantity and consequently the work done by the gas is negative.

If the volume does not change then dV is zero and consequently no work is done.

If we integrate the formula (4) between the limit values of the volume function (Vi and Vf, respectively) we obtain: [12].

$$W = \int_{V_i}^{V_f} PdV \qquad (5)$$

The operation of the Stirling engine is based on the difference in temperature generated between the engine's heat sources, a low-temperature source (cold source) and a high-temperature source (hot source). [16]. This difference causes the gas used (it can be hydrogen, air, etc.) to enter a thermodynamic cycle, in which the gas moves cyclically by convection, thus allowing the pistons to move in each cycle. Let us look at a graph (figure 2) where this cycle is illustrated: [13].

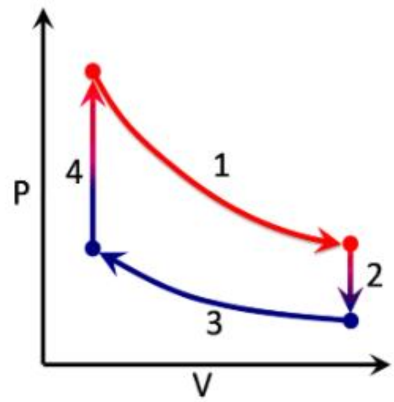

Fig. 2 Stirling engine duty cycle [13].

This graph shows the relationship between volume and pressure, at different temperatures, where T_1 is greater than T_2 . It can also be seen that these curves do not intersect each other, and that they show an inversely proportional relationship between volume and pressure. In other words, it fulfils the ideal gas relation: [11].

$$PV = nRT \qquad (6)$$

The cycle starts at position 1, where the gas has a higher pressure at all states. This moves to position 2 where the gas relaxes and starts to increase in volume at the same temperature and the pistons can move. To return to its starting position, the gas is cooled by moving from position 2 to position 3, where the curve is lower temperature T_2 , so the gas begins to contract, the cycle ends in figure 3 when the pistons return to their starting position and the gas to the same volume as at the beginning, but at lower pressure. Then the gas is reheated to a temperature T_1 and the

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cycle starts again. In the case of the thermoacoustic engine, which is the focus of the study, a single piston is used, moving along a single chamber containing the gas, and where both temperatures T_1 and T_2 are set. [14]

B. Types of Stirling engines

All Stirling engines are similar in operation, but can be classified into different types according to the position of the power piston and the displacer. There are three main groups into which these engines can be differentiated. [14]

The β-type engine was the original design by Robert Stirling. It consists of a cylinder with two zones, one hot and one cold. Inside the cylinder there is also a displacer that enables air movement, and concentric with this is the power piston, which is offset at 90^0 with respect to the displacer. This type of engine is the most efficient, but also the most complex and bulky. [14]

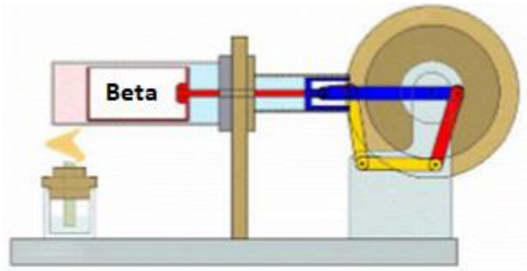

Fig. 3 Stirling engine type β [14].

The α-type engine was designed by the American Rider. This model, unlike the beta type, has two cylinders, one where the cold zone is located and the other where the hot zone is located. In each cylinder, there is a piston that is 90° out of phase with each other. The cylinders are connected to each other by a crankshaft, which makes the power/volume ratio high. The mechanism of this type of engine is quite simple, but it is difficult to prevent air from escaping, especially in the hot cylinder, as the high temperatures deteriorate the materials. [14]

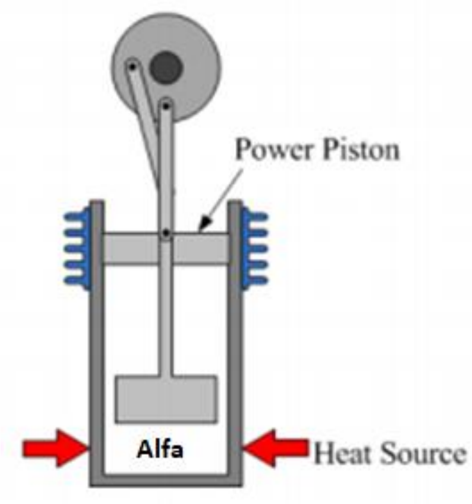

Fig. 4 Stirling engine type α. [14]

The γ-type engine is very similar to the β-type engine, but is simpler to build. What differentiates the β and the γ is that the γ has the power piston and displacer in different cylinders, which are 90° out of phase. The two cylinders are connected by a crankshaft. This engine is simpler, but its power output is lower than the β type. [14]

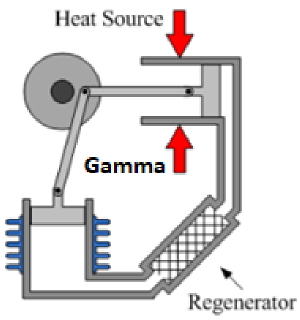

Fig. 5 Stirling engine type γ [14].

In 1905 Ossian Ringbom invented an engine derived from the γ-type engine, with greater simplicity, as the displacer piston is not connected to the power piston, but oscillates freely, moved by the difference in pressure and gravity.

Subsequently, small modifications to the original Ringbom engine were discovered, which made possible a very simple engine as fast as any of the classic engines (α, β, γ). [14]

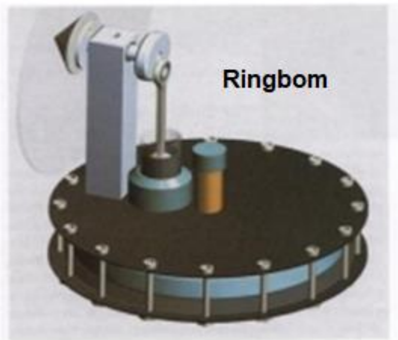

Fig. 6 Ringbom motor [14].

Another variant is the liquid piston engine. In this type of engine, the piston and displacer are replaced by a liquid. It consists of two tubes filled with a liquid; one of the tubes acts as a displacer and the other acts as a piston. It requires complicated calculations, and in some cases a third tube called a tuner is necessary. [14]

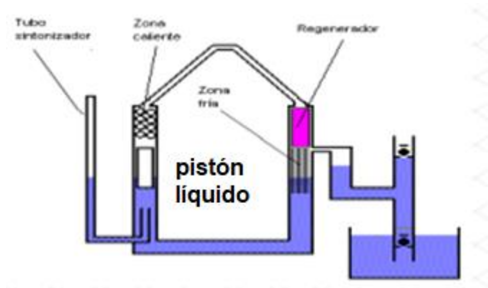

Fig. 7 Liquid piston engine [14].

Probably the latest development is the thermoacoustic engine. In this engine, the mechanical configuration is simplified as much as possible. There is no displacer piston and therefore no coupling system between the two pistons of the original engine. It works thanks to pressure waves generated in the gas cylinder, hence the name "acoustic", thanks to the heat supplied by the hot source [14].

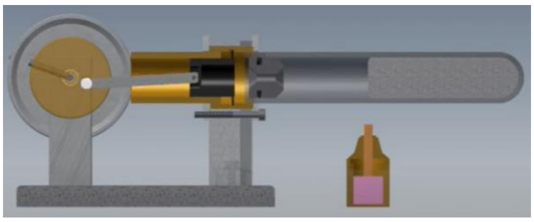

Fig. 7 Thermoacoustic Stirling engine [15].

The efficiency of a heat engine is the portion of heat energy that is transformed into mechanical energy. Understanding that heat is the energy flowing between two sources at different temperatures, it can be expressed as: [16].

$$\eta = \frac{W}{Q_c} \qquad (7)$$

Where W is the work obtained and Q_c the heat flowing from the hot to the cold source The ideal would be an engine with efficiency 1 (i.e. 100%) so that all the heat is transformed into work and nothing is "wasted", however, there is a physical principle that shows that this is not only practically and theoretically impossible, and the maximum that can be reached in theory is to have an efficiency that follows this expression: [16].

$$\eta = 1 - \frac{T_f}{T_c} \qquad (8)$$

Where T_f y T_c are the temperatures of the hot and cold source respectively.

From this expression it is inferred that for the yield to be as close to 1 as possible, we would need to take the temperature of the hot source to infinity, which is impossible. [16]

C. Kinetic energy of rotation

The moment of inertia of a rigid solid is defined as: [17].

$$I = \int R^2 dM \qquad (9)$$

Where R is the distance from the rotating point to the axis of rotation and M is the total mass of the rigid body.

The kinetic energy of rotation is the energy produced when a rigid body rotates about a fixed axis. This energy depends on the moment of inertia of the rigid solid (I) and the angular velocity (ω) of rotation according to the equation: [17]

$$E_{CR} = \frac{I\omega^2}{2} \qquad (10)$$

[3] Results

A. Engine construction and instrumentation

A prototype of a thermoacoustic Stirling machine was built. For this purpose, a glass test tube was used for the hot chamber, which was cut to 68.6 mm. A commercial piston from Airpot® Corporation was used. This served as the cold chamber. Both chambers were coupled by means of an aluminium heat exchanger, ensuring the tightness of the system with 4 o-rings arranged in two pairs: one for the hot chamber and one for the cold chamber. A relatively high mass disc was used as a flywheel to help achieve the effect more quickly. The piston crank was coupled to the flywheel by means of a screw. In the hot chamber, steel wool was used on the inside to achieve a higher temperature differential between the two chambers. The heat exchanger was connected to an aluminium bar through a hole. Similarly, the flywheel was coupled to another aluminium bar with a hole, thus allowing the flywheel shaft to rotate. Both rods in turn were coupled to an aluminium sheet as a base. An alcohol burner was used as a heat source for the machine. Figure 1 shows the assembled engine from different perspectives:

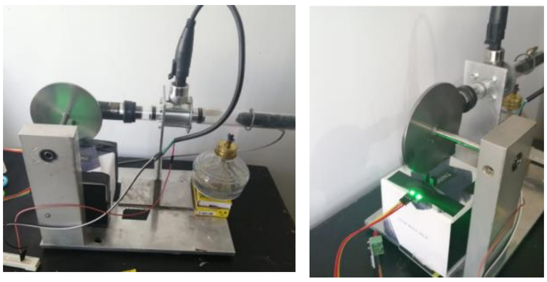

Fig. 9 Instrumentation of the thermoacoustic Stirling engine

The engine design parameters were as follows:

TABLE 1: ENGINE DESIGN PARAMETERS.

Parameter	**Dimension**
Length of the cold chamber	L_{CF} = 66.4 mm
Inner diameter of the cold chamber	$D_{int_{CF}}$ = 16.6 mm
Outer diameter of cold chamber	$D_{ext_{CF}}$ = 18.4 mm
Hot chamber length	L_{CC} = 120 mm
Inner diameter of the hot chamber	$D_{int_{CC}}$ = 17.8 mm
Outer diameter of hot chamber	$D_{ext_{CC}}$ = 18.9 mm
Regenerator length mm	L_R = 60 mm
Regenerator bore diameter	D_{int_R} = 7.9 mm
Regenerator outside diameter	D_{ext_R} = 17.1 mm
Piston stroke	L_P = 17.7 mm
Flywheel diameter	D_V = 82.5 mm
Crank length	L_M = 72.3 mm

B. Temperature measurement

The time variation of the temperature was measured in order to find the critical temperature values in the hot and cold chambers, respectively, as well as the critical value of the temperature differential between the two chambers for the Stirling effect to occur. The measurement started the instant the alcohol burner was lit.

To measure the temperature value over time, a Thermocouple MAX6675 thermocouple was used, coupled to an Arduino UNO, which made it possible to obtain the temperature data over time for subsequent statistical processing.

The temperature of the hot chamber and the temperature of the cold chamber were measured to determine the evolution of the temperature differential over time (figure 10).

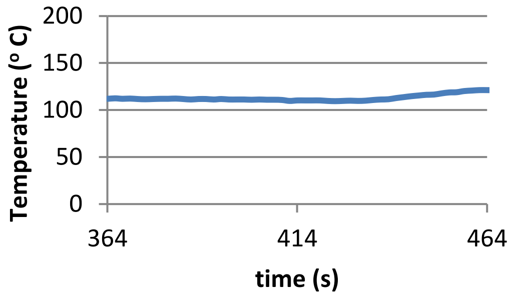

Fig. 10 Temperature differential in time

The Stirling effect starts approximately when a temperature differential of 80°C is reached, within 364 seconds, after the heat source (alcohol burner) was switched on within 470 seconds, even though the heat source is not removed.

C. Pressure measurement

A fundamental parameter of the engine is the pressure inside the chamber and it is precisely due to pressure changes that the thermoacoustic wave that causes the effect propagates. A loss of the critical pressure means that the Stirling effect disappears. The pressure was measured with a Cuifati-04 100 PSI pressure transducer.

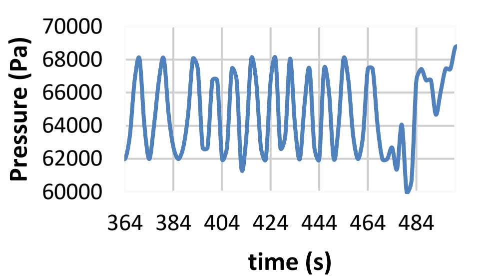

Fig. 11 Pressure variation versus time while the Stirling effect is occurring

The pressure was kept oscillating in a range between 62000 and 68000 Pa, approximately, which ensures that these are the critical upper and lower limits, respectively, for sustaining the thermoacoustic wave that determines the effect of the machine.

D. Measurement of the flywheel angular velocity and calculation of the conversion efficiency

The measurement of revolutions per minute was carried out using an optical encoder of the type Motor Encoder RPM Speed Counter Interrupter Sensor Mudule FC-03 with an Arduino UNO. The evolution of the angular velocity over time is shown in the following graph (figure 12):

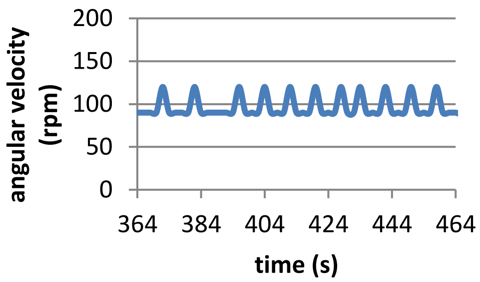

Fig. 12 Revolutions per minute versus time

Integrating the peaks of the curve shows that the Stirling effect causes an average angular velocity of 90 rpm and this maximum remains practically constant over time, with only infinitesimal intervals of fluctuation.

The heat delivered by the burner is calculated by heating water to boiling point. The initial temperature was 14°C and the final temperature was 100°C.

The volume of water heated was 2.84 mL and taking into account that the density of water is 1g/mL, the mass of heated water is 2.84 g. The heat capacity of water is approximately 1kcal/ kg °C [18]. Five different measurements were performed and the results averaged.

Then it was obtained: [18]

$$Q = mc_{H_2O}\Delta T = 0.24 \text{ kcal} \qquad (11)$$

As the diameter of the flywheel according to table 1 is D_V =82.5 mm, and its width is A=3.2 mm, then its volume will be:

$$V_V = \frac{\pi {D_V}^2 A}{4} = \frac{\pi(82.5)^2}{4} = 17106 \text{ mm}^3 = 17.12 \text{ cm}^3$$

The specific gravity of aluminium is 2.7 g/cm³ [18], so the mass of the flywheel will be:

$$M_V = 2.7V_V = 2.7\frac{g}{cm^3}x17.12\ cm^3 = 46.2\ g = 46.2x10^{-3}\ kg$$

Integrating into equation (9), the moment of inertia of a solid disc is given by the expression:

$$I_V = \frac{1}{2}\frac{M_V D_V{}^2}{4} = 0.4\ kgm^2$$

The kinetic energy of rotation will be (equation 10):

$$E_{CR} = \frac{I\omega^2}{2} = \frac{0.4\ kgm^2 * (9.42\ rad/s)^2}{2} = 17.7\ J = 0.042\ kcal$$

Then, the convection efficiency of the engine (equation 7) is:

$$\eta = \frac{E_{CR}}{Q_c} * 100\% = \frac{0.042\ kcal}{0.24\ kcal} * 100\% = 17.5\%$$

[4] Discussion of Results

The Stirling effect starts approximately when a temperature differential of 80°C is reached, within 364 seconds, after the heat source (alcohol burner) was switched on within 470 seconds, even though the heat source is not removed.

The reason why the effect disappears early, even with a heat source, is due to the rapid heating of the system, which leads to a rapid expansion of the gas and consequently to a rapid exchange of gas flow from the hot to the cold zone. The most likely cause is that the heat exchanger is not very large and therefore too much of the hot gas flows into the cold chamber, preventing the temperature gradient from being sustained for a long time.

The pressure inside the engine was kept oscillating in a range between 62000 and 68000 Pa, approximately, which allows us to ensure that these are the critical upper and lower limits, respectively, for sustaining the thermoacoustic wave that determines the occurrence of the Stirling effect in our configuration.

The Stirling phenomenon in the machine causes an angular velocity of approximately 90 rpm and this maximum remains practically constant over time, with only infinitesimal intervals of fluctuation.

This relatively low value of efficiency is in accordance with the experiment, where it can be seen that the number of revolutions of the flywheel is relatively low.

[5] Conclusions

Thermo-acoustic Stirling engines have major advantages over traditional Stirling engines. The main advantage over the others is that they are much simpler and therefore less costly to build, as they are of simple mechanical design.

The ideal theoretical efficiency of the engine depends primarily on the temperature difference between the hot and cold bulbs.

A thermo-acoustic Stirling machine was built and its operating conditions were established.

By measuring the pressure it can be concluded that with a relatively low value of this parameter the desired effect can be achieved.

The relatively low value of the conversion efficiency is in accordance with the experiment, where it can be seen that the number of revolutions of the flywheel is relatively low.

It is possible to build machines for converting thermal energy into mechanical energy, taking advantage of the Stirling phenomenon, which is based on the difference in temperature generated between the motor's focuses, one focus at a low temperature and the other at a high temperature.

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