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Research of Stirling engine's applications in vehicle, electricity, heating and cooling

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Abstract. Natural resources are becoming more and more scarce while pollution continues to increase. It is imperative to reduce emissions and improve energy efficiency. As an efficient, low-emission machine, the Stirling engine may be an answer on the road to emission reduction and improved efficiency. Stirling engine has been used in some areas, such as nuclear-powered submarine engines, combined heat and power and Stirling cryocoolers. However, there are still several problems that cannot be ignored in Sterling generators themselves. Stirling generators, characterized by high efficiency and potential for reducing greenhouse gas emissions, face challenges, including high material and assembly costs, complex waste heat treatment processes, and the need for durable, high-temperature resistant materials. Despite current limitations, ongoing research aims to enhance conversion efficiency, minimize size, and lower manufacturing costs, with promising applications in various sectors, including transportation and household energy, representing a significant stride towards green energy power generation in the future.

Keywords: Stirling engine, emission reduction, electricity, heating and cooling

1. Introduction

Nowadays, global warming is getting increasingly serious. But the emissions of greenhouse gas are still rising stably. The largest absolute sectoral increase in emissions in 2022 was from electricity and heat generation, which grew from 14.38Gt to 14.65Gt. And that of transport is next, which is 250Mt. From 2000 to 2022, Global energy-related greenhouse gas emissions increased to 41.3 Gt CO_2-eq reached a new high, and the use of fossil fuels and process of industry contributed 89% of that [1]. These data show that improving the energy efficiency of fossil energy and reducing emissions on electricity, heat generation and transport are crucial in alleviating global warming.

The Stirling engine (SE) is competitive, has potential in these areas and is more environmentally friendly than common internal combustion engines (ICE) and gas turbines. SE is a type of heat engine that runs through the cyclic expansion and compression of air or other working fluid, thus converting heat energy into mechanical work. SE is an external combustion engine, which means the heat it needs is provided externally, so the hot area of SE can be heated by any external heat source.

SE was invented by Robert Stirling in 1816 and was improved during the 19th and 20th centuries. It was considered the safer substitute for the steam engine in the late 19th century. However, SE was still not taken seriously and was only used for small domestic engines as medium or low power sources such as pumping water. Then SE was superseded by electromotor and small ICE in the early 20th century. However, there still are some new types of SE that were invented, such as MP1002CA, an SE invented by Philips in 1951. Though those SEs failed to be widely used, they still made a big difference in the research and development of SE. Now, SE is becoming popular in the military, CHP, Stirling cryocoolers and so on. In addition, there were many experiments done on possible applications of SE for reducing emissions or energy consumption. For example, NASA made an automotive SE called MOD II in 1986. This research argued the stereotype that SE is always expensive, heavy and occupies a large space [2]. It was a success in research on SE. In addition, the performance of SE in nuclear-powered submarines is remarkable. The latest SE for submarines has reached 320KW and 40% efficiency. It is very considerable data because it may mean that there is a way to resolve the power problem of SE. It can be seen that the future SE will be used in more applications.

Compared to common ICE, SE is quieter, more reliable and cheaper in maintenance cost. Moreover, SE can use more types of heat sources easily, such as solar, geothermal, biological, nuclear energy and even waste heat from industrial progress so that SE can be low-emissions and environmentally friendly. So, if SE can be widely used in energy and transport areas, it will be an important part of achieving energy conservation and emission reduction to protect the environment.

In addition, the higher efficiency of SE can bring more output, competition and profit. For example, a domestic micro-combined heat and power (CHP) system with SE can provide 75.6% of the total energetic demand of a common household and decrease CO_2 emission by 36.2% [3]. And it is really considerable data. However, because of some disadvantages of SE, such as high initial cost, there is only some interest in it and a lack of use of this device.

Hence, advocating for the adoption of SE in the domains of electricity generation, heat production, and transportation is both practical and essential. This essay primarily aims to undertake an analysis of SE and its utilization, challenges, research orientations, and future potentials within these specific domains. The essay is structured into three main sections, each dedicated to examining the application of SE within distinct sectors: the initial section pertains to SE's integration in the realm of transportation, followed by its utilization in electricity generation in the second section, and concluding with its deployment in heating and cooling systems in the final part.

2. SE in vehicle

In 1986, NASA built an automotive SE (ASE) named MOD II and tested it in a Chevrolet celebrity (Table 1).

Table 1. Some data comparison about Mod II

	Spark Ignition	**Mod II**
Power, kW	69 at 4800r/min	62.3 at 4000r/min
Torque, N*m	182 at 2800r/min	212.2 at 1000r/min
Gross Vehicle Weight, kg	1740.6	1740.6
Acceleration, 0-97km/h, s	13.0	12.4

It is obvious that the property of Mod II is on par with the inter-combustion engine in cars. Research also indicated that Fuel economy was improved by 45%, and emissions were greatly reduced [2]. This means that using SE widely in vehicles is possible and can reduce emissions significantly. However, after that period, ASE was gradually out of the public view because of its unacceptable high cost.

Though ASE is difficult to recognize in competition with ICE as an automotive engine, SE is still in the spotlight. For cars, SE is an excellent complementary technology. It is quiet, clean and environmentally friendly. Benefiting from its flexibility in the heat source, SE has a wider prospect of hybrid electric vehicles or recycling the waste heat of the Otto cycle engine. And it is very hopeful to replace the conventional ICE. In 2007, Precer in Sweden introduced a type of hybrid electric vehicle with SE, which can use solid biological fuel [4]. In 2021, Ghanem CR, Gereige EN et al. found that the

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Regenerative Reheat two stages serial Stirling (RRe-n2-S) is the best choice for the auxiliary power unit (APU) of cars. This option of engine uses 12.1% less fuel than an internal combustion engine [5].

In addition, SE use on recycling waste heat of ICE is hopeful. Barry Cullen et al. researched it by mathematical model in 2009. They built the models of SE and matched them to data of ICE, then simulated and analyzed the results. From three iterations of Schmidt analysis, they found using SE in waste heat recovery of ICE can increase shaft power by approximately 30% [6]. However, this experiment used some ideal conditions, so it can only show feasibility from a theoretic energy system. In 2018, Nosratollah Izadiamoli et al. presented a type of combined Otto-Stirling system, which can generate electricity and cool by recovering the waste heat and gas. This system has already overcome the problem that SE is hard to be stable during the car's whole driving cycle, and it can run steadily when working conditions of the engine between 1000 rpm and 6000 rpm. With this system, cars can save about 15.3% of their fuel and reduce 27.6% of emissions of CO_2 a year. The extra cost of this system can be paid back in 9 years if it runs 39 min a day for a private car and only in 1 year for a public car if it runs 4 hours a day [7].

For SE, fast change of speed is a big challenge. This problem causes ASE to be hard to realize. Though some methods can solve it, they still have some problems with the wide use of vehicles. For example, using a piston can control the power levels changing in a short time, but it will make the structure complex and the volume bigger than common ICE [8].

So, compared to ASE, using SE on waste heat recovery of vehicles seems more reliable and hopeful. It already has a rudiment of SE waste heat recovery system; this system can reduce CO2 emission and run steadily. However, the cost of the system is hard to pay back in a short time for private cars, so it can only be used in public vehicles at present. The lower cost of the SE waste heat recovery system is the most hopeful way to make SE widely used in vehicles in the future.

3. SE in electricity

3.1. SE in large-scale power station

Now, gas turbine (GT) is widely used in power stations because of their fast speed and low cost. However, GT has some obvious drawbacks, such as the heat loss caused by high-temperature waste gas and the low heat efficiency of the GT cycle. And if SE is in the process of generating electricity, the heat loss will decrease much.

Compared to GT, the GT-SE system can increase the total output power of the power station by 68.5% and lower the levelized cost of electricity to only 8.52 cents/kWh, which decreases by 10.3% [9]. Beyond that, SE has great potential in nuclear power. The traditional nuclear-powered Stirling engines in electric power generation plants use steam turbines to produce electricity. If replaced by SE, the plant can be simplified and more efficient. Because the water/sodium heat exchanger is necessary for using the heat in the steam plant, SE can cancel all need for water in the cycle. And the reduction of sodium can make the plants safer. And the radioactive byproduct from nuclear power stations can be reduced.

Meanwhile, in a typical nuclear power plant, two-thirds of the thermal energy produced by the reactor is waste heat [10]. The waste heat has the potential to be used as an additional source of electricity by SE, which means SE can make nuclear power more efficient. The improvement of nuclear power can also reduce the energy requirement for fossil fuels. This can also reduce emissions indirectly. And the development of nuclear-powered SE can also help improve space exploration. Therefore, there are many benefits to nuclear-powered SE.

In short, SE has already satisfied the technical condition to be one of the most promising power generation technologies. However, the main problem with carrying out SE in power generation widely is its investment cost. The investment cost accounts for 55% of SE cost [11]. The total investment cost of the GT-SE system in the power station maybe 6.32 times the equipment purchase cost [10].10 But this cannot deny the feasibility of SE in power stations; the technology can be used no matter whether it is now or in the future. One of the most important things to reduce the cost of SE is finding a green and cheap energy source such as biomass. And by the development of technology and large-scale

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commercialization can influence the relevant factors and decrease the cost. This makes SE potential competitive in electricity generation in the future.

3.2. SE in distributed and small-scale power generation

There is a large population living in a rural or remote area that is isolated from the power grid, especially in developing countries. Fossil fuels are increasingly scarce now. Therefore, using recycled resources in these areas to generate electricity is necessary. And SE can use solar and biological power expediently. Therefore, it is feasible to use SE in solar power generation, and the solar-powered SE can be used in remote and off-grid areas to provide electricity. In off-grid areas, distributed generation can be an excellent solution to the problem of providing electricity to rural areas. By means of a storage device, using a solar-powered SE system, building a solar plant in an off-grid area can guarantee the yearly stability of the power supply. By means of a simulation experiment made by Y.Kadri et al., the solar-powered SE system holds the voltage at 320V, which can satisfy household electricity in remote and off-grid areas in most of the world. The illumination where can meet the conditions [12].

In addition, a micro-CHP system with SE for households has the potential to be widely used. Juan Antonio Auñón-Hidalgo et al. introduced a micro-CHP system with SE combined with solar photovoltaic and thermal to provide domestic demand for heat and power. It can satisfy 66.4% of daily electricity demand, and SE contributes 20.7% of it. Meanwhile, SE also provides 63.8% of heat demand. In the best case, the efficiency of SE can reach 93.9%. This system reduces the emission of CO_2 by 36.2% compared to normal circumstances, and it is noiseless and nonradiative [3].

The technology of SE using solar power and micro-CHP is already mature, and many people are focusing on and looking forward to it. For example, in 2016, Inspirit Energy in British introduced a product named Inspirit Charger, which can produce 3kW of electricity and 15kW of heat. However, SE still has some problems. The electricity efficiency of SE is low, and most of the energy will be produced in heat, which means it probably exceeds the heat requirement for a household and cannot satisfy electricity demand only by SE. In addition, the fuel used now cannot offset the high initial cost of the SE system, which makes the advantage of SE in fuel less prominent. It can take 10 years to pay back the extra cost of the SE system [13]. It is really unreasonable to change the original heat system to a micro-CHP system with SE. Solving the problem of cost or finding a new cheap fuel are the most essential and possible parts for SE systems in micro or small-scale electricity generation to be carried out.

4. SE in heating and cooling

4.1. Stirling cryocoolers

SE has been widely used in cooling, such as cooling electronic sensors as well as microprocessors. Because Stirling cryocoolers (SC) can decrease the temperature to 73K and not be limited by the refrigerant, and at this temperature, Rankine cooling is not effective because of the limit on refrigerant. In addition, SCs are silent, vibration-free, can be scaled down to small sizes, and have very high reliability and low maintenance. So far, low-cost SC has been improved by many times. For example, in 2023, Daming Sun et al. introduced a two-stage large cooling capacity Stirling cryocooler. It can be used in temperatures below 30K and can get 138.1W of cooling efficiency while relative Carnot efficiency is 12.87% [14]. Therefore, SC is competitive in this area and is commercialized successfully.

4.2. Striling heat pumps

In the area of heat pumps, SE is also excellent. Compared to conventional heat pumps, Stirling heat pumps often have a higher coefficient of performance. However, Stirling systems have seen limited commercial use due to their cost.

From the research of the University of Chinese Academy of Sciences in 2021, when input electric power of 1kW to Stirling heat pumps, ambient temperature is -20 °C and heating temperature is 40°C, the gross coefficient of performance (COP) can reach 2.41 and relative Carnot efficiency reach 46.2%

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[15]. It is a very high COP for heat pumps. This research proved the efficiency and excellence of Stirling heat pumps. And give a way to solve the problem that heat pumps are hard to use in low-temperature environments. This can reduce the use of coal heating in cold regions. Furthermore, it can reduce greenhouse gas emissions by burning fossil fuels. In conclusion, use is expected to increase along with market demand for energy conservation, and adoption will likely be accelerated by technological refinements.

5. Technology and environmental advantage of SE

SE is an external combustion engine, which gives the ability to multiple choices and applications of fuel to it. SE can use green, renewable fuel such as biomass, ethyl alcohol and hydrogen, which is hard to use for conventional engines. And low-carbon renewable fuel only accounts for 25% of power generation, but in the net zero scenario, it needs to reach 90% before 2050, while transport needs to decrease the emission by 20%. And SE don't need to use fossil fuel. Therefore, SE is very potential, competitive and necessary to carry out. In addition, during the SE working process, the only emission comes from the heat source of SE, and a low-emission or even emission-free fuel can solve it. Therefore, this is the advantage of SE in fuel and gas emissions on energy conservation and emission reduction. Therefore, there is no doubt that SE can easily satisfy the emission limit.

6. Conclusion

Due to current technological limitations, Stirling generators cannot be used in various industries on a large scale. Although the workmanship is efficient, several problems cannot be ignored in Sterling generators themselves. If they cannot be solved, the application development of Sterling generators is likely to be greatly limited. The materials and assembly costs for a high-temperature heat exchanger typically account for 40% of the total engine cost.

The heat exchanger of the Stirling generator is always in a high-temperature state, and high-temperature-resistant materials are necessary. As one of the most efficient engines, Stirling generators are bound to be used in large vehicles, such as high-speed rail and submarines. Therefore, the materials for making Stirling generators must also be resistant to high pressure. Moreover, the first is the problem of expenses. The materials used to make or carry Stirling generators must be tough enough, wear-resistant, pressure-resistant and high-temperature. The current price of materials with so many attributes is very expensive. It may pay back in energy conservation, new cheap fuel and low maintenance costs during later work, which many people are making an effort to realize.

In addition, the treatment of waste heat is also an essential process, but the waste heat treatment process of the Stirling generator is very complicated. Therefore, the size of the radiator is also a problem to consider.

With the increasing shortage of traditional energy and environmental pollution, Stirling generators will become one of the important choices in the field of new energy in the future. In addition to aviation, aerospace, geological exploration and other fields, Stirling generators can also be used in small household heating and energy storage. For example, China's latest research and development of a Stirling engine for submarines has reached 320 kW and 40% efficiency. Although the size and cost are still a problem for cars, it also represents an important progress of Stirling engines if they can be universal. Use can greatly reduce greenhouse gas emissions.

In addition, except for the complete use of the Stirling engine in the car, the Stirling engine can be used to use further the waste heat of the car exhaust, such as converting it into electrical energy for the supply of car lighting, etc., to improve the efficiency of energy utilization.

In the future, Stirling Generator is expected to become an excellent representative of green energy. At present, the research and development of the Stirling generator focuses on improving its conversion efficiency, reducing volume and reducing manufacturing costs. In terms of core technology, it is also necessary to explore more efficient working media, more optimized circulation methods and more sophisticated control methods. In a word, Stirling generators are an important part of green energy power generation in the future.

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