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Feasibility study by simulation of a small sized Stirling engine for cooling generation.

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1. Introduction

Over the years, the demand for energy is increasing worldwide mainly due to population and consumption growth. At this point, Stirling engines play a very important role due to their high efficiency and reliability and their simple and compact mechanism. The Stirling engine bases its operation on the Stirling cycle if the objective is to obtain energy from the heat transfer between the hot focus and the cold focus [1] [2]. In the same way, stirling cycles can be used in reverse mode. In this type of machines, the mechanical energy produced by an electric generator is used to extract heat from the cold focus and reduce its temperature, the applications of these cycles can range from a few degrees (maintenance of beverages, etc...) to cryogenic temperatures.

The objective of this work is to analyze the operation of a low temperature Stirling of the company PHYWE, transparent model 04372-00. A CFD simulation has been developed using ANSYS software and the model has been validated by means of laboratory tests and results of experimental tests carried out by the manufacturer.

2. Engine description

Fig. 1. Stirling engine with measureLAB components installed.

Fig. 2. PHYWE Stirling engine.

As can be seen in Fig. 1, the machine is composed by the Stirling Engine, the torquemeter, and a test bench with complementary measurement devices.

The Stirling engine of the Fig. 2 is submitted to a load by means of an adjustable torquemeter, or by a coupled generator. Rotation frequency and temperature changes of the Stirling engine are observed. Effective mechanical energy and power, as well as effective electrical power, are assessed as a function of rotation frequency. The amount of energy converted to work per cycle can be determined with the assistance of the PV diagram. The efficiency of the Stirling engine can be estimated.

The Stirling engine has a gamma (γ) type configuration in "V" with both cylinders located at 90°. The cylinders are made of transparent heat resistant glass so that it is possible to see the movement of the pistons. The working fluid is air. Although it can work with different heat sources, a flame generated from pure alcohol has been used for the tests, which corresponds to the hot side. The cold side is in ambient conditions. To demonstrate the reversibility of this kind of machine, it can be operated in three operating modes: as a motor, as a heat pump or as a refrigerating machine. The tests of this work have been carried out with the motor working as a refrigerating machine.

The system uses a connecting rod-crank mechanism for the movement of the piston and the displacer. The working piston moves 90 degrees ahead of the displacer piston, as shown in Fig. 3. Fig. 4 shows the moving parts of this system, which are the pistons, which move back and forth or up and down depending on which piston is being referred to, a connecting rod and two cranks that drive each of the pistons. The connecting rod transmits the motion to the cranks, and is designed to function as a counterweight, so that additional force is added to the system if necessary. The displacer piston and working piston, which respectively displace and compress the working fluid, are also moving elements that are considered rigid solids.

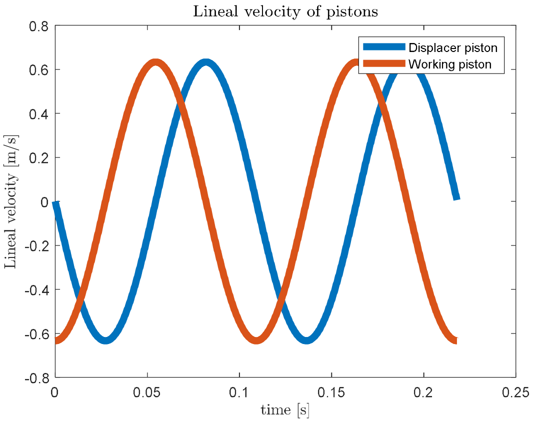

Fig. 3. Kinematics of the displacer piston and working piston

3. Planar two-dimensional CFD Modelling of the Stirling engine

Prior to the CFD modelling of the Stirling engine operation process, a two-dimensional CFD mathematical model has been used to analyse the engine performance [3]. To describe the heat transfer and gas dynamics inside the engine, the standard k-Ω SST turbulence model for flow of incompressible air has been used. According to [4], this type of simulation gives results that are close to the real ones.

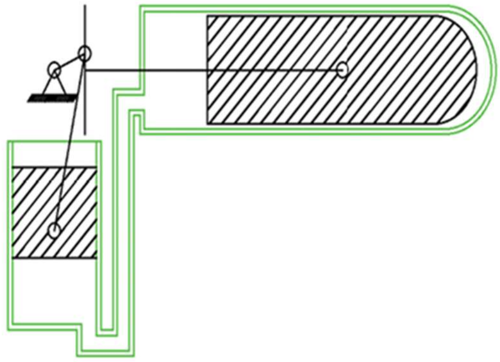

Fig. 4 Geometry of the stirling engine and mechanism

With the intention of improving the computational costs of the simulation, the arrangement of the cylinders has been modified (Fig. 5). Both cylinders share the same axis of symmetry and are arranged at 180° from each other, geometrically it is a modification but from the point of view of thermal analysis of the cylinder the be-haviour is the same, since the phase difference between the cylinders, velocity, displacement, etc. are maintained. Figures 5-6 describe the modelling process and meshing followed. To give movement to the piston and displacer, a User-Defined-Function (UDF) with the kinematic functions has been used.

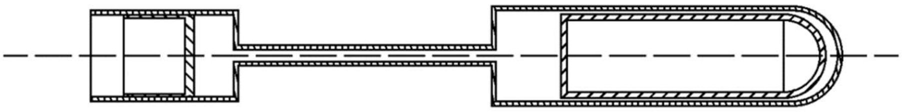

Fig. 5 Cylinder arrangement on CFD Model

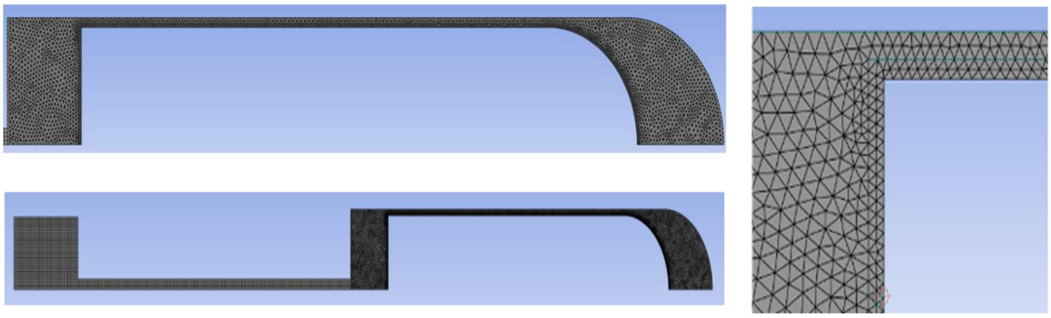

Fig. 6 Model meshing details

The materials used for the simulation can be seen in Table 1 and the fundamentals variables that describe the model are shown in Table 2.

Table 1. Material properties

Material	$\rho\left[\frac{kg}{m^3}\right]$	$Cp\left[\frac{J}{kg\cdot K}\right]$	$K\left[\frac{W}{m\cdot K}\right]$	$\eta\left[\frac{kg}{m\cdot s}\right]$
Air	Ideal gas	1006.43	0.0242	$1.7894\cdot 10^{-5}$
Aluminium	2719	871	202.4	-

It is important to note that to obtain the work done by the pistons, the equations have been used, which calculate the work and yield produced from the values of pressure, volume, temperature, and entropy obtained from the simulation. Ec. 1,2

$$W = \int_{V_1}^{V_2} P\, dV \tag{1}$$

$$P = W \cdot t \tag{2}$$

Table 2. Fundamental variables of the model

Variable	Value	Units
$\emptyset_p$	28	mm
$\emptyset_d$	28.6	mm
S	22	mm
δ	90	°
V_{swp}	13.546	cm^3
V_{swd}	14.133	cm^3
V_d	0	cm^3
V_{max}	44.335	cm^3
V_{min}	32.02	cm^3

4. Validation of the model working as a generator

Model validation was carried out by comparing simulation results with experimental test results under different operating conditions, especially different operating speeds and hot source temperatures. Both in the simulation and in the tests, the engine was operated in motor mode: heat energy is supplied and heat is produced. The key variable chosen to validate the model is the power developed by the power piston during a cycle once the system has reached steady state. The results obtained can be seen in Table 3. Experimental and simulated data obtained working as a generator.

After comparing the power results of the experimental tests performed with the power results obtained in the simulation, a precision of the results is estimated with a deviation of 7% with respect to the values of the experimental analysis, where the maximum difference is ±0.15 w of power.

Table 3. Experimental and simulated data obtained working as a generator

Ω[rpm]	T_C [K]	T_H [K]	P_{exp} [W]	P_{sim} [W]
276	347.5	447.9	1.85	2.03
572	347.5	577.3	2.37	2.15

5. Analysis of results working as cold machine

Based on the validated model of the Stirling machine working as an engine, the results obtained for the machine working as generator at different revolutions have been analysed (Table 4). As can be seen, there is a relationship between the engine revolutions and the thermal power obtained. The most important value of the data obtained is the temperature difference between the focus, of the order of 37 ºC, so that as soon as a minimum cooling is applied to the hot source (fins and air flow) and it is kept at ambient temperature (above 25 ºC) the values of the cold source can be placed in useful temperatures for the applications mentioned above.

Table 4. Results obtained from the Stirling model in refrigeration mode at different revolutions

ω [rpm]	T_C [K]	T_H [K]	P_{sim} [K]	ΔT[K]	H [%]
450	290.5	327.2	0.69	36.8	11.24
500	290.3	327.4	0.70	37.1	11.32
550	290.3	328.0	0.88	37.7	11.50
600	290.3	328.0	0.87	37.7	11.49
650	291.1	328.2	0.70	37.1	11.29
700	291.5	328.5	0.69	37.0	11.25

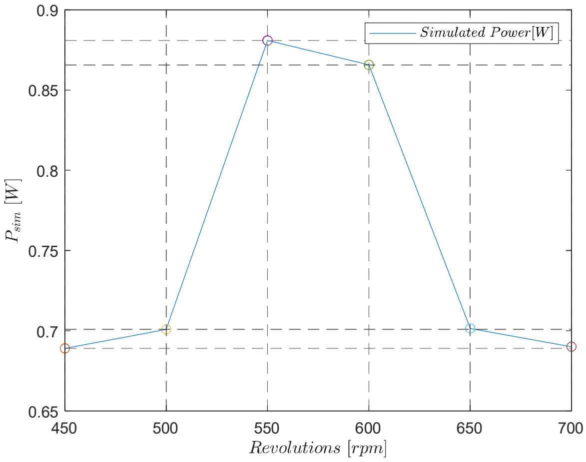

Fig.7 Simulated power vs revolutions

Table 5. Main parameters obtained

	P [Pa]	V [m³]	T [K]	s [J/KgK]
P1	131781	36.9073	304	-210.15
P2	206912	30.3414	327	-184.80
P3	140238	36.9395	308	-169.54
P4	94887	42.6564	290	-184.68

The relationship between n revolutions and power has also been analysed, representing the values in the Fig. 7. It has been observed that the optimum range of revolutions is between 500 and 650 [rpm]. Outside this range, engine power drops significantly.

Other values of the most important parameters obtained in the simulation are summarised in table 5.

As can be seen in the figure (Fig. 8), the elliptical shape of a real Stirling cycle operating in refrigeration mode is obtained. The figure obtained is flat since the real engine has a very low power due to its dimensions, since it accepts a smaller volume of air. On the other hand, the reason for the flat shape that has been obtained is since pressure is more influenced by volume changes at constant temperature (Isothermal processes) than by pressure changes at constant volume (Isochoric processes). In the graph, the longest oblique lines are those that show the pressure difference when the system is absorbing or releasing heat from the environment, while the vertical lines, which are almost non-existent, indicate that there is no heat regenerative system. The materials of the pistons are the ones that act in part as a heat recuperator and hence the small width of the diagram that has been represented.

A closed diagram is obtained since the simulation to a steady state for the temperature vs entropy diagram (Fig. 8). Specific entropy is defined as the energy that is produced but cannot be harnessed to do work. In the lateral parts of the oval, irregular areas with peaks can be seen, influenced by the entropy just in the lower and up-per dead centres of the power piston. At those points, the system continues to produce energy, but the piston cannot transmit it.

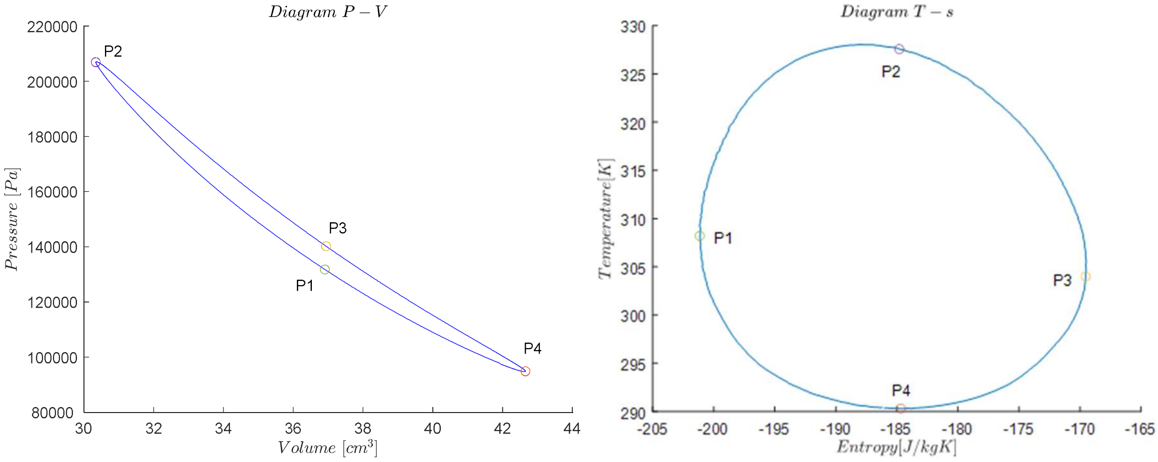

Figure 8. P-V and T-s diagrams obtained.

6. Conclusions

After verifying the simulation model by means of experimental tests carried out with operation in engine mode, the simulation of the inverse Stirling cycle (generator mode) was carried out to reduce the temperature of the working cold source. In the simulation, a minimum temperature of 290 K has been obtained, which means a temperature difference of 37 K with respect to the hot focus, working at a speed of 550 rpm and an ambient temperature of 298 K (25 ºC).

The "Pressure - Volume" diagram of the working cycle has been obtained where the power developed by the cycle is calculated and the efficiency of the machine work-ing under these conditions is 0.8809 W and 11.50% respectively.

The data obtained confirm that with small modifications in the engine hot focus (ventilation to lower the temperature) temperatures can be obtained in the cold focus with values between 0 and 20 ºC, valid temperatures for small applications of food preservation, beverages, etc.

From the data obtained, very simple prototypes can be developed, although somewhat more complex than the model used, and the feasibility of their use in the mentioned applications can be studied.

Acknowledgments:
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7. References

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