engineering proceedings

Proceeding Paper

Enhancing Gamma Stirling Engine Performance through Genetic Algorithm Technique †

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† Presented at the 4th International Electronic Conference on Applied Sciences, 27 October–10 November 2023; Available online: https://asec2023.sciforum.net/.

Abstract: The Stirling engine, invented in 1816, was initially lacking comprehensive scientific understanding, which only surfaced after a considerable 50-year period. In the present era, impressive strides have been made in enhancing the performance of Stirling engines by implementing thermodynamic cycles. Despite these advancements, there remains untapped potential for further improvements by applying soft computing methods. To address this, the focal point of this research paper centres around optimizing the Stirling engine, specifically focusing on a gamma-type double-piston Stirling engine and leveraging genetic algorithms to achieve the desired enhancements. The results from this analysis are meticulously compared with experimental data, validating the approach's efficacy. Additionally, this paper explores the potential impact of utilizing cryogenic fluids as coolants on the Stirling engine's performance.

Keywords: Stirling engine; thermodynamics; power; efficiency; genetic algorithm

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Citation: Asary, A.R.; Abdul, B.; Samad, A.; Shibly, M.A.H. Enhancing Gamma Stirling Engine Performance through Genetic Algorithm Technique. *Eng. Proc.* **2023**, *56*, 29. https://doi.org/10.3390/ASEC2023-15264

Academic Editor: Santosh Kumar

Published: 26 October 2023

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1. Introduction

There is a growing interest in exploring alternative energy sources to preserve fossil fuels and mitigate greenhouse effects. Among these options, renewable energy resources like biomass, solar, geothermal, and wind energy are highly promising due to their clean, efficient, and sustainable nature [1]. The Stirling engine serves as an example of an externally heated engine and comes with several advantageous features. It operates as a thermally regenerative system with a straightforward design, ensuring minimal noise and safety. Moreover, it exhibits adaptability to a diverse range of heat sources, encompassing solar, biomass, geothermal energy, and even industrial waste [2,3]. In an ideal situation, Stirling engines function on a highly efficient thermodynamic cycle, with the engine's internal gas undergoing four distinct processes: two isothermal heat exchange processes (expansion and compression) and two isochoric heat exchange processes (heating and cooling) [4,5].

The regenerator plays a crucial role as an essential component within the engine. Acting as an internal heat exchanger, it functions like a thermal sponge, absorbing and releasing heat throughout the cycle, thus enhancing the engine's power and efficiency. The amount of heat absorbed and restored to the gas in the regenerator during one cycle is typically four times greater than the heat that passes through the heater in the same cycle [6]. The first-order analysis was initially introduced by Schmidt [7], providing a closed-form analytical method based on mass and energy conservation algebraic equations.

This method enables the prediction of engine power and efficiency in cases of sinusoidal volume variation.

Various engineering problems, including skyline computation and vehicle routing issues, have utilized multi-objective optimization techniques. In the 18th century, evolutionary algorithms (EAs) were introduced as stochastic approaches to tackle problems of this nature [8].

In this study, the Stirling engine is optimized through a genetic algorithm, and four decision variables are adopted: the volume of the heater, regenerator, cooler, and phase angle. These are the important variables in designing the performance of the Stirling engine. The results obtained through optimization are compared with experimental and other thermodynamic results.

2. Engine Data

The engine under study is a gamma-type double-piston Stirling engine. In this engine, the exhaust gas of the diesel engine is used as the heat source. To heat the heater tubes of the Stirling engine, a cap is specially made for the Stirling engine. Further details of the engine data are given in Table 1 below.

Table 1. Engine data of gamma-type double-piston Stirling engine [1].

Engine Data	Values	Engine Data	Values
Cooler temperature	294	Pressure (bar)	3.58
Heater temperature	424	Rotational speed (rpm)	882
Cooler volume	223×10^{-6}	Phase angle (degree)	88°
Heater volume	87.28×10^{-6}	Regenerator volume (m^3)	308.93
Expansion swept volume (m^3)	221×10^{-6}	Compression swept volume (m^3)	194×10^{-6}
Expansion clearance volume (m^3)	24×10^{-6}	Compression clearance volume (m^3)	35×10^{-6}

3. Senft Method for Gamma Stirling Engine

Senft suggested the following mathematical isothermal for developing the isothermal model for the gamma Stirling engine. The expression for the calculation of the instantaneous total volume of the engine and pressure is given by

$$V = \frac{V_T}{\kappa+1}\left(1+\frac{\kappa}{2}(1+\cos(wt))+\chi\right) \tag{1}$$

$$P = \overline{P}\left(\frac{\sqrt{Y^2-X^2}}{Y+X\cos(wt-\theta)}\right) \tag{2}$$

$$X = \sqrt{\kappa^2-2\kappa(1-\tau)\cos(\alpha)+(1-\tau)^2} \tag{3}$$

$$Y = 1+\tau+\kappa+\frac{4\tau\chi}{1+\tau} \tag{4}$$

$$\theta = \arccos\left(\frac{\kappa-(1-\tau)\cos(\alpha)}{X}\right) \tag{5}$$

$$W = \int PdV \tag{6}$$

In the above equations, V_1, V_2, and V_T are the displace, piston swept volume, and total volume, V_D is dead volume, T_H, T_C, and T_D are the hot, cold space temperature, and dead space temperature, P is pressure, ω is angular velocity of the crankshaft, α is crank angle, $\kappa = V_2/V_1$ is piston swept to displace swept volume, $\chi = V_D/V_1$ is dead volume ration, $\tau = T_C/T_H$ is temperature ratio, and ωt is the instantaneous angular position of crank.

4. Genetic Algorithm

Genetic algorithms (GAs) are a class of stochastic optimization methods that draw inspiration from the biological principle of survival in nature. The concept of GA theory was initially introduced and published by Holland in 1975, and later, in 1989, Goldberg successfully applied it in practical applications [9]. The fundamental principle of GAs is rooted in the idea of "survival of the fittest," where a population of variables undergoes evolutionary processes to generate a new population with individuals that exhibit improved traits or characteristics. This iterative process involves selecting individuals with higher fitness values, the application of genetic operators like crossover and mutation to create offspring, and replacing less fit individuals in the population. Over successive generations, the GA algorithm converges towards optimal solutions, making it a powerful tool for solving complex optimization problems across various domains [9]. There are four engine parameters, which are defined as variables of chromosomes, namely heater (Z_H), regenerator (Z_R), cooler volume (Z_C), and phase angle (α). Thus, the chromosomes can be represented as follows:

Chromosomes = (Z_H; Z_R; Z_C; Z_α)

The upper and lower boundaries for each variable are the following:

- $100 \times 10^{-6} \leq Z_H \geq 1 \times 10^{-6}$ where Z_H is a volume of heater (m);
- $390 \times 10^{-6} \leq Z_R \geq 1 \times 10^{-6}$ where Z_R is a volume of regenerator (m);
- $400 \times 10^{-6} \leq Z_C \geq 1 \times 10^{-6}$ where Z_C is a volume of cooler (m);
- $57.29 \leq Z_\alpha \geq 97.40$ where $Z\alpha$ is a phase angle in degrees.

The objective function used is the following:

Power = f(chromosomes) = f(Z_H; Z_R; Z_C; Z_α)

5. Results and Discussion

The p-V is drawn in Figure 1 for the validation results and compared with the literature results [1]. While Table 2 shows the summary of thermodynamic models and a comparison of results with the optimized model, Table 3 depicts the optimized parameters obtained through the genetic algorithm. The results show that the power obtained through genetic algorithms is closely related to the experimental results. The experimental power is obtained at 111.43 W [1] and the optimized power at 113.04.

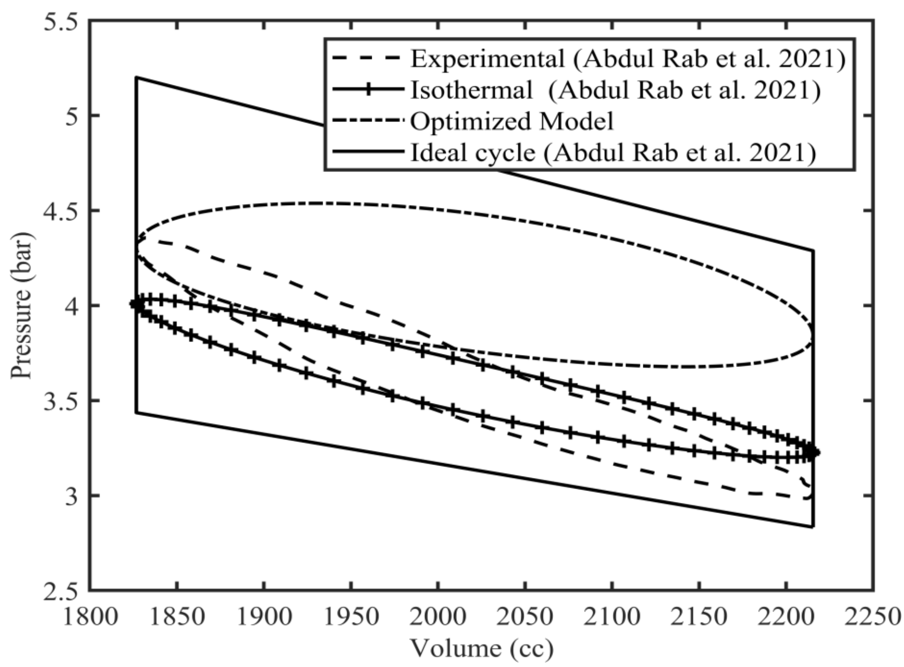

Figure 1. Comparison of the optimized model with another thermodynamic model [1].

Table 2. Summary of thermodynamic models [1].

Parameters	Ideal Cycle	Isothermal	Experimental	Optimized Isothermal
Work (J)	54.11	9.08	7.50	7.68
Power (W)	795	133.8	111.43	113.04
Efficiency (%)	30.6	30.70	24.70	30.10

Table 3. Optimized parameters obtained through genetic algorithms.

Parameters	Values
Heater volume (m^3)	100×10^{-6}
Regenerator volume (m^3)	390×10^{-6}
Cooler volume (m^3)	290×10^{-6}
Phase angle (θ)	57.40

In Table 3, the optimized volume of the heater is found to be 100E-6 (m^3). In the previous volume, there were 42 heater tubes [1] in the optimized model. To reach the optimum power and efficiency, 73 heater tubes were found in the volume. This is because by increasing the area of heat transfer, more will be transferred. Therefore, there is an improvement in the power and efficiency of the Stirling engine. The case for the volume of the regenerator and cooler is similar. Another important element is the phase angle of the displacer piston connecting rod, which leads to the power piston motion. It is found that it should be 57.40 degrees. This is the most important factor found in this research work. The literature [1,4] also found that phase angle plays an important role in the performance improvement of the Stirling engine. So, for the gamma-type Stirling engine, a 57.40 phase angle is found, which gives us a new optimized value.

Cryogenic fluids, like liquid air/nitrogen, are recognized for their efficiency as energy storage mediums due to their high storage density of 0.77 (MJ/kg). These fluids can be produced by liquefying air/N2 during off-peak periods or using renewable energy sources. The well-established cryogenic industry infrastructure facilitates their storage and transportation. This research explores the feasibility of using cryogenic fluid, specifically liquid nitrogen, as a coolant. Liquid nitrogen operates within a temperature range of −10 to −150 °C. By utilizing liquid nitrogen at a temperature of −140 °C as a coolant, the research demonstrates that the maximum power achieved is 300 W, employing the Senft isothermal model.

6. Conclusions

In this research work, the Stirling engine's optimization process involves utilizing a genetic algorithm, a powerful evolutionary technique. Four crucial decision variables are considered in this optimization: the volumes of the heater, the regenerator, the cooler, and the phase angle. These variables play a significant role in determining the design and performance of the Stirling engine. The values of these decision variables are iteratively evolved and refined through the genetic algorithm to achieve the most efficient and optimal configuration for the Stirling engine. This approach allows for the exploration of a wide range of potential solutions. It helps find the best combination of design parameters to enhance the engine's overall performance and efficiency. By employing the genetic algorithm and focusing on these critical variables, engineers can unlock the full potential of the Stirling engine and pave the way for advanced, high-performance applications in various industries.

Author Contributions: Conceptualization, A.R.A. and B.A.; methodology, A.R.A.; software, A.S.; validation, A.R.A. and B.A.; formal analysis, M.A.H.S.; investigation, M.A.H.S.; resources, A.R.A.; data curation, A.S.; writing—original draft preparation, A.S.; writing—review and editing, A.S.; visualization, M.A.H.S.; supervision, A.R.A.; project administration, A.R.A.; funding acquisition, A.R.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: The data presented in this study are available within the article and are presented in graphs. There are no more data apart from the presented information.

Conflicts of Interest: The authors declare no conflict of interest.

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