Efficiency Improvement and Key Opportunities of Stirling Engine

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Abstract. Amidst the backdrop of an evolving societal landscape, the impending scarcity of energy resources has intensified the quest for innovative energy solutions. The Stirling engine, conceived by the Scottish clergyman Robert Stirling in 1816, emerges as a promising avenue to address contemporary energy challenges. This external combustion engine operates on the fundamental principle of harnessing work from heat transfer coupled with the expansion and contraction of gases. Its versatility lies in its capability to transmute diverse natural energy sources, ranging from wood and solar radiation to gases, into utilizable mechanical and electrical energy. The potential applications of Stirling engines are vast, encompassing roles as propulsion systems for space exploration, contributors to nuclear power generation, efficient refrigeration devices, and solar energy electricity generators. Nonetheless, the Stirling engine's Achilles' heel remains its suboptimal efficiency. This paper investigates diverse domains to optimize the performance of Stirling engines, shedding light on potential avenues for future research and development with the overarching aim of optimizing this venerable engine's contributions to sustainable energy solutions.

Keywords: Stirling engine, efficiency improvement, external-combustion engine, energy utilization.

1. Introduction

In today's increasingly tense energy needs, Stirling engines can effectively solve the problem of energy shortage for us [1,2]. Next, provide a detailed explanation. In 1816, London pastor Robert Stirling proposed the concept of a piston hot gas engine - a Stirling engine, which is a closed-cycle engine with external heating. Its working principle is based on the Stirling cycle, which mainly includes Isothermal expansion. There are four processes: constant volume, isothermal compression, and constant volume. Stirling engines have the characteristic of fuel flexibility. Any form of heat source, including solar energy, fossil fuels, biomass, nuclear energy, etc., can be transformed into mechanical or electrical energy through Stirling engines. Moreover, the emissions of Stirling engines are usually cleaner than internal combustion engines. In addition, Stirling engines can also operate as heat pumps, which convert mechanical energy into thermal energy for refrigeration and other purposes. However, Stirling engines have a fatal drawback, which is their low energy efficiency.

Therefore, how to improve the efficiency of Stirling engines has become a challenge that needs to be overcome in today's world [3]. This article mainly summarizes several effective ways to improve the efficiency of Stirling engines in recent years. This mainly includes increasing the number of sub-regenerators, using high porosity regenerators and selecting appropriate length regenerators (at high speeds), using Convective Meta Thermal Concentration (CMTC) materials, installing a new type of heat transfer fin shapes in the solar Stirling engine heater, and using AWPS phase shift in the PTR/Stirling engine. And discussed three areas that require more in-depth research in the future, including Using neural networks to optimize Stirling engine performance, developing fuel cell Stirling engine composite systems to utilize energy more efficiently, and exploring nuclear-powered Stirling systems to provide sustainable and reliable energy supply.

2. Improvement of Stirling Engine Efficiency

2.1. Increase the Quantity of Sub-Regenerators

The regenerator is one of the components of the Stirling engine, and its function is to store heat from one cycle and reuse it in the next. To increase the efficiency of a Stirling engine, regenerators are often made of materials such as aluminum foil, steel wool, or metal sponge. A sub-regenerator is a separate thermally isolated component of the regenerator used to produce a linear temperature distribution [1]. The model is built as shown in Fig. 1. Through mathematical computation and experimental testing of the Stirling Engine Performance, the following data can be obtained.

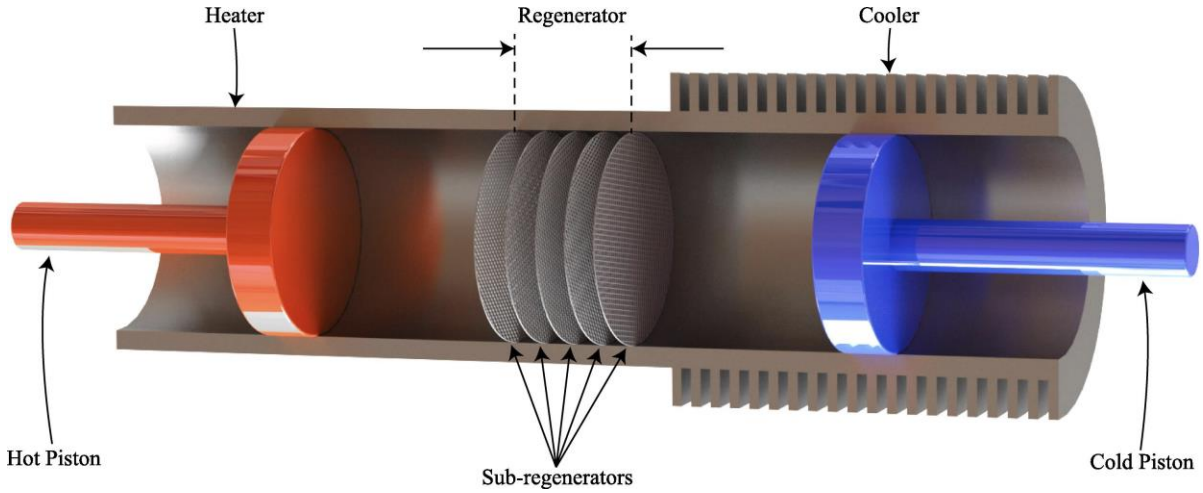

Fig. 1 Stirling engine model [1]

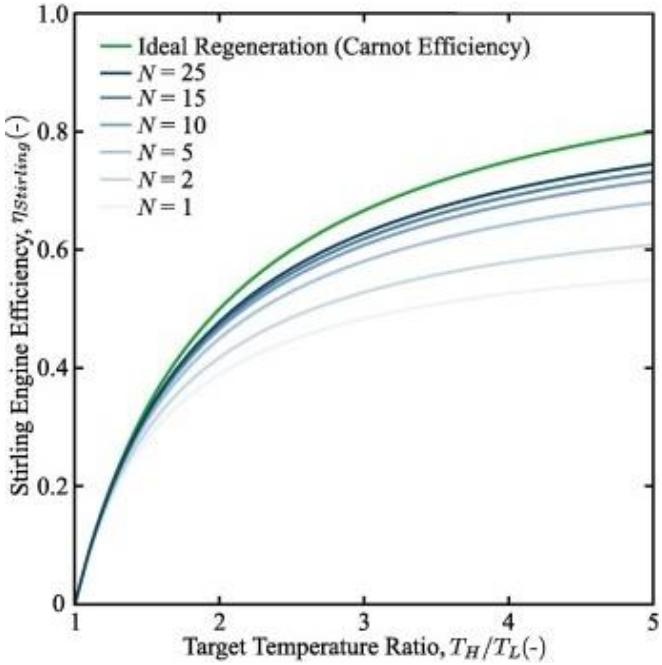

Fig. 2 Efficiency of the Stirling engine in relation to the target temperature ratio, with variations in the count of sub-regenerators N [1]

Through the construction of the mathematical model and the testing of the experimental equipment, it comes to the following conclusions: Fig. 2 demonstrates the relationship between the target temperature ratio and the efficiency. Here, N denotes the count of sub-regenerators. As can be seen from the figure, the higher the quantity of sub-regenerators, the higher the efficiency of the Stirling engine. However, the increase in efficiency brought about by the increase in quantity gradually slows down while the cost required increases. Therefore, it is essential to find a balance between economic efficiency and efficiency.

2.2. Applying CMTC Materials to Stirling Engines

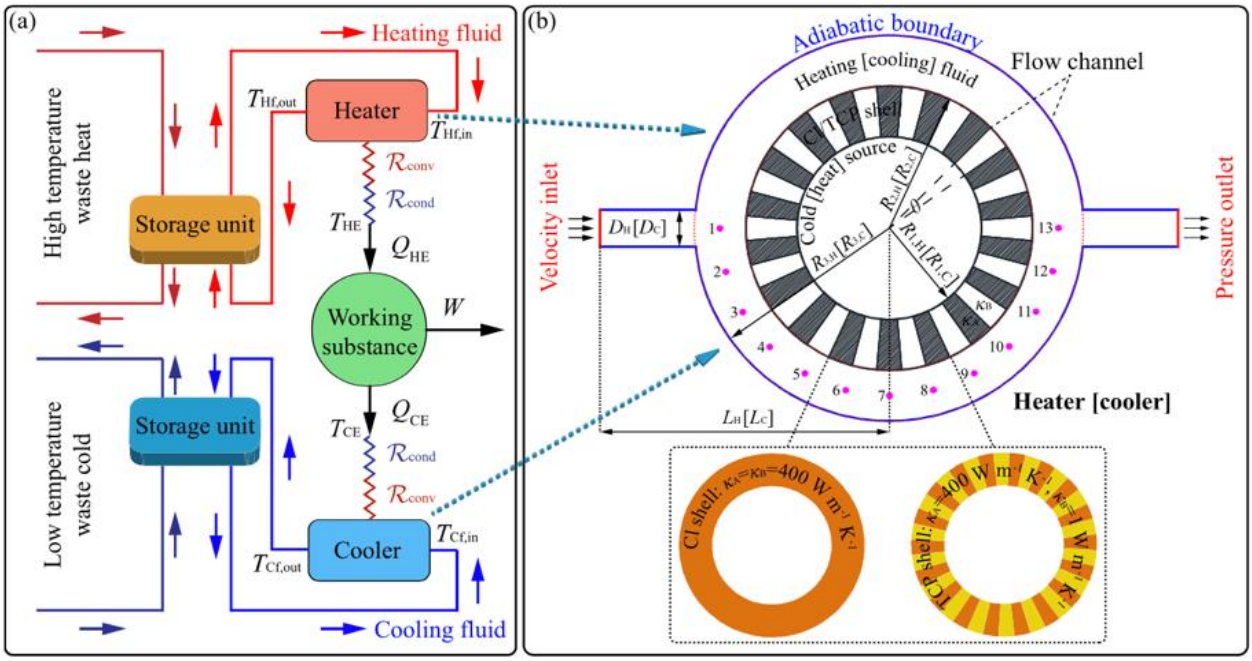

Fig. 3 Schematic diagram of (a) a Stirling engine system that effectively utilizes waste heat and cold and (b) the heater (cooler) under convective heating (cooling) modes [2]

CMTC refers to "Convective Meta Thermal Concentration", which is an anisotropic thermal conductive material that can regulate the temperature distribution of heat exchange fluids. Introducing CMTC between the cold and hot ends of a Stirling engine can enhance the heating and cooling process of the engine. Fig. 3a refers to a schematic diagram of a Stirling engine system with waste heat and cold utilization, and (b) depicts a heater (cooler). The two structures of the casing. One is a CI shell made of classic high thermal conductivity materials, and the other is a TCP shell made of alternating high conductivity and low conductivity. TCP is the abbreviation for Thermal Concentration, which refers to a shell structure with thermal concentration technology. This technology is mainly applied in Stirling engines by introducing CMTC materials, while CI is a shell structure without CMTC materials [2]. According to the data in Fig. 4, the average temperature of TCP with CMTC material in the heater was higher than that of TCP with CI material, while in the cooler, the average temperature of TCP with CMTC material was lower than that of TCP with CI material.

The reason for this phenomenon is that TCPs using CMTC materials increase the average temperature of the heating fluid in the heater while decreasing the average temperature of the cooling fluid in the cooler. The use of CMTC materials can increase the temperature difference between the heater and the cooler, thus improving the thermal efficiency of the Stirling engine. This is due to the fact that increasing the temperature difference can significantly enhance the conversion efficiency of heat energy. This means that TCP materials are capable of achieving significant thermal efficiency improvements under certain conditions.

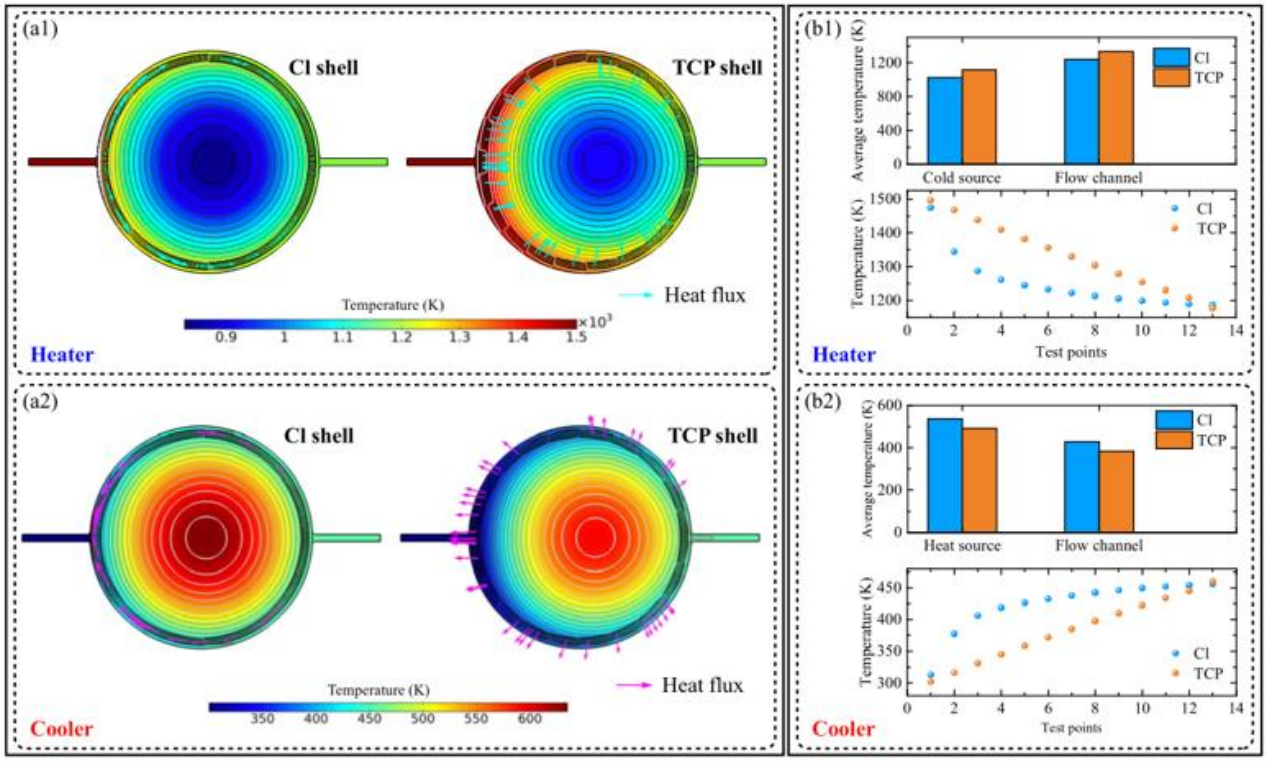

Fig. 4 Temperature spreading distribution in (a1) Heater and (a2) Cooler with CI shell and with TCP shell. The average temperature of (b1) cold and (b2) heat source and flow channel in the Heater (Cooler). And scatter plot of test points vs. temperature [2]

2.3. Applying NiTiNOL Materials to Stirling Engines

NiTiNOL is a shape-memory alloy whose most important feature is the shape-memory effect. It remembers its original shape under certain temperature conditions and automatically returns to its original shape when the temperature returns to the original setting, even after bending or twisting. After adding NiTiNOL springs to the Stirling engine, the improved engine is called the Stirnol engine, which is the model shown in Fig. 5. The difference in performance between the Stirnol and Stirling engines is investigated by changing its base plate material and the Stirnol with integrated NiTiNOL springs [3].

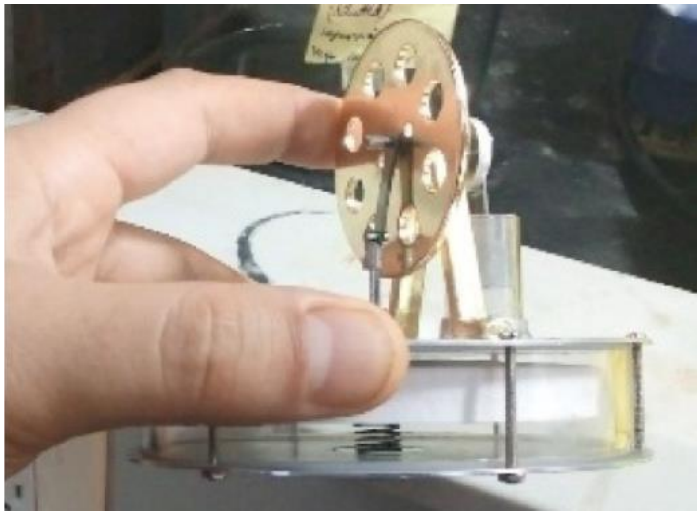

Fig. 5 Stirling engines with NiTiNOL springs [3]

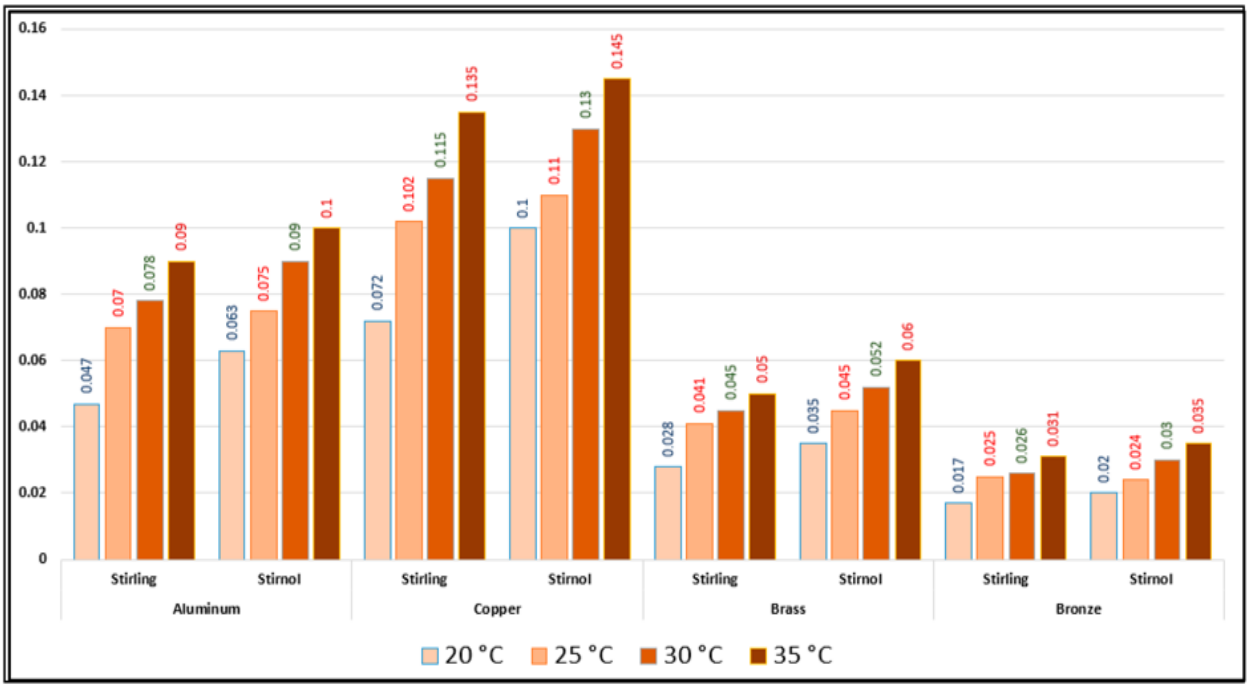

Fig. 6 Difference in efficiency between Stirling and Stirnol engines on different material baseplates [3]

Through the results of the experiments in the laboratory, as shown in Fig. 6, the overall efficiency of the engine with the addition of NiTiNOL springs is high, indicating that shape memory alloys have a certain influence on engine performance. However, the increase in efficiency is minimal compared to the traditional Stirling engine, although this design is simple in structure and low in cost and provides a new way to explore Stirling efficiency in the future.

2.4. Improvement of GPU-3 Stirling Engine Regenerator

GPU-3 is one type of Beta Stirling engine. As shown in Fig. 7, the power piston and displacement device of the engine are installed in the cylinder, and a diamond drive carries out the drive of two pistons. Mohammad Sheykhi and Mahmood Mehregan proposed a new adiabatic model (irreversible adiabatic), which is mainly based on the Runge-Kutta algorithm for engine modeling and uses a genetic algorithm for parameter optimization. It can accurately simulate the operation of a Stirling engine. Using this algorithm and continuously changing parameters to explore the efficiency, the following data were obtained based on this model [4].

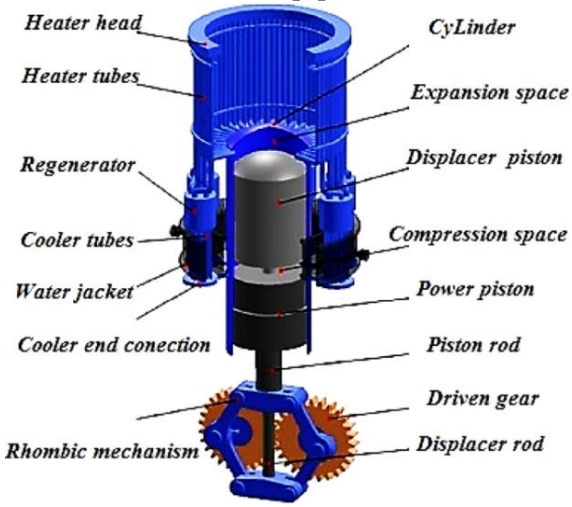

Fig. 7 GPU-3 Stirling engine [4]

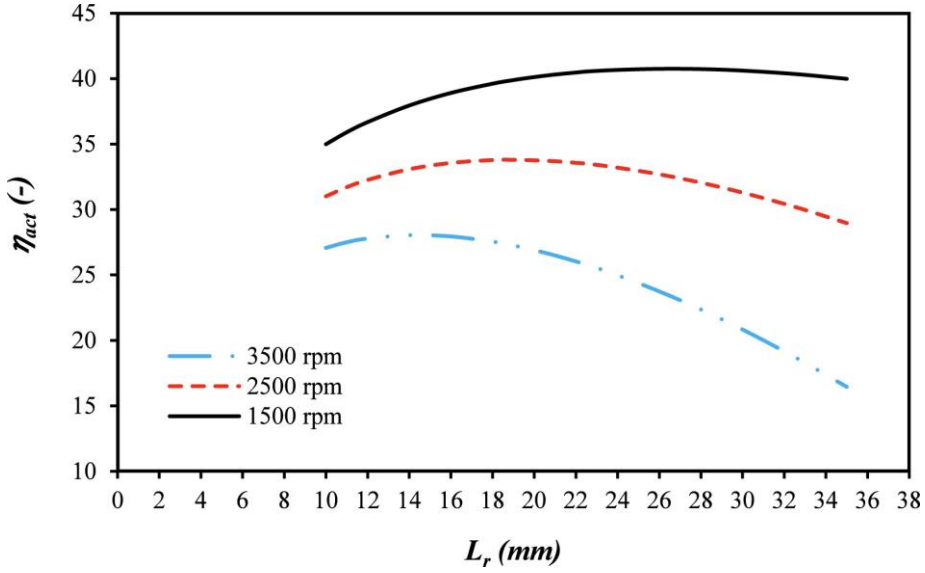

Fig. 8 The effect of different lengths of regenerators on efficiency at different speeds [4]

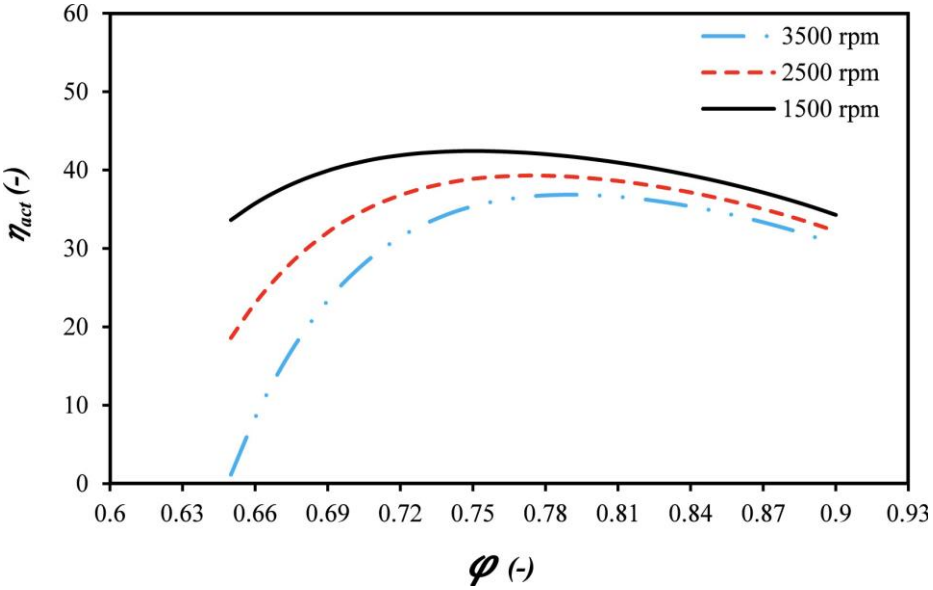

Fig. 9 Variation of regenerator porosity as a function of thermal efficiency for different rotational speeds [4]

From Fig. 8, η represents Stirling Engine efficiency. The relationship between different lines represents different rotational speeds. Within a certain range of pressure, there is a non-linear relationship between the length and efficiency of the regenerator, showing a trend of first increasing and then decreasing. However, as the speed increases, the efficiency of the regenerator decreases as the length changes. Therefore, optimal performance at high speeds is achieved by using a shorter regenerator.

From Fig. 9, As shown in the figure, the engine efficiency exhibits a pattern of initially increasing and subsequently decreasing with rising porosity levels. This is because the increase in porosity leads to an increase in dead volumes, resulting in a decrease in engine efficiency. As the speed increases, the change in efficiency with polarity becomes less significant, and when the polarity is high, even if the speed is different, the efficiency of the engine tends to be consistent.

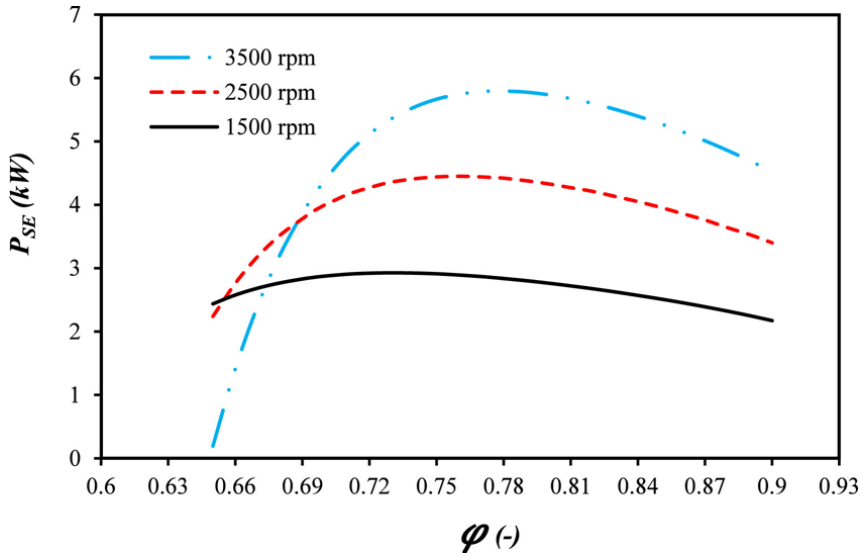

Fig. 10 Relationship between different regenerator porosities and power generation at different rotational speeds [4]

Overall, for the Stirling engine, increasing the regenerator length too much at high rpm will result in a decrease in efficiency. The regenerator pressure decreases significantly at high rpm and low regenerator porosity conditions (Fig. 10). Therefore, recommended to use regenerators of appropriate length and high porosity to optimize power output and thermal efficiency at high rotational speed conditions.

3. Improvement of Stirling Engine Efficiency in Other Applications

3.1. Installing Fin on a Solar Stirling Engine to Improve Efficiency

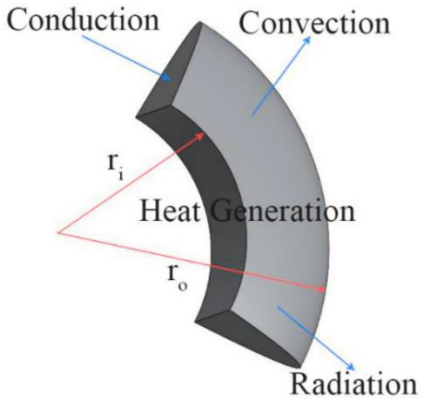

Fig. 11 The geometry of the Fin [5]

A new type of heat transfer fin shape can effectively improve the thermal efficiency of solar Stirling engines. Below, provide a detailed introduction to this type of heat transfer fin shape. Firstly, need to understand that FGM (Functionally Graded Material) has two characteristics. The first characteristic is that the properties of the material change with size, and the second characteristic is that its weight is very light, but it can still maintain strength and lightness. The thermal conductivity of Fin made of this material varies with temperature and position, making it more suitable for different heat transfer needs. As shown in Fig. 11, the FGM Fin's thickness is intended to change in accordance with the power law of radius, which allows Fin to have different thicknesses at different radii, thus providing better heat transfer performance. This model, along with other designs, takes into account three categories of heat transfer phenomena: conduction, convection, and radiation. The heater section of the solar Stirling engine, after the installation of the Fin, was evaluated using PSVL (polytropic analysis of Stirling engine with variable losses) [5].

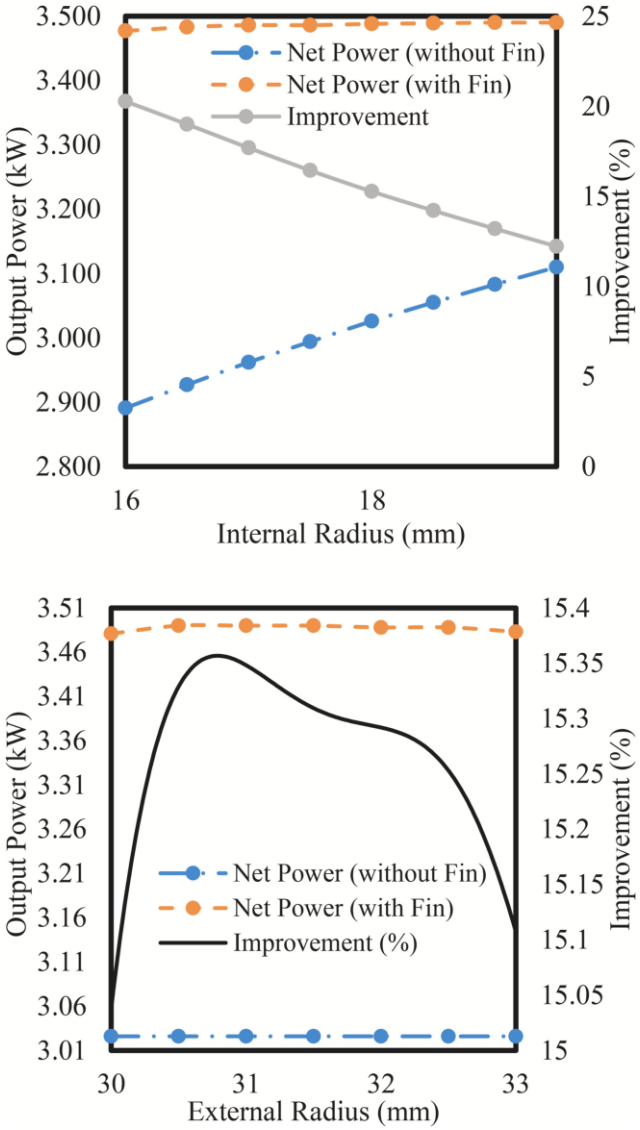

Fig. 12 The effect of heat transfer fin inner diameter and radius on the net power of a Stirling engine, yellow for Fin installed, blue for no Fin installed [5]

From Fig. 12, the observation is clear that Stirling engines fitted with a Fin exhibit higher output power compared to those without a Fin installed, regardless of whether it is Internal or External radius. From Fig. 13, it can be seen that with the increase of the Concentrator diameter, there is a growth trend regardless of whether it is equipped with Fin. However, the growth rate of engines with Fin is faster than that of engines without Fin. When the Concentrator diameter exceeds about 2.5m, the output power of engines with Fins is higher than that of engines without Fin. In solar DNI, both Stirling engines with and without fins have increasing output powers as Solar DNI grows. However, Stirling engines with fins have a much higher output power than engines without fins.

Overall, the addition of Fin to the heater is the primary factor behind this phenomenon. By incorporating Fin into the heater, the contact area between the fluid and Fin is increased, resulting in enhanced heat transfer efficiency. Furthermore, the presence of Fin alters the fluid flow pattern and promotes turbulence, thereby further improving heat transfer efficiency. Stirling engines with a Fin installed in the heater show a significant increase in thermal efficiency and minimize heat loss under identical heat source or receiver conditions. Research indicates that the installation of Fin in solar Stirling engines can boost output power by at least 15%. This signifies that by optimizing the design and arrangement of Fin, the heat transfer surface area of the heater is enlarged, leading to improved fluid heat transfer efficiency and ultimately enhancing the performance of the Stirling engine.

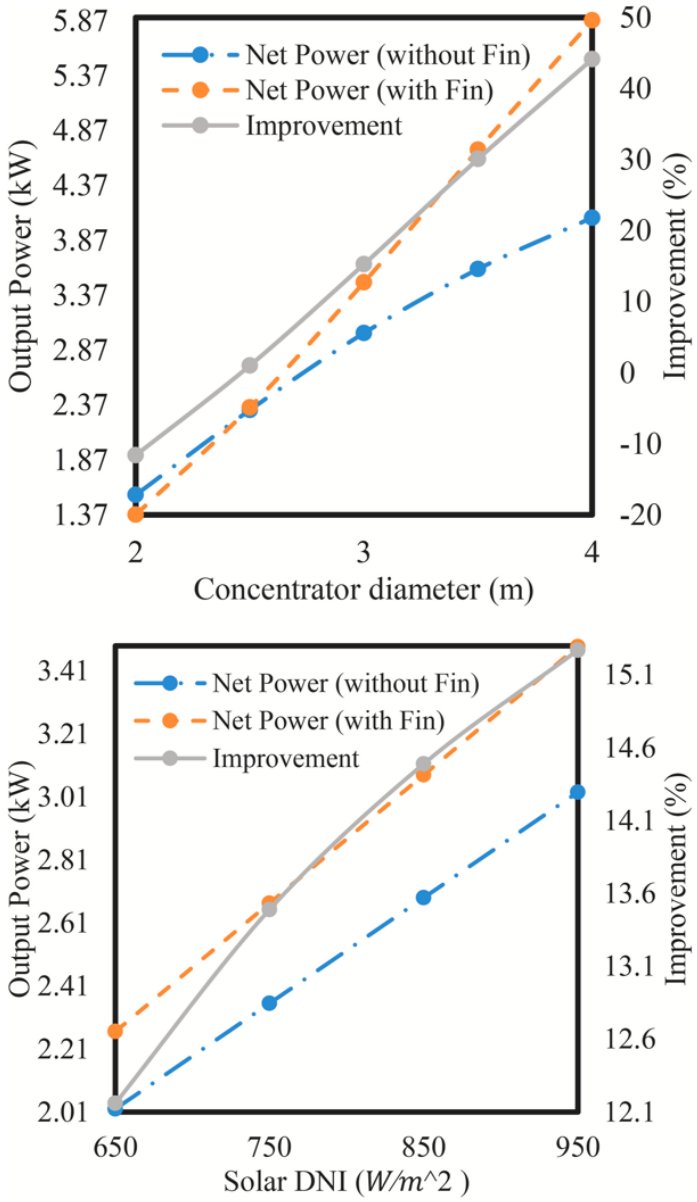

Fig 13 The effects of the concentrator's diameter and solar direct normal irradiance (DNI) on the net power output of the Stirling engine are investigated, considering both the presence and absence of the Fin [5]

3.2. PTR/Stirling Engine

PTR/Stirling engine: PTR stands for Pulse Tube Refrigerator and is a refrigeration unit based on the thermoacoustic effect. It utilizes a compressor to convert electrical energy into acoustic energy, which is then converted into refrigeration by components such as pulse tubes and cooling heads that dissipate the heat through a cooler. The Stirling engine/pulse tube hybrid cooler combines the advantages of the Stirling engine and the PTR and excels in reliability, efficiency and compactness [6]. In order to improve energy conversion efficiency, a new active phase shifter called AWPS has been developed. AWPS introduces a power recovery device into the cooling system that reuses the acoustic power dissipated as heat at the hot end, thus providing additional cooling capacity. In this way, the cooling system can provide cooling in two different temperature regions at the same time by testing three well-designed phase shifter types: ITR, APS and AWPS [7]. As shown in Fig. 14, the relationship between phase shifter type and power is shown, where rCOP denotes the relative Carnot effect. The rCOP of AWPS is significantly higher than that of ITR and APS. Therefore, the efficiency of the Stirling-type PTR can be effectively increased by using the AWPS phase shift.

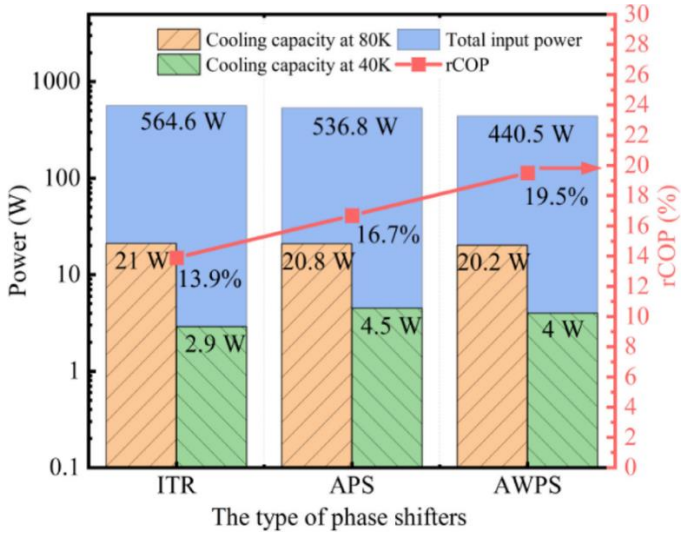

Fig. 14 Relationship between different types of phase shifters and power [7]

4. Future Development Areas

4.1. Optimizing Stirling Engines Using the Artificial Neural Networks Algorithm

Artificial Neural Network (ANN) is a computational model that mimics the structure and function of biological neural networks. Neural networks can learn to perform various tasks by training on large datasets. Therefore, combining artificial neural networks with Stirling engines and training large datasets through neural networks can learn and predict the optimal operating conditions of Stirling engines. This not only improves engine efficiency and performance but also reduces noise and emissions. In addition, by using neural network algorithms to monitor the operating status and performance data of the engine, potential faults can be detected, and maintenance measures can be taken in advance, thereby improving the reliability of the engine and reducing maintenance costs. However, there is currently relatively little research literature in this area, so there is still great room for development [8].

4.2. Fuel Cell Stirling Engine System

The Fuel Cell Stirling Engine System is a hybrid system that combines a fuel cell and a Stirling engine. This system leverages the operational principles of The system to realize the joint generation of electricity and heat by combining the working principles of the fuel cell and Stirling engine. Technologies to achieve simultaneous electricity and heat generation. A fuel cell is an electrochemical device that converts hydrogen and oxygen into electrical energy. In the fuel cell Stirling engine system, the fuel cell generates electricity to meet the electrical demand while also producing a substantial amount of waste heat.

On the other hand, a Stirling engine is a thermodynamic cycle engine that utilizes temperature differences to produce mechanical work. In the fuel cell Stirling engine system, The waste heat produced by the fuel cell is utilized by the Stirling engine, converting it into additional electricity or fulfilling other thermal energy requirements. Composite systems offer environmental and energy efficiency advantages. The fuel cell's electricity and waste heat are effectively utilized by the Stirling engine, ensuring efficient energy utilization. Moreover, the fuel cell Stirling engine system operates with minimal pollutant emissions and has a low environmental footprint, positioning it as a sustainable energy solution [9].

4.3. Nuclear-Powered Stirling System

Nuclear-powered Stirling system is a Stirling engine system that utilizes nuclear energy to power the system. It achieves energy conversion by converting nuclear energy into thermal energy and using

Stirling engines to convert the thermal energy into electrical energy. The nuclear-powered Stirling system is characterized by high efficiency, high power density and compactness, and therefore has the potential to provide a long-term reliable power supply system. This makes it valuable for important applications in space exploration missions. However, the research and evaluation of nuclear-powered Stirling systems face a number of challenges. First, due to the special nature of nuclear energy, nuclear-powered Stirling systems are difficult to measure experimentally. Therefore, current research mainly relies on numerical simulation and computational methods for the evaluation and analysis of system performance. In order to further improve the design and performance of nuclear-powered Stirling systems, people need to understand better the thermodynamic properties and loss mechanisms of the systems. By thoroughly investigating the thermodynamic processes, heat transfer and heat radiation losses of the system, the potential room for optimization of the system can be revealed. This understanding can guide the development of more efficient and reliable nuclear-powered Stirling systems and a more reliable power supply for space exploration missions [10].

5. Conclusion

With the development of society, the increase in demand for energy has become a key issue. The Stirling engine, as an efficient energy converter, is capable of utilizing various sources of energy in life. Therefore, this paper aims to explore ways to improve the thermal efficiency of Stirling engines and to point out relevant areas for further in-depth research in the future.

Firstly, studies have shown that increasing the number of secondary regenerators can be effective in improving thermal efficiency. But its corresponding cost will also increase. Therefore, a balance needs to be found between economy and efficiency. In addition, there is a material called Convective Meta-Thermal Concentration (CMTC) that modulates the temperature distribution of heat exchange fluids, thereby enhancing the heating and cooling processes of Stirling engines and thus improving thermal efficiency. Recent findings have shown that CMTC can increase efficiency by up to 1,460 percent. In addition, it has been shown that the use of a high polarity regenerator and a regenerator of appropriate length can optimize power output and thermal efficiency in a high-speed GPU-3 Stirling engine.

For solar Stirling engines, new heat transfer fin shapes can effectively increase efficiency. Recent research also suggests that installing such fins in solar Stirling engines could increase power output by at least 15 percent. On the other hand, combining a pulse tube refrigerator (PTR) in a Stirling engine and utilizing AWPS phase shift can effectively improve cooling. In future development, the optimization of Stirling engines using artificial neural networks, the combined use of fuel cells and Stirling engines, and nuclear-powered Stirling engine systems are all worthwhile areas of development and have promising application prospects.

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