18th Brazilian Congress of Thermal Sciences and Engineering
November 16-20, 2020 (online)

ENC-2020-0444
CHARACTERIZATION OF A PROTOTYPE BETA TYPE FREE PISTON STIRLING ENGINE TO CONVERT THERMAL ENERGY INTO ELETRIC POWER FOR THE SPACE APPLICATION

Rafael Theodoro
Instituto Tecnológico de Aeronáutica – ITA
Praça Marechal Eduardo Gomes, 50, 12228-900 Vila das Acacias, SP, Brazil
rafael_theodor@hotmail.com

Ana Carolina dos Santos
Instituto Tecnológico de Aeronáutica – ITA
Praça Marechal Eduardo Gomes, 50, 12228-900 Vila das Acacias, SP, Brazil
anna.carolsantos21@gmail.com

Valéria Serrano Faillace Oliveira Leite
Instituto de Estudos Avançados – IEAv, Divisão de Suporte Tecnológico
Trevo Coronel Aviador José Alberto Albano do Amarante, 01, 12228-001, São José dos Campos, SP, Brazil
valeria@ieav.cta.br

Lamartine Nogueira Frutuoso Guimarães
Instituto de Estudos Avançados – IEAv, Divisão de Energia Nuclear
Trevo Coronel Aviador José Alberto Albano do Amarante, 01, 12228-001, São José dos Campos, SP, Brazil
Lamar.guima@gmail.com
lamartinelnfg@fab.mil.br

Abstract. *This paper deals with the capture of operating data from a prototype free piston Stirling engine (FPSE) through electronic data acquisition system. Also, a numerical simulation is built for the FPSE to understand the thermodynamic behavior of this system. First, there is a brief discussion about the engine design parameters and about the heat exchangers. After that, it is described the data acquisition system, and the equations to model the thermodynamic parameters of the FPSE. Based on a certain operating frequency of the FPSE, the prototype data is are collected for that power. Next, the characterization of the springs is performed once the spring is a primordial component that helps the movement of the pistons. Finally, with all the characterizations, it is possible to understand how the FPSE works around determined temperature. The operation and mechanical data of the prototype FPSE are collected and analyzed. That data can help future optimizations of the mechanical system, in such a way to obtain more power and efficiency of the Stirling engine.*

Keywords: *Free Piston, Stirling Engine, Power Converter.*

1. MOTIVATION AND PURPOSE

One of the greatest challenges to keep the man in the space, for a long time, is to obtain energy to power the life maintenance systems. In this way, the TERRA project (Advanced Fast Reactor Technology), conducted by IEAv (Institute for Advanced Studies), is interested in systems and technologies focused in energy generation, especially in generating electricity power in the space. This is the same problem to generate electric power in the remote zones, as well. One of the ways to generated electric energy in space is using nuclear fissions occurring in a microreactor coupled to a thermal engine which converts thermal energy into electricity, as the Stirling engine.

In space near Earth, one may capture and transform energy using photovoltaic panel due to their proximity to the Sun. The RTG's (Radioisotope Thermoelectric Generators) are another way of electricity generation, that uses the decay of the plutonium (PU238) for this purpose. However, it is thermal efficiency is around 6%, a rather low value. Studies regarding power generators shows that Stirling engines, using the same decay source, have a thermal to electricity conversion efficiency around and above 23% (ANDERSON, 2005). This technology is called ASRG

(Advanced Stirling Radioisotope Generator), this technology is still in development but has great potential. Nuclear micro-reactors nowadays are another heat source and had a great development during the Kilopower design.

Figure 1 shows the thermodynamic P-V diagram of a Stirling cycle. One may observe four stages: 1→2) isothermal compression, 2→3) isochoric heating, 3→4) isothermal expansion and 4→1) isochoric cooling.

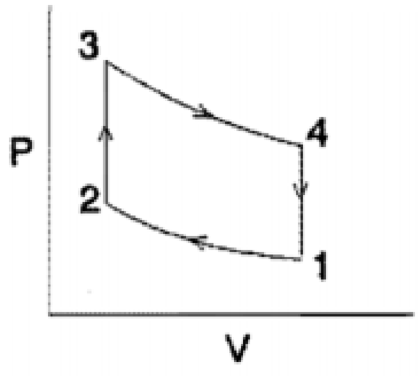


Figure 1. P-V diagram of the Stirling cycle (CLUCAS, 1993).

Kwankaomeng developed a simplified FPSE (Free Piston Stirling Engine), shown in Fig. 2a. They analyzed the energy generation and the efficiency of the converter. Their studies were based on the different operation frequencies. The results showed that the maximum power was 0,68 W for an operation frequency of 6 Hz (KWANKOAMENG et al, 2014). Zare and Tavakolpour-Saleh (ZARE et al, 2016) focused their research in the frequency of the FPSE. In Zare and Tavakolpour-Saleh project of the FPSE two different methods were used to do the numerical evaluation, with a prototype manufactured (Fig. 2b). They achieved the same results in both simulation and in the experimental work. The temperatures in the heat exchanger, at the hot and the cold region, were 603 and 297 K respectively. The frequency of operation was in the order of 10 Hz and the phase between the movement of the displacement piston (or displacer) and the power piston (or only piston) was in the order of 58 degrees.

(a) (b)

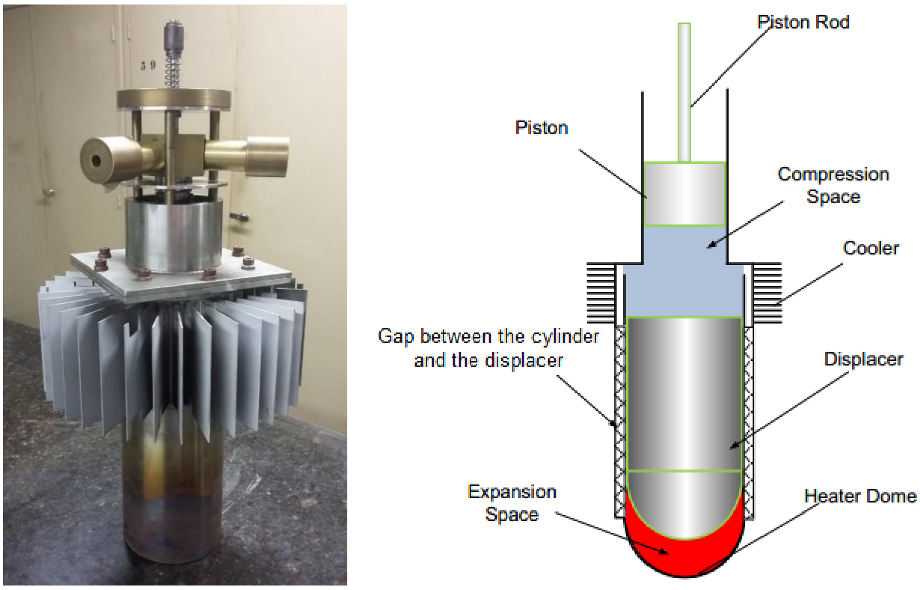
Figure 2. Prototypes analyzed by (a) Kwankoameng (KWANKOAMENG et al, 2014) and (b) Zare (ZARE et al, 2016).

On this way, the present paper focuses in the characterization of the beta-type FPSE prototype, which was manufactured in the IEAv. The objective is to obtain the data of the FPSE prototype operation, using electronic measurements and numerical simulations to understand the thermodynamic behavior of that particular system.

2. METHODOLOGY

2.1 Beta-type FPSE

First of all, it is interesting to give a brief explanation about the Stirling engine design and about the heat exchangers. The prototype is composed basically by two pistons (a displacement and a power pistons) which are placed inside the same cylinder. The heat exchangers, a heater dome and a cooler, are part of the same cylinder. In Fig. 3a one visualizes the prototype of the beta-type FPSE, manufactured in IEAv, used for the studies of the present paper. The scheme shown in the Fig. 3b gives an idea of how the system items are inside of the prototype.



(a) (b)

Figure 3. (a) IEAv's beta-type FPSE: prototype and (b) schematic - adapted of a beta FPSE (KWANKAOMENG et al, 2014).

An important difference between the two prototypes is that the IEAv's FPSE does not have a regenerator in the system, as other types have. There is just a small free gap between the cylinder and the piston. This gap works as a very inefficient (which is desired) heat exchanger as it is not isolated. However, the working fluid goes from the expansion to the compression space so quickly that there is no time to affect the fluid temperature. So, for practical reasons, it will be considered only the expansion and the compression space as heat exchangers. It is also important to highlight that the working fluid of the prototype is air.

2.2 Eletronic system to collect the operation data

The movement of the displacer and the power piston is important to be understood, as well as, to know how the pistons will respond in time. This is particularly important because at the end of the piston rod it will be placed the magnets that will generate electric power. In this way, a data acquisition system using two ultrasonic sensors, HC-SR04 (Fig. 4), to measure the displacement and the frequency of the rod, were installed.

To measure the temperature at the surface of the heat exchangers, three thermocouples, type K, were used. Each thermocouple was positioned in a different region of the heat exchanger. One thermocouple was positioned at the heater dome, one was positioned at the region between the heater and the cooler and the last one at the cooler of the Stirling engine.

To characterize the springs, of the mechanism for the rod movement, a force sensor Pasco, model Cl-6537 was used (Fig. 5).

With the data/values obtained with the force sensor was possible to make the calculations necessary to characterize the springs. The calculations for the design of the three springs followed the methodology described in Melconian's book (MELCONIAN, 2009).

Figure 4. Electronic data acquisition system

Figure 5. System for measuring the spring elastic constants.

2.3 Thermodynamic simulation

To understand the thermodynamic properties of the system, a program was developed using the Excel software, based on the equations consolidated in the work of Martini, 2004 (MARTINI, 2004). To use the set of equations some considerations are necessary as for instance: the pistons move sinusoidally, the gas temperature is known in all parts of the engine, there is no leak in the system, the working fluid respects the laws of the perfect gases in each instance of the cycle, and the pressure is the same inside each working fluid control volume.

Thus, the hot volume was calculated using Eq. (1), the cold volume using Eq. (2), the total volume using Eq. (3), the pressure along the engine using Eq. (4), the energy per operating cycle of the Beta-type Stirling engine using Eq. (5) and, finally, to calculate the power of the engine it was used the Eq. (8).

In the equations below, VL is the maximum hot live volume and VK is the maximum cold live volume associated with the displacer. H(N) and C(N) are hot volume and cold volume respectively. V(N) and P(N) are the total gas volume and the pressure at any crank angle respectively. VL is the maximum hot live volume. F is the angle of crank. HD, CD and RD are the hot dead volume, the cold dead volume and the regenerator dead volume respectively. AL is the phase angle between the pistons. M and R are engine gas inventory (g·mol) and universal gas constant (8.314 J/g-mol·K). TH, TC and TR are effective the hot gas temperature, the effective cold gas temperature and the effective regenerator gas temperature. PX is the maximum pressure attained during each cycle. The Eq. (6) and (7) are basically a complement of the Eq. (5).

$$H(N) = \frac{VL}{2}[1 - \cos(F)] + HD \quad (1)$$

$$C(N) = \frac{VK}{2}[1 + \cos(F)] + CD + \frac{VP}{2}[1 - \cos(F - AL)] \quad (2)$$

$$V(N) = H(N) + C(N) + RD \quad (3)$$

$$P(N) = \frac{M \cdot (R)}{\frac{H(N)}{TH} + \frac{C(N)}{TC} + \frac{RD}{TR}} \quad (4)$$

$$W = \frac{\pi \cdot \left(1 - \frac{TC}{TH}\right) \cdot PX \cdot (VL) \cdot \left(\frac{VP}{VL}\right) \cdot \sin(AL)^2}{\sqrt{Y \cdot (Y^2 + X^2)}} \cdot \sqrt{\frac{Y - X}{Y + X}} \quad (5)$$

$$X = \sqrt{\left(\frac{TC}{TH} - 1\right)^2 + 2 \cdot \left(\frac{TC}{TH} - 1\right) \cdot (XY) \cdot \cos(AL) + (XY)^2} \quad (6)$$

$$Y = \frac{TC}{TH} + \frac{4 \cdot \left(\frac{RD + HD + CD}{VL}\right)}{\left(1 + \frac{TC}{TH}\right)} + \sqrt{1 + (XY)^2 - 2 \cdot (XY) \cdot \cos(AL)} \quad (7)$$

$$P = W \cdot f \quad (8)$$

3. RESULTS

3.1 Temperature in the heat exchangers

After 50 minutes of testing, the temperatures in the heat exchangers reached a steady state. The temperatures at the heater, at the region between the heater and the cooler and at the cooler are in the order of 317 °C ± 5 °C, 256 °C ± 5 °C and 50 °C ± 5 °C. The temperatures can be seen in the diagram on Fig. 6.

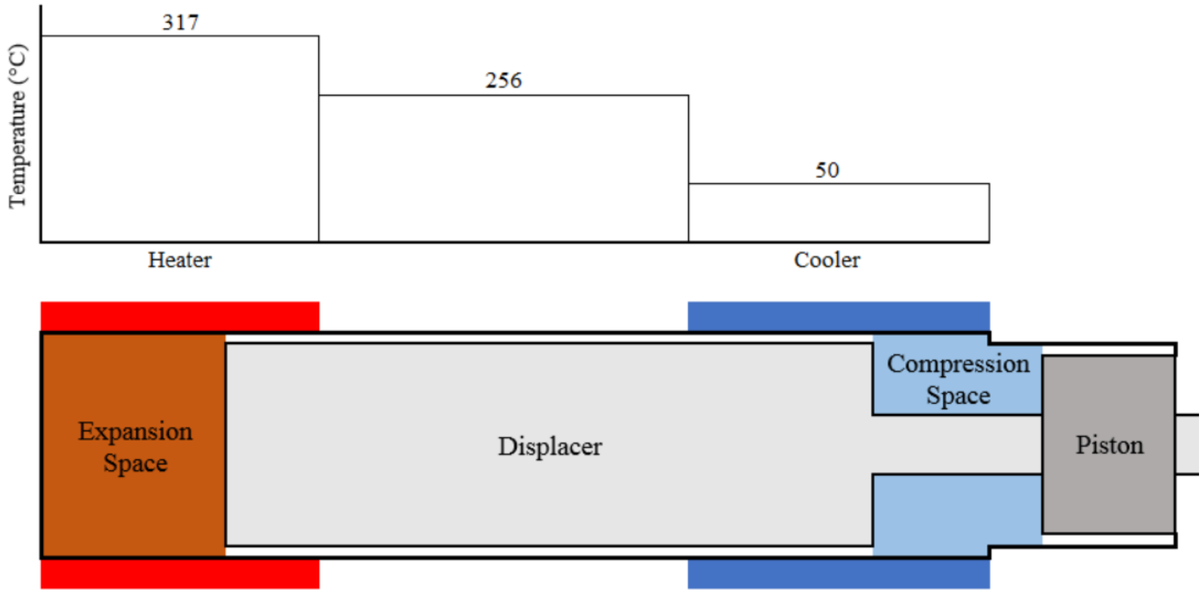


Figure 6. Temperatures at the (a) heater, at the (b) region between the heater and cooler and at the (c) cooler.

3.2 Kinetic data of the piston

From the data obtained it was possible to generate the graph shown in Fig. 7. It was observed that the pistons present an operation period and frequency of 140 ms and 7 Hz, respectively. A displacement lag was measured on the order of 84 degrees. The displacement variations of the displacer and power pistons were determined in the order of 12 and 6 mm, respectively.

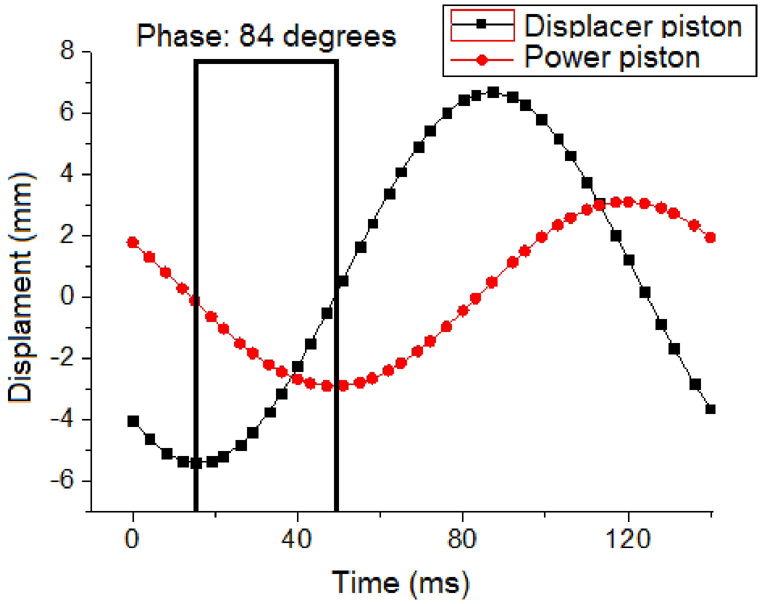


Figure 7. Displacement of the displacer and the power piston.

3.3 Thermodynamic data

To determine the thermodynamic data, calculated by the Eqs. (1) to (8), it was necessary to obtain the data of the geometry, the temperature during the operation and the volume of the free piston Stirling engine prototype used in this work. As a result, the variation of total volume and the variation of pressure in relation to the angle of the operation cycle are plotted in the P-V diagram, shown in Fig. 8.

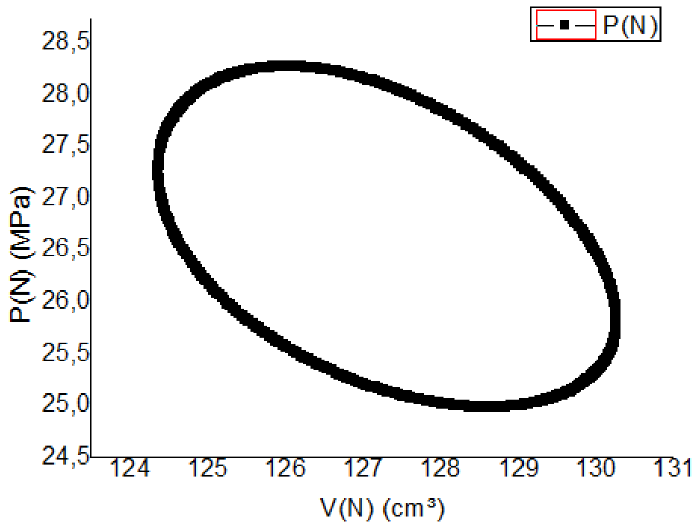


Figure 8. P-V diagram obtained from experimental data.

Knowing that the produced work, that was calculated, is equal to 13.914 J, and the operating frequency, is equal to 7.2 Hz, it was possible to determine that the power of the prototype is in the order of 100W.

The geometric aspect resulting from the simulation carried out from experimental data in this work is very similar to the theoretical Stirling cycle represented in Fig. 1. The comparison between the theorical and experimental Stirling cycle performed by Meijer also presented results like those obtained in this paper ((MEIJER, 1960).

3.4 The parameters of the Stirling engine springs

From all the data obtained, it was possible to obtain the characteristics of the springs of the prototype (Fig. 9) without change the displacement of the pistons and maintain all the operational characteristics of the prototype. All the data of the characterization of the springs were shown in Tab. 1. To determine the spring constant of the prototype in operation is fundamental to plan and design future optimizations for the IEAv's FPSE mechanical system.

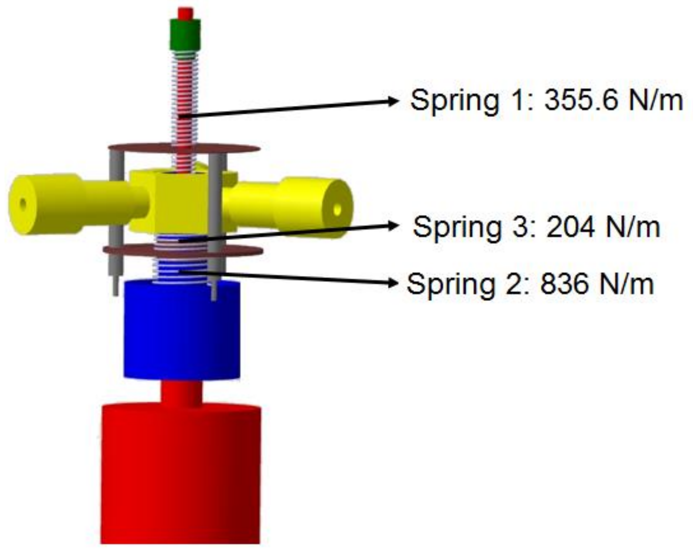


Figure 9. Springs of the beta-type FPSE prototype.

Table 1. Data of FPSE springs characterization.

Item	Spring 1	Spring 2	Spring 3	Unity
Average spring diameter	8.95	24.86	24.86	mm
Wire diameter	0.7	1.3	1.3	mm
Spring deflection	12	6	6	mm
Spring elastic constant	0.3556	0.8356	0.204	N/mm
Spring pitch	4	4	4	mm
Number of active turns	10	2.36	9.69	Active spire
Curvature index	12.79	19.12	19.12	Non-dimensional
Wahl factor	1.1117	1.07	1.07	Non-dimensional
Shear stress acting	315.32	154.55	37.73	N/mm^2
Transverse elastic modulus	85.03	85.03	85.03	GPa
Spring length	41.4	12.04	41.36	mm
Closed spring length	8.4	5.67	15.2	mm
Maximum spring deflection	33	6.37	26.16	mm
Maximum working load	11.74	5.34	5.34	N
Maximum acting voltage	867.5	164.61	164.51	N/mm^2
Spring deflection by spires	1.2	2.54	0.62	mm/spire
Spring tilt angle	8.1	2.6	2.6	degrees

4. CONCLUSIONS

The present paper focuses mainly on the experimental development of a methodology to measure the temperature, the displacement and the frequency of the piston rod of the IEAv's FPSE prototype. All the information used for the simulations as input data, were obtained from a measurement or data acquisition. The FPSE prototype showed a consistent operating capacity, where the balance of the weights, the positioning of the springs and the temperature of operation are all part of a single device.

Based on the information obtained in this work, the prototype of the IEAv's FPSE showed a proper capacity for energy conversion, converting thermal energy into mechanical energy and then into electric power. In this way, future developments of new systems will be facilitated. These developments also will require adjustments on the performance of the mechanical components of the engine. The methodology developed in the present work, such as the characterization of the prototype, the theoretical and experimental studies, and the data analysis, will help the design and construction of future free piston Stirling engine devices. And these devices will help to generate the necessary electric power for long-term space exploration missions in the near future.

5. ACKNOWLEDGEMENTS

Acknowledgments are provided to the TERRA project and to IEAv, to allow the development of this paper. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

6. REFERENCES

ANDERSON, D. J. NASA Radiosotope Power Conversation Technology NRA Overview. NASA, 2005.

CLUCAS, Donald Murray. Development Of A Stirling Engine Battery Charger Based On A Low Cost Wobble Mechanism. 316 f. Tese (Doutorado) - Curso de Doctor Of Philosophy In Mechanical Engineering, University Of Canterbury, Christchurch. New Zealand, 1993.

KWANKOAMENG S, Silpsakoolsook B, Savangvong P. Investigation on stability and performance of a free piston Stirling engine. Energy Procedia 2014;Vol. 52:598e609.

MARTINI, W. R. Stirling Engine Design Manual. Honolulu, Hawaii: University Press of The Pacific, 2004. 409 p.

MEIJER, R. The Philips Stirling thermal engine. 137 p. Tese (Ph.D. diss) — Delft University of Technology, 1960.

MELCONIAN, Sarkis. Elementos de Máquinas. 9. ed. Brasil: Editora Érica, 2009.

W. R. MARTINI. Stirling engine design manual. US Department of Energy, Office of Conservation and Solar Applications, Division of Transportation Energy Conservation, 1978.

ZARE, Sh.; Tavakolpour-Saleh, A.r.. Frequency-based design of a free piston Stirling engine using genetic algorithm. Energy, [s.l.], v. 109, p.466-480, ago. 2016. Elsevier BV. http://dx.doi.org/10.1016/j.eergy.2016.04.119.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.