Promising Stirling Engine: Advancement and Applications

Cheng Yang*
School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, 710049, China
*Corresponding author: 1484324939@stu.xjtu.edu.cn

Abstract. Due to the merits of simple structure and high efficiency, the Stirling engine has been considered to have great potential since its invention. This paper provides a literature review on the Stirling engine's recent advancement in models, configurations and analysis methods. Applications of Stirling engines under the overall background of global warming, pollution and space exploration are also covered. Some basic knowledge about the Stirling engine, such as history, basic configurations and theories are also introduced. The objective of this research is to assess the Stirling engine's value in today's society and stimulate inspiration for future development so as to make full use of the Stirling engine's advantages. The conclusion is that many advancements of the Stirling engine are still being proposed, and future applications of the Stirling engine are still promising, especially when humanity is now facing so many problems that have posed threats to people's health and the natural environment. Some possible future developments are mentioned in the conclusion for further discussion in the future.

Keywords: Stirling engine; advancement; application.

1. Introduction

The Stirling engine is a highly efficient machine using the Stirling cycle whose theoretical efficiency can equal to Carnot cycle. However, when the internal combustion engine started to progress, the disadvantages of low power output, demanding heat resistance of the material and other problems kept the Stirling engine from being widely used. Later, with the development of heat-resisting materials and new energy, the Stirling engine was able to use its advantages to solve or relieve some serious problems. Global warming is a serious problem mankind is now facing. Statistics in Fig.1 show that the average global surface temperature has been rising since the 1940s.

An estimation from the research also shows that in the late 21st century, the global temperature will rise about 1-3.9 ℃, causing irreversible climate change, which could lead to severe consequences for human society [1]. In addition, global warming has also caused glacier melting and sea levels to rise, threatening the natural environment. The main cause of global warming is actually moisture [2]. Normally, global warming won't happen only when the concentration of water is increasing. However, as the density of greenhouse gases continues going up, the temperature of the atmosphere keeps rising, which enhances the atmosphere's capacity to contain water vapor, leading to global warming [3]. This means necessary actions should be taken to reduce the emission of greenhouse gases. Stirling engine's ability to use any heat energy source can cut down the use of fossil fuels, which could reduce the emission of greenhouse gases.

Besides global warming, pollution is also a major problem for today's society. Among all of the main risk factors, pollution possesses a much greater impact on people's health, as shown in Fig. 2 [4]. Obviously, the causes are also human's agricultural and industrial activities. Conclusions from the research declare that traffic congestion, traffic mode and the expansion of city scale could significantly intensify air pollution [5]. Fortunately, many countries have started to develop new energy like solar energy. These energies can be used as heat sources for Stirling engines with less harmful emissions, offering an effective way to mitigate pollution.

Further, although the interest and the demand for space exploration are increasing, some critical problems are still getting in the way. One of them is how to supply energy for the areas where solar energy is not available. In this situation Stirling engine combined with nuclear energy can solve the problem easily with the reliability, self-starting ability of the Stirling engine and the durative of nuclear energy in space [6]. This combination also has the potential to provide power for humanity's further exploration into deep space.

The objectives of this report are to explore the Stirling engine's value under the overall background of global warming, severe pollution and space exploration. To achieve this purpose, this paper provides basic knowledge about the Stirling engine's history, theories and different configurations. Recent technology advancement and diverse applications of Stirling engines are also covered. It is hoped that this report can reveal the value of the Stirling engine and provide inspiration for further advancement.

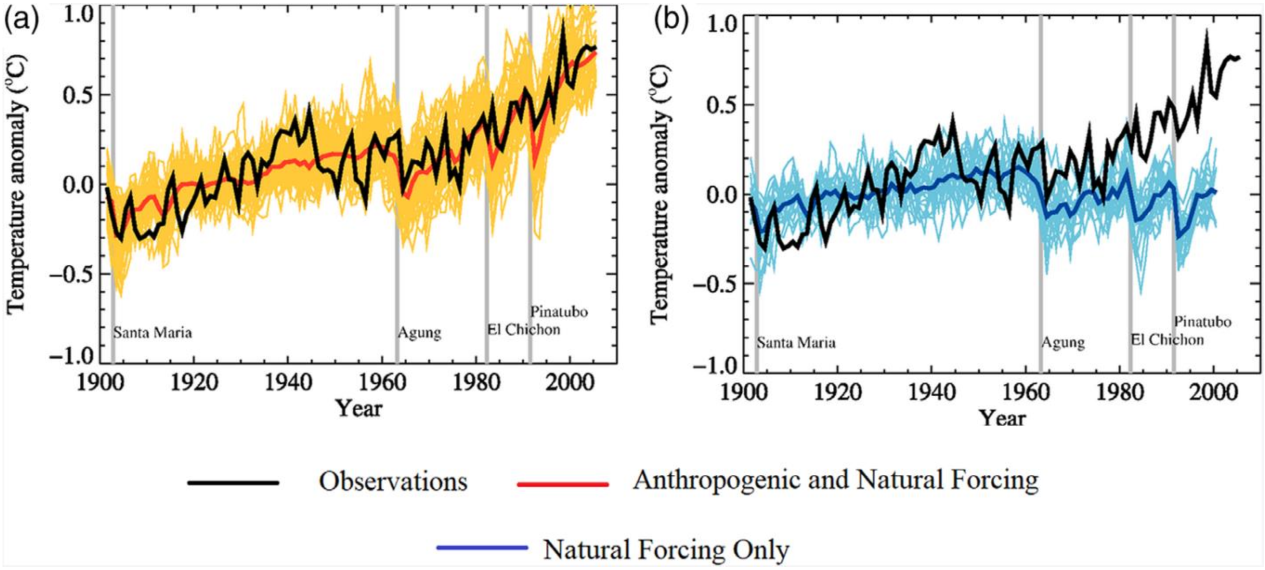

Fig. 1 Observed global temperature anomalies and the simulated anomalies driven by both natural and human forces and driven by only natural forces [3]

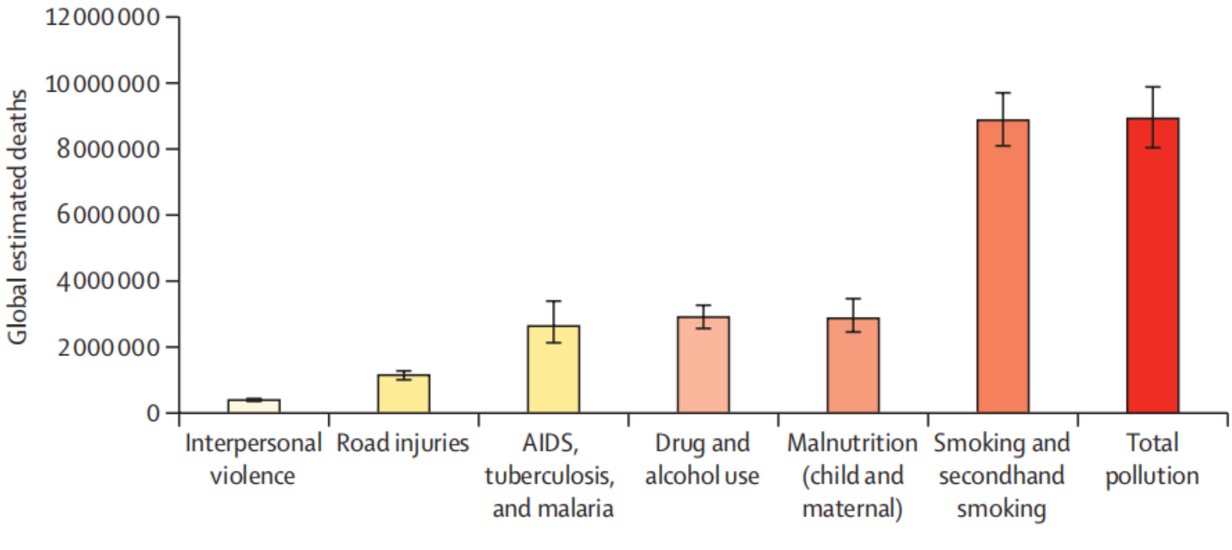

Fig. 2 Estimated global deaths caused by major risk factors [4]

2. Basics of Stirling Engine

2.1. Development History

The first heat engine to use a regenerative cycle was the Stirling engine, which was invented in 1816 by Robert Stirling. When first invented, the Stirling engine was very small and had a very low power output [7]. As a result, when electric motors and internal combustion engines started to develop rapidly, the Stirling engine's development was overlooked. In 1937, the Philips Research Laboratory further developed the Stirling engine to a higher level. Since then, the advancement of the Stirling engine has been non-stop. Early Stirling engine projects were mostly about the improvement of small electric generators and machinery used in distant and rural places [7]. In the 1950s, NASA started to study the Stirling engine with the purpose of developing a highly effective aero-engine that produces minor noise. What's more, General Motors also signed a contract with Philips to study the applications of the Stirling engine in cars and other variations of the Stirling engine in 1958. Projects for improving the Stirling engine kept progressing until today.

2.2. Different Configurations of Stirling Engine

A power cylinder, a displacer piston, a power piston, a heater, a regenerator, and a cooler are the conventional components of a Stirling engine [7]. The expansion and compression of the working fluid happen in the cylinder with a power piston. The working fluid is transferred through the regenerator, cooler and heater at a consistent volume using the displacer piston. Basically, there are three common configurations-alpha, beta and gamma as shown in Fig. 3.

For alpha configuration, a displacer piston is taken out. Instead, there is a hot piston and a cold piston, which could provide constant-volume heating and cooling processes for the fluid. Compression is done on the cold side, and expansion is done on the hot side when the fluid is completely in one cylinder. During the compression or expansion, one piston is held stationary while the other one moves. The advantage of alpha configuration is that the insulation between the cold side and hot side is better, which could gain a higher temperature difference and enhance thermal efficiency. However, it also requires demanding impermeability, which would result in increasing frictional damping in the engine [8].

For beta configuration, only a single cylinder contains both the power piston and displacer. The power piston is used to expand the fluid when it's moving to the hot side and compress the fluid when it's in the cold side. The displacer is employed to transfer the fluid through the heater, regenerator and cooler from and to the hot side and cold side. As a result of the incorporation of the two pistons, this configuration could be more compact but also requires a more complex power transmission system [8].

For gamma configuration, the power piston and displacer are used for identical purposes in beta configuration but with separate cylinders for each piston. Theoretically, this configuration has the highest possible efficiency with fairly good self-pressurization. However, for the purpose of reducing bushing friction, the cylinders are required to be in vertical type [7].

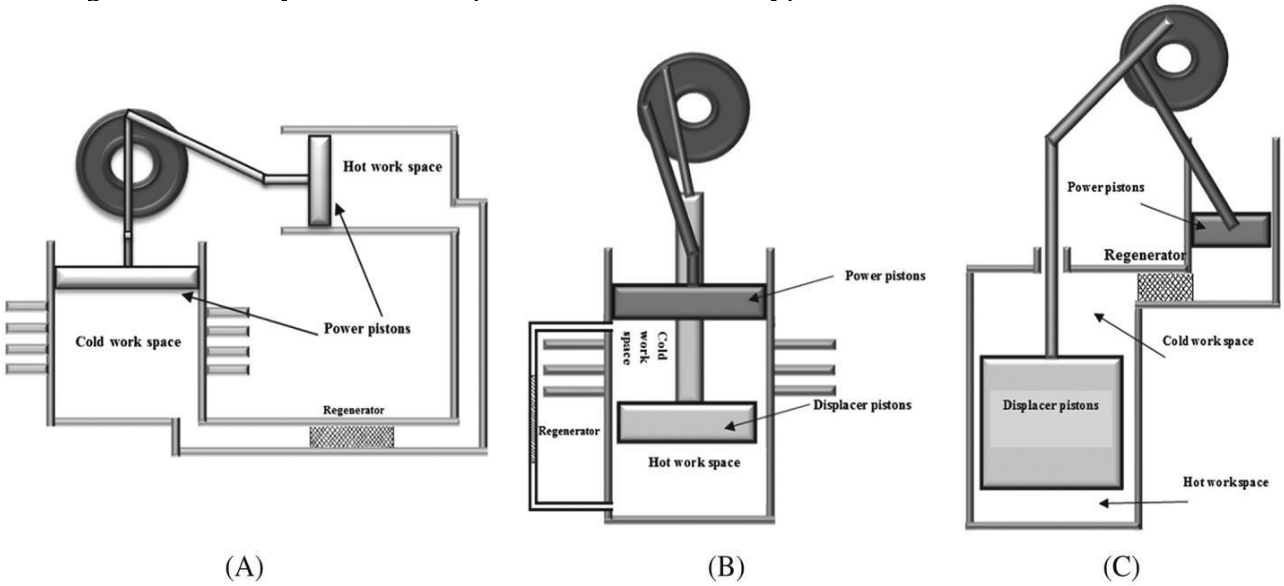

Fig. 3 Three different configurations of the Stirling engine [8]

2.3. Theories about the Stirling Cycle

As shown in Fig. 4, isothermal compression, constant-volume heating, isothermal expansion and constant-volume cooling are the four ideal processes of the Stirling cycle. Analysis of the ideal situation of the four processes is as follows. For isothermal compression process 1–2, after the working fluid was chilled in the regenerator and pushed to the cylinder's cold side in process 4–1, the displacer remained stationary in the top dead center (TDC). Then, powered by the momentum of the flywheel, the power piston is forced to its TDC from its bottom dead center (BDC), compressing the working fluid from state 1 to state 2 under a constant temperature of T1. For constant-volume heating processes 2–3, after the compression of the fluid, the power piston reaches its TDC and keeps at rest, waiting for the pressure to increase from the fluid's expansion. Drawn from the cold side, the fluid runs through a regenerator with heat absorbed from process 4-1 into the hot side as the displacer transitions from TDC to BDC at the same time.

For isothermal expansion processes 3–4, after the pressure increases to its maximum, the power piston is pushed to BDC from TDC, creating mechanical energy and driving the flywheel to move while the displacer stays still at BDC. Meanwhile, the fluid is expanding with the heat absorbed from the hot side, maintaining a constant temperature of T4. For constant-volume cooling process 4–1, the power piston is held immobile at BDC following the expansion of the working fluid while it waits for the flywheel's momentum to propel it back to TDC. The displacer is simultaneously switching to its TDC from BDC, forcing the fluid through the regenerator, where the fluid is cooled and heat is absorbed. Then, the fluid comes back to state 1 on the cold side, and the second cycle starts. With ideal regeneration, the heat released from the constant-volume cooling process can be applied to the constant-volume heating process. As a result, the cycle's efficiency only relies on the heat absorbed from outside and the work produced, which is the same as the Carnot cycle. Under real situations where extreme regeneration is unable to be achieved, the required heat from the external heat source is still greatly reduced, and the thermal efficiency is improved.

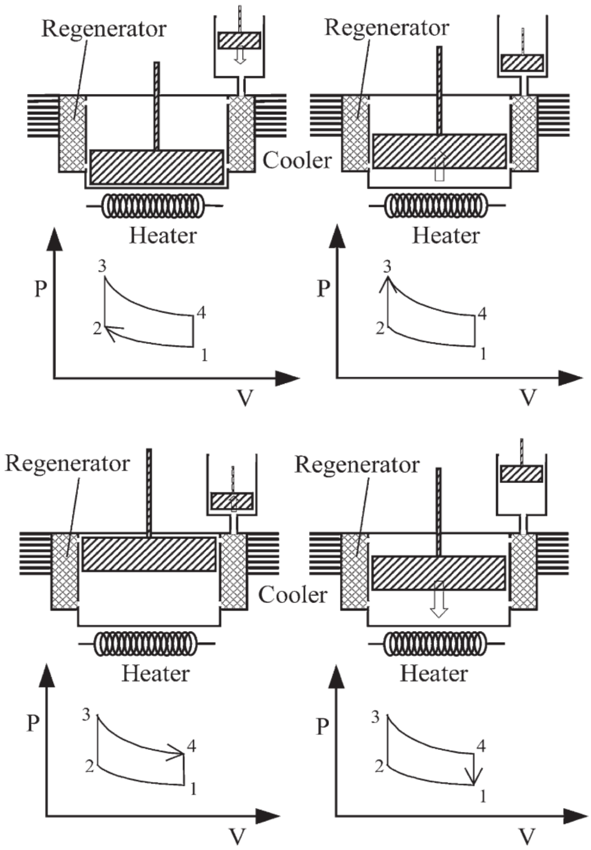

Fig. 4 Stirling engine operation [7]

3. Recent Advancement

3.1. Advancement in the Configurations

For the purpose of further improving the efficiency, reliability and other properties of the Stirling engine, many advancement has been made. Paul et al. developed a method to optimize the Stirling cycle cryocoolers' piston paths [9]. Based on the theory of optimal control, researchers optimized the piston paths using an indirect gradient method. The model contains a series of coupled ordinary differential equations while considering a few loss phenomena. It's concluded that this optimization could offer potential improvement of COP and cooling power.

Zhao et al. presented a variable trajectory α-Stirling engine that can realize the active control of piston displacement by controlling the length of the double piston connecting rod and thus enhancing the thermodynamic performance [10]. This research put forward a parametric piston trajectory control method, established a curve design simulation algorithm and studied the influence of piston trajectory and orbit change on output performance. The performance test platform was also built to testify to the numerical calculation. The results showed a higher net output than the traditional fixed-phase engine.

Liu et al. designed a hundred-watt β type Stirling engine, carried out a three-dimensional numerical simulation and built an experimental system with heat and temperature control and data acquisition [11]. The experimental and numerical simulation results showed great consistency. Based on the jet phenomena that happen inside the Stirling engine, the researcher optimized the heat transfer and structure of the regenerator and found an optimal porosity value of 0.798 and a suggested optimal ratio of regenerator gap length λ (0.037-0.130).

3.2. Advancement about Analysis of Stirling Engine

Since the analysis of Stirling engines is essential to its further improvement, many advancements in the methods of analyzing the Stirling engine have been made. WU et al. researched to analyze the thermodynamic cycle of a Stirling engine with low-temperature differential using the second-order Simple model [12]. Researchers analyzed the pumping loss, heat return loss and actual heat transfer by deriving the actual heat transfer equation of a non-ideal heat exchanger in a Stirling engine with a low-temperature differential. The Simple model's accuracy was testified by comparing the calculated output power of the low-temperature differential Stirling engine with the actual results under different heating temperatures. The errors are fairly small, which verified the Simple model's accuracy.

Kommadath et al. optimized several parameters of three different types of Stirling engines using Single Phase Multi-Group Teaching Learning Based Optimization (SPMGTLO) [13]. Varying from the Teaching Learning Based Optimization (TLBO), SPMGTLO has a relatively lower computational complexity. Several groups were divided, and the teaching phase and the learner phase were updated solely. The results showed that the ability of SPMGTLO to converge faster and resolve a better solution could outperform the genetic algorithm function, which is built into MATLAB, indicating its supremacy in optimizing the Stirling engine.

4. Diverse Applications

4.1. Applications of Stirling Engine in a Micro Combined Heat and Power System

A micro combined heat and power (CHP) system using a Stirling engine was proposed in 2020 [14]. The system uses methane and bio-syngas as heat energy sources. A perforated platinum tube was employed in the system and cofired with a mixture of air and methane to alleviate variability of the fuel and intermittent supply. Natural gas will be transferred to the micro-combustor's outer chamber, while the bio-syngas, such as a hydrogen/carbon oxide-air mixture, will be transferred into the inner chamber. As Fig. 5 shows, the platinum reactor will provide heat to the Stirling engine's hot side and also to a thermophotovoltaic (TPV) cell array, which can convert heat into electricity.

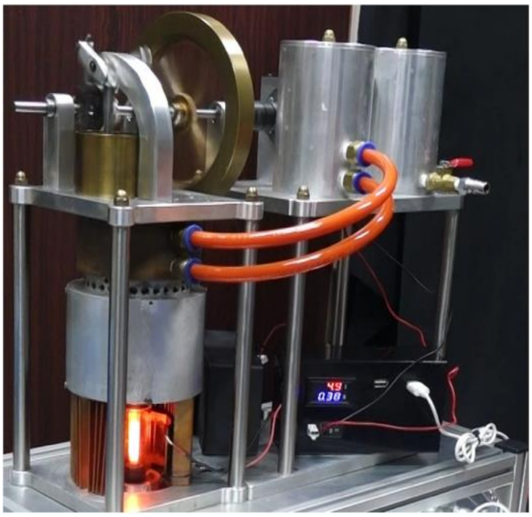

Fig. 5 Micro-CHP system made up of an array of TPV cells, a power generator and a Stirling engine [14]

Such a system like this has many advantages. Firstly, as the experimental results listed in Table 1, it is a highly efficient system with an overall efficiency of 35% with a fuel composition of 50% hydrogen and 50% carbon oxide. Secondly, the system has a simple structure and is very reliable under various fuel composition, which means it can be applied in rural and remote areas where bio-syngas and natural gas is abundant. Also, since it uses a cleaner energy source, there is less greenhouse gas emission and pollution.

Table 1. Experimental results of the Micro CHP system [14]

H2:CO	30%:70%	50%:50%	70%:30%
Energy acquired by water (W)	303.5	272.1	261.6
Electric power efficiency (η_e)	0.63	0.58	0.52
Overall efficiency ($\eta_{t,CHP}$, %)	39.4	35.0	33.3

4.2. Applications about Stirling Engine in Space

A free-piston Stirling engine (FPSE), which uses nuclear energy in space, was introduced in a 2021 research [6]. Fig. 6 shows the basic structure of the FPSE. The FPSE is connected to the heat pipe reactor with a heat pipe, and heat will be conveyed to the FPSE's hot side. Then, the waste heat will be rejected from the cold side through a radiator or cooling loop. Table 2 presents the main parameters of FPSE, and its designed power is 20kW. According to the numerical result of 21kW, the power output of the FPSE could satisfy the requirement.

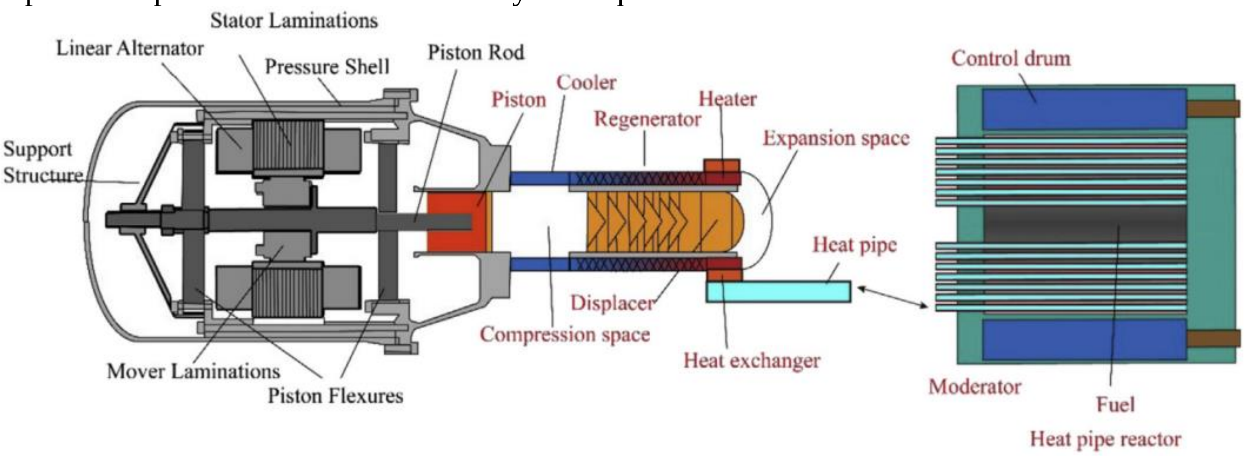

Fig. 6 FPSE assembled with a heat pipe reactor [6]

Table 2. Main parameters of FPSE [6]

parameter	value
Displacer phase angle (°)	90
Frequency (Hz)	70
Design power (W)	20,000
Efficiency (%)	30.6
Average pressure (MPa)	10

This type of Stirling engine could solve the energy supply issue in light-less areas. For example, on the south pole of the moon, a lunar night could last for 14 days. In this case, the Stirling engine combined with nuclear energy can solve the problem easily. Because the Stirling engine has a simple structure, a prompt start-up cycle and produces only minor vibrations and less noise, it's reliable for long-term use. There would also be almost no emissions and pollution since nuclear energy is clean. The result of the numerical simulation in Table 2 shows that the efficiency is about 30.6% percent, which could almost rival solar power. Thus, using the Stirling engine could be a pragmatic substitution for solar power in space, giving humanity a chance to explore deep space.

4.3. Applications about a Tower-Type Light Gathering Power Generation System Using Free Piston Stirling Generator

A Tower-type light-gathering Stirling power generation system was presented in 2016 [15]. It uses a tower to collect light and a free-piston Stirling generator. The working fluid would absorb the heat from the light gathered by the tower and then be transferred to the hot side of the Stirling generator. Molten salt and supercritical water are chosen as the working fluid. That's because molten salt has a low melting point, which can help it stay liquid when functioning, and it requires lower pressure, which is safer and more reliable. Also, because molten salt has a high thermal inertia, the intermittent of the system will improve [16]. As for supercritical water, it's because it has high specific heat and thermal conductivity, and it's also cheaper than molten salt.

A system like this could effectively reduce the emission of greenhouse gases and pollution since solar power is very clean. It also has advantages over regular tower-type solar power plants. The regular ones use the Rankine cycle, which could produce a higher power output, such as the 100MW power plant in Gansu, China. However, it also has drawbacks - complicated structure, long production cycle and high initial investment. With the Stirling cycle, these problems can be solved easily and also have a higher efficiency, cutting down greenhouse gas emissions.

5. Conclusion

This paper introduced basic knowledge about the Stirling engine, provided recent advancements in the Stirling engine's models, configurations and analysis methods and presented future applications of Stirling engines. For the purpose of evaluating the value of the Stirling engine under the overall background of global warming, severe pollution and space exploration, several researches are described. Recent advancements in configurations are mainly about the optimization of piston paths, active control of piston displacement and improvement of the structure of the regenerator. Recent advancements in analysis methods are focusing on the second-order Simple model, and a special method - SPMGTLO, is also very promising.

Future applications proposed recently are a Micro CHP system using a Stirling engine, an FPSE using nuclear energy and a Tower-type light gathering Stirling power generation system. These applications could use the Stirling engine's high efficiency to reduce the emission of greenhouse gases and polluting substances. Space exploration could also progress further with these applications. The conclusion is that there is still much room for the advancements of the Stirling engine, and possible future applications of the Stirling engine can play an essential role in solving or alleviating the problems that have troubled humanity for decades.

However, Stirling engines still have some limitations. For instance, the power output is relatively low compared with other heat engines, it is complicated to design an FPSE, and the heat loss is still massive. For future development, it's possible to further improve the analysis method by using different models and algorithms. Optimization of the regenerator can still be further discussed. Stirling engines also can be applied as a cooler for electronic equipment such as servers.

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