

PROSPECTS AND ENGINEERING FEATURES OF THE USE OF STIRLING ENGINES IN MODERN MECHANICAL ENGINEERING

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Анотація

У роботі розглянуто сучасні тенденції розвитку двигунів Стірлінга як альтернативних теплових машин для промислового застосування. Особливу увагу приділено конструктивним обмеженням, енергетичній ефективності, а також можливостям інтеграції до системи розподіленої генерації тепла. Запропоновано інженерні підходи до підвищення надійності та конкурентоспроможності даних установок.

Ключові слова: двигун Стірлінга, теплові двигуни зовнішнього згоряння, енергетичне машинобудування.

Abstract

This paper examines current trends in the development of Stirling engines as alternative heat engines for industrial applications. Particular attention is paid to design limitations, energy efficiency, and the potential for integration into distributed heat generation systems. Engineering approaches to improving the reliability and competitiveness of these systems are proposed.

Keywords: stirling engine, external combustion heat engines, power engineering

Introduction

Modern mechanical engineering faces the need to improve energy efficiency and reduce environmental impact. In this context, Stirling engines are once again attracting attention as external combustion heat engines offering a number of unique advantages: high theoretical efficiency, fuel versatility, and low emissions.

Despite a history spanning more than two centuries, these engines have yet to achieve widespread industrial adoption. This is due not so much to fundamental shortcomings as to a combination of engineering and technological limitations that require a comprehensive approach to overcome them.

Operating process features and design limitations

The Stirling engine operates in a closed cycle with heat recovery, which theoretically allows for efficiency close to that of the Carnot cycle. However, in real-world conditions, efficiency is significantly reduced due to:

- heat losses in the regenerator;
- heat exchange limitations;
- mechanical losses in the kinematic mechanisms;
- working fluid leaks.

The regenerator is a key component—a heat exchange unit that accumulates and returns heat to the working fluid. Its efficiency determines up to 30–40% of the overall engine efficiency. This creates a tradeoff between:

- increasing the heat exchange surface area;
- increasing hydraulic resistance.

An additional challenge is ensuring tightness at high pressures (up to 10–20 MPa) and temperatures (up to 700–800°C), especially when using hydrogen or helium.

The Stirling cycle consists of four phases and is separated by two transition phases: heating, expansion, transition to a cold source, cooling, compression, and transition to a heat source. Thus, during the transition from a warm source to a cold source, the gas in the cylinder expands and contracts.

1. An external heat source heats the gas at the bottom of the heat exchange cylinder. The resulting pressure pushes the working piston upward (note that the displacer piston does not fit tightly against the walls).

2. The flywheel pushes the displacer piston downward, thereby moving the heated air from the bottom into the cooling chamber.

3. The air cools and compresses, and the working piston descends.

4. The displacer piston rises, thereby moving the cooled air to the bottom. And the cycle repeats.

In a Stirling engine, the motion of the working piston is offset by 90° relative to the motion of the displacer piston. Depending on the sign of this offset, the engine can be either an engine or a heat pump.

Basic Stirling Engine Configurations

Stirling engines are divided into three different types.

Alpha Stirling – contains two separate power pistons in separate cylinders, one hot and one cold. The cylinder with the hot piston is located in a higher-temperature heat exchanger, while the cylinder with the cold piston is located in a colder heat exchanger. This type of engine has a fairly high power-to-volume ratio, but unfortunately, the high temperature of the "hot" piston creates certain technical difficulties. The regenerator is located between the hot and cold sections of the connecting tube.

Beta Stirling – has only one cylinder, hot at one end and cold at the other. A piston (from which power is extracted) and a displacer, separating the hot and cold cavities, move within the cylinder. Gas is pumped from the cold section of the cylinder to the hot section through the regenerator. The regenerator can be external, as part of the heat exchanger, or can be integrated with the piston-displacer.

The Gamma Stirling also has a piston and a displacer, but it has two cylinders: one cold (where the piston moves, extracting power), and the other hot at one end and cold at the other (where the displacer moves). The regenerator can be external, in which case it connects the hot end of the second cylinder to the cold end and simultaneously to the first (cold) cylinder. The internal regenerator is part of the displacer.

Main Disadvantages

Bulkiness and material consumption are the main drawbacks of piston engine variants. External combustion engines in general, and the Stirling engine in particular, require cooling of the working fluid, which significantly increases the weight and size of the power plant due to larger radiators.

To achieve performance comparable to that of an internal combustion engine, high pressures (over 50-100 atm) and special types of working fluid—hydrogen and helium—are required.

Heat is not supplied directly to the working fluid, but only through the walls of the heat exchangers. The walls have limited thermal conductivity, resulting in lower efficiency than expected. A hot heat exchanger operates under very intense heat transfer conditions and at very high pressures, requiring the use of high-quality and expensive materials.

To rapidly change engine power, methods different from those used in internal combustion engines are used: a variable-volume buffer tank, changing the average working fluid pressure in the chambers, and changing the phase angle between the working piston and the displacer. In the latter case, the engine's response to the driver's control input is almost instantaneous.

Main advantages

Nevertheless, the Stirling engine has advantages that compel its development.

Omnivorous engine capability – like all external combustion engines (or rather, external heat input engines), the Stirling engine can operate with almost any temperature difference: for example, between different layers of ocean water, from the sun, from a nuclear or isotopic heater, a coal or wood stove, etc.

Simple design – the engine's design is very simple, requiring no additional systems such as a valve timing mechanism. It starts automatically and requires no starter. Its characteristics allow the elimination of a gearbox.

Extended service life – the simplicity of the design and the absence of many "delicate" components allow the Stirling engine to provide a service life unmatched by other engines, reaching tens and hundreds of thousands of hours of continuous operation.

Efficiency – for utilizing certain types of thermal energy, especially at small temperature differences, Stirling engines are often the most efficient engine types. For example, when converting solar energy into electricity, Stirling engines sometimes offer higher efficiency (up to 31.25%) than steam-powered heat engines.

Environmentally friendly – the Stirling engine has no exhaust, meaning its noise level is much lower than that of piston internal combustion engines. The Beta Stirling engine with its rhombic mechanism is a perfectly balanced device and, with sufficiently high manufacturing quality, has extremely low vibration levels (vibration amplitude is less than 0.0038 mm). The Stirling engine itself has no parts or processes that could contribute to environmental pollution. It does not consume working fluid. It is also worth noting that ensuring complete combustion of fuel in an external combustion engine is easier than in an internal combustion engine.

Engineering Approaches to Improving Efficiency

Heat Exchanger Optimization. To improve efficiency, it is necessary to:

- use porous metal structures in regenerators;
- use additive manufacturing to create complex channel geometries;
- minimize thermal resistance.

Additive manufacturing opens the possibility of creating regenerators with a gradient structure optimized for specific operating conditions.

Improving Working Fluids. Helium and hydrogen are traditionally used. However, promising options include:

- gas mixtures with controlled thermophysical properties;
- use of supercritical fluids.

The choice of working fluid affects:

- heat transfer;
- viscosity;
- leakage;
- operating safety.

Reducing Mechanical Losses. This is achieved through:

- use of gas bearings;
- magnetic levitation of pistons;
- use of oil-free designs.

This is especially important for stand-alone installations where maintenance must be kept to a minimum.

Applications

The Stirling engine is suitable for applications requiring a small, simple thermal energy converter, or when the efficiency of other thermal engines is lower: for example, when the temperature difference is insufficient to operate a steam or gas turbine.

Versatile power sources. Stirling engines can be used to convert any heat into electricity. They hold promise for solar power systems. They are also used as stand-alone generators for tourists. Some companies produce generators that run off a gas stove burner. NASA is exploring Stirling-based generators powered by nuclear and radioisotope heat sources. A specially designed Stirling generator with a radioisotope power source (the Advanced Stirling Radioisotope Generator (ASRG)) was used in NASA's Titan Saturn System Mission.

Pumps. The efficiency of heating or cooling systems increases if a forced-feed pump is installed in the circuit. Installing an electric pump reduces the system's lifespan, and in non-autonomous household energy systems, it's a nuisance because it significantly increases the electricity meter's bill. A pump using the Stirling engine principle solves this problem. A Stirling engine for pumping liquids can be much simpler than the traditional engine-pump system. In a Stirling engine, the pumped liquid can be used instead of a working piston, which simultaneously serves to cool the working fluid.

A Stirling engine-based pump can be used to pump water into irrigation canals using solar heat, or to supply hot water from a solar collector to the home (in heating systems, the heat accumulator is installed as low as possible so that water flows to the radiators by gravity).

Heat pumps. Heat pumps help save on heating costs. They operate on the same principle as an air conditioner, but an air conditioner typically cools a room by heating the surrounding space, while a heat pump typically heats a room by cooling outside air, well water, or another low-grade heat source. Heat pumps powered by electricity are commonly used. However, in some countries, electricity is generated at combined heat and power plants burning gas, coal, or fuel oil, and the resulting heat from such a heat pump is no cheaper than that obtained from burning gas. A device that combines a Stirling engine and a Stirling heat pump improves this situation. The Stirling engine transfers waste heat from the "cold" cylinder to the heating system, and the resulting mechanical energy is used to pump additional heat, which is extracted from the environment. A hybrid Stirling-Stirling heat pump is simpler than a combination of two Stirling engines. The device has no working pistons at all. Pressure differences generated in the engine are directly used to transfer heat by the heat pump. The device's interior is sealed, allowing the working fluid to be used under very high pressure.

Refrigeration equipment. Almost all refrigerators use the same heat pumps. Their fate in refrigeration systems has been more fortunate. A number of household refrigerator manufacturers are planning to install Stirling engines in their models. They will be more energy efficient and will use ordinary air as the working fluid.

A Stirling engine can also operate as a refrigeration machine (reverse Stirling cycle). For this, it is driven by any other external engine (including another Stirling engine). Such engines have proven effective for liquefying gases. If large volumes are not required (for example, in a laboratory setting), Stirling engines are more cost-effective than turbine units.

Solar power plants. A Stirling engine can be used to convert solar energy into electrical energy. For this purpose, the Stirling engine is mounted at the focal point of a parabolic reflector (similar in shape to a satellite dish) so that the heating area is constantly illuminated. The parabolic reflector is controlled in two axes while tracking the sun. Solar energy is focused onto a small area. The mirrors reflect approximately 92% of the incident solar radiation. The working fluid of a Stirling engine is typically hydrogen or helium.

In February 2008, Sandia National Laboratory achieved an efficiency of 31.25% in a setup consisting of a parabolic reflector and a Stirling engine.

Conclusion

Stirling engines represent a technology with high potential, which has so far only been partially realized. The main limitations are not related to the operating principle, but to the engineering implementation: heat transfer, sealing, and cost.

The development of additive technologies, new materials, and control systems is creating the conditions for their wider adoption. In mechanical engineering, Stirling engines could find a sustainable niche in segments where environmental friendliness, autonomy, and the use of secondary energy resources are critical.

Therefore, further development of this technology should be considered as one of the avenues for improving industrial energy efficiency and the transition to sustainable energy systems.

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