The study on a gas-coupled two-stage stirling-type pulse tube cryocooler

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Abstract. A two-stage gas-coupled Stirling-type pulse tube cryocooler (SPTC) driven by a linear dual-opposed compressor has been designed, manufactured and tested. Both of the stages adopted coaxial structure for compactness. The effect of a cold double-inlet at the second stage on the cooling performance was investigated. The test results show that the cold double-inlet will help to achieve a lower cooling temperature, but it is not conducive to achieving a higher cooling capacity. At present, without the cold double-inlet, the second stage has achieved a no-load temperature of 11.28 K and a cooling capacity of 620 mW/20 K with an input electric power of 450 W. With the cold double-inlet, the no-load temperature is lowered to 9.4 K, but the cooling capacity is reduced to 400 mW/20 K. The structure of the developed cryocooler and the influences of charge pressure, operating frequency and hot end temperature will also be introduced in this paper.

1. 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 [1-7]. At present, SPTC working at around 80 K can achieve a relative Carnot efficiency larger than 20% [8]. For example, Wang has developed a SPTC which has achieved a cooling capacity of 26.4 W/80 K with an input power of 290 W. Its relative Carnot efficiency is as high as 24.2%. 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 within 300 W input power [10], but by using the multi-bypass structure, a larger cooling capacity could be achieved. For example, Chen has developed a multi-bypass type SPTC with a no-load temperature of 15.5 K and a cooling capacity of 2.5W/35 K with 240 W input power [11]. The no-load temperature reduced to 13.9 K when part of the regenerator matrix was replaced by Er_3Ni, which is the

lowest temperature record for single-stage SPTC [12]. To achieve a lower temperature, a multi-stage is generally needed. At present, the lowest no-load temperature record for two stages and three stages using helium 4 were 3.98 K and 3.93 K, respectively. Both of them were fabricated as thermal coupled structures and driven by two compressors [6]. The lowest no-load temperature record for multi-stage SPTC using helium 3 is 3.0 K [3-5]. 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 millwatts can be achieved at 10-15 K [3-6]. Therefore, there is still a long way to go for practical application.

In this paper, a two-stage gas-coupled SPTC driven by a linear dual-opposed compressor aiming for providing 200 mW cooling capacity at 15 K has been developed. The structure of the cryocooler and the experimental results will be introduced.

2.   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 of the developed two-stage gas-coupled SPTC. The multi-bypass, 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 hot end of the second stage was connected to the cold end of the first stage. The 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 regenerator of the first stage is a variable cross-section configuration with two sections of different diameters and lengths. The multi-bypass was employed in the joint of the two sections. The regenerator of the first stage was filled with 300 mesh, 400 mesh and 500 mesh stainless steel screens. The regenerator of the second stage was filled with the 635 mesh stainless steel screens and Er_3Ni. The flow straighteners of the first stage were made of 80 mesh copper screens, while the straighteners of the second stage were made of 200 mesh copper screens.
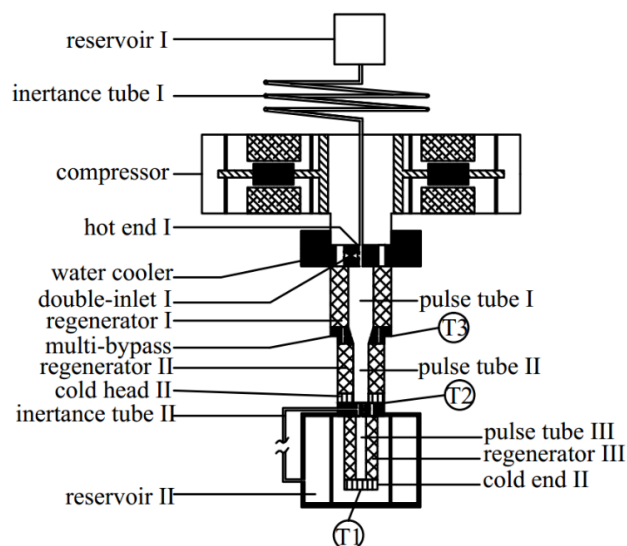

Figure 1. The schematic of the developed gas-coupled two-stage pulse tube cryocooler.

The detail design parameters of the developed cryocooler are summarized in ţable 1. The detail parameters of the linear compressor are listed in table 2. The temperatures were measured by means of Rh-Fe resistance sensors (calibration range: 2-300 K). The cooling capacity was measured by means of thermal heat balance method. The temperature of the hot end of cryocooler was controlled by a chiller.

Table 1. Parameters of the cold tip.

Parameters	Values (mm)
1st section of regenerator I	Φ26*25(350#)+Φ26*30(400#)
2nd section of regenerator II	Φ18*36(500#)
Regenerator II	Φ13*44(635#+Er3Ni)
1st pulse tube	Φ11.7*104
Pulse tube II	Φ5.5*44
Inertance tube I	Φ1.3*600+Φ2*600+Φ3*1500
Inertance tube II	Φ0.6*10+Φ0.8*20
Reservoir I	600 cc
Reservoir II	23 cc

Table 2. Parameters of the compressor.

Parameters	Values
Diameter of piston	40 mm
Maximum amplitude (zero to peak)	10 mm
Mass of positon	2.1 kg
Compression volume	58.5 cc
Buffer volume	2*0.92 L
Maximum pressure	3.5 MPa

3.   Experimental results and discussion

3.1.   Cooling performance

Figure 2 shows a typical cooling curve of the cryocooler. T1 represents the temperature of the cold end of second stage. T2 represents the temperature of the cold end of first stage. T3 represents the temperature of multi-bypass. With a charging pressure of 1.7 MPa, an operating frequency of 23.5 Hz and an input power of 450 W, a no-load temperature of 11.28 K can be achieved, while the temperature of T2 and T3 is 55.04 K and 107.80 K, respectively.

Figure 3 shows the temperature fluctuation of the cold end of the second stage during 30 mins. The temperature fluctuation amplitude without any extra controlling method is less than ±20 mK.
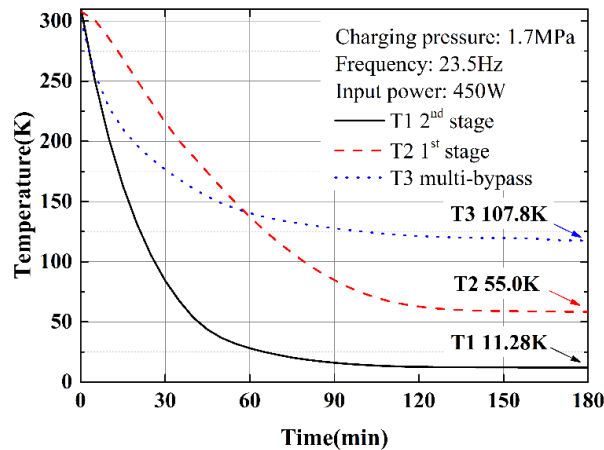
Figure 2. The cooling curve of the developed cryocooler.
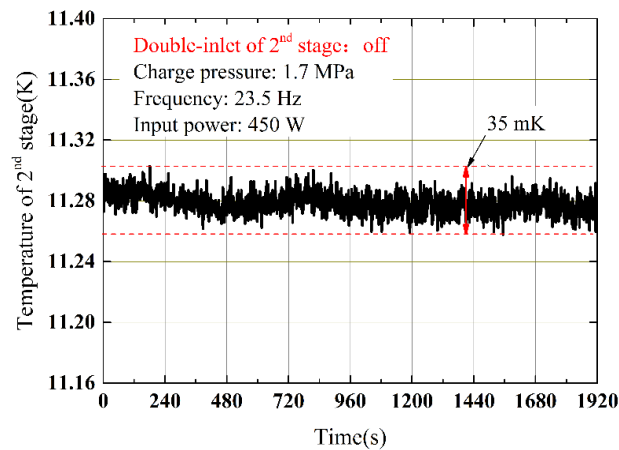

Figure 3. Temperature stability of the cold head of the second stage.

The cooling capacity of the cryocooler was measured, as shown in figure 4. The figure presents the temperature of each stage when a heat load of 0 mW, 100 mW, 200 mW and 400 mW was applied to each stage on the condition of a 1.7 MPa charging pressure, a 23.5Hz operating frequency and 450 input power. For example, the cryocooler can provide 100mW/12.5K and 100mW/56K at the second and the first stage, simultaneously. A cooling capacity of 400mW/17.1K and 400mW/60.3K at second and first stage can also be achieved, simultaneously.

The influence of double-inlet of the second stage on the cooling performance is as shown in figure 5. It can be found that the no-load temperature of cold end of the second stage decreases from 11.28 K to 9.4 K by the use of cold double-inlet. However, the slope of the cooling capacity curve is much less than that without cold double-inlet, which means the cooling capacity in the higher region will be much lower when the double-inlet is employed. For example, the cooling capacity with and without double-inlet at 20 K are 400 mW and 620 mW, respectively.
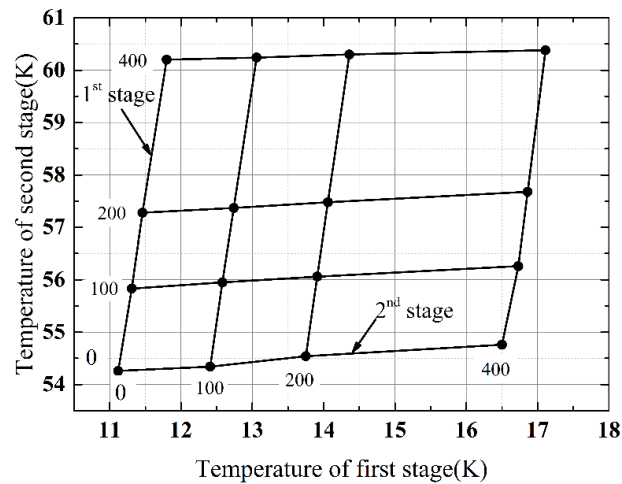
Figure 4. The cooling capacity of the cryocooler.

The performance of the cryocooler is also influenced by the charging pressure. As shown in figure 5, it is easier to get a lower temperature with a lower charging pressure, which is due to lower regenerator flow loss. At the same time, the maximum input power of compressor increases with a higher charging pressure: the maximum input power of compressor is 456 W and 480 W at the charging pressure of 1.7 MPa and 2.1 MPa, respectively. Therefore, the increasing of the power consumption also helps to further increase the cooling capacity.
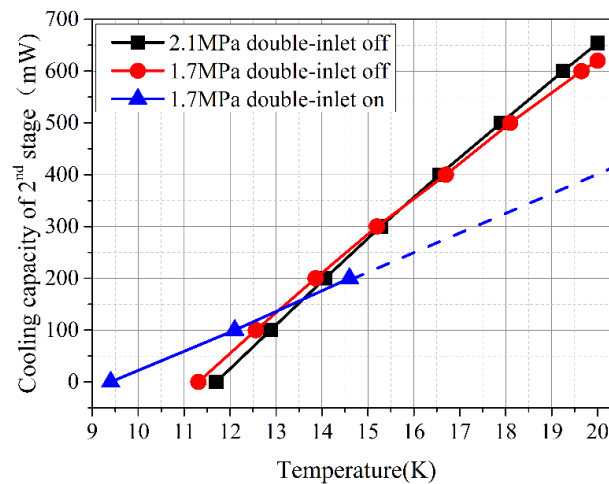

Figure 5. The cooling capacity of the second-stage.

3.2. Effects of operating frequency on cooling performance
The influence of operating frequency on the performance of the cryocooler has been investigated as shown in figure 6. There is an optimum operating frequency for the cold end of second stage, that is about 23.5 Hz. However, as the operating frequency decreases, the temperature of first stage decreases monotonically, i.e., the optimum operating frequency of the

first stage is lower than that of the second stage, which indicates that the inertance tube of the first and second stage need to be optimized further to achieve a better cooling performance.
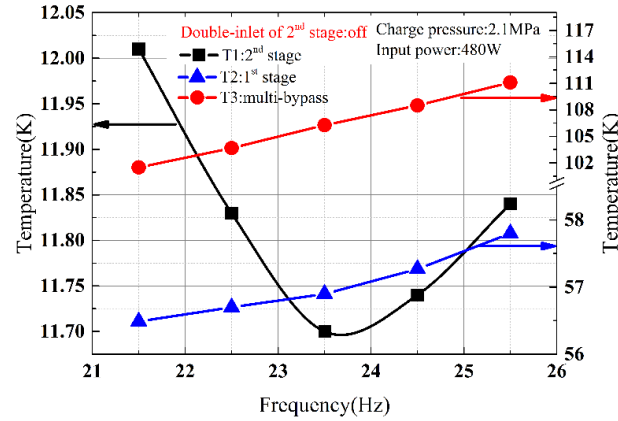

Figure 6. Effect of operating frequency on the temperature of cold head.

3.3. Effects of hot end temperature on the cooling performance

figure 7 shows the influence of hot end temperature, which is controlled by a chiller, on the cold head temperature of the first and second stage. It can be found that the temperatures of the first and second stage vary linearly with the temperature of hot end. The temperature of the second stage increases 0.72 K when the temperature of hot end increases from 278 K to 308 K, while the temperature of first stage and multi-bypass increases 2.72 K and 7.2 K, respectively. The test results indicate that the multi-stage cryocooler has a less sensitive compared with single-stage cryocooler when the hot end has a large temperature fluctuation.
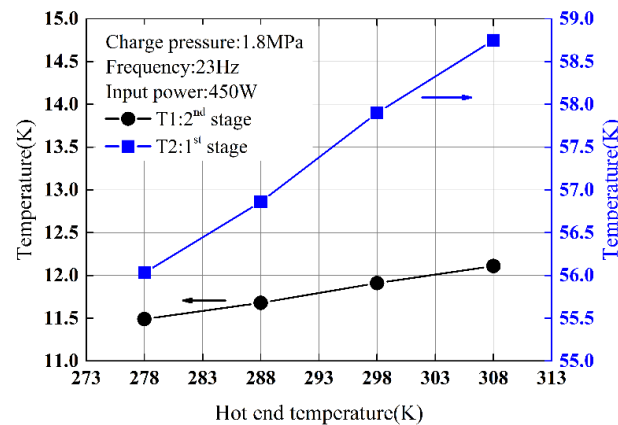

Figure 7. Effect of the temperature of hot end of the cryocooler on the cooling performance.

4.   Conclusions

   A two-stage high-frequency pulse tube cryocooler driven by a linear dual-opposed compressor has been designed, manufactured and tested. Both of the two stages are coaxial structures for compactness. The test results show that the cold double-inlet of the second stage

will help to achieve a lower cooling temperature, but it is not conducive to achieve a higher cooling capacity. The no-load temperature reduced from 11.28 K to 9.4 K, while the cooling capacity decreases from 620 mW to 400 mW at 20 K when the cold double inlet of the second stage was employed. The cooler can provide 100mW/12.5K at the second stage and 100mW/56K at the first stage, simultaneously. When the temperature of the hot end of the first stage increases from 278 K to 308 K, the temperature of the cold head of the second stage increases 0.24 K.

5.   References

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