

25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-2345

DESIGN AND MANUFACTURE OF A SMALL-SCALE GAMMA-TYPE STIRLING ENGINE PROTOTYPE AND ANALYSIS OF EFFICIENCY AND POWER USING FIRST-ORDER DESIGN METHODS

Jean-Marc Stephane Lafay

Francisco Augusto Aparecido Gomes

Federal University of Technology - Paraná, campus Pato Branco, Brazil

jeanmarc@utfpr.edu.br

franciscogomes@utfpr.edu.br

Klünger Arthur Éster Beck

Federal Institute of Education, Science and Technology of Santa Catarina, campus Xanxerê, Brazil

klunger.beck@ifsc.edu.br

Abstract. *This work consists of the development, manufacture and instrumentation of a small-scale gamma-type Stirling engine prototype with the purpose of research the efficiency and the power using the First-Order Design Methods through the sensitivity of parameters of the engine. The processing of the instrumentation of the engine was accomplished utilizing a microcontroller LAUNCHXL-F28069M. The programming of the microcontroller was developed in the platform open-source software Code Composer Studio (CCS). The destined signals of the entrance to feed the microcontroller were composites for the measurements of pressure, temperatures, the angle and the rotation of turn of the engine through industrial sensors of high precision. The corresponding values of pressure were accomplished by a piezoelectric sensor of pressure of family 33 MBS – model 060G3038 connected in the entrance of the internal chamber of combustion of the prototype, that occurs the work through the power piston. The measurements of the internal temperature of the engine of the Stirling cycle were accomplished using two k type thermocouples, connected in both sources cold and hot of the engine. Through the election of a range of experimental results (pressure, temperatures, rotation of the engine and the angle of the engine) of the prototype, it was possible to calculate the efficiency and power described for the First-Order Design Methods. This method obtained maximum values of efficiency and power of 41,04 % and 48,56 W, respectively. This study verified that the pressure and rotation of the engine are essential parameters in the results of efficiency and power. Concluding that the model can be used for the initial design analysis of the project.*

Keywords: *Efficiency, Electronic Instrumentation, First-Order Design Methods, Stirling Engine, Thermodynamics.*

1. INTRODUCTION

The 21st century presents great challenges for humanity, one of them is the increasing demand for energy, therefore new forms and methods of generation and distribution of energy are being studied and searched. The safe, efficient and abundant energy has a direct impact on the quality of life of the future generations and in the development of the nations (Yang *et al.*, 2016).

Stirling engine is an ideal and promising technology to operate in these situations, therefore it is an engine of external combustion that uses any source of heat, combustible of also low quality, that is, low energetic efficiency when accomplished an exergy analysis and low demand of maintenance due to the few movable parts, range between 5–8 thousand hours for engines with less than 20 kW of power (Organ, 2013; Riley, 2015).

The Ericsson and Stirling external combustion engines have attracted the interest of several researchers, engineers and physicists due to their potential to provide high-efficiency conversion energy (Walker, 1980; Sowale *et al.*, 2018).

The First-Order model is a simple method that can be used for the early phases of project development. In this model there is no need to specify the mechanism in detail. The measurement of the parameters of temperature, pressure and rotation thermal machines of external combustion is important to characterize these, called motor Stirling, with these data are possible to obtain the efficiency and power through the First-Order model (Rupesh *et al.*, 2017; Bataineh, 2018).

The parameters used in this model are cycle pressure, velocity and volume variation to measure power. For efficiency analysis is measured both the temperatures of the hot and cold source, but know the indicated efficiency, the efficiency of the heater, mechanical efficiency and assembly parameter. A range of values for these parameters are available in the

literature but should be specified for each row project.

With the purpose to contribute to the studies concerning this subject and broaden the knowledge about these parameters of efficiency and mechanical assembly described in the literature this work it developed and it manufactured a Stirling engine configuration gamma-type to analyze the efficiency and the power for initial projects aiming at the work generation.

2. STIRLING ENGINE

Robert Stirling was a clergyman born in Perthshire, Scotland (1790-1878) inventor of the Stirling engine and other optical and electronic devices (Loveridge, 1978).

Nowadays the technology of the Stirling engine has been widely disseminated, and this being verified the possibility of this technology be applied mainly in the mode of microgeneration, and its main applications include the generation of electrical energy in aerospace, military, space probes, solar power plants of various capacities, thus representing an excellent alternative to the electrification of remote communities, or that are not assisted by the conventional power grid, as they can work with any heat source (Oelrich and Riddell, 1988; Hachem *et al.*, 2018).

This Stirling engine verified in Fig. (1) operates in a closed regenerative thermodynamic cycle, with cyclic compression and expansion of the working fluid at different temperatures, its flow is controlled by the volume variation, so there is a net heat conversion rate for the work (Martini, 1983; Alain, 2017).

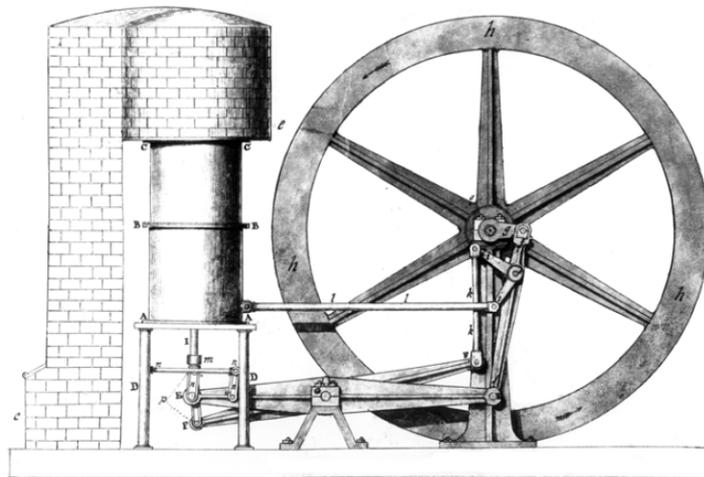


Figure 1: Schematic of the Stirling engine originally developed by Robert Stirling (1816).
 Adapted by Organ (2007).

The engine consists of a thermal machine, that in theoretical analysis can be described as being a reversible and closed thermodynamic cycle, as seen, that it converts heat into work from the expansion and of the contraction of a gas, that alternating between a thermal gradient, being called an engine of external combustion of a simple mechanism, of low maintenance, low emission of pollutants, low level of noise and mechanical vibration. This engine operates in closed regenerative thermodynamic cycle, with cyclical compression and expansion of the fluid of work in different temperatures, being its controlled flow for the volume variation, so that it has a fee of liquid conversion of heat for the work (Organ, 2013; Sowale *et al.*, 2018).

In Fig. 2 the four processes internally are reversible: isothermal compression of the state 1 – 2 at a temperature T_L (constant), constant state volume heating 2 – 3, isothermal expansion of the state 3 – 4 at a temperature T_H (constant), and cooling the constant volume of the state 4 – 1 to complete the cycle.

The maximum obtainable efficiency for engines based on the Stirling cycle is a function pressure, volume, phase angle and temperatures in heat sink and heat source. The efficiency of the Carnot cycle (η_c) described in Eq. (1) can be used to calculate the theoretical efficiency of a Stirling cycle machine (η_{ts}) considering the work

$$\eta_c = \left(1 - \frac{T_L}{T_H}\right), \quad (1)$$

where T_L is the temperature of cold source in K and T_H it is the temperature of hot source in K, (Heywood, 2018; Bataineh, 2018).

As the ideal gas can undergo both isochoric and isobaric transformations, we define specific heat in two types, the constant volume (C_v) and constant pressure (C_p). The efficiency can be calculated by the quantity of heat (Q) provided by the work (W). The calculation of the efficiency of a Stirling cycle machine (η_{ts}) considering the irreversibility described

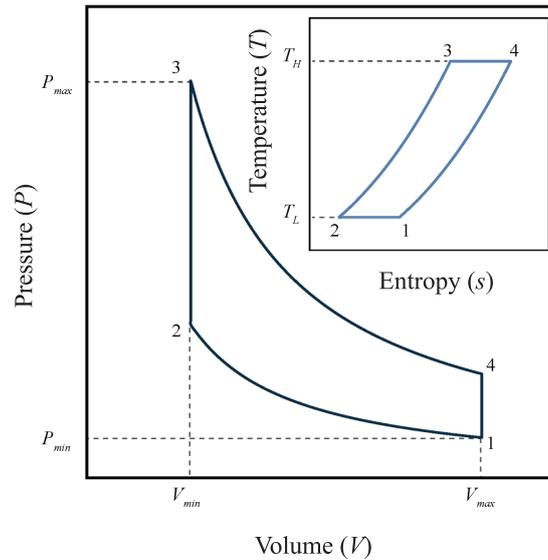


Figure 2: Diagram $P - V$ and $T - s$ for a reversible Stirling engine.
Adapted by Borgnakke and Sonntag (2012).

in Eq. (2)

$$\eta_{ts} = \left| \frac{W_{3-4} + W_{1-2}}{Q_{2-3} + Q_{3-4}} \right|, \quad (2)$$

where W_{3-4} is work route 3 – 4 in J, W_{1-2} is work route 1 – 2 in J, Q_{2-3} is heat transferred route 2 – 3 in J and Q_{3-4} is heat transferred route 3 – 4 in J.

Where the work can be calculated by the Eq. (3) and (4)

$$W_{1-2} = n_{mols} R T_H \ln \frac{V_{min}}{V_{max}}, \quad (3)$$

$$W_{3-4} = n_{mols} R T_L \ln \frac{V_{max}}{V_{min}}, \quad (4)$$

where n_{mols} are the number of moles in mol K and R is the universal constant of gases in $\text{m}^3 \text{ Pa K}^{-1} \text{ mol}^{-1}$. The quantity of heat can be calculated by the Eq. (5) and Eq. (6)

$$Q_{2-3} = n_{mols} C_v \Delta T = n_{mols} C_v (T_H - T_L), \quad (5)$$

$$Q_{3-4} = n_{mols} R T_H \ln \frac{V_{max}}{V_{min}}. \quad (6)$$

The quantity of heat (Q_{2-3}) is referring to the heat input of the regenerating. Thermodynamic variations are considered constant for a period of a Stirling engine cycle (Walker, 1980; Moran *et al.*, 2014; Bataineh, 2018). The energy variation (ΔU) is zero in the isotherm ($Q_{3-4} = W_{3-4}$) and $\ln \frac{V_{max}}{V_{min}} = - \ln \frac{V_{min}}{V_{max}}$.

Through in Eq. (7) the thermodynamic cycle can be calculated considering the irreversibilities related to the regenerator, approaching the theoretical thermodynamic cycle of the actual cycle of a thermal machine

$$\eta_{ts} = \frac{n_{mols} R T_H \ln \frac{V_{max}}{V_{min}} + n_{mols} R T_L \ln \frac{V_{min}}{V_{max}}}{n_{mols} C_v (T_H - T_L) + n_{mols} R T_H \ln \frac{V_{max}}{V_{min}}}. \quad (7)$$

Solving and simplifying the Eq. (7) results in the Eq. (8)

$$\eta_{ts} = \frac{R \ln \left(\frac{V_{max}}{V_{min}} \right) (T_H - T_L)}{C_v T_H \left(1 - \frac{T_L}{T_H} \right) + R T_H \ln \frac{V_{max}}{V_{min}}}. \quad (8)$$

Replacing Eq. (1) in (8) and rearranging the terms results in the Eq. (9)

$$\eta_{ts} = \frac{R \ln \left(\frac{V_{max}}{V_{min}} \right) T_H \eta_c}{C_v T_H \eta_c + R T_H \ln \frac{V_{max}}{V_{min}}}. \quad (9)$$

Solving and simplifying the Eq. (9) results in the Eq. (10), Eq. (11) and Eq. (12)

$$\eta_{ts} = \frac{R \ln \left(\frac{V_{max}}{V_{min}} \right) T_H \eta_c}{T_H \left(C_v \eta_c + R \ln \left(\frac{V_{max}}{V_{min}} \right) \right)}, \quad (10)$$

$$\eta_{ts} = \frac{R \ln \left(\frac{V_{max}}{V_{min}} \right) \eta_c}{R \ln \left(\frac{V_{max}}{V_{min}} \right) \left(\frac{C_v \eta_c}{R \ln \left(\frac{V_{max}}{V_{min}} \right)} + 1 \right)}, \quad (11)$$

$$\eta_{ts} = \frac{\eta_C}{1 + \frac{C_v \eta_C}{R \ln \frac{V_{max}}{V_{min}}}}. \quad (12)$$

2.1 First-Order Design Methods

The First Order model is a method that can be used in the initial phases of project development. This method relates some basic characteristics to the engine, in its great majority related of the comments accomplished for professor Beale. These expressions present the power and the efficiency of a machine analyzing the temperatures of the hot source and cold source, the displacement from the engine and the speed (Walker, 1980; Walker and Senft, 1985).

The efficiency of an engine with thermodynamic cycle Stirling is related to the efficiency of the Carnot cycle, that naturally is related to the specified temperatures of the source of heat and the wasteful element of heat and can be calculated by

$$\eta_{1sr} = \frac{P_{shaf}}{P_{in}} = \left(1 - \frac{T_L}{T_H} \right) \eta_i \eta_h \eta_m k_t, \quad (13)$$

where η_{1sr} is the efficiency estimation by First-Order design methods in %, P_{shaf} is the shaft power of engine in W, P_{in} is the power input supplied for the quantity of heat injected in the system in W and η_i is the indicated efficiency in %, η_h is the efficiency of the heater in %, that it considers the flow of energy between the heater and the fuel, η_m is the coefficient of mechanical efficiency in %, k_t is the correction factor auxiliary in %, and its value is generally is equal to 0,95 for sets of maximum efficiency. T_L and T_H are the temperatures of the cold and hot source, respectively.

The indicated efficiency relates to the state of the art of Stirling technology by limiting efficiency < 1 . The efficiency of the heater is related to the furnace design and considers the heat propagation issues of the hot source. Heat can be dissipated by convection, conduction and radiation processes. Mechanical efficiency relates to mechanical design parameters with mechanical properties of the material. Resulting design parameters such as sealing and friction have an impact on overall efficiency. The auxiliary correction factor is intended to adapt the efficiency values related to the assembly and adjustment of the mechanical design of the Stirling engine (Walker, 1980).

The power of the Stirling engines can be adjusted roughly by the Eq. (14) approximately

$$P_{1sr} = B_n Pr_{cl} f_m \Delta V_{cl} \quad e \quad P_{1sr} = 0,015 Pr_{cl} f_m \Delta V_{cl}, \quad (14)$$

where P_{1sr} is the power estimated by First-Order design methods in W, B_n is the number of Beale, typically with the value of 0,015, Pr_{cl} is the instantaneous average pressure of the cycle in Bar, f_m is the frequency of the engine in Hz and ΔV_{cl} is the variation of volume in the cycle in cm^3 , (Heywood, 2018). This of First-Order Design Methods is recommended for designers who have the intention to evaluate the possibility of use of a Stirling engine for technological applications (Heywood, 2018; Bataineh, 2018).

3. EXPERIMENTAL SETUP

The experimental work consists of the manufacture of a conventional prototype of the Stirling engine configuration gamma-type, in the instrumentalization and characterization. The conventional prototype can be verified in Fig. (3).

By constructive simplicity and greater thermodynamic efficiency, was opted for a Stirling engine gamma type configuration, the principle of operation of this engine is explained in detail with the theory of Schmidt.

The prototype of the developed Stirling engine operates with a sealed air-fluid in the internal chambers and with a shifter and a power piston adjusted to produce the hot and cold volumes respectively, as can be seen in Fig. (4).

In the initial stage, the development of the project and manufacture of the conventional prototype of the Stirling engine was accomplished configuration gamma-type of small scale. So that in the next stage the prototype could be instrumentalized and be characterized. The experimental work was developed according to the described stages to follow:

1. To development and the manufacture the prototype with an emphasis on the relation of volumes, mechanical gasket and friction;

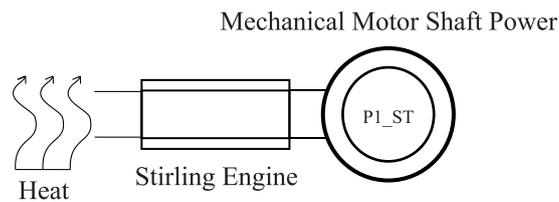


Figure 3: Schematic of the mechanical assembly conventional prototype of the Stirling engine configuration gamma-type.

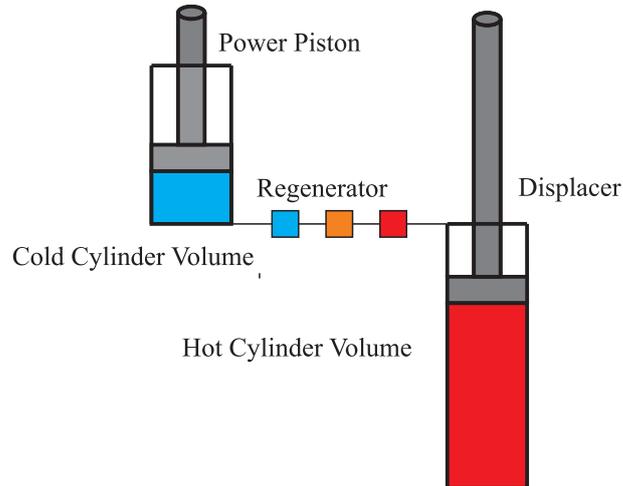


Figure 4: Schematic of the mechanical assembly conventional prototype of the Stirling engine configuration gamma-type.

2. Instrumentalize and to characterize the of a small-scale gamma-type Stirling engine prototype;
3. Analysis of efficiency and the power using the model estimated by First-Order.

The data of pressure in the camera of compression, the angle of turn of the engine, the temperatures of the cold and hot chamber of the engine were acquired, as well as the rotation. The processing of the instrumentalization of the engine was accomplished utilizing a microcontroller LAUNCHXL-F28069M (TMS320x2806x). The programming of the microcontroller was developed in the platform free Code Composer Studio, of Texas Instruments. The destined signals of the entrance to feed the microcontroller were composites for the measurements of pressure, temperatures, the angle and the rotation of turn of the engine through industrial sensors of high precision. The measurement of the corresponding values the pressure was accomplished by a piezoelectric sensor of pressure of family 33 MBS - model 060G3038 connected in the entrance of the internal chamber of combustion of the prototype, that occurs the work through the power piston.

The measurements of the internal temperature of the engine of the Stirling cycle were accomplished using two thermocouples type K, connected in the sources cold and hot of the engine. The measurement of the pressure was accomplished through a pressure transmitter, with referential of absolute pressure, so that the negative measurement of pressure in respect to atmospheric was considered. Other important data are the temperatures of the hot source and the cold source. Beyond these parameters, the rotation of the axle of the engine was registered through the encoder of incremental quadrature.

The measurement uncertainties were analyzed based on the certificate of calibration of the instruments emitted by the manufacturers.

4. RESULTS

4.1 Development and Manufacture of the Prototype

To evaluate the functioning of the prototype, after its construction was accomplished diverse modifications aiming at to optimize the set and increase of its efficiency.

The prototype was manufactured and assembled according to the design and the main geometric data of the gamma-type Stirling engine can be verified in Table 1.

In Fig. (5) can check the indication of the main parameters DPD , DCD and FPD of the displacer piston.

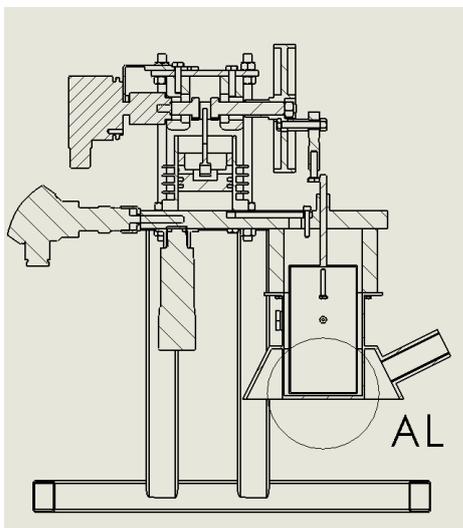
In Fig. (6) can check the indication of the main parameter DPP of the power piston.

The prototype of the Stirling engine configuration type gamma manufactured and mounted as the project can be verified in Fig. (7).

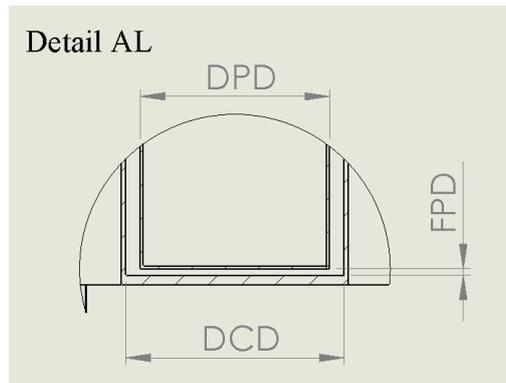
Table 1: Data geometric and constructive data of the Stirling engine configuration type gamma.

Description	Nomenclature	Value	Units
Displacement Piston Diameter	DPD	63.5	mm
Diameter Displacer Piston Rod	DH	6.00	mm
Displacement Piston Shifter	LPD	25.00	mm
Diameter Displacer Cylinder	DCD	73.50	mm
Length Shifter Cylinder	LCD	120.00	mm
Piston Shifter Gap-End	FPD	2.50	mm
Diameter of the power piston	DPP	50.80	mm
Piston Power End-Gap	PPP	2.00	mm
Displacement Power Piston	LPP	25.00	mm
Phase angle	θ_{dm}	1.57	rad

(1) Dead volumes were considered constant.

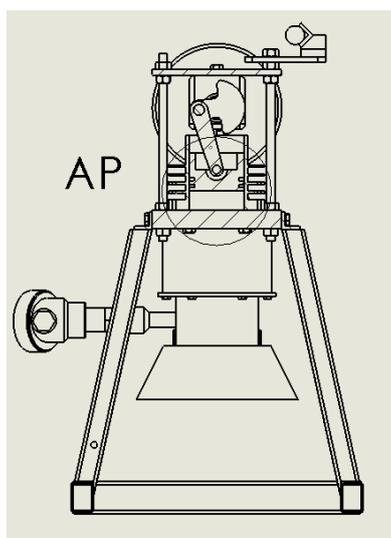


(a) Stirling engine assembly drawing with AL detail

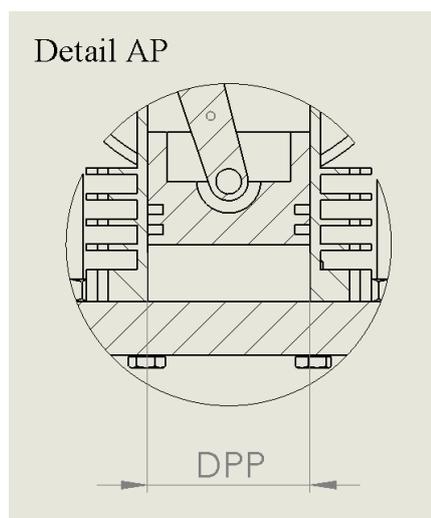


(b) Detail AL of the Stirling engine's assembly design

Figure 5: Descriptive drawing of the displacer piston Stirling engine.



(a) Stirling engine assembly drawing with AP detail



(b) Detail AP of the Stirling engine's assembly design

Figure 6: Descriptive drawing of the displacer piston Stirling engine.

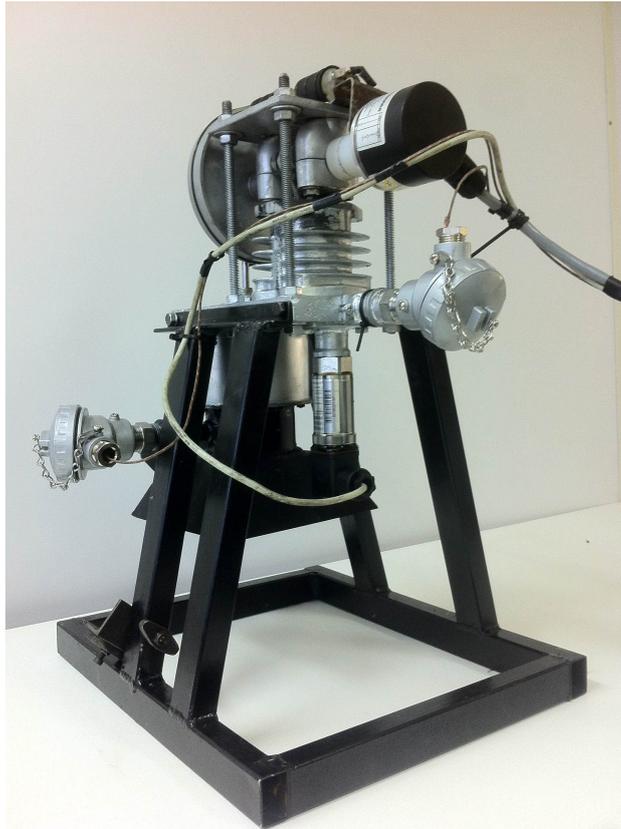


Figure 7: Prototype of the gamma-type Stirling engine manufactured for assembly of the experimental set aiming at energy generation.

4.2 First-Order Model

The temperature of the cold source (T_C) was considered fixed in 300 K. For calculating the power and the efficiency for the described model of First-Order were used the values of experimental pressure and rotation. They were considered data geometric and constructive data of the Stirling engine configuration type gamma in the table Tab. (1). The dead volumes were considered constant.

The maximum values recommended were considered for the parameters indicated in this model, as being 0,80 for indicated efficiency (η_i), $\eta_h = 0,90$, $\eta_m = 0,90$ e $k_t = 0,95$ that it considers sets of maximum efficiency. Analyzes of measurement uncertainties related to efficiency ($w_{\eta_{1ST}}$) and power ($w_{P_{1ST}}$) are considered in the calculation.

As the ideal gas can undergo both isochoric and isobaric transformations, we define thermal capacity in two types of, the constant volume (C_v) and constant pressure (C_p). The calculation of the efficiency of a Stirling cycle machine (η_{ts}) considering the values of the constant pressure (C_p) and constant volume (C_v) equal 1,004 kJ/kg K and 0.718 kJ/kg K, respectively.

The efficiency can be calculated by the quantity of heat (Q) provided by the work (W). The calculation of the irreversibility described in Table 2.

Table 2: Experimental results of Stirling engine configuration gamma type for of First-Order model.

T_H (K)	η_c (%)	η_{ts} (%)	η_{1ST} (%)	P_{1ST} (W)
500	40.00	35.55	24.62	10,40
600	50.00	43.23	30.78	18,21
700	57.14	48.47	35.18	29,48
800	62.50	52.27	38.48	37,28
900	66.67	55.15	41.04	48,56

(1) The values of accuracy uncertainty relative to efficiency ($w_{\eta_{1ST}}$) and power ($w_{P_{1ST}}$) of the First-Order model was disregarded according to the maximum values are not significant, i.e. low order of magnitude. The highest values for efficiency and power equal to $20.52 \times 10^{-2} \%$ and 24.28×10^{-2} W, respectively.

The First-Order model presented power (P_{1ST}) with a variation of 10.40 W – 48.56 W and the values obtained for the efficiency Carnot (η_c), maximum theoretical efficiency of the Stirling engine efficiency (η_{ts}) and efficiency First-Order model (η_{1st}), were from 40.0 – 66.67 %, 35.55 – 55.15 % and 24.62 – 41.04 %, respectively.

5. CONCLUSION

The assembly containing a prototype of a motor developed, manufactured and instrumentalized of the Stirling engine configuration gamma type small scale for analysis of the First-Order model has been completed.

The analysis of this model considers the main internal irreversibilities of the Stirling engine.

The prototype of the developed Stirling engine allowed to measure the desired parameters of temperature, pressure, volume and rotation. With the parameters measured from the prototype and through the First-Order model, it was possible to observe some characteristics of this Stirling engine. These characteristics observed in the motor functioning are important for the comprehension and study of the applied thermodynamic phenomena.

The theoretical efficiencies related to the operating ranges of the prototype were obtained. The efficiency η_c is greater than the efficiency η_{ts} and the efficiency η_{ts} is greater than the efficiency η_{1st} . The values are expected, however, the creation of equations with variables that are whistled at irreversibilities allows an improvement of the prototype from the initial phase.

The efficiency values η_{1st} obtained were lower than the efficiency η_c , which may have been due to irreversibilities, for example the friction, loss of pressure due to the absence of an effective seal, the difficulty of heat dissipation by the regenerator due to the high temperatures in the engine body.

The values indicated by the literature of indicated efficiency (η_i), the efficiency of the heater (η_h), the coefficient of mechanical efficiency (η_m) and the correction factor auxiliary (k_t) demonstrated to be high due to irreversibilities. Ideally, you should implement a model that considers these parameters in calculating efficiency.

The reduction of efficiency (η_{1st}) compared to the theoretical Carnot (η_c) and theoretical Stirling machine (η_{ts}) can be explained due to the mechanical losses and thermodynamic irreversibilities occurring mainly in the regenerator. A new model should be investigated to complement the losses associated with the irreversibilities of the hot source.

The efficiency of the Stirling engine is also changed by the incoming heat flow from the hot source. The heat flow is lost to the external medium, and due to the loss of irreversibility of the engine as previously mentioned, these losses can be corrected by performing a suitable design for heat-generating furnace, eliminating mainly the thermal losses of convection and irradiation, and improvements in engine sealing.

With the results of the power and efficiency of First-Order model will be possible in the future to investigate the irreversibilities of the prototype and compare experimental results.

6. ACKNOWLEDGEMENTS

This study was financed in part by the Coordination of Improvement of Higher Education Personnel - Brazil (CAPES) - Finance Code 001". National Council for Scientific and Technological Development (CNPq), from Foundation Araucária (FA) and from Financier of Studies and Projects (FINEP).

The Federal University of Technology - Paraná (UTFPR) and Federal Institute of Education, Science and Technology of Santa Catarina (IFSC) contributed in this study providing human resources and laboratories for conducting this research.

7. REFERENCES

- Alain, D., 2017. "Carnot factor of a vapour power cycle with regenerative extraction". *Journal of Modern Physics*, Vol. 08, No. 11, pp. 1795–1808. doi:10.4236/jmp.2017.811107.
- Bataineh, K.M., 2018. "Numerical thermodynamic model of alpha-type Stirling engine". *Case Studies in Thermal Engineering*, Vol. 12, pp. 104–116. doi:10.1016/j.csite.2018.03.010.
- Borgnakke, C. and Sonntag, R.E., 2012. *Fundamentals of Thermodynamics*. Wiley, 8th edition. ISBN 978-1118131992. 912 pages.
- Hachem, H., Gheith, R., Aloui, F. and Nasrallah, S.B., 2018. "Technological challenges and optimization efforts of the Stirling machine: A review". *Energy Conversion and Management*, Vol. 171, pp. 1365–1387. doi: 10.1016/j.enconman.2018.06.042.
- Heywood, J., 2018. *Internal Combustion Engine Fundamentals*. McGraw-Hill Education, 2nd edition. ISBN 1260116107. 1056 pages.
- Loveridge, D.W., 1978. "Robert stirling—preacher and inventor". *Transactions of the Newcomen Society*, Vol. 50, No. 1, pp. 1–10. doi:10.1179/tns.1978.001.
- Martini, W.R., 1983. *Stirling Engine Design Manual*. NASA contractor report, 168088. Springfield, Washington, second edition.
- Moran, M.J., Shapiro, H.N. and Boettner, D.D., 2014. *Fundamentals of Engineering Thermodynamics*. JOHN WILEY

& SONS INC. ISBN 1118412931.

- Oelrich, I.C. and Riddell, F.R., 1988. "Evaluation of potential military applications of stirling engines". Technical Report ADA201000, INSTITUTE FOR DEFENSE ANALYSES. URL <http://www.dtic.mil/dtic/tr/fulltext/u2/a201000.pdf>. Final rept. Jan-Jun 88.
- Organ, A.J., 2013. *Stirling Cycle Engines*. John Wiley & Sons Ltd. doi:10.1002/9781118818428.
- Organ, A.J., 2007. *The Air Engine: Stirling Cycle Power for a Sustainable Future*. Woodhead Publishing, Cambridge, England. ISBN 1845692314.
- Riley, P.H., 2015. "The myth of the high-efficiency external-combustion stirling engine". *Engineering*, Vol. 07, No. 12, pp. 789–795. doi:10.4236/eng.2015.712068.
- Rupesh, P., Thamaraikannan, M., Raja, K., Ahammed, S., Ramjathan, P., Yadav, P. and RamVineeth, K., 2017. "Design and fabrication of a vertical gamma type stirling engine-a conceptual prototype". *International Journal of Mechanical Engineering and Technology (IJMET)*, Vol. 8, pp. 410–417. ISSN 0976-6340.
- Sowale, A., Kolios, A.J., Fidalgo, B., Somorin, T., Parker, A., Williams, L., Collins, M., McAdam, E. and Tyrrel, S., 2018. "Thermodynamic analysis of a gamma type Stirling engine in an energy recovery system". *Energy Conversion and Management*, Vol. 165, pp. 528–540. doi:10.1016/j.enconman.2018.03.085.
- Walker, G., 1980. *Stirling Engines*. Oxford University Press. ISBN 978-0198562092. 554 pages.
- Walker, G. and Senft, J.R., 1985. "Free-piston stirling engines". In *Lecture Notes in Engineering*, Springer Berlin Heidelberg, pp. 23–99.
- Yang, Y., Cui, S., Ni, Y., Zhang, G., Li, L. and Meng, Z., 2016. "Key technology for treating slack coal blockage in cbm recovery: A case study from multi-lateral horizontal wells in the qinshui basin". *Natural Gas Industry B*, Vol. 3, No. 1, pp. 66 – 70. ISSN 2352-8540. doi:<https://doi.org/10.1016/j.ngib.2016.02.007>.

8. RESPONSIBILITY NOTICE

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