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Stirling engines: Advancements, applications, and environmental benefits

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Abstract. The increasing adoption of Stirling engines in contemporary industries is driven by their potential to address critical issues of energy efficiency and emissions reduction. Stirling engines offer higher energy efficiency, lower noise and emissions, and versatility in utilizing various heat sources, making them a promising solution for enhancing environmental preservation and energy diversity. This paper examines the growing adoption of Stirling engines in diverse industries, driven by the urgent need to address energy efficiency and emissions challenges. The paper outlines the core principles and advantages of Stirling engines, highlighting their potential to enhance energy efficiency, preserve the environment, and diversify energy sources. Furthermore, the paper underscores significant industrial and aviation applications of Stirling engines, particularly in vehicle propulsion, heat pumps, and electricity generation. Notably, the automotive Stirling engine excels in fuel efficiency and emissions reduction, offering a viable alternative to traditional internal combustion engines. Stirling engines also prove effective in heat pump systems, contributing to efficient building heating and cooling. In conclusion, despite challenges such as material requirements and heat loss, Stirling engines hold great promise as sustainable and eco-friendly thermal engines. As global concerns regarding energy and the environment intensify, Stirling engines offer a compelling pathway to improved energy efficiency, reduced emissions, and a more diversified energy landscape, driving innovation across sectors.

Keywords: Stirling Engine, CO_2 Reduction, Stirling Engine Application

1. Introduction

In contemporary times, an increasing number of industries are embracing the adoption of Stirling engines. This trend is driven by the recognition that Stirling engines are poised to emerge at the forefront of thermal generation, primarily due to their capacity to conserve energy and mitigate emissions, thereby contributing significantly to environmental preservation. There are two main problems that people face now: energy efficiency issues and emission issues. For efficiency problems, engines often have energy losses when they consume fuel, which means they are not efficient enough. To address this problem, researchers and manufacturers have been working to improve the combustion efficiency of internal combustion engines to increase their energy efficiency. This includes the use of advanced combustion technologies such as direct injection and turbocharging to increase combustion efficiency and reduce fuel waste. In regard to the emission problem, exhaust pollutants from engines have a negative impact on air quality and the global climate. To reduce these emissions, governments and manufacturers have

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taken a variety of measures. This includes using cleaner fuels, such as natural gas and bio-diesel, to reduce emissions [1]. In addition, the adoption of stricter emission standards and the use of exhaust control technologies, such as particulate matter filters and nitrogen oxide traps, have helped reduce emissions.

In order to solve these problems, the use of Stirling engines is a great idea, and there are many good features of Stirling engines. Firstly, Stirling engines have higher energy efficiency. Its working principle involves gas expansion and compression through a heat exchange process without the need for an internal combustion explosion. This way of working allows the Stirling engine to convert heat energy into mechanical work more efficiently. Secondly, it is able to work in an environment that has low noise and emissions. Compared with traditional internal combustion engines, Stirling engines operate smoothly with almost no noise and vibration. This makes them ideal for applications that require low-noise operation, such as electric power generation and aviation. In addition, it produces relatively low emissions, especially when they run on clean fuels or renewable energy. This helps to reduce environmental pollution and reduce greenhouse gas emissions. Thirdly, it is suitable for multiple heat sources. The Stirling engine can utilize a variety of heat sources, including solar energy, biomass, natural gas, and waste heat. This gives them flexibility in different applications, allowing them to choose the most suitable heat source as needed. As a result, the importance of studying Stirling engines is to improve energy efficiency, protect the environment, and research energy diversity.

2. The working principle and advantages of the Stirling engine

Single-acting engines and double-acting engines are the two common types of Stirling engines, which are divided according to the function of the piston. Single-acting engines mean that two pistons are integrated into a circulating loop, each constituting a complete operating system.

Dual acting engine refers to the piston of the cylinder, which can meet the two functions of the hot-end piston and the cold-end piston. In this way, we can see that the dual-acting engine must be implemented in a multi-cylinder machine. The Stirling engine operates on the principle of using an ideal thermal cycle. The Stirling engine was invented by British physicist Robert Stirling in 1816. It outputs power through a cycle of cooling, compression, heat absorption, and expansion in the cylinder. The Stirling engine, an external combustion engine, operates based on the Carnot cycle, encompassing four stages: isothermal expansion, adiabatic expansion, isothermal compression, and adiabatic compression, which collectively contribute to its efficiency lying between that of gasoline and diesel engines. Despite the theoretical ideal of the Carnot cycle suggesting 100% efficiency, real-world engines cannot achieve this, but the cycle serves as a vital efficiency benchmark, with the Carnot efficiency formula given as $\eta = 1 - (Tc/Th)$, where Tc and Th are the absolute temperatures of the cold and hot sources, respectively.

The Stirling engine exhibits remarkable fuel flexibility, devoid of significant limitations. Any heating apparatus capable of consistent heating above 300°C qualifies as a suitable external heat source for this engine. It efficiently operates on a diverse range of fuels including, but not limited to, conventional liquid fuels (such as diesel, gasoline, broad distillate oil, and alcohol), gaseous fuels (like methane, propane, gas, natural gas, and hydrogen), and solid fuels (including coal, wood, and agricultural residues). Additionally, the Stirling engine can harness various other forms of energy, including solar, nuclear, and chemical energy, underscoring its position as a genuinely multifuel engine [2].

Stirling engine has high conversion efficiency. The ideal cycle efficiency of a Stirling engine is Carnot efficiency. The Carnot efficiency is the highest efficiency of the thermal cycle. However, due to various losses, the actual cycle efficiency of the Stirling engine is about 70% of the efficiency of the Carnot. After considering the external combustion system efficiency and mechanical efficiency. The effective efficiency of the Stirling engine is about 55% of the efficiency of Carnot. For example. The efficiency of the car's Sterling engine at maximum power is 33%. At partial load, the efficiency is as high as 37%. To a certain extent, it is better than the internal combustion engine of the same type of vehicle. The lowest cycle of a Marine Stirling engine. The ring temperature is lower than that of an internal combustion engine. Therefore, it has a higher Carnot efficiency, and the effective efficiency is higher [2].

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It also has good environmental characteristics when the Stirling engine runs on diesel or gasoline. Because the fuel is continuously burned at close to atmospheric pressure. Thus burning completely. The harmful components in the exhaust are low. It is significantly lower than the most stringent current requirements. If the Stirling engine uses a heat accumulator, solar energy, and chemical reaction thermal energy to work. There will be no exhaust pollution. Compare that to the internal combustion engine. Stirling engine because there is no valve mechanism, high-pressure oil pump, supercharger, intense combustion of fuel, and the phenomenon of exhaust and piston knocking under high-pressure difference, so the noise of Stirling engine is also low. The noise of the Stirling engine without noise treatment is generally about 70 dB(A), and some Stirling engine noise is even as low as 45 dB(A) [2].

3. Industrial and aviation applications

Owing to its exceptional characteristics, including high fuel adaptability, superior thermal efficiency, minimal emissions, reduced noise and vibration, and smooth operation, the Stirling engine boasts extensive applicability. The subsequent discussion will concentrate on exploring the diverse applications of the Stirling engine.

3.1. Vehicle application

With the increasingly serious problems such as environmental pollution and energy crisis, it is urgent to develop new vehicle power. Due to its good environmental characteristics (low emissions and noise), strong fuel adaptability, high reliability, and durability, the Stirling engine has received renewed attention from the industry. After a series of optimizations, the automotive Stirling engine has a high level and can fully compete with gasoline and diesel engines [3].

The Stirling engine exhibits fuel efficiency comparable to high-speed diesel engines, with exhaust emissions in compliance with pertinent standards and noise levels significantly lower (10 dB to 15 dB less than gasoline engines and 20 dB to 25 dB less than diesel engines). Post-combustion, the fuel in the Stirling engine generates heat, of which 40% to 45% is expelled outside the engine body by a circulating cooler, a figure notably higher than the approximate 20% observed in internal combustion engines. This characteristic necessitates a larger radiator for automotive Stirling engines to manage the increased heat dissipation [4]. Given the substantial impact of the circulating cooling water's inlet temperature on the Stirling engine's efficiency and power, the integration of a high-efficiency, compact automotive radiator is essential. Looking ahead, automotive Stirling engines are anticipated to employ non-polluting regenerative models, utilizing heat accumulators to provide the energy source needed to heat the working medium.

Electric or gas heat charging can be substituted at specific locations once exhausted, with a completed heat accumulator. For enhanced convenience, a combination of the Stirling engine, heat accumulator, and combustion equipment can be employed. This amalgamation allows for pollution-free city driving utilizing the heat accumulator, and the use of combustion equipment for suburban driving while concurrently charging the heat accumulator [5].

The Stirling engine holds promise for application in mining vehicles. Current diesel-powered vehicles in mining environments pose significant health and safety risks to operators due to prolonged exposure to exhaust gases, contributing to health issues and increasing fire and explosion hazards. The Stirling engine, with its notable benefits such as operational silence, low exhaust temperatures, and reduced harmful emissions, stands as a viable alternative. Its use in mining vehicles is anticipated to substantially mitigate environmental pollution and enhance the working conditions for operators, offering a safer and healthier operational environment.

3.2. Heat pump

A heat pump, typically integrated into a building's climate control system, functions for both heating and cooling purposes. For heating, it extracts heat from ambient sources like rivers, lakes, or the ground, elevating the heat to a higher temperature for distribution within the building. This energy eventually dissipates from the building at near ambient temperatures through conduction and convection.

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Conversely, for refrigeration, the building absorbs internal heat, expelling it into an external heat source like a river or lake at lower temperatures.

When employing a Stirling engine as a heat pump, two primary applications emerge: (1) utilizing the engine itself as a heat pump, and (2) employing the engine to drive a heat pump as a prime mover. The energy generated by the Stirling engine can operate a heat pump, absorbing heat from an ambient temperature source and releasing it at a higher temperature into the building's heating system. At lower ambient temperatures, the Stirling engine, used as a heat pump, absorbs heat at a lower temperature and emits it into the heating system at a higher temperature. During the expansion process, it draws heat from external sources at ambient temperature, and during the compression process, it releases this heat into the building, providing heating [6].

To facilitate this operation, external mechanical work is necessary, achievable through various power sources like an electric motor, another thermal engine, or another Stirling engine used as the prime mover. Post-combustion in the Stirling engine, the acquired heat from combustion products transfers to the working medium via heating equipment. A portion of this heat converts into work in the Stirling engine as the prime mover, while the remainder is released into the building's heating system in the cooler.

3.3. Generate Electricity

In communication relay stations and automatic weather stations, power generation equipment that can achieve long-term automatic operation without frequent maintenance is needed, and Stirling engines are just suitable for this field, because such engines can work with different energy sources, and have high thermal efficiency and good reliability. Because the efficiency of the Stirling engine is higher than that of the steam turbine and other thermal engines, the high-power Stirling engine is also suitable for power generation. At the same time, because the Stirling engine will only produce low noise and exhaust. Therefore, it is also suitable for peak-load power stations in urban centers [7].

4. Combination of solar energy and multi-source thermal energy supply system

4.1. Necessity of developing solar Stirling heat engine

Since the birth of human beings have been dependent on the sun's energy, and human life can not leave solar energy. The economy science and technology are developing rapidly, and human technology in the application of solar energy is also constantly improving. With the passing of time, fossil energy has declined sharply, and environmental pollution is serious, solar Stirling heat engines will be paid attention to again. As far as the current solar energy utilization market is concerned, solar Stirling heat engines and solar cells are in a competitive state. However, the production of solar Stirling heat engines is easy, and the materials required are not the same as solar cells, and the solar energy utilization rate is also high. The materials required for solar cells are expensive and difficult to recycle, waste batteries are easy to pollute the environment, do not meet long-term development interests, and their investment cost is much higher than the solar Stirling heat engine. Therefore, the solar Stirling heat engine should be widely promoted in industrial production, and agricultural production. Especially in developing countries like China, solar Stirling heat engines should be developed and utilized [8].

4.2. Solar Stirling heat engines

Since the inception of the solar Stirling heat engine, its technological and developmental attributes can be categorized into two distinct developmental trends. Let's distill these two types of solar Stirling heat engines.

Firstly, the High-Tech Solar Stirling Heat Engine represents the most genuine application of Stirling heat engine technology. It employs helium and hydrogen as working substances within a sealed chamber, utilizing the most advanced materials throughout the engine. The most forefront technologies and scientific minds are engaged in its processing, manufacturing, planning, and design. Initially used as an automotive motor, the evolution of science and technology has facilitated the successful development of the solar Stirling heat engine, now employed for electricity generation in numerous countries. For

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instance, the most advanced dish solar power generation system comprises a dish-type condenser, a solar Stirling heat engine, a generator, and a power generation control system [9].

Furthermore, the Simple Solar Stirling Heat Engine employs a low-pressure hot air Stirling engine. The working medium within the Stirling engine cylinder is low-pressure air, constructed with standard materials, embodying a straightforward, pollution-free technical structure. In contrast to the high-cost and maintenance-intensive high-tech Stirling engine, the low-pressure hot air Stirling engine stands out for its affordability and ease of maintenance, projecting extensive utilization, particularly in developing nations. Dr. Hill's renowned invention of the low-pressure atmospheric Stirling engine, widely adopted in Pakistan and India, epitomizes this category. As science and technology advance, enhancements in manufacturing processes, raw materials, heat transfer technology, and lubrication technology have refined the original low-pressure atmospheric Stirling engine, infusing it with superior technology. This modern era presents opportunities for optimizing the use of the low-pressure atmospheric Stirling engine. The application of numerous advanced technologies to the low-pressure atmospheric Stirling engine has inspired scientists to propose innovative design concepts for a new generation of low-pressure atmospheric Stirling engines [10].

5. Conclusion

Even though the Stirling engine can be adapted to a variety of fuels and has a high conversion efficiency and a high overload capacity, the Stirling engine has some limitations.

(1) High material requirements: the heater and expansion chamber of the Stirling engine need to be maintained at a high temperature for a long time, which puts forward higher temperature requirements for the material. However, with the increasing development and maturity of new material technology, the shortcomings of high material quality requirements will gradually be solved.

(2) Large heat loss: maintaining high temperatures for a long time makes a lot of heat lost through direct transfer and thermal radiation. With the gradual market application of thermal insulation system technology, the defect of Stirling engine heat loss has been greatly overcome.

(3) Large volume: In order to improve thermal efficiency, the system needs to be insulated, which makes the volume of the Stirling engine too large because of the increase of a series of devices to delay heat loss. In recent years, the gradual market application of the modular system splicing concept has reduced the volume of Stirling engines to a relatively reasonable range.

(4) Slow reaction: Because the heat source comes from the outside, the heat transfer takes time, resulting in a period of time for the engine to change the temperature of the cylinder. The application of new heat transfer materials can greatly improve the overall heat transfer efficiency of the Stirling engine.

(5) Contradiction between sealing and lubrication: Since the working medium is limited, the engine system has higher requirements for sealing. In order to reduce friction loss, the engine system also puts forward higher requirements for lubrication because the vaporization of lubricating oil will condense on the regenerator, causing blockage, so the lubricating oil can not be used, only dry friction, resulting in a reduction in the lubrication effect of the engine system.

Stirling engine is a kind of efficient and environmentally friendly thermal engine. It has both profound historical deposits and brand-new development opportunities. Considering the current increasingly serious energy and environmental protection issues. Stirling engine in the future national economic development and industrial and agricultural construction. It will play an important role, and the Stirling engine also has better applicability. As a kind of energy-saving machine that can adapt to a variety of fuels, it is still in the development stage and can not compete with the traditional internal combustion engine in most areas, but as an alternative model of the internal combustion engine and as a technical reserve, the Stirling engine still has a good development prospect. Finding alternative fuels and developing new models are two important solutions to the depletion of oil resources, so many countries in the world are committed to the research of the Stirling engine. At present, the Stirling engine has been widely used in Marine power and other fields, with the gradual development of technology and the continuous optimization of cost, the Stirling engine will be more widely used.

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