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Simulation and experimentation of a two-stage pulse tube cooler at 20 K

Chushu Fang[1,2], Xuming Liu[3*], Changzhao Pan[3*], Laifeng Li[1,2] and Yuan Zhou[1,2]

[1]Technical Institute of Physical and Chemical, Chinese Academy of Sciences, Beijing 100190, China

[2]University of Chinese Academy of Sciences, Beijing 100190, China

[3]Shenzhen International Quantum Institute (SIQI), Shenzhen 5180045, Guangdong Province, China

[*]E-mail: liuxm3@sustech.edu.cn; pancz@sustech.edu.cn.

Abstract. Small Stirling-type pulse tube cryocooler can be used to cool small optical devices due to the absence of moving elements in the cold head, long life, low vibration, and compactness. This paper reports a small two-stage Stirling-type pulse tube cryocooler that achieves a no-load minimum temperature of 20 K with 500 W of input electrical power and has 0.5 W@25 K cooling capacity. In addition to this, the effect of the second stage double-inlet on the P-U phase of the regenerator and the pulse tube is also simulated. The results show that the double-inlet has a significant effect on increasing the P-U phase difference between the inlet of the regenerator and the outlet of the pulse tube, which is much better than the effect of the length of inertial tube of this stage on the P-U phase.

1. Introduction

Pulse tube cooler is regarded as the development direction of space cryocooler due to its cold head without moving parts, low vibration, long life and compact structure. As a kind of pulse tube cryocooler, Stirling-type pulse tube cryocooler benefits from the development of Stirling compressor, which uses linear compressor with low vibration and no oil pollution, and it is an important development direction for small pulse tube cryocoolers, which can be used to cool small optical devices in space detectors[1-2].

A two-stage high-frequency pulsed-tube cryocooler was developed by L.W. Yang et al. at Giessen University, achieving a minimum temperature of 19.6 K[3]. A single-stage pulsed-tube cryocooler was developed by Chen Liubiao et al. using muti-bypass down to 18.4 K with 0.5 W@24.1 K of cooling capacity[4]. A minimum cooling temperature of 13.9 K was obtained using Er_3Ni as a cold storage material by Zhou Qiang et al[5]. A high efficiency thermally-coupled two-stage Stirling type pulse tube cryocooler working at 35 K for HgCdTe long wave infrared detector cooling is designed and tested by Yijun Chao, et al. The cryocooler provides a cooling power of 1 W at 35.1 K with an input electrical power of 150 W, which indicates a relative Carnot efficiency of 5 %[6].

In this paper, a two-stage Stirling-type pulse tube cryocooler is developed, which can be used to pre-cooling a three-stage pulse-tube cryocooler in the liquid helium temperature region.

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2. Cryocooler sizing and simulation calculations

The schematic diagram of the two-stage pulse tube cryocooler is shown in Figure 1. The cold finger is arranged in a coaxial arrangement, i.e., the pulse tube is arranged inside the regenerator, which is very compact.

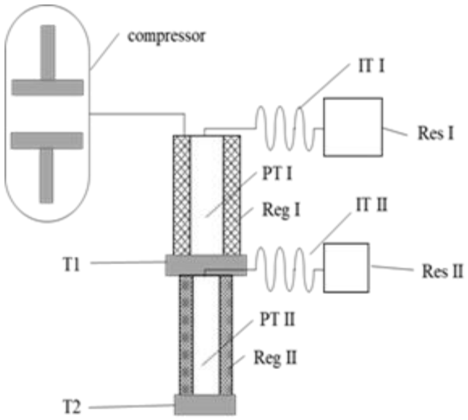


Figure 1. The schematic diagram of the two-stage pulse tube cryocooler

The whole machine uses only one compressor, and the first stage cold end and the second stage hot end are connected using a flange with air holes, so that part of the gas from the cold end of the first stage goes into the first stage pulse tube for refrigeration, and the other part goes into the second stage regenerator to take part in the refrigeration cycle of the second stage.

Before building the pulsed tube cryocooler, we need to perform a simulation study of the whole machine dimensions, usually using the commercial software SAGE. The structural parameters of the STPC are shown in Table 1.

Table 1. Two-stage Stirling-type pulse tube cryocooler cold head size parameters.

Parameters	PT I	PT II
cold storage material	300#SS	400#SS
Length of regenerator	36 mm	36 mm
Inner and outer diameter of regenerator	15 mm/30 mm	9 mm/18 mm
IT	φ2 mm-0.7 m+φ3 mm-2 m+φ4 mm-4 m	Φ1 mm-0.5 m+φ2 mm-0.5m
Reservoir	600 cc	100 cc

2.1 double-inlet

A double-inlet is added to the cold end of the first stage and the hot end of the second stage and the effect of its opening size on the performance of the cryocooler is simulated and the results are shown in Fig. 2.

As the area of the small hole representing the double-inlet gradually increases, the first stage cold end temperature gradually decreases, but the second stage cold end temperature shows an anomalous first increase and then decrease. This is somewhat similar but not identical to the parabolic case described in many papers, where the effect of bi-directional openings on the minimum cooling temperature of the cryocooler is calculated as a cubic case in the simulations of this paper. This may be an effect of DC which is an interesting phenomenon that deserves continued study.

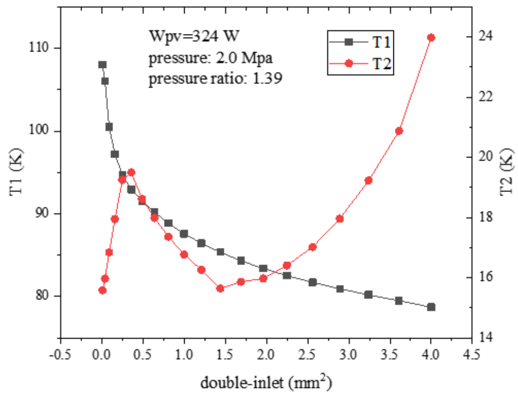
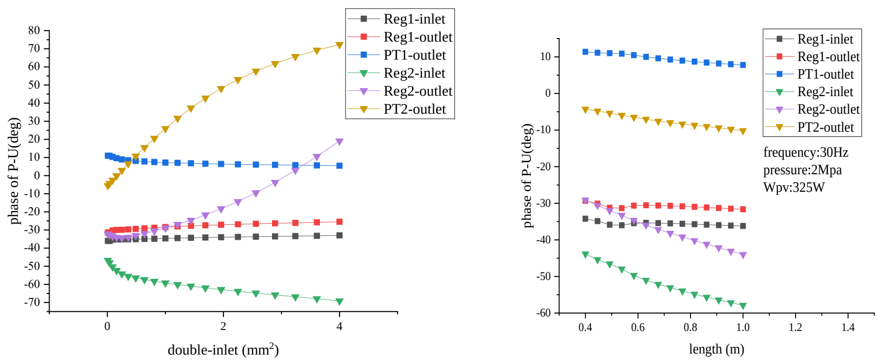


Figure 2. Trend of minimum cooling temperature with frequency at different operating pressures

2.2 Phase of P-U

Fig. 3(a) investigates the effect of double-inlet opening variation on the P-U phase at the inlet and outlet of the cryocooler regenerator as well as at the outlet of the pulse tube. Fig. 3(b) shows the P-U phase variation of the inlet and outlet of the regenerator and vein tubes after changing the length of the first section of the inertia tube of the second stage.



(a) (b)

Figure 3. Variation curve of P-U phase with double-inlet openings and IT II - φ1mm

The comparison shows that the effect of double-inlet on the phase of P-U in the vasculature is significantly greater than that of the inertial tube and mainly affects the phase of P-U in the second stage. Therefore, when temperatures are relatively low and the phase regulation capability of the inertia tube and gas bank combination is insufficient, the addition of double-inlets will greatly enhance phase regulation, thereby improving cryocooler performance.

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3. Experimentation

3.1 Experimental equipment

The experimental prototype is shown in Fig. 4. The use of the compressor is the CP5570 type dynamic ferromagnetic linear compressor, rated power of 500 W, the quality of 24 kg. In the first stage and the second stage of the cold head at the layout of the platinum resistance thermometer, the second stage of the platinum resistance thermometer using their own calibration of the PT100, 20 K when the error is about ± 0.1 K. The power supply uses the Kikusui power supply. Circulating cooling water is connected to the compressor outlet and the pulse tube cold head connection at a temperature of 283 K.

Figure 4. Experimental prototype

3.2 Experimental results

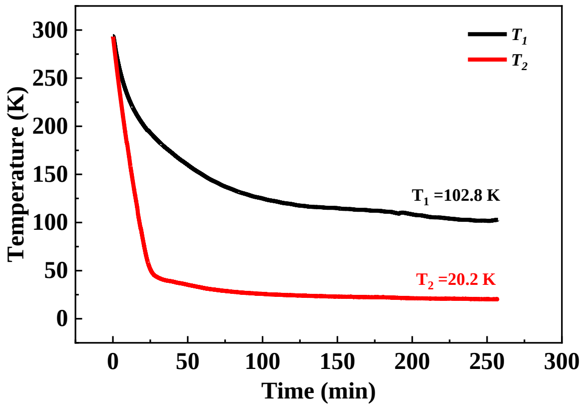

Figure 5. Cooling curve of cryocooler

Table 2 shows the experimental operating parameters. Initial inflation pressure is 2.0 MPa, after 3 hours of cooling, the pressure is reduced to 1.8 MPa. Specific cooling curve is shown in Figure 5. About 1.6 h after, the second level of the lowest temperature drops to below 25 K. And after 4.8 hours, the cryocooler reached a minimum cooling temperature of 20.0 K.

Table 2. experimental operating parameters.

Parameters	value
frequency	30 Hz
Input power	500 W/375 W(PV)
pressure	1.8 MPa
pressure ratio	1.41
Double-inlet	0.09 mm^2

Figure 6 shows the difference between the actual and simulated cooling capacities and their relative Carnot efficiencies. The software used for the simulation is the commercial refrigeration software SAGE, and the modelling process ignores the effects of radiant heat leakage and other influences, so there is a difference in the refrigeration capacity, but the trend of the calculated relative Carnot efficiency with the temperature matches the results of the actual experiments, and it can be assumed that the model has a certain degree of predictability.

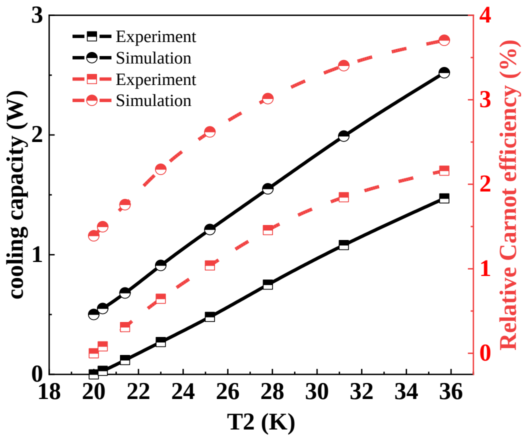

Figure 6. cooling capacity and relative Carnot efficiency of cryocooler with temperature

4. Conclusion

In this paper, a two-stage pulse tube cryocooler with a minimum cooling temperature of 20.2 K at 500 W input electrical power and a cooling capacity of 1.5 W@35 K has been developed, which can be used as a pre-cooling stage for the third-stage pulse tube cryocooler in the liquid helium temperature region.

The P-U phase changes in the inlet and outlet of the regenerator and the inlet and outlet of the pulse tube due to the change in the area of the double-inlet and the change in the length of the first section of the second-stage inertial tube were calculated respectively, and it was found that the addition of the double-inlet causes a drastic change in the inlet and outlet of the regenerator and the pulse tube in the phase of that stage, which is unattainable by the inertial-tube phase adjustment.

Acknowledgments

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