A 15K two-stage gas-coupled Stirling-type pulse tube cryocooler

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Abstract: A gas-coupled two-stage Stirling-type coaxial pulse tube cryocooler (SPTC) driven by a dual opposed-piston configuration linear compressor was designed and experimental test. Both of the two stages adopted coaxial structure for compactness. At the cold end of first stage, a part of working gas was introduced to the regenerator of second stage, while the others were returned to the pulse tube of the first stage. A lowest temperature of 7.3 K and 0.3 W/15 K cooling capacity can be achieved with 250 W PV power by simulation. At present, a lowest temperature of 8.1 K and 0.56 W/15 K cooling capacity can be achieved with 600 W the input power. The influence of the frequency, amplitude of the positon and the hot end temperature were studied. This paper presents the simulation results and primary test results of the designed cryocoolers.

1. Introduction

SPTC is widely used in physical experiments, aerospace applications and some other fields for its compactness structure, high efficiency, and low vibration. Generally, it is hard for a single-stage SPTC to achieve the temperature below 20 K [1-3]. With the adopt of multi-bypass structure, a lowest temperature of 15.5 K was achieved by using the stainless steel mesh only as the regenerators [4]. The mechanism of the multi-bypass is still clear yet, but it is more like a quasi-two-stage SPTC.

To achieve a lower temperature, multi-stage structure should be adopted [5-7]. Multi-stage SPTC can be divided into two types: gas-coupled and thermal-coupled. For a thermal-coupled SPTC, the gas system of every stage is separated, so the operating parameter of each stage may be different. Due to this, the operating parameter of each stage of thermal-coupled SPTC can be adjusted independently easily which makes it possible for every stage to work at its best condition. But the structure of a thermal-coupled SPTC is complicated, because only one stage is driven by a compressor. For a gas-coupled SPTC, both stages have to work at the same condition, which means both stages must work at the same charging pressure and operating frequency. There for, the influence between stages are significant. These became the difficulties in developing a gas-coupled pulse tube cryocooler. However, compared with the thermal-coupled SPTCs, gas-coupled SPTCs use only one compressor to provide the pressure wave, which make the system more compact than thermal-coupled SPTCs. It can achieve a higher efficiency at the results of higher heat transfer efficiency between the two stages.

Many attempts have been made to achieve a lower temperature with gas-coupled MSPTC. Yang developed a gas-coupled two-stage pulse tube cryocooler which can reach the no-load temperature of 15K.
19.6 K [2]. Zhu has developed a two-stage gas-coupled SPTC based on a multi-bypass single-stage SPTC, it has achieved a no-load temperature of 12.1 K with an input electric power of 260 W [8]. Pang has developed a two-stage gas-coupled SPTC with a lowest temperature of 13.6 K and a cooling capacity of 1.06 W at 20 K with 224 W acoustic power [8]. Wu has achieved a lowest temperature of 11.28 K based on a high cooling capacity single-stage SPTC [10].

In this paper, a two-stage gas-coupled SPTC has been developed based on Sage software. The simulation model of the cryocooler and the experimental results will be introduced.

2. Design of the cryocooler and simulation models

Figure 1 shows the schematic structure of the developed SPTC. The cryocooler is driven by a dual-opposed linear compressor. The optimum frequency of the compressor is about 25 Hz. And the optimum charging pressure is 2.5 MPa. Both of the two stages adopt coaxial structure for compactness. At the cold end of first stage, a part of working gas is introduced to the regenerator of second stage, while the others are returned to the pulse tube of the first stage. The regenerator of the first stage is filled with stainless steel screens. And the second stage is filled with stainless steel screens and Er3Ni powder. The double-inlet valve, inertance tube and gas reservoir were adopted as the phase shifter for the first stage. The cold inertance tube and cold gas reservoir were adopted as the phase shifter for the second stage. The second stage reservoir is thermal-coupled to the cold head of the first stage.

![Figure 1. The schematic diagram of the cryocooler](image)

The numerical model of the single-stage PTC made by Sage software is shown in Figure 2. The numerical model mainly contains three parts, the dual-opposed linear compressor, the first stage of the cryocooler and the second stage of the cryocooler. As the result of coaxial structure, the radial heat transfers between the regenerator and the pulse tube is considered. The PV power is controlled by the amplitude of the piston. The hot end temperature of cryocooler is kept 279 K.

3. The simulation results

3.1. The influence of the frequency

The influence of the frequency on the cryocooler is shown in figure 3. Under the condition of 2.3 MPa operating pressure and 250 W PV power, it can be found that the optimum frequency of the second stage and the first stage is 25 Hz and 24 Hz, respectively. It can match the compressor (designed optimum frequency 25 Hz) properly. The temperature increases when the frequency deviates from the design's frequency observably.
3.2. Amplitude of the cryocooler

The influence of the cryocooler on the temperature and PV power are shown in figure 4. It can be found that the PV power increased nearly linearly with the amplitude of the piston. However, at the results of limited regenerative capacity, the rate of lowest temperature decline decreases with the increase of the amplitude of the piston.

3.3. The cooling power of the cryocooler

The cooling power of the cryocooler is shown in figure 5. The cooling capacity of the cryocooler increases linearly with the temperature. It can achieve 0.3 W cooling power at 15 K with 250 W PV power. And the slope of the cooling power curve is 40 mW/K. The cooling power also influences the distribution of gas flow. We can find that the mass flow rate to the second stage decreases when the cooling power increases.
3.4. The influence of the hot end temperature

The hot end temperature has influence on the performance of the cryocooler as shown in figure 6. With the increase of the hot end temperature, the temperature of the first stage and the second stage of the cryocooler increases linearly. And the temperature change slope of the second stage and the first stage is 30 mK/K and 112 mK/K.

![Figure 5. The cooling power of the cryocooler](image1)

![Figure 6. The influence of the hot end temperature](image2)

4. Preliminary experimental result

The preliminary experiment was carried out based on the simulation model as shown in Figure 7. It takes about two hours to lower to its lowest temperature. Under the condition of 450 W input electric power and 26 Hz operating frequency, a lowest temperature of 8.5 K was achieved. When the input power increased to 600 W, a lowest temperature of 8.1 K was achieved and can provide 0.56 W cooling power at 15 K.

![Figure 7. The cooling down curve of preliminary experiment](image3)

5. Conclusion

A two-stage high-frequency pulse tube cryocooler driven by a linear dual-opposed compressor has been designed and simulated by Sage software in this paper. It has achieved a lowest temperature of 7.3 K and 0.3 W cooling power at 15 K with 250 W PV power by simulation. At the same time the influence of operating frequency, amplitude of the positon and the hot end temperature on the performance of the cryocooler are studied. At present, a lowest temperature of 8.1 K and a cooling power of 0.56 W @ 15K can be achieved with an input electric power of 600 W in the primary experiments.
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