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Research on The Advantages, Practical Applications and Optimization of Stirling Cryocoolers

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Abstract:
The Stirling cryocooler machine is a refrigeration device that uses the Stirling cycle. It can quickly reduce the temperature to a very low level. Compare with other refrigeration machines, it is environmentally friendly and high efficency. That is the reason why it is widely used in various fields, such as aerospace technology research (James Webb Space Telescope), low-temperature physics experiments (Achieves millikelvin-level cooling), medical devices (MRI systems), and equipment used in Antarctic scientific research. Stirling cryocoolers also have the advantage of vibration-free operation, so it is widely used in precision processing. Its operation process consists of four steps Isothermal Compression, Isochoric Regeneration, Isothermal Expansion, Isochoric Heat Storage. It works based on thermodynamic principles. Stirling cryocoolers contain five core components: the compressor, the cooler, the regenerator, the expander and the working fluid. Each of them plays the important role in machine. However, Stirling cryocoolers still face risks and challenges. So there are many ways to optimize them such as improve structures, use better materials and so on.

Keywords: Stirling cryocoolers; core components; optimize.

1. Introduction

Stirling cryocoolers have become an important method for low-temperature refrigeration demands in both scientific and industrial fields. In the 19th and 20th century, with the continuous transformation of industrial levels, energy resources became increasingly scarce, and the environment was also affected by the production of a large amount of industrial waste. People had a great need for production machines that could improve resource utilization and be environmentally friendly. Against this backdrop, with the success of the Stirling cycle device. Stirling cryocoolers, due to their high efficiency and relatively more environmental friendliness, emerged as an inevitable trend in the refrigeration industry. Based on the Stirling cycle machine, which is a type of closed thermodynamic cycle machine invented in 1816 by

Robert Stirling as a heat engine to convert thermal energy to mechanical energy. The Stirling cryocooler was first recognized in 1832 (Kohler, 1968) [1]. With the continuous improvement of thermodynamic theory, Stirling cryocoolers have undergone multiple changes and evolved into various types, which are applied in different situations and their efficiency has also increased accordingly. Stirling cryocoolers with their excellent temperature control effect and good stability, have become one of the important choices for people's rapid cooling.

The main aim of this report is to present Stirling cycle refrigerating machine. In the paper, the working principles, type differences and practical applications of Stirling refrigerators will be reviewed. Finally, summarize and talk about the future prospects.

2. Discussion

2.1 The Main Composition of Stirling Cryocoolers

Different types of Stirling cryocoolers have different compositions, but generally they are composed of five parts: the compressor, the cooler, the regenerator, the expander and the working fluid.

A compressor is used to compress the working fluid, providing propulsion. During compression, the temperature and pressure of the working fluid increase, and it also prepares for subsequent cooling. The function of the cooler is to cool the working fluid that has been heated due to compression. The working fluid will pass through the cooler, transferring heat to the surrounding area to achieve cooling. The function of a regenerator is to absorb heat when the working fluid changes from hot to cold and release heat when it changes from cold to hot, thereby improving efficiency. To pursue higher efficiency, the material of regenerators is generally made of metals with good thermal conductivity, such as using the hybrid regenerator made of copper and nylon [2]. To enhance performance and efficiency. The expander achieves the cooling effect by expanding the fluid, and finally the working fluid. The working fluid is the medium used to transfer energy during the operation of a Stirling cryocooler. To ensure smooth operation, they typically require good thermal conductivity.one which employs helium as the working fluid, offer an alternate choice for those looking for a cooling system that offers both ecological friendly and energy-efficient [3]. The combination of the main components forms a perfect heating, cooling and compression cycle. In specific cases, other parts may also be added to help improve the working efficiency and performance of the Stirling cryocooler.

2.2 Advantages of Stirling Cryocoolers

The reason why Stirling cryocoolers can be widely used is based on many of their advantages. They have extremely high efficiency. As shown in the figure1, the efficiency of different thermodynamic cycles is related to the maximum cycle temperature and the ratio of low temperature to high temperature. The efficiency of the Stirling cycle is relatively high.

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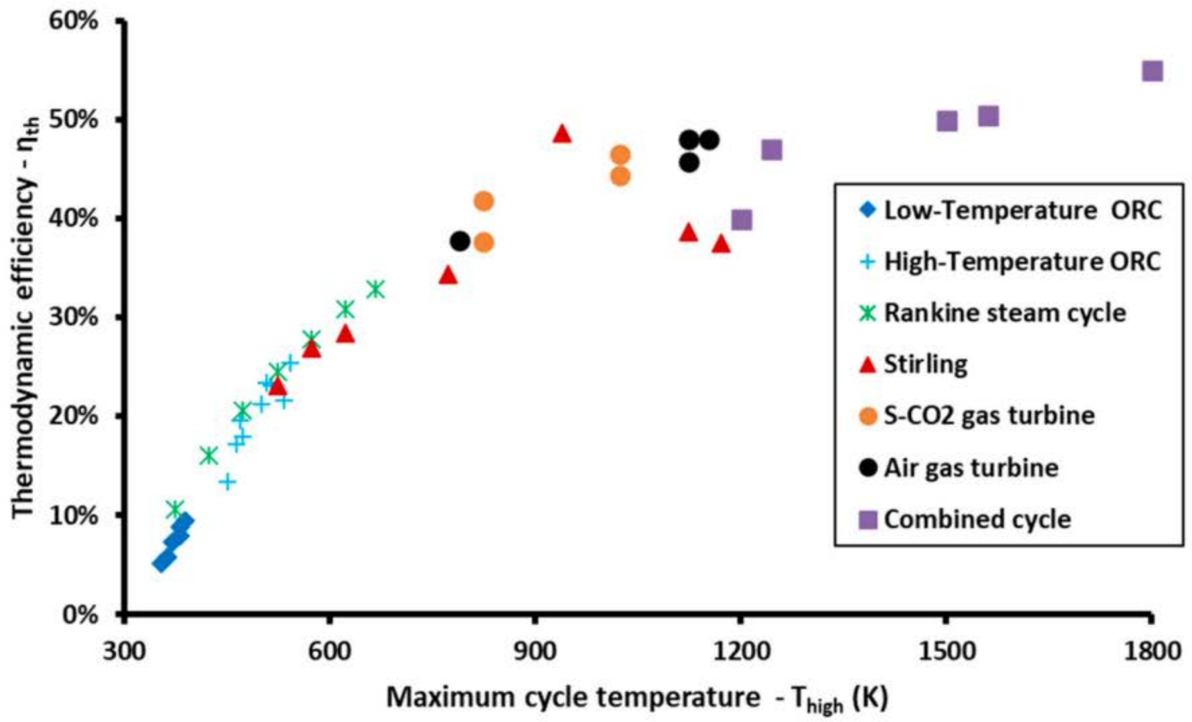
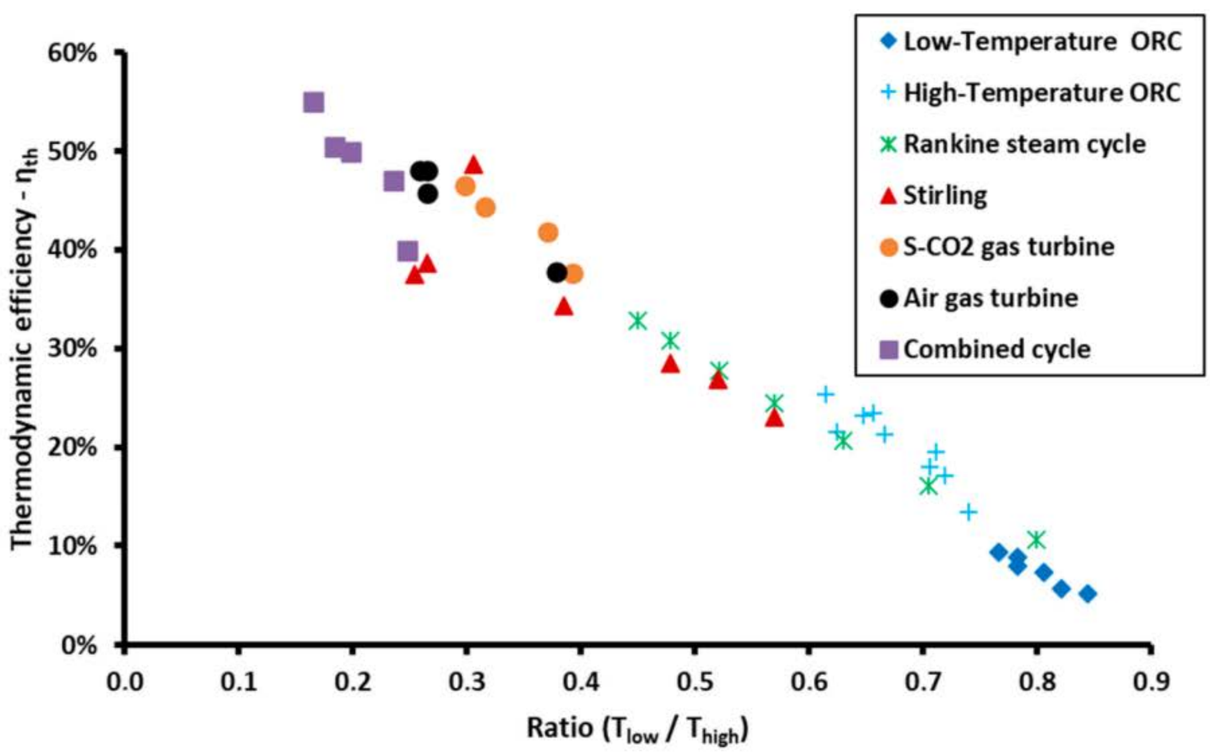


(a)



(b)

Fig.1 Thermodynamic cycle efficiency for different cycles (a) as a function of the high cycle temperature (Thigh); (b) as a function of the temperature ratio (Tlow/Thigh) [4].

What's more, the Stirling cryocooler machine has a high adaptability. It can be driven by various materials, such as the sun and natural gas. Among them, the most energy-efficient and practical one is the solar-driven Stirling cryocooler system.

This experiment is examining a Dish-Stirling/Stirling cryocooler system for the purpose of obtaining cold. The system's non-toxic working fluid makes it environmentally friendly and more efficient than the existing solar cryocooler systems. The system consists of a solar collector to transform solar energy into heat, a Stirling engine to convert mechanical thermal energy, a gear system to couple the refrigerator and Stirling engine, and a refrigerator Stirling for cold production. The findings indicate that the Dish-Stirling/Stirling refrigerator has a low COP and has a large cooling capacity, contrasting to the photovoltaic/Stirling cryocooler. [5]. Stirling cryocoolers can better adapt to solar systems and have a higher conversion rate, demonstrating their high efficiency and strong adaptability.

Moreover, Stirling cryocoolers also have an environmental protection function. The operation of Stirling cryocoolers is based on the Stirling cycle to achieve cooling effects. The Stirling cycle utilizes thermodynamic principles and the compression, expansion, and heat exchange between gases to transfer heat, thereby achieving a cooling effect. Therefore, Stirling cryocoolers typically use inert gases such as helium as raw materials for cooling. This greatly reduces the damage to the air environment.

2.3 Optimization of Stirling Cryocoolers

To enhance the overall performance and refrigeration efficiency of Stirling cryocoolers, there are many directions for optimization. First comes thermodynamic optimization. Thermodynamics is the fundamental principle on which Stirling cryocoolers operate. Therefore, optimizing thermodynamics can significantly enhance their performance. For instance, through thermodynamic analysis, the temperature ratio and volume compression ratio of the working fluid can be optimized. Mechanical losses can be observed in the experiment, as well as heat leakage, thermal resistance, and regeneration loss. Four optimization objectives were optimized using the NSGA-II algorithm, which was based on the temperature ratio x of the working fluid and the volume compression ratio. Multi-objective optimization results are superior when selecting appropriate decision-making strategies, as shown by the results [6]. Therefore, it can be known that we need to consider multiple factors such as optimizing the temperature ratio and volume compression ratio simultaneously.

Secondly, we can consider improving the structure and optimizing the materials. As for structure, An approach that incorporates structural design and material selection has been studied to reduce the environmental impact of mechanical parts. The aim of minimizing environmental impact was achieved by building a hybrid optimization model by adding the discrete variable of material to an ordinary structure optimization model. Using this index to compare all materials in the optional material set can result in the discovery of the optimal material and the calculation of the structural solutions [7]. In conclusion, the influence of the environment on the refrigeration effect can be reduced by optimizing the structure. And about materials, as mentioned earlier, the material of the regenerator should be changed to a material with good thermal conductivity, and a metal with a large contact area should be selected for the regenerator. However, some studies have shown that though the regeneration efficiency is improved as the volume of the regenerator is increased, and as the area of the heating surface is increased, on the other hand as the pressure loss of the inside increases, the output of the engine is lowered [8].So we do not merely need to consider one way to enhance efficiency in terms of materials, but rather, through research, think about how to improve the overall efficiency.

Moreover, we can also consider optimizing detailed data such as control system parameters to specifically calculate the most efficient data, thereby enhancing the stability of Stirling Croyocoolers and better applying them in medical fields and other areas that require precise calculations.

2.4 Real World Application of Stirling Cryocoolers

Stirling cryocoolers are widely used in daily life due to their high stability and excellent cooling effect, ranging from large space system components to small refrigerator appliances. Below, I will describe several practical applications of Stirling cryocoolers. Using Stirling refrigerators instead of chlorofluorocarbons as the refrigeration system for refrigerators can reduce damage to the ozone layer and is an environmentally friendly refrigeration solution for refrigerators. In order to determine if a freon-free machine can replace the current household refrigerator, a Stirling cryocooler prototype has been tested using helium as its working fluid. The design and testing of a displacer-type Stirling cycle machine with a capacity of 100 W was conducted by changing the frequency. The power transmission mechanism between the motor and the piston caused a significant amount of work to be lost, leading to a lower COP than the designed one. The Stirling cryocooler has been made clear on its operational characteristics. The Stirling cryocooler is shown to be a promising candidate for a new refrigeration system based on these results [9]. This experiment indicates that Stirling cryocooler are

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expected to be mass-produced in the future and can make the living environment healthier.

Stirling cryocoolers are also used as backup power generation for rural power supply. In the countryside, Solar and wind's intermittent nature due to meteorological conditions pose a significant challenge in providing reliable power generation. However, solar and wind possess complementary qualities in most areas. To eliminate fluctuations, an energy storage device is an essential component of a wind/solar hybrid system. The hybrid cooling strategy is utilized to cool the area, with air conditioner, fan assistant natural ventilation, and turbine exhaust from compressed air energy storage during discharge. Simulation results conducted under design conditions show that there is a 0.988% chance of losing power supply [10]. When wind and solar power generation is unstable, alternative generators with Stirling cryocoolers come into play. Under their combined operation, the power supply problem in rural areas has been well solved, and Stirling cryocoolers can also contribute to power generation projects by taking advantage of their cooling effect.

3. Conclusion

Stirling cryocoolers, with their high stability, high adaptability and excellent cooling effect, are widely used in various fields and offer significant assistance in real life. However, in the future, to adapt to the environment, Stirling cryocoolers still need to move towards miniaturization (to meet the cooling requirements of more small machines). The development in the directions of intelligence (real-time detection of cooling data) and multi-energy (utilization of more environmentally friendly energy) has great potential to shine in the future.

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