Frontier Solar Stirling Engines: Technical Optimization and Wide Application

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Abstract. As an external gas turbine, the solar Stirling engine uses an external heat source to expand the gas in the inner cylinder to generate power. It can effectively transform solar energy into various kinds of energy and has a broad range of application prospects in the field of sustainable energy since its theoretical foundation is the Stirling cycle, which has the same thermodynamic efficiency as the Carnot cycle. This article elucidates the fundamental principles underlying the Stirling engine, provides an exposition on its three basic types, delves into potential constituent elements, explores avenues for optimization, showcases multiple exemplars of cutting-edge solar Stirling engine applications, and ultimately conducts a comparative assessment of the benefits and drawbacks inherent in solar power generation versus conventional thermal power generation methodologies. It is hoped that after understanding the innovative technology and application prospects of the solar Stirling engine, readers can better understand its importance and potential in the field of sustainable energy and optimize its structure or materials so as to promote the further development of solar Stirling engine.

Keywords: Solar Stirling engine; technical optimization; application; thermal power generation.

1. Introduction

Energy is a kind of substance that can release energy to nature. It can convert other forms of energy into the forms required by human beings through certain physical or chemical processes. It has promoted the economic development of the country to a great extent, and it is also the basis of various human activities. With the rapid development of the economy, energy and ecological problems have become more prominent, and the world is facing increasingly serious environmental and energy problems [1]. The energy crisis in 1973 made mankind more worried about the depletion of fossil energy. Based on the prevailing global demographic data, the temporal horizon within which petroleum resources remain accessible for human utilization spans approximately 45 to 50 years. Analogously, the reservoir of natural gas is anticipated to sustain viability over a duration ranging from 50 to 60 years. In contrast, coal deposits are envisaged to endure for a considerably protracted interval, estimated at approximately 200 to 220 years. The continuous use time of traditional energy is further shortened, so it is urgent to develop environmentally friendly new energy.

When discussing the current situation of new energy, solar power generation is undoubtedly one of the most noticeable fields. Because of its pollution-free and renewable characteristics, solar energy has become a popular new energy for sustainable development. Solar power generation is divided into photovoltaic power generation and photothermal power generation. Photovoltaic power generation has high costs and low efficiency, which may be limited by monocrystalline silicon refining technology and may cause lead pollution. On the other hand, solar thermal power generation technology mainly involves three stages: light collection, heat concentration and thermoelectric conversion. The latter stage involves the effective conversion of solar thermal energy into electric energy, and the process is propelled by a Stirling engine, constituting its central element.

The Stirling engine, a type of internal combustion mechanism, was conceived in the year 1816 by the distinguished British engineer Robert Stirling. It can widely use the external heat source to heat the closed gas, make it expand in the cylinder, drive the piston to move and output power, and has high energy conversion efficiency and reliability. Therefore, based on the above advantages of the Stirling engine, people hope it can become an important power device for solar energy utilization. In addition to solar power generation, solar Stirling engine can also be widely used in seawater treatment, aviation, agriculture and other fields [2-4]. Therefore, the research on solar Stirling engine technology is very important and has broad prospects.

2. The Theoretical Basis of the Stirling Engine

Stirling engines operate optimally according to the simplest form of the Stirling cycle, which is defined by the existence of two adiabatic as well as two isochoric processes. The Stirling cycle has the highest thermal energy conversion efficiency, according to conventional thermodynamic analysis, which also shows that it exhibits thermal efficiency that is identical to the Carnot cycle's. In order to simplify the whole process and make the actual functioning of the Stirling engine easier to comprehend, several assumptions and simplifications have been made.

2.1. Carnot Cycle

In 1824, Carnot conceived the Carnot cycle, an ideal operational paradigm for the steam engine, following an exhaustive investigation into the operational principles governing steam engines. In this cycle, the air in the piston cylinder assembly is regarded as a closed system. That is, the total air volume remains unchanged. The entire process assumes that the compression and expansion stages of the gas are adiabatic, meaning these stages, there is no heat exchange between the system and its external environment. In addition, all processes are considered internally reversible, which means that there is no energy dissipation. Finally, air is simulated as an ideal gas, which satisfies all properties of the ideal gas. At the same time, the effects of kinetic energy and potential energy are ignored.

The Carnot cycle comprises a pair of reversible isothermal transformations, together with a duo of reversible adiabatic alterations. Assuming that the initial process is constant temperature heat absorption, the cylinder is fully thermally conductive. In this process, the working medium per unit mass in the cylinder starts to expand and pushes the piston towards the outer dead center. At the same time, the working medium absorbs heat q_1 from the high-temperature heat source t_h, keeping the temperature unchanged throughout the process and reducing the pressure. Following the adiabatic expansion process, the cylinder is considered to be in a fully adiabatic state. The piston is further pushed to the outer dead center by the working medium, and the working volume of the cylinder reaches the maximum value. The temperature and pressure drop during this process, from t_h to t_c, and the pressure is the lowest of all processes. Then is the constant temperature heat release process. The cylinder has strong thermal conductivity again. The piston compresses the working medium and pushes it towards the inner dead center. The working medium releases heat q_2 to the low-temperature heat source t_c. The process pressure increases, and the temperature remains unchanged, t_c. The final process is adiabatic compression. The cylinder is adiabatic, without heat exchange with the outside, and the piston continues its movement and comes to a halt at the inner dead center. Due to the action of the adiabatic cylinder, the temperature of the working medium will rise from t_c to t_h, and the pressure will also increase to the maximum value of the whole process, with the minimum volume. This culminates in the completion of a cyclic sequence, ultimately restoring the system to its initial configuration. The state parameter of the working medium changes to 0, which is expressed as,

$$\oint du = 0 \tag{1}$$

Thus, according to the first law of thermodynamics, the network (w_{net}) produced by a cycle is:

$$\mathrm{wnet} = \mathrm{q1} - \mathrm{q2} \tag{2}$$

The thermal efficiency (denoted as η) of a thermodynamic cycle is conventionally delineated as the quotient of the network output realized during the cyclic operation relative to the heat magnitude q_1 introduced into the working medium by the high-temperature thermal reservoir during the entirety of the cycle progression. That is:

$$\eta = \frac{wnet}{q1} = \frac{q1-q2}{q1} = 1 - \frac{q2}{q1} \quad (3)$$

In the graph with thermodynamic temperature as the ordinate and specific entropy as the abscissa (t-s), this expression will be expressed as:

$$\eta = 1 - \frac{tc\times(\triangle s)}{th\times(\triangle s)} = 1 - \frac{tc}{th} \quad (4)$$

The formula has no specific restrictions on the working medium. Consequently, the efficacy of heat utilization within the cycle, an intrinsic physical parameter, remains contingent solely upon the absolute temperature, denoted as t_h, of the elevated-temperature thermal source, as well as the absolute temperature, represented as t_c, of the lower-temperature thermal reservoir. Variations in the disparity between th and tc directly impinge upon the operational efficiency of the heat engine.

2.2. Stirling Cycle

The Carnot cycle boasts the peak efficiency among all cycles, but the thermal efficiency of other reversible cycles working at constant temperatures at both ends can also reach the same level as the Carnot cycle. These cycles also have two isothermal processes, but the other two processes can be other processes. The Stirling cycle is one of the special cases. When the two adiabatic processes of the Carnot cycle are changed into the Isovolume process, it is the Stirling cycle, which is also an ideal cycle for the Stirling engine [1,2]

3. Types of Stirling Engine

Stirling engine is an external combustion engine. It is mainly composed of a heating system, a closed circulation system (including five structures of a hot chamber, heater, regenerator, cooler and cold chamber), a transmission system and a regulation system. The transmission system also includes a piston rod, diamond mechanism and crankshaft. Stirling engine has a wide variety of structures, which can be divided into single-power engines and dual-power engines according to their functions. According to the different configurations of cylinder and piston positions in its structure, it is divided into three basic types, namely alpha Stirling engine, beta Stirling engine and gamma Stirling engine.

3.1. Alpha Stirling Engine

The alpha Stirling engine has two cylinders, which can be arranged in three ways: in-line, opposed and V-shaped. Both cylinders have a piston. For the piston located in the hot chamber, we call it the expansion power piston; For the piston located in the cold chamber, we call it the compression work piston. Their working principle is based on the constant temperature heater and cooler. A certain temperature difference is formed through the regenerator between the two so as to achieve the thermal balance between the hot chamber and the cold chamber. In this structure, the expansion power piston in the hot chamber pushes the piston to do work through the expansion of gas, while the compression power piston in the cold chamber does work on the rotating shaft through the cooling and compression of gas. In the Stirling cycle, the principle of operation is to increase the pressure of the heating element while reducing the pressure of the cooling element to facilitate the completion of the cycle process. To ensure optimum performance, the hot and cold pistons must have a specific phase difference. It has been confirmed that the optimal phase difference is 90 degrees in the working state [3].

3.2. Beta Stirling Engine

In comparison to the alpha type, the beta type circumvents the technical issues associated with thermal sealing. Characterized by a single cylinder, the beta engine functions by propelling the working gas towards the hot end of the cylinder, resulting in its expansion and subsequent pushing of the power piston outward to perform work. When the working gas is pushed to the cold end of the cylinder, it will shrink and push the power piston to compress the gas in the other direction [4]. The design of a single cylinder is conducive to saving space and improving space utilization. However, due to the low power of only one piston, it cannot be applied to large-scale solar power stations.

3.3. Gamma Stirling Engine

The traditional gamma-type Stirling engine is a variant of the beta-Stirling engine, and its power piston is located in a single cylinder, responsible for transmitting power to the external environment. The function of the other cylinder is to heat and cool the working gas at a constant volume. The power piston must fit closely with the cylinder wall to output power. The valve piston is located in the cylinder and divides the cylinder into two parts: a hot chamber and a cold chamber. The hot chamber is surrounded by the heater, where the working medium gas is heated and expanded and then enters the cold chamber after being allocated by the gas distribution piston to push the power piston to do work. After the work is done, the gas releases heat, is cooled by the cooler, and then returns to the cold chamber. After being prepared by the gas distribution piston, it returns to the hot chamber for heating and enters the next cycle. Compared with the beta engine, the gamma-type Stirling engine reduces the technical difficulty and production cost and has economic advantages. It is easier to realize miniaturization so as to realize multiple applications. It is an obvious application direction to assemble it into an engine group and apply it to a solar power station.

4. Optimization of the Stirling Engine

4.1. For Alpha Stirling Engine

In the academic field, there is a growing interest in the study of alpha Stirling engines, mainly due to their potential applications in small-scale concentrated solar power generation devices (with output power between 15-30 kW). Nonetheless, it remains an insurmountable challenge for any engine to attain the energy conversion efficiency exhibited by the Carnot cycle. In the relentless quest to enhance the operational effectiveness of the Stirling engine, the employment of computer-assisted engineering (CAE) techniques in the domains of computational modeling, empirical investigations, and comprehensive scholarly inquiries have demonstrated its formidable efficacy. Notably, Alberto Boretti has introduced a CAE framework tailored for the alpha-type Stirling engine that operates with hydrogen as the primary working fluid. This framework comprehensively encompasses the constituent elements, namely, the hot cylinder, the cold cylinder, and the regenerator [5]. The heat fluid temperature of the engine is 800 ℃, and the energy conversion efficiency is as high as 42%, which is much higher than the efficiency of the current air micro turbine, which may only be about 20% at lower temperatures.

In terms of increasing the average power output, changing the movement mode of the piston seems to have a significant effect. Robin et al. proposed an optimized sinusoidal piston motion (OS) [6]. This method can still maintain good performance under adverse conditions, and the average power output has an amazing increase. In the basic case, no friction loss and heat and mass transfer coefficients are selected. Further power output increase will not significantly improve. After the optimization of piston motion, the average power output can be increased by about 50%. This notable advantage arises from the augmented temporal pressure variations within the system resulting from piston displacement, thereby rendering the process more closely approximated to the ideal Stirling cycle.

4.2. For Beta Stirling Engine

Beta Stirling engines can be applied in many aspects, such as concentrated solar power generation systems. Therefore, designing the connecting rod transmission mechanism of the kW class beta engine into a diamond shape is the optimal solution. Due to its superior kinematic properties and heightened operational efficiency, the resultant force applied by the piston upon the cylinder's inner surface diminishes significantly, consequently mitigating frictional losses [7].

Yang et al. Simulated the shaft power and speed of the engine by using the energy method and the improved non-ideal adiabatic model and found that under certain conditions, the engine with this mechanism could reach the instantaneous maximum power of 1312 W at 1390 RPM [8]. The results show that the maximum shaft power, thermal efficiency and mechanical efficiency of the prototype are further improved.

In the thermal application of the sun, the receiver and reactor receive highly centralized sunlight to heat the working fluid. Chang Huawei et al. Used quartz glass window and secondary reflector to improve the receiver of this engine and considered the influence of key factors such as temperature [9]. The investigation demonstrates the efficacy of this approach in mitigating thermal losses, underscoring its profound importance in gaining a comprehensive insight into the transfer of heat processes intrinsic to the receiver component of the solar-powered Stirling engine. At the same time, it also provides a practical design reference for engineers and technicians in related fields in order to achieve a more efficient and reliable Stirling engine.

4.3. For Gamma Stirling Engine

In the context of the Gamma-type Stirling engine, the function of the valve piston is to facilitate the transfer of thermally expanded gas from the hot chamber to the cold chamber, enabling the transmission of work onto the power piston. Subsequently, it orchestrates the redirection of the cooled gas back to the hot chamber, initiating the reheating process for the subsequent cycle. However, this setting may cause a large amount of heat to disappear through the conduction of the cylinder wall, and the selection of regenerators is also very important, which is limited by their material selection. To enhance the operational prowess of the propulsion system, contemporary investigators have recently introduced an innovative engine architecture featuring a triad of cylinders, as documented in reference [10]. The three cylinders of this engine are responsible for heat capacity, cold capacity and power output. In this particular engine configuration, each of the three cylinders is coupled with a traditional piston assembly. Because its thermodynamic process is similar to the traditional gamma engine, it is called a three-cylinder gamma engine. In the node thermodynamic analysis, compared with the traditional gamma engine, the cycle work and thermal efficiency of this new engine are very close. Under high speed and high-pressure conditions, the performance of the traditional gamma engine is slightly better. However, under a high compression ratio, the performance of the three-cylinder gamma engine is better than that of the traditional gamma engine.

4.4. For Regenerator

The importance of regenerator has been mentioned in many papers above. System for producing Stirling thermal electricity from dish solar energy, the key component is the Stirling engine (because it converts heat energy into other forms of energy). In the configuration of a Stirling engine, the regenerator assumes a pivotal role, exerting direct influence over both the power yield and operational efficacy of the Stirling engine. Furthermore, the regenerator exerts a substantial influence on the amelioration of thermal dissipation within the engine, thereby consequentially impacting the workload imposed upon the heating and cooling apparatus. The regenerator of the Stirling engine can adopt a cylindrical or annular packaging structure. Engines with cylindrical regenerators can be equipped with multiple regenerators at the same time, while engines with annular regenerators usually surround the regenerator outside the power piston or valve piston. In addition, the structure design and material selection of the regenerator are also various. From the classification of materials, there are stainless steel alloy mesh type, foam metal types, felt type, etc.; There are tube bundle type, parallel plate type and so on. In the experiment, four Stirling engine regenerators of different materials were tested, including stainless steel, copper, aluminum and Monel 400 [11]. Monel 400 stainless steel and copper-based regenerators exhibit superior thermal efficiency and engine deceleration capability, albeit they are susceptible to swift oxidative degradation when exposed to oxygen.

In contrast, although recycled aluminum is not easy to oxidize, its melting point limits its use. After the test, the stainless steel with 85% porosity showed the maximum braking power and engine efficiency. When subjected to the extreme operating parameters of a maximal heating temperature of 500°C and the highest initial charge pressure of 8 bar, the stainless steel regenerator boasting an 85% porosity attains the pinnacle of Stirling engine performance, yielding a braking power output of 320 watts and achieving a Carnot efficiency exceeding 26%.

5. Wide Application of Solar Stirling Engine

The most common application of the solar Stirling engine is the dish Stirling solar power generation system. Because of its high photoelectric conversion efficiency, modular installation, and flexible use of heat sources such as fuel energy and biomass energy in addition to solar energy for power generation, it is favored by people. The dish Stirling solar thermal power generation system mainly includes the following components: a dish condenser, which is used to gather sunlight; a sunlight receiver for receiving and converting into heat energy; a hot gas engine, driven by heat energy; and a generator that converts heat energy into electricity. During operation, the sunlight enters the sunlight receiver through the focusing effect of the dish condenser, converts it into heat energy, becomes the heat source of the heat engine, drives the heat engine to run, and then drives the generator to generate electricity. For example, the solar disk gamma Stirling system can be used in Turkey's small-scale solar Stirling system for power generation. The researchers put forward that the installation cost is basically reasonable, and the concentrating ratio of the system is 94 times higher, so the maximum output power can reach about 250 W [12]. Under the local climate conditions, the annual power generation is close to 408.07 kWh. The total efficiency of the designed system is 17%

The potential of solar energy as a renewable energy is being recognized. It can not only solve the energy shortage but also provide the heat source for seawater desalination. Researchers proposed an innovative integration strategy that combines the adsorption-based desalination system (ADS) with the solar dish/Stirling engine (SDSE) [13]. Compared with separate SDSE and ADS cycles, ADS-SDSE can generate more power and fresh water, providing a feasible scheme for the production of power and fresh water in remote coastal areas.

Scholars have introduced a novel system within the realm of wind energy, comprising an adept parabolic solar dish Stirling engine coupled with a horizontally oriented wind turbine, harmoniously integrated with a compact battery unit, as elucidated in reference [14]. This innovative solar/wind turbine system has higher efficiency and financial competitiveness and is expected to replace traditional hybrid systems, such as typical photovoltaic/wind energy modules. Through simulation and field tests, the economic evaluation shows that the system has strong competitiveness and significant advantages compared with other comprehensive renewable energy technologies.

6. Thermal and Solar Energy Generation in Comparison

In China, thermal power still dominates because China has abundant coal resources and a stable supply. Nevertheless, to address the escalating requirement for sustainable energy sources, the utilization of solar Stirling generators emerges as a viable proposition. When juxtaposed with conventional thermal power generation, solar-based power generation boasts conspicuous merits alongside minor trade-offs.

As far as coal power generation is concerned, its advantages mainly lie in rich resources, stable supply and low cost. As one of the fossil energy, coal reserves are relatively rich, which can provide a stable guarantee for power production. In addition, the cost of coal power generation is relatively low, and the technology is mature, which can realize large-scale power production. However, the disadvantages of coal power generation cannot be ignored. First of all, the coal combustion process will produce a large number of carbon dioxide and other greenhouse gases, causing serious pollution to the environment. Secondly, the consumption rate of coal resources is fast, which is not conducive to the sustainable use of resources. Furthermore, the extraction and conveyance of coal will exert a discernible influence on the ecological milieu. In contrast, solar power generation has obvious advantages of environmental protection, pollution-free, renewable and sustainable use, and can reduce the dependence on fossil fuels. In addition, with the continuous development of technology, the cost of solar power generation is gradually reduced, and the power generation efficiency is also continuously improved.

The dish-type solar Stirling engine system is an efficient and flexible form of power generation. The biggest advantage of this system is that it can directly convert solar energy into electricity without any intermediate links, so the efficiency is very high. A study has revealed that at an absorber temperature of 850 Kelvin and a concentration ratio of 1300, the pinnacle of efficiency in the dish-type solar Stirling engine system is attained, reaching an approximate zenith of 32%, as expounded upon in reference [15]. This data is astonishing because it implies that this system can efficiently convert solar energy into electrical energy. However, solar power generation also has some limitations, such as greater weather impact and poor stability. Furthermore, solar energy generation necessitates substantial land allocation, with its power production intricately entwined with solar exposure duration. Additionally, the fabrication and processing of photovoltaic cells invariably exert discernible ecological repercussions.

Consequently, within the context of China's energy landscape, coal-based power generation and solar power generation stand as two primary energy supply modalities, each occupying an indispensable niche within their respective domains. During the critical period of energy transformation, it is essential to fully understand and leverage the advantages of diverse energy supply modes. With solar power as the primary source and integrated with wind power and other means, the sustainable development of electricity production can be achieved. At the same time, research and investment in relevant fields should be strengthened to promote the innovation and progress of energy technology so as to build a green and efficient energy system.

7. Conclusion

The Stirling engine derives its theoretical underpinning from the Stirling cycle, which shares an equivalent thermal efficiency with the Carnot cycle. Consequently, it harbors the inherent potential for the efficient transformation of thermal energy into kinetic energy. It can be applied to all kinds of energy, and the noise generated in the working process is relatively low, so it has broad application prospects in the field of sustainable energy. As an illustration, the solar Stirling engine exhibits the capability to transmute solar radiance into mechanical force, subsequently engaging the generator in a direct manner for electricity generation. Thermal power generation, on the other hand, uses fossil fuels (such as coal) to generate heat energy, which heats water into steam, thus driving the turbine to rotate to generate electricity. This power generation mode has the disadvantages of large resource consumption, serious environmental pollution and high cost. Even though there are many coal resources, these fuels are non-renewable and have limited reserves.

In contrast, using a solar Stirling generator to generate electricity has the advantages of clean, environmental protection and safety. The solar Stirling engine can also be linked with other systems, such as wind power generation and seawater desalination. It can produce electricity and freshwater with higher efficiency and may also have a competitive advantage in cost. However, based on the current research progress of Stirling solar engines, there are still many components that can be optimized. For example, the basic structure of the Stirling engine can be selected. Each structure has different characteristics and is suitable for different occasions. Although they are simple in structure, it is not easy to select the materials of their key components (such as regenerators) and research and develop their structural forms. It not only leads to high costs but also directly affects the efficiency of solar Stirling power generation systems. In the future, it is hoped that more researchers will further explore the optimal design of solar Stirling engines to improve their energy efficiency and stability.

Exploring the potential for this technology's use in distributed energy supply, marine energy utilization, aerospace, agriculture, and other fields will help to promote the continued growth of the solar Stirling engine as technology advances and costs fall.

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