A 10K Gas-Coupled Two-Stage 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 manufactured with numerical simulation and experiment test. The regenerators' materials and filling method were simulated by Sage™ software. The mixed stainless steel screen with different meshes were adopted as the first stage of regenerator, and the Er_3Ni and stainless steel screen were adopted as the second stage of the regenerator. The double-inlet and inertance tube together with room-temperature reservoir were adopted as phase shifter for the first stage, and the cold inertance tube and cold reservoir were adopted as phase shifter for the second stage. Under the condition of a 2.5 MPa charging pressure and a 27 Hz operating frequency, the second stage of the cryocooler has achieved a lowest no-load temperature of 8.87 K, and the temperature of the first stage was 38.0 K. A cooling power of 350 mW at 15K can be achieved with an input power of 400 W.

INTRODUCTION

SPTC has the advantages of compactness, small size, low vibration, long life and high reliability because there are no moving parts at the cold end. Thus it has attracted many researchers' interests. At present, SPTC working at around 80 K can achieve a relative Carnot efficiency greater than 20%. For example, Wang has developed a SPTC which has achieved a cooling capacity of 26.4 W at 80 K with an input power of 290 W [1]. At a lower temperature zone, the efficiency of the SPTC will be much lower, it usually can achieve a cooling capacity of 0.2-1 W at 35 K with 300 W of input power, but by using the multi-bypass structure, a larger cooling capacity can be achieved. For example, Chen has developed a multi-bypass type single-stage SPTC with a no-load temperature of 15.5 K and a cooling capacity of 2.5 W at 35 K with 240 W input electric power [2]. The no-load temperature can be reduced to 13.9 K further when part of the regenerator matrix was replaced by Er_3Ni power, which is the lowest temperature record for single-stage SPTC [3]. To achieve a lower temperature, a multi-stage cold head is generally needed. 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 [4]. Pang has developed a two-stage gas-coupled SPTC with a lowest no-load temperature of 13.6 K and a cooling capacity of 1.06 W at 20 K with 224 W acoustic power. It achieved a relatively high Carnot efficiency of 6.5% by using a stepped warm displacer to be the phase shifter [5]. At present, the lowest no-load temperature

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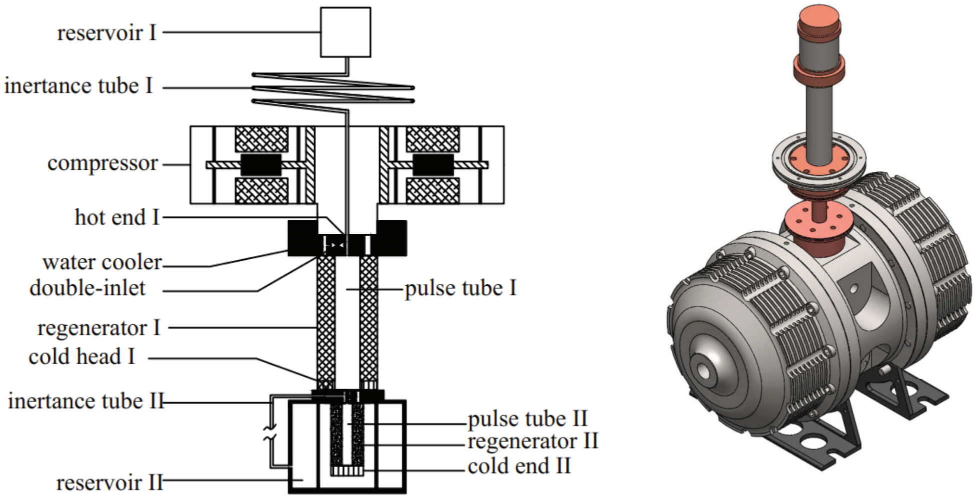

Figure 1. The schematic and 3D diagram of the developed gas-coupled two-stage SPTC.

record for two stage and three stage by using ^{4}He were 3.98 K and 3.93 K, respectively [6]. Both of them were fabricated as thermal coupled structures and driven by two compressors. Although the lowest no-load temperature of multi-stage SPTC can reach a temperature below 4.2 K, its cooling capacity at 10 K or higher is relatively small, only tens of milliwatts can be achieved at 10-15 K. Therefore, there is still a long way for practical application.

In order to achieve a better performance for a two-stage gas-coupled SPTC, a high efficiency single-stage SPTC has been developed, it has achieved a lowest no-load temperature of 23.6 K, and it achieved a cooling capacity of 5 W at 40 K with an input power of 450 W [7]. In this paper, a two-stage gas-coupled SPTC based on the single-stage SPTC has been developed. The structure of the cryocooler and the experimental results will be presented.

DESIGN OF THE CRYOCOOLER

A two-stage gas-coupled SPTC driven by a linear dual-opposed compressor was designed and fabricated. Figure 1 shows the schematic and 3D diagram of the two-stage gas-coupled SPTC. Both of the two stages adopted a coaxial structure for compactness. Optimization of the SPTC configuration was done with SAGE software. The design parameters of the SPTC are summarized in Table 1. Each of the regenerator and pulse tube possessed a constant diameter. The regenerator of the first stage was filled with 300#, 400# and 500# stainless steel screens. The second stage was filled with 635# stainless steel screens and Er_3Ni powder. The home-made double-inlet, inertance tube and gas reservoir were adopted as the phase shifter for the first stage. The cold double-inlet, cold inertance tube and cold gas reservoir were adopted as the phase shifter for the second stage. The

Table 1. Parameters of the cold head.

Parameters	Values (mm)
Regenerator I	Φ26*91
Regenerator II	Φ13*44
Pulse tube I	Φ12.5*104
Pulse tube II	Φ5.5*41
Inertance tube I	Φ2*1200+Φ3*1800+Φ4*4000
Inertance tube II	Φ1*1500+Φ2*2300
Reservoir I	600cc
Reservoir II	23 cc

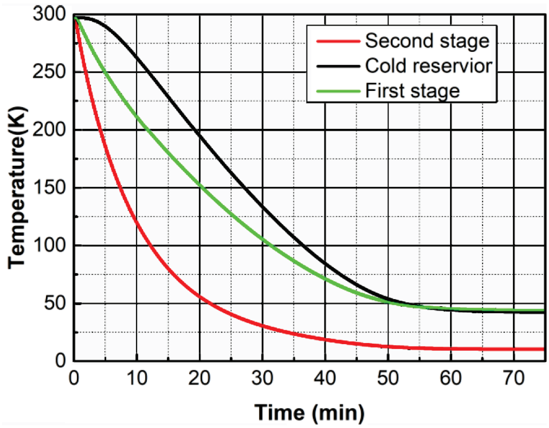

Figure 2. The cooling curve of the developed cryocooler.

gas reservoir of the second stage was an annular configuration which is placed between regenerator and vacuum shield, and it can work as a radiation shield to reduce the radiation heat loss between the outer wall of regenerator and the vacuum shield in room temperature. The flow straighteners of the second stage were made of 80# copper screens. The hot end of the second stage was thermal connected to the cold end of the first stage. At the cold end of first stage, a part of the working gas was introduced to the regenerator of second stage, while the others were returned to the pulse tube of the first stage.

EXPERIMENTAL RESULTS

Figure 2 shows a typical cooling curve of the cryocooler with a charging pressure of 2.5 MPa, an operating frequency of 27 Hz with the double-inlet valve at its optimum opening. With an input electric power of 400 W, a no-load temperature of 8.87 K can be achieved, while the temperature of the first stage is 38.0 K. The pressure ratio of the compression space of compressor is 1.36. It takes about 70 minutes to cool down to the lowest temperature.

Figure 3 shows the temperature stability of the cold end of the second stage within 1500 seconds after running 12 hours. The mean temperature is 8.87 K. And the temperature fluctuation amplitude without any extra controlling method is less than ±14 mK.

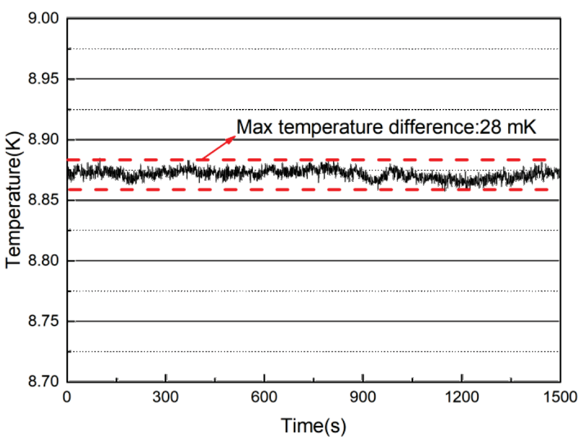

Figure 3. Temperature stability of the cold head of the second stage.

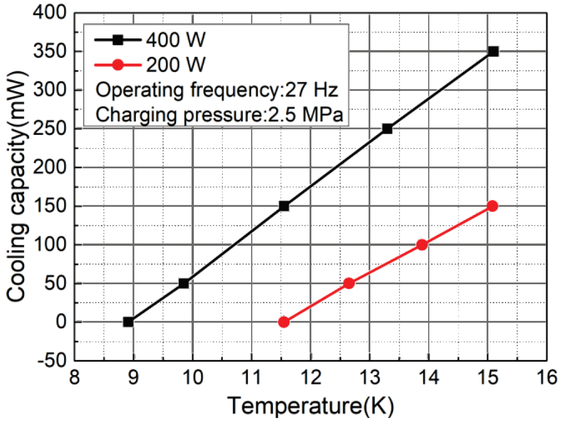

Figure 4. The cooling capacity of the cryocooler.

The cooling capacity of the cryocooler is measured, as shown in Figure 4. With 200 W input electric power, the pressure ratio is 1.28, and the lowest temperature is 11.5 K. It can provide 150 mW cooling capacity at 15 K. When the input power increases to 400 W, the lowest temperature decreases to 8.87 K and the cooling capacity increases to 350 mW.

Figure 5 shows the influence of hot end temperature of the first stage on the cryocooler. It can be found that the temperatures of the first stage and second stage vary linearly with that of the hot end. The temperature of the second stage increases 0.7 K when the temperature of hot end increases from 279 K to 309 K, while the temperature of the first stage increases 2.7 K. The test results indicate that the second stage has a less sensitive compared with the first stage when the hot end has a large temperature fluctuation.

CONCLUSIONS

A two-stage high-frequency SPTC based on a high efficiency single-stage SPTC has been designed, manufactured and tested. Both of the two stages are coaxial structure for compactness. It takes about 70 minutes to cool down to its lowest temperature. It achieves a lowest no-load temperature of 11.5 K and provides 150 mW cooling capacity at 15 K with 200 W input electric power. When

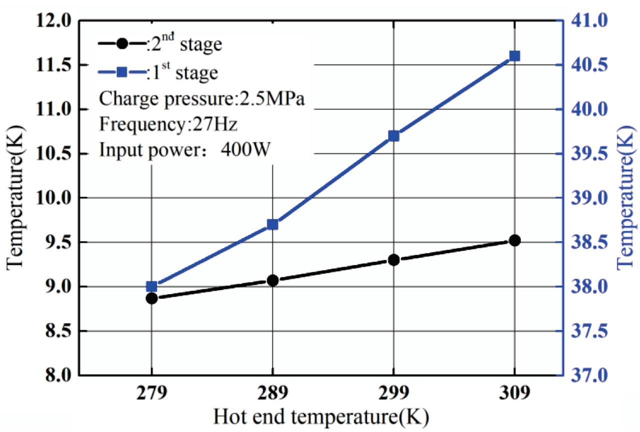

Figure 5. Effect of the temperature of hot end of the cryocooler.

the input power increases to 400 W, the temperature decreases to 8.87 K and the cooling capacity increases to 350 mW. It has a reliable temperature stability during experiments, the temperature fluctuation is less than ±14 mK. The lowest temperature of the second stage and first stage increases 0.7 K and 2.7 K, respectively, when the temperature of the hot end of the first stage increases 30 K.

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