# EXAMINATION OF STIRLING ENGINE PARAMETERS EFFECT ON ITS THERMAL EFFICIENCY USING PROSA SOFTWARE

by

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*This paper uses second-order software for evaluating five Stirling engine parameter's effect on its performance to select an appropriate configuration with optimal dimensions for its use in a concentrated solar power plant. Appropriate configuration, heater shape, bundle tube heat exchanger size, and regenerator type and geometry are studied. Results show that alpha type Stirling engine is the most suitable for high temperature differences, U-shaped tubes are advantageous in combining good efficiency and fewer pressure losses. Shortening inner diameter and increasing U-shaped tubes number is a good strategy to increase engine efficiency also an increase in tubes length generates a reduction in engine efficiency. Regarding the regenerator, the wire mesh regenerator presents a good compromise between minimum pressure drop and heat losses and provides better engine efficiency. For its size, better efficiency is obtained for a thicker mesh.*

Key words: *Stirling engine, PROSA software, Stirling efficiency, regenerator, Stirling configuration, heater, working fluid.*

## Introduction

The Stirling engine was designed and manufactured by Robert Stirling and he patented it in 1816 [1], long before the Diesel engine (1893), the gasoline engine (1860), and the electric engine (1869) [2]. It is a closed-cycle regenerative externally heated engine. Stirling engine contains a working fluid that is generally compressed in its colder part and expanded in the hotter part producing a net conversion of heat into work [3]. Considering its characteristic of external combustion, the Stirling engine allows diversity in hot source choice, thereby, the Stirling engine has recently received much attention to clean, renewable, and free energy to reduce the amount of employed fossil fuels resources [4].

There are three types of Stirling engines, depending on cylinders arrangement in the engine [2, 5]:

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- Alpha type: the simplest Stirling engine design, it contains two separate power pistons, in *hot* and *cold* cylinders.
- Beta type: it consists of a simple power piston placed coaxially with a displacer.
- Gamma type: the oldest and most bulky configuration. It provides an appropriate complete separation between heat exchangers related to the displacer cylinder and, compression and expansion workspace related to the piston.

The three types have the same operating principle. However, performance varies depending on each type [6].

Ye *et al.* [3] built 1-D thermodynamic model to quantify exergy loss in the regenerators. The effects of oscillating flow pressure drop, the exergy loss to flow friction, the exergy losses to conduction heat transfer at the hot and cold side of the regenerator, and the percentage of Carnot efficiency of Stirling engine were presented and studied. Munir *et al.* [7] proposed an axisymmetric CFD model able to define pumping loss for a free piston Stirling engine. It was validated with 12.5 kW component test power converter and effectively calculated indicated power, efficiency, pressure amplitude, pressure drop, and gas temperature in expansion and compression space at different piston amplitudes with 6% maximum deviation. Caetano *et al.* [8] presented a methodology that resolves not only of indicated power estimate error decrease in beta-type Stirling engines, but also simplifies extrapolation without the need for experimental data. Aksoy *et al.* [9] built and investigated a beta type Stirling engine with a rhombic-drive mechanism. Assessments were carried out at hot end temperatures of 600 °C and 800 °C for five various stages of charge pressure going from 1 to 5 bar with 1 bar increments. Bataineh [10] developed a precise practical thermodynamic model for alpha-type Stirling engine with Ross Yoke mechanism. The model is utilized to predict output power and thermal efficiency then it is validated against experimental data. Geometric and operation parameters, regenerator effectiveness, dead volume ratio, regenerator thermal conductivity, and heat source temperature effect on engine performance were also evaluated. Cinar *et al.* [11] built and investigated the performance, at atmospheric pressure, of a beta-type Stirling engine. Tests were made with an electrical heater. Rabhi *et al.* [12] inspected seven parameters that influence a Gamma type Stirling engine performance. The engine was coupled to Linear Fresnel Solar Collector, *via* an under vacuum trapezoidal receiver.

This paper uses second-order software for evaluating five Stirling engine parameters effect on its performance to select an appropriate configuration with optimal dimensions for its use in a CSP plant. Appropriate configuration, heater shape, bundle tube heat exchanger size and regenerator type and geometry were studied.

## Stirling engine modelization

Program for Stirling machine analysis (PROSA) 2.0.4 was used to examine five Stirling engine parameters in order to choose the configuration with optimal dimensions to maximize Stirling engine performance for its use in a CSP plant. The PROSA is a second-order evaluation software for Stirling engines with a crank or with free pistons, used as prime mover, cooling or heat pump machines. Different types of heat exchangers, regenerators and working fluids can be chosen. In addition, a modification of parameters and optimization are implemented in order to design Stirling engines offering optimal performances [13]. The software structure is modular, to make available addition of components: a new heat exchanger, regenerator configurations, or other thermodynamic cycles. By utilizing a common second-order model, the Stirling engine can be separated into five volumes: two cylinders, two heat exchangers, and one regenerator. The mean working gas temperature is considered constant for each cylinder and heat exchanger. The temperature profile in the regenerator is approximated by a linear function. As regards the temperature profile in the regenerator, it considerably differs from a real machine with a linear function, which necessitates a closer look. The model used in the regenerator PROSA, for this reason, consists of four finite elements. Such elements encourage a good relation between the rise in accuracy of calculated results and in model complexity, requiring a large computational time [13].

The input data selection in PROSA software starts when starting the software. Two windows are shown. At the first one, named *cycle 1 configuration*, one must choose: thermodynamic cycle (Stirling, Vuillemier, Duplex-Ericso), application (prime mover, cooling machine, heat pump), cylinder configuration (alpha, beta, gamma), and piston movement (sinusoidal or free piston). In the second window (cycle 2 configuration) shows the options: type of heat exchangers (hot and cold; if they are tube bundle or fin type), type of regenerator (wire mesh, foil or felt type), and type of working fluid (hydrogen, helium or air). The next window contains seven tabs, in which all the technical engine data are introduced.

The PROSA is based on a model that takes into account all major losses. It has also been successfully validated compared to experimental data for different Stirling engines [14].

### ***Configuration effect on Stirling engine performance***

The Stirling engine is one kind of external combustion engine that work either in receiving mode (heat transfer) or in driven mode (produced work). The hot source can be from renewable energy (solar, biomass, *etc.*) and the cold source can be ambient air, water, or frigorific fluid. The Stirling engine is working in a closed cycle. The working fluid inside the engine can be air, helium, $CO_2$, nitrogen, hydrogen, *etc.* According to the combination of its compartments, the Stirling engine can be categorized in three configurations: alpha, beta, and gamma. The alpha configuration is the simplest one, known by its compactness. The beta configuration is principally composed of a simple piston placed coaxially with a displacer. The gamma configuration is the oldest and the most cumbersome one. It is composed of two separate working spaces [15].

The comparison of mechanical power and efficiency of three types of Stirling engines ($\alpha$, $\beta$, and $\gamma$) is carried out in this section. Engines were considered as a prime movers with crank and sinusoidal piston motion. Hot source (HS) and cold source (CS) temperatures were 1073.63 K and 293.15 K, respectively. Fins type heat exchanger was employed for cold source while the hot source was a tube bundle heat exchanger. Wire mesh regenerator was chosen. Helium was utilized as a working fluid with an average pressure of 17 bars. Parameters values used as PROSA 2.0.4 software input are presented in tab. 1.

As indicated in tab. 1 and in order to make a successful comparison between the three types of engine, all parameters were taken in common, namely:
- engines general data (average pressure, phase angle...),
- engines dimensions (cylinders diameters, materials, piston stroke...),
- regenerator, and
- heat exchangers (shape and size).

**Table 1. Considered parameters for the 3 types of Stirling engine**

| Engine data | $\alpha$-configuration | $\beta$-configuration | $\gamma$-configuration |
|---|---|---|---|
| General data | | | |
| Mean working gas pressure [bar] | 17 | 17 | 17 |
| HS Temperature [°C] | 880.48-100.48 | 880.48-100.48 | 880.48-100.48 |
| CS Temperature [°C] | 20 | 20 | 20 |
| Phase angle [°] | 90 | 90 | 90 |
| Working fluid | Helium | Helium | Helium |
| Geometry | | | |
| Cold cylinder diameter [mm] | 57.23 | 57.23 | 57.23 |
| Thickness of cylinder wall [mm] | 10 | 10 | 10 |
| Cylinder wall material | Stainless steel | Stainless steel | Stainless steel |
| Piston clearance [mm] | 8.1347 | 8.1347 | 8.1347 |
| Piston stroke [mm] | 42 | 42 | 42 |
| Hot cylinder diameter [mm] | 57.23 | 57.23 | 57.23 |
| Thickness of cylinder wall [mm] | 10 | 10 | 10 |
| Cylinder wall material | Stainless steel | Stainless steel | Stainless steel |
| Displacer clearance [mm] | 8.1347 | 8.1347 | 8.1347 |
| Displacer stroke [mm] | 40.4 | 40.4 | 40.4 |
| Wire mesh regenerator | | | |
| Matrix outer diameter [mm] | 71.8 | 71.8 | 71.8 |
| Matrix inner diameter [mm] | 60.7 | 60.7 | 60.7 |
| Matrix length [mm] | 64.46 | 64.46 | 64.46 |
| Number of layers | 362 | 362 | 362 |
| Wire diameter [mm] | 0.0889 | 0.0889 | 0.0889 |
| Matrix material | Stainless steel | Stainless steel | Stainless steel |
| Porosity | 0.84 | 0.84 | 0.84 |
| Cold heat exchanger (fin type) | | | |
| Height of fins [mm] | 3.76 | 3.76 | 3.76 |
| Width of fins [mm] | 1 | 1 | 1 |
| Fin material | Cuivre | Cuivre | Cuivre |
| Number of fins | 135 | 135 | 135 |
| Length occupied by fins [mm] | 79.2 | 79.2 | 79.2 |
| Hot heat exchanger (tube bundle) | | | |
| Number of tubes | 34 | 34 | 34 |
| Tube length [mm] | 183.4 | 183.4 | 183.4 |
| Inner diameter [mm] | 2.362 | 2.362 | 2.362 |

Figures 1 and 2 show variation of engines efficiency and their output mechanical power according to heater temperature variation, respectively. Since the cooler temperature was kept constant, the increase in heater temperature generates an increase in temperature difference between heater and cooler.

According to fig. 1, the alpha type Stirling engine can reach high efficiency, equal to 45%, for temperatures above 350 °C, thus temperature differences between the heater and cooler higher than 330 °C.

For temperature differences less than 330 °C, gamma type Stirling engine is the most efficient, followed by beta type and then alpha type with an efficiency of 10% for 200 °C.

As regards engines output mechanical power, fig. 2 indicates that alpha type Stirling engine keeps its high performance compared to the other two types. In fact, it reaches high power from a temperature difference between heater and cooler ranging from 480 °C. For lower temperatures, alpha type engine becomes the least efficient compared to the two others types.

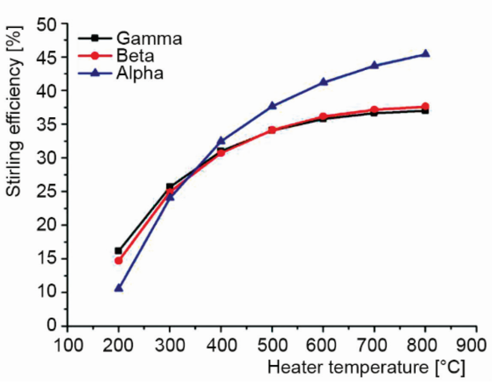

**Figure 1. Efficiency variation of the three types of Stirling engine with heater temperature variation**

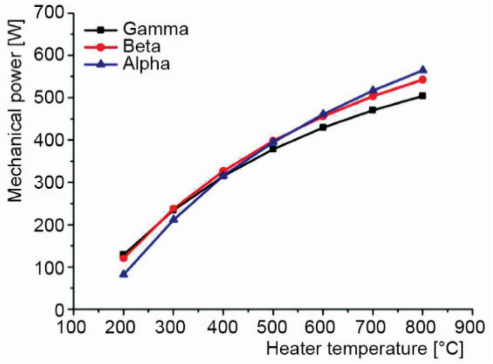

**Figure 2. Output mechanical power variation of the three types of Stirling engine with heater temperature variation**

From the two previous figures, alpha type Stirling engine was selected for this study where a CSP plant was envisaged thus large temperature differences were considered. Other conclusions can be drawn from this study: the temperature difference between heater and cooler determines operating range of each Stirling engine type, also, power and efficiency of the three types increase by increasing heater temperature.

Abuelyamen and Ben-Mansour [6] compared the output power and thermal efficiency of three types of Stirling engines ($\alpha$, $\beta$, and $\gamma$), without the regenerator. Stirling engine was set to operate between 300 K and 800 K where the air is adopted as working fluid. It has been found that $\gamma$-type Stirling engine generates the highest power output and thermal efficiency (9.223 W and 9.8%). Followed by $\beta$-type Stirling engine (8.634 W and 7.5%). However, minimum performance is attained by the $\alpha$-type Stirling engine (0.908 W and 1.8%). Consequently, the $\alpha$-type Stirling engine is adjusted to have an annular linking pipe rather than circular one. As a result, its performance enhanced considerably to generate 9.856 W with a thermal efficiency of 10.5%. The difference between this study and that conducted in the present paper is not considering a regenerator that constitutes a very important part of the engine; in fact, a Stirling engine without a regenerator needs five times more energy to obtain the same performance as an engine including a regenerator [15]. Another difference is selected working fluid, Helium in the present study and air in Abuelyamen and Ben-Mansour [6] study.

## *Heat exchangers influence on engine performance*

In heat exchangers choice, the ability to provide or reject the required amount of heat to or from the engine is a primary criterion. The exchange surface then becomes a decisive factor.

Stirling engine parameters must be optimized to avoid heat loss and obtain good performance for all engine components, in particular heater and cooler.

### *Heater shape effect*

The present study purpose is Stirling engine parameters optimization for later use in its coupling with Fresnel mirrors within a CSP plant. Like what was done by Rabhi *et al.* [12] The coupling will be done *via* the heater. A hot heat exchanger will ensure heat transfer from absorber tubes to Stirling engine, which makes it an essential element to optimize. Fin type heat exchanger is usually utilized for cold heat exchanger because it is inexpensive and for its ease of manufacturing [16], it was then chosen for this study. Two types of hot heat exchangers are examined: fin type and tube bundle heat exchangers. Considered dimensions are detailed in tab. 2. Since the exchangers geometry are different, parameters to be defined are different. Values were chosen according to the corresponding dimensions. Indeed, if we take for example the number of tubes, it corresponds to the number of fins and length occupied by fins corresponds to tube length and so on.

**Table 2. Considered dimensions for the two hot heat exchangers**

| Fin-type | | Tube bundle | |
|---|---|---|---|
| Length occupied by fins, [mm] | 183.4 | Tube length, [mm] | 183.4 |
| Height of fins, [mm] | 2.362 | Inner diameter, [mm] | 2.362 |
| Width of fins, [mm] | 0.591 | Tube material | Stainless steel |
| Fin material | Stainless steel | Number of tubes | 34 |
| Number of fins | 34 | – | – |

Heat losses variation of the two types of hot heat exchangers (fins and tube bundle) depending on engine speed is illustrated in fig. 3. Helium was used as working fluid with average pressure of 15 bar.

Figure 3 shows that both heaters have close heat losses values but bundle tube heat exchanger provides slightly lower heat losses, indeed, for all engine speeds tube bundle heat losses are lower than those produced by a fin-type heat exchanger, with a small difference that can reach 0.1344 W for a speed of 600 rpm.

The Stirling engine efficiency is also an indispensable criterion for heat exchangers choice. Figure 4 allows visualizing hot heat exchanger type influence on engine efficiency for different speeds.

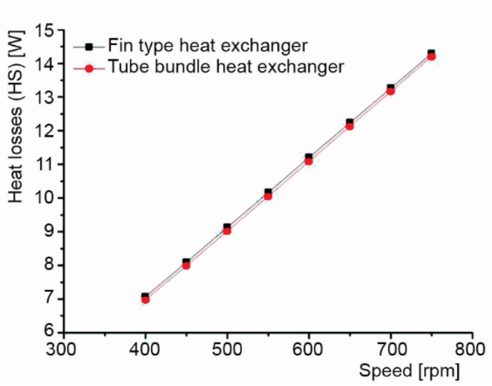

**Figure 3. Relationship between heat losses and engine speed for two types of hot heat exchangers**

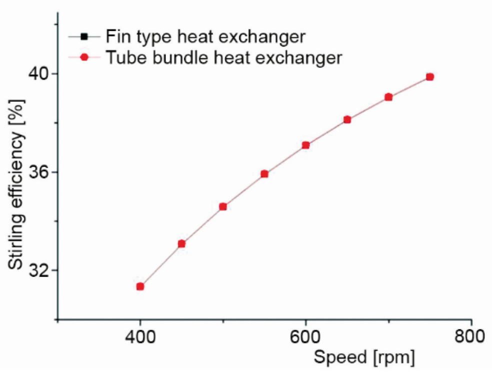

**Figure 4. Hot heat exchanger types influence on Stirling engine efficiency for different speeds**

Figure 4 shows equal engine performance for the two types of heat exchangers. As can be concluded, to combine good efficiency and slightly fewer heat losses, a tube bundle heat exchanger is chosen. A tube bundle hot heat exchanger increases exchange area with a working fluid thus promoting heat transfer between heater and working fluid [2, 15]. To achieve exchanger high efficiency, a large exchange area is required [17]. It should be noted that the heating tubes of most Stirling engines are *U*-shaped and it has been experimentally found that heat transfer of *U*-shaped tubes is generally higher than that of straight tubes [18].

### *Impact of bundle tube heat exchanger size*

As previously noted, Stirling engine parameters must be optimized to reduce heat losses while having high efficiency and this is for all engine components, particularly heat exchangers.

After choosing the hot heat exchanger type comes it's dimensions optimization which is important too. Figures 5-7 show the impact, respectively, of inner diameter, number and length of tubes on Stirling engine efficiency, and heat losses.

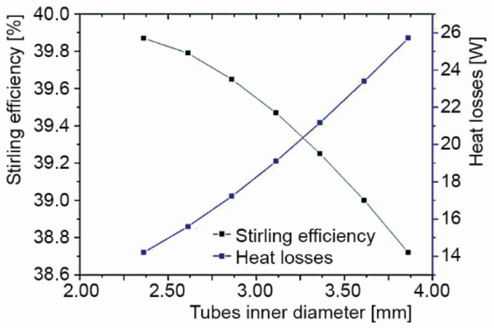

**Figure 5. Tubes inner diameter influence based on Stirling engine efficiency and heat losses**

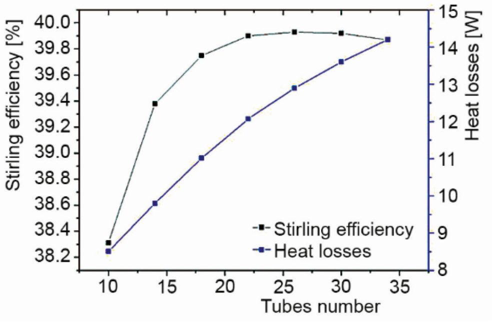

**Figure 6. Tubes number impact on Stirling engine efficiency and heat losses**

According to fig. 5, Stirling engine efficiency is inversely proportional to the tubes inner diameter while heat losses are proportional to the same dimension. This result is similar to what was found by Araos Ramos [19] who indicated that for fixed tubes lengths, the increasing diameter decreases both efficiency and power of an engine.

According to fig. 6, by increasing tubes number efficiency increases as well as heat losses.

An appropriate strategy could be concluded that consists of increasing Stirling engine efficiency by shortening inner diameter and increasing tubes number. This result corresponds to the importance of a compact and large heat exchanger [19] to increase exchange area with a working fluid, thus promoting heat transfer between heater and working fluid [2, 15].

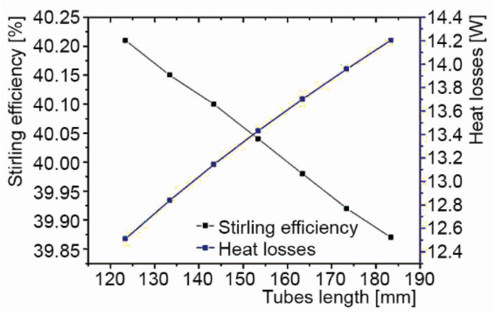

**Figure 7. Influence of tubes length based on Stirling efficiency and heat losses**

Figure 7 shows that engine efficiency decreases while heat losses increase when tubes length decreases. Thus, Stirling engine efficiency is maximised and heat losses are minimal by reducing tubes length. Araoz Ramos [19] also concluded that Stirling engine efficiency decreases with the increase in tubes length, but this applies for diameters greater than 0.05 m. However, for diameters close to 0.03 m, the decrease is almost negligible.

### *Regenerator optimization*

The regenerator is often defined as a key element of Stirling engines. It is generally a porous material in form of an assembly of small grids, fine metallic fabrics or microballs [20]. A Stirling engine without a regenerator needs five times more energy to obtain the same performance as an engine including a regenerator [21]. Furthermore, Stirling engines can reach maximum theoretical efficiency mainly through the use of a regenerator that exchanges thermal energy with working fluid after each stroke of isothermal compression and expansion. This minimizes the thermal energy amount that the heater or cooler must either add or reject, respectively.

Matrix geometry type adopted for a regenerator has an important effect on its efficiency [22]. Three types of regenerator can be evaluated by PROSA software: felt type regenerator, which is less expensive to manufacture than wire mesh regenerator [23] and the third type foil regenerator.

In order to compare the different regenerators with different geometries, equal values have been assigned to the same parameters in order to make an exact comparison. Since the generators are different, different (number of layers, wire diameter, mean width of channel…) as well as similar parameters have been found.

Dimensions and characteristics of studied regenerators are detailed in tab. 3.

**Table 3. Dimensions and characteristics of studied regenerators**

| Dimensions | Wire mesh regenerator | Foil regenerator | Felt type regenerator |
|---|---|---|---|
| Matrix outer diameter, [mm] | 71.8 | 71.8 | 71.8 |
| Matrix inner diameter, [mm] | 60.7 | 60.7 | 60.7 |
| Matrix length, [mm] | 64.46 | 64.46 | 64.46 |
| Number of layers | 362 | – | – |
| Wire diameter, [mm] | 0.0889 | – | 0.0889 |
| Thickness of foil | – | 0.0889 | – |
| Mean width of channel, [mm] | – | 4.667 | – |
| Mean height of channel, [mm] | – | 0.4667 | – |
| Width of axial fins, [mm] | – | 0.0889 | – |
| Mesh size, [mm] | 0.4445 | - | – |
| Matrix material | Stainless steel | Stainless steel | Stainless steel |
| Porosity | 84% | - | 84% |

#### *Regenerator type effect on Stirling engine performance*

The regenerator is where significant thermal losses take place, namely: mechanical energy dissipation by pressure drop [24] and losses by internal [25], and external [26] conduction. Therefore, the main criteria for choosing a regenerator type are less pressure drop and losses. Figures 8 and 9 show, respectively, pressure drop and heat losses as a function of speed for the three types of regenerators.

According to fig. 8, maximum pressure drop results from felt type regenerator use comes after wire mesh regenerator then foil regenerator gives minimum pressure drop. By observing fig. 9, it is clear that foil regenerator causes maximum heat losses and minimum heat losses result from felt type and wire mesh regenerators. In addition, pressure drop and heat losses vary according to Stirling engine speed variation, in fact, by increasing Stirling engine speed, pressure drop and heat losses increase too. From the two investigated parameters, the wire mesh regenerator presents a good compromise between less pressure drop and inferior heat losses. The regenerator type selection becomes more evident with Stirling engine efficiency examination using the three types of regenerators.

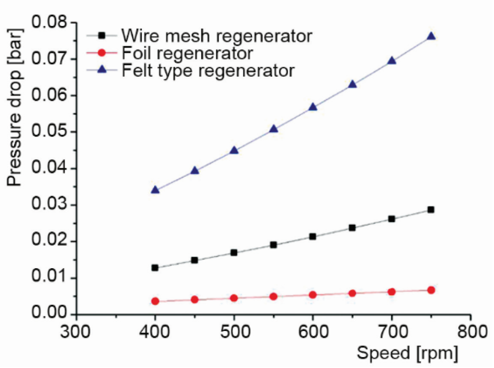

**Figure 8. Pressure drop variation for different regenerator types, depending on the Stirling engine speed**

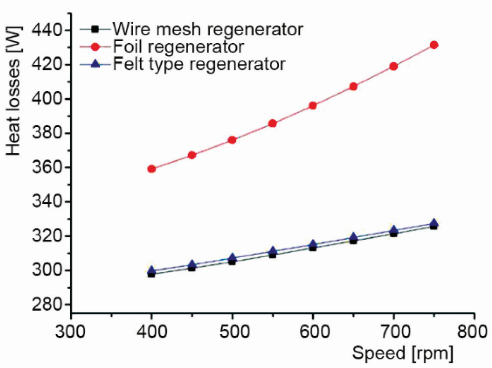

**Figure 9. Heat losses variation for different regenerator types, depending on Stirling engine speed**

Figure 10 illustrates efficiency variation for the three regenerators depending on Stirling engine speed. According to it, wire mesh regenerator provides better engine efficiency that makes it the regenerator to choose for good CSP plant performance.

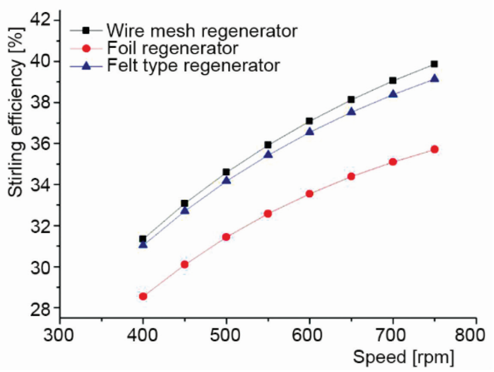

**Figure 10. Stirling engine efficiency change, according to its speed, for three types of regenerator**

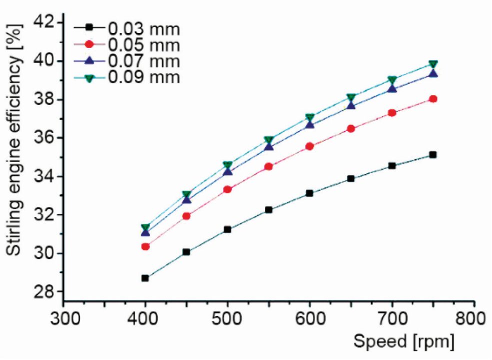

**Figure 11. Engine speed effect on its efficiency for different mesh diameters**

### *Regenerator geometry effect on Stirling engine performance*

Regenerator geometry effect on Stirling engine performance can be carried out by observing several parameters, namely: inner and outer matrix diameter, matrix length, mesh diameter, *etc.* In the present investigation the considered parameter is the matrix mesh diameter based on previous studies [27, 28]. Figure 11 reveals a similar result to that concluded by Mahmoodi *et al.* [29] who found that when regenerator porosity increases, Stirling engine efficiency and output power decrease. By increasing the mesh diameter matrix porosity decreases; in other words, the result of Mahmoodi *et al.* [29] is: when mesh diameter decreases, Stirling engine efficiency and output power decrease. This is in perfect agreement with what is found in this study. Better efficiency is then obtained for thicker mesh and for all engine speeds, Stirling engine efficiency increases with mesh diameter increase.

## Conclusions

This work addresses an investigation, using PROSA 2.0.4 software, of five parameters effects on Stirling engine performance: configuration, heater shape, bundle tube heat exchanger size, regenerator type, and geometry. This study aims to maximize engine performance considering high hot source temperatures in order to use it in a CSP plant.

The investigation revealed that the alpha type Stirling engine is the most suitable for high temperature differences between heater and cooler. It can reach high efficiency, equal to 45%, for temperature differences higher than 330 °C, otherwise, the gamma type Stirling engine is the most efficient. Therefore alpha type is chosen for later use in CSP plants. Regarding hot heat exchangers, it was found that for all engine speeds tube bundle heat losses are lower than those produced by a fin-type heat exchanger with a small difference that can reach 0.1344 W for a speed of 600 rpm. Then to combine good efficiency and less pressure losses, *U*-shaped tubes were chosen. After choosing the *U*-shaped hot exchanger, tube size was studied. It was found that Stirling engine efficiency was inversely proportional to tubes inner diameter while heat losses are proportional to the same dimension and by increasing the tubes number efficiency increased as well as heat losses. Therefore, a suitable strategy was proposed to increase engine efficiency by shortening inner diameter and increasing tube number. It was also concluded that increasing tubes length generates a reduction in engine efficiency. The regenerator, which is considered a key component of Stirling engines, has been inspected for type and geometry based on pressure drop and resulting heat losses. It is deduced that a wire mesh regenerator presents a good compromise between minimum pressure drop and heat losses and provides better engine efficiency. Regarding regenerator size, better efficiency is obtained for a thicker mesh and increases with mesh diameter increase and this is for all rotation speeds.

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## References

[1] Walker, G., *Stirling Engines*, Oxford : New York: Clarendon Press, Oxford University Press, Oxford, UK, 1980
[2] Gheith, R., Experimental and Theoretical Study of Stirling Engines with External Heat Input: Application to Beta and Gamma Type Machines (in French), Ph. D. thesis, Nantes University, Nantes, France, 2011
[3] Ye, W. *et al.*, Exergy Loss Analysis of the Regenerator in a Solar Stirling Engine, *Thermal Science, 22* (2018), Suppl. 2, pp. S729-S737
[4] Rahmati, A., *et al.*, Dimensional Synthesis of the Stirling Engine Based on Optimizing the Output Work by Evolutionary Algorithms , *Energy Rep., 6* (2020), Nov., pp. 1468-1486
[5] Nasrollah, N., Stirling Engine Cycle Efficiency, Ph. D. thesis, University of Applied Sciences, Finland, 2012
[6] Abuelyamen, A., Ben-Mansour, R., Energy Efficiency Comparison of Stirling Engine Types ($\alpha$, $\beta$, and $\gamma$) using Detailed CFD Modeling, *Int. J. Therm. Sci., 132* (2018), Oct., pp. 411-423

[7] Munir, U., *et al.*, The CFD Methodology for Simulating Pumping Loss from Displacer and Piston Seals of Free Piston Stirling Engine, *Thermal Science, 26* (2022), 1A, pp. 13-23
[8] Caetano, B. C., *et al.*, A Novel Methodology on Beta-Type Stirling Engine Simulation Using CFD, *Energy Convers. Manag., 184* (2019), Mar., pp. 510-520
[9] Aksoy, F., *et al.,* 1.2 kW Beta Type Stirling Engine with Rhombic Drive Mechanism: 1.2 kW Beta Type Stirling Engine with rhombic drive mechanism, *Int. J. Energy Res., 41* (2017), 9, pp. 1310-1321
[10] Bataineh, K. M., Numerical Thermodynamic Model of Alpha-Type Stirling Engine, *Case Stud. Therm. Eng., 12* (2018), Sept., pp. 104-116
[11] Cinar, C., *et al.*, Beta-type Stirling Engine Operating at Atmospheric Pressure , *Appl. Energy, 81* (2005), 4, pp. 351-357
[12] Rabhi, L. *et al.*, Parametric Investigation on a Gamma Type Stirling Engine Efficiency Coupled to Linear Fresnel Solar Collector, *Proceedings*, 1st International Conference on Innovative Research in Applied Science, Engineering and Technology, Meknes, Morocco, 2020, pp. 1-4
[13] Paula, R. B., *et al.*, Thoretical Assessment of a Stirling Engine "Amazon" by using Prosa and Mathcad, *Rev. Eng. Termica, 10* (2011), 1-2, p. 32
[14] Prieto, J.-I., Garcia, D., Analysis of Simulations Obtained by Means of the PROSA Software for Several Prototypes, *Proceedings,* 12th International Stirling Engine Conference and Technology Exhibition (Ed. T. K. Makhamov), Durham University, Durham, UK, 2005, pp. 398-415
[15] Gheith, R., *et al.*, 4.6 Stirling Engines, in: *Comprehensive Energy Systems,* Elsevier, Amsterdam, The Netherlands, 2018, pp. 169-208
[16] Qiu, S., Solomon, L., *Free-Piston Stirling Engine Generators, in Energy Conversion – Current Technologies and Future Trends,* IntechOpen, Rijeka, Croatia, 2019, pp. 105-125
[17] Abdullah, S. *et al.*, Design Consideration of Low Temperature Differential Double-Acting Stirling Engine for Solar Application, *Renew. Energy, 30* (2005), 12, pp. 1923-1941
[18] Ni, M., *et al.*, Heat Transfer Characteristics of the Oscillating Flows of Different Working Gases in U-Shaped Tubes of a Stirling Engine, *Appl. Therm. Eng., 89* (2015), Oct., pp. 569-577
[19] Araoz Ramos, J. A., Thermodynamic Analysis of Stirling Engine Systems Applications for Combined Heat and Power, Ph. D. thesis, Industrial Engineering and Management, KTH Royal Institute of Technology, Stockholm, 2015
[20] Poncet, E., Characterization Technique of a Thermal Mini-Regenerator for Stirling or Pulse Tube Mini-Refrigerator (in French), *Mecanique Ind., 2* (2001), 5, pp. 455-464
[21] Reader G. T., Hooper, C., *Stirling Engines*, Cambridge Univ. Press, London,1983
[22] Gelu, T. A., Analysis of Stirling Engine and Comparison with other Technologies Using Low Temperature Heat Sources, M. Sc. thesis, Tecnico LISBOA, University of Lisbon, Lisbon, 2014
[23] Gedeon, D. R., Wood, J. G., Oscillating-Flow Regenerator Test Rig: Hardware and Theory With Derived Correlations for Screens and Felts, Report No. 198442, Lewis Research Center, NASA, 1996
[24] Timoumi, Y. *et al*., Performance Optimization of Stirling Engines, *Renew. Energy, 33* (2008), 9, pp. 2134-2144
[25] Popescu, G. *et al.*, Finite-Time Thermodynamic Optimization of the Endo- and Exo-Irreversible Stirling Engine (in French), *Rev. Generale Therm., 35* (1996), 418-419, pp. 656-661
[26] Thombare, D. G., Verma, S. K., Technological Development in the Stirling Cycle Engines, *Renew. Sustain. Energy Rev., 12* (2008), 1, pp. 1-38
[27] Abbas, M., Optimisation des Performances d'un Moteur Stirling de Type Gamma, *Rev. Energ. Renouvelables, 13* (2010), 1, pp. 503-514
[28] Bulinski, Z., *et al.*, A Computational Fluid Dynamics Analysis of the Influence of the Regenerator on the Performance of the Cold Stirling Engine at Different Working Conditions, *Energy Convers. Manag., 195* (2019), Sept., pp. 125-138
[29] Mahmoodi, M., *et al.*, Numerical Simulation of Beta Type Stirling Engine Considering Heat and Power Losses, *Iran. J. Mech. Eng. Trans. ISME, 15* (2014), 2, pp. 5-27

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