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1 W@28.2 K micro single-stage coaxial pulse tube cryocooler operating at 52 Hz using precooling

Chenglong Liu[1,2,3], Bin Yang[1,2,3], Bo Tian[1,2,3], Mingtao Pan[1,2,3], Yuefeng Niu[1,2,3], Yanen Li[1,2,3], Min Gao[1,2,3], Jia Quan[1,2], Qingjun Tang[1,2*], and Jinghui Cai[1,2,3]

[1] Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China
[2] State Key Laboratory of Cryogenic Science and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China
[3] University of Chinese Academy of Sciences, Beijing 100190, China

[*]E-mail: tangcorresponding@163.com

Abstract. With the advancement of deep cryogenic detection technology, spacecraft are required to operate at a background temperature of 100 K or lower, necessitating the use of pulse tube cryocooler as a critical support component. Traditionally, the compressor and hot end heat exchanger of pulse tube cryocooler function at an ambient temperature of 300 K. Multi-stage pulse tube cryocoolers typically require precooling to a temperature range of 80 K to 100 K before the second stage can commence operation. The transient regenerator serves as the thermal buffer between the ambient temperature compressor and the secondary pulse, leading to significant PV power losses and reduced cryocooler efficiency. Additionally, two-stage pulse tube cryocoolers often exhibit low operating frequencies, large volumes and weights, and high launch costs. This paper presents the design of a micro single-stage coaxial pulse tube cryocooler capable of direct operation in the 80 K temperature range. The cryocooler is powered by liquid nitrogen precooling and a linear compressor, with a total mass of 2.6 kg. It employs inertance tube and gas reservoir as phase shifters. The cold finger has a diameter of 14 mm and a fill length of 55 mm. Preliminary experiments yielded the following results: at an operating frequency of 60 Hz, an input power of 20 W, a hot end temperature of 80 K, and an operating pressure of 1.5 MPa, the minimum no-load temperature achieved was 13 K, and a cooling capacity of 1 W at 28.2 K was obtained at 52 Hz.

Keywords: pulse tube cryocooler · liquid nitrogen · 80 K · micro · 52 Hz

1. Introduction

Owing to the unique operational environment of space vehicles, cryogenic coolers must adhere to stringent requirements. Pulse tube cryocoolers (PTCs) are extensively utilized due to their straightforward design, robustness, minimal vibration, extended operational lifespan, and the absence of moving components within the cold head. Future deep space probes may encounter operational temperatures significantly below standard condition (in full sunlight), potentially reaching liquid nitrogen temperature range or lower. However, there is a paucity of research on

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low-temperature PTCs tailored for detectors with reduced heat dissipation temperatures. In 2008, CEA-SBT introduced a phase-modulated piston mechanism, which facilitated subsequent investigations into 80 K and 50 K regenerators and intermediate stage precooling for pulse tubes [1]. By 2014, CEA had substituted the G-M cryocooler with a larger-scale PTC to provide precooling for the low-temperature PTC. This system employs active phase modulation at room temperature and achieves a cooling capacity of 0.3 W at 15 K with an input power of 290 W and a precooling temperature of 110 K [2]. In 2012, Qiu Limin and colleagues from Zhejiang University developed a two-stage thermally coupled PTC equipped with its own precooling unit. Their phase shifter consists solely of an inertance tube and a gas reservoir. The midsection of the second stage pulse tube is linked to the precooling stage, enhancing the rapid heat dissipation from the hot end of the pulse tube and minimizing losses. This configuration enabled the attainment of a no-load temperature of 15.87 K at the cold end [3]. In 2014, Northrop Grumman Space Technologies (NGAS) operated a linear compressor at an ambient temperature of 150 K, achieving a cooling capacity of 0.17 W at a cold end temperature of 35 K [4]. Also in 2014, the Institute of Physics and Chemistry successfully developed a thermally coupled two-stage PTC capable of reaching temperatures as low as 8 K. This device connects the hot end of the two-stage pulse tube and the low-temperature inertance tube gas reservoir to the first stage's cold head, utilizing a multi-bypass two-stage regenerator. The first stage provides a precooling temperature of 58.8 K, while the second stage achieves a no-load temperature of 4.5 K and a cooling capacity of 31 mW at 8 K [5]. In 2016, Chen Liubiao and associates from the Institute of Physics and Chemistry implemented liquid nitrogen precooling for a two-stage PTC and conducted experimental studies. The liquid nitrogen precooling intermediate heat exchanger of the cryocooler was filled with stainless steel wire mesh #635, and the low-temperature inertance tube-gas reservoir and dual air intake were combined for phase modulation. The no-load temperature of the secondary cold head reached 10.3 K, demonstrating superior cooling capacity of 0.26 W at 15 K [6]. In 2018, Chen Liubiu and his team applied liquid nitrogen precooling to the hot end heat exchanger, inertance tube, and gas reservoir, optimizing the type and size of the cold storage equipment under conditions ranging from 4 to 20 K, achieving a minimum no-load temperature of 3.6 K. A cooling power of 6 mW/4.2 K was also obtained with 25 0W input power and a precooling power of 12.1 W/77 K. [7]. In 2017, Jiho Park and colleagues from the Korea Advanced Institute of Science and Technology submerged a linear compressor in a liquid nitrogen tank, achieving an average efficiency of 85% across various operating frequencies. The minimum no-load temperature of the PTC was 18.7 K, and it delivered a cooling capacity of 0.4 W at 20 K [8].

The present paper sets forth the design of a micro single-stage coaxial PTC that is capable of direct operation within the 80 K temperature range. Utilising an operating frequency of 60 Hz, an input power of 20 W, a hot end temperature of 80 K, and an operating pressure of 1.5 MPa, the minimum no-load temperature achieved was 13 K. Furthermore, a cooling capacity of 1 W at a temperature of 28.2 K was obtained at a frequency of 52 Hz.

2. Experimental system composition

A series of tooling designs were implemented to thoroughly precool the compressor, hot end heat exchanger, inertance tube, and gas reservoir to liquid nitrogen temperature (approximately 80 K). The schematic and physical diagrams of the experimental system are presented in Figure 1 and Figure 2 below.

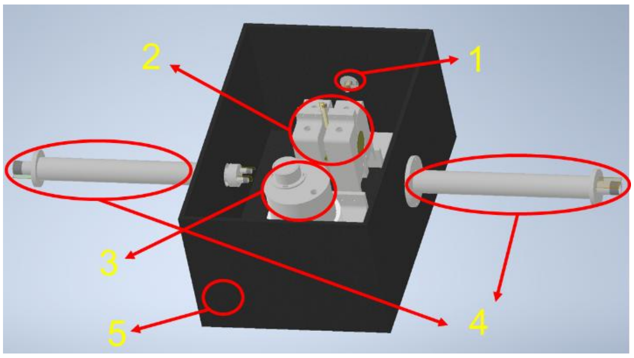

Figure 1. Schematic diagram of experimental system.

1. Inflation device; 2. Compressor cooling device;
3. Hot end heat exchanger and phase shifter cooling device; 4. Conveying liquid nitrogen sleeve and pipeline device; 5. Sealing design of vacuum box.

Figure 2. Physical diagram of the experimental system.

The inflation device is utilized to fill the system with helium. The compressor cooling device is employed to cool the compressor. The cooling device for the hot end heat exchanger and the phase shifter is designed to cool the hot end heat exchanger, the inertance tube, and the gas reservoir. Conveying liquid nitrogen sleeve and pipeline device are used to convey liquid nitrogen to the cooling unit. The vacuum chamber seal is engineered to evacuate the entire experimental system. For the liquid nitrogen conveying system, the liquid nitrogen dewar is connected to the vacuum casing, the outer tube of the casing is affixed to the vacuum box, the inner tube penetrates the wall of the vacuum box, and the casing is linked to the cooling device via a corrugated pipe.

The relevant parameters of the cryocooler are detailed in Table 1. The total weight of the cryocooler, excluding the precooling device, is 2.6 kg.

Table 1. Main parameters of this PTC.

Component	Parameter
Compressor	55.5 mm in diameter and 128 mm in length
Piston	12 mm in diameter
Cold Finger	14 mm in diameter and 55 mm in fill length
Regenerator	#635 and #500 stainless steel screen
Inertance Tube	A total length of 2.5 m, Φ2*0.5+Φ3*1+Φ4*1
Gas reservoir	50 cc in volume
Operating Pressure	1 MPa，1.5 MPa，2 MPa，2.5 MPa

3. Experimental results and discussion

At the beginning of the experiment, liquid nitrogen is continuously injected into the precooling device. After about 1.5 hours, the compressor, phase shifters and hot end heat exchanger can be cooled to about 80 K. When the temperature of each component reaches about 80 K, the test will start.

The performance of cryocooler under different operating pressure is tested by experiment. Due to the short piston stroke of the compressor, cylinder collision is easy to occur under low operating pressure and high power, so the measured data are not complete. In the experiment, multi-point temperature monitoring was carried out, including the side of the compressor, the air outlet of the compressor, the gas reservoir, the hot end, and the cold finger and cold head. In order to ensure the accuracy of the data, Carbon resistance thermometer and PT100 thermometer were used to jointly monitor and compare the cold finger and cold head, and PT100 thermometer was used to monitor the other points. The precooling temperature and stable operating temperature of each component are shown in Table 2 below.

Table 2. Precooling temperature and stable operating temperature of each component.

Monitoring points	Precooling temperature /K	Stable operating temperature /K
Compressor shell	79.5	78.5-82.5
Compressor outlet	86.5	80.0-82.5
Gas reservoir	81.0	79.0-81.0
Hot end heat exchanger	79.0	79.5-81.0

The minimum no-load temperature of cold finger and cold head is tested with frequency under different operating pressure and input power of 10 W and 20 W. When the operating pressure is 1 MPa and the input power is 20 W, the cylinder will collide, so the data in this case has not been tested. The temperature changes are shown in Figures 3 and 4.

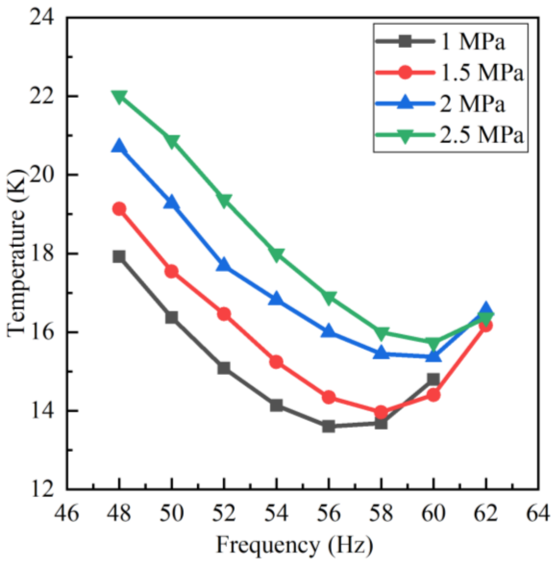

Figure 3. The minimum no-load temperature varies with frequency at 10 W input power.

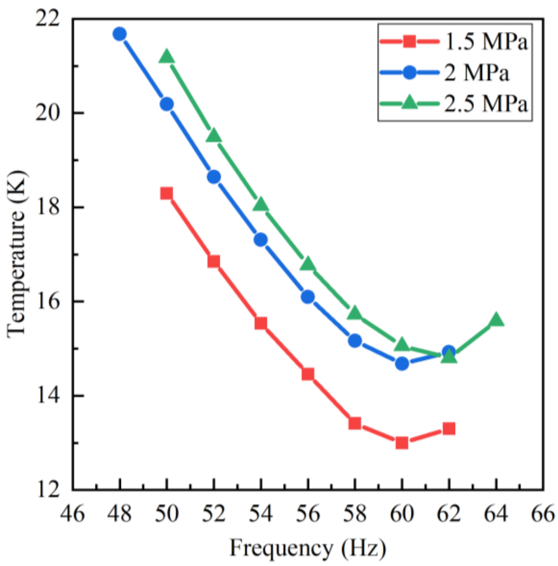

Figure 4. The minimum no-load temperature varies with frequency at 20 W input power.

It can be found from the figure that the optimal frequency of the lowest temperature is between 54 Hz and 64 Hz, and when the power is constant, the optimal frequency increases with the increase of the operating pressure. When the operating pressure is constant, the optimal frequency increases slightly with the increase of the input power. When the input power is 10 W, the operating pressure is 1 MPa, and the frequency is 56 Hz, the minimum no-load temperature of 13.6K can be obtained. When the input power is 20 W, the operating pressure is 1.5 MPa, and the frequency is 60 Hz, the minimum no-load temperature is 13 K.

The relative Carnot efficiency and cold finger cold head temperature change with frequency were tested under different operating pressures with input power of 10 W and 20 W, 0.5 W and 1 W cooling capacity. The temperature changes are shown in Figure 5, Figure 6 and Figure 7. After the heating is turned on, the optimal frequency will decrease, and the greater the heat added, the greater the decrease in the optimal frequency. For the same heating energy, the greater the input power, the smaller the decrease in the optimal frequency.

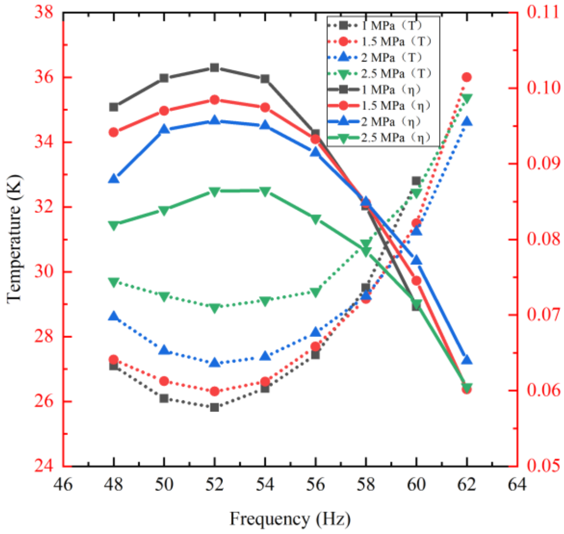

Figure 5. Temperature and relative Carnot efficiency as a function of frequency at 10 W input work and 0.5 W cooling capacity.

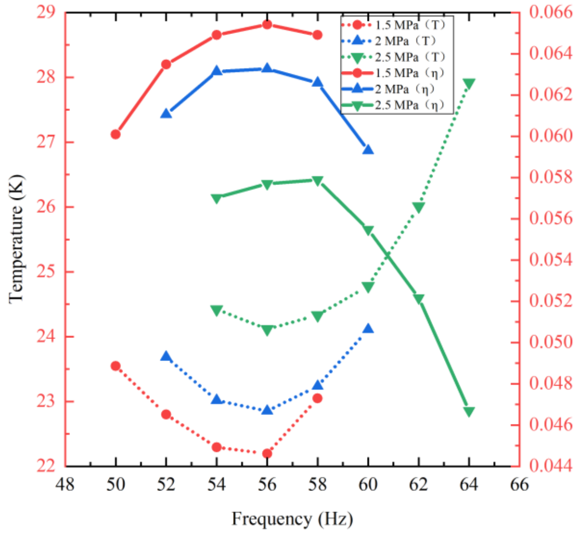

Figure 6. Temperature and relative Carnot efficiency as a function of frequency at 20 W input work and 0.5 W cooling capacity.

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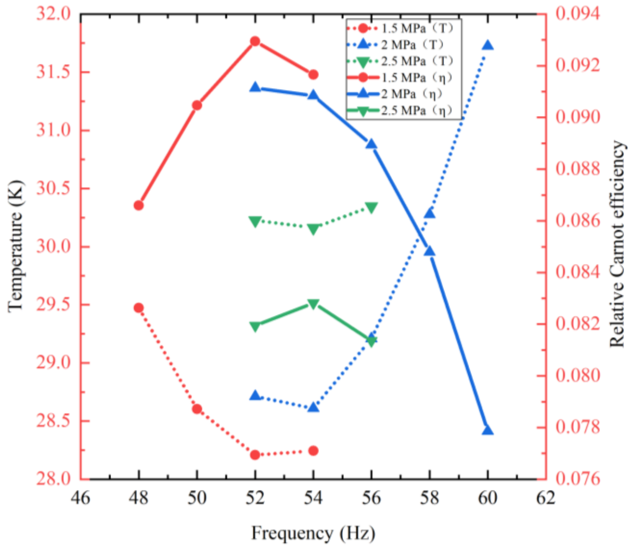

Figure 7. Temperature and relative Carnot efficiency as a function of frequency at 20 W input work and 1 W cooling capacity.

When the input power is 10 W, the operating pressure is 1 MPa, and the frequency is 52 Hz, 0.5 W@25.8 K can be obtained, and the highest relative carnot efficiency is 10.3%. When the input power is 20 W, the operating pressure is 1.5 MPa, and the frequency is 56 Hz, 0.5 W@22.2 K can be obtained, and the highest relative carnot efficiency is 6.5%. 1 W@28.2 K can be obtained at 52 Hz, where the highest relative carnot efficiency is 9.3%.

The relationship between temperature and cooling capacity was tested at 54 Hz, 10 W and 20 W input power. This is shown in Figures 8 and 9. When heating at 0.5W, the optimal operating pressure is near 1 MPa; When heating at 1 W, the optimal operating pressure is around 1.5 MPa; With the increase of heat, the optimal operating pressure increases.

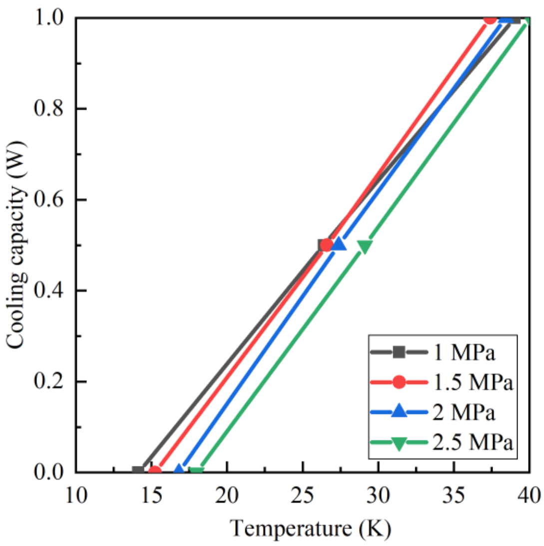

Figure 8. The relationship between temperature and cooling capacity at 10 W input power.

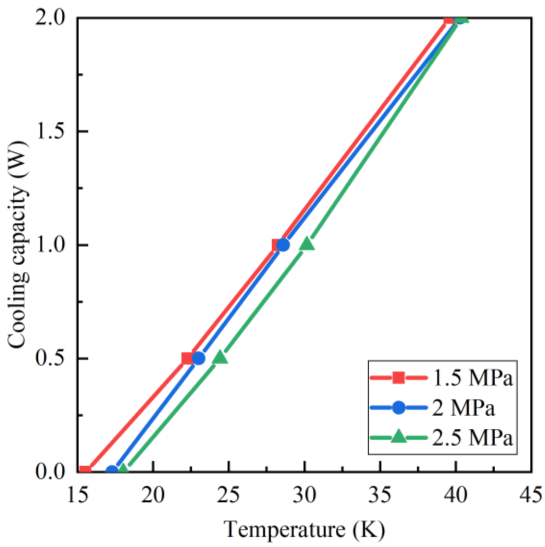

Figure 9. The relationship between temperature and cooling capacity at 20 W input power.

In accordance with the initial clause of the First Law of Thermodynamics, under the assumption that the vacuum box's insulation performance is satisfactory, and given the cooling capacity furnished by the precooling stage. High frequency PTC can be used as the precooling source, the precooling power results of the calculation are 10 W, 10.5W, 20 W, 20.5 W and 21 W. At present, the relative efficiency of the cryocooler in the 80 K temperature range can reach 24%, and the hot end temperature is 300 K. If such a cryocooler is used for precooling, the preliminary experimental results obtained and the performance data converted into the precooling cryocooler are shown in Table 3 below (The conversion relative Carnot efficiency is calculated using the conversion total input power).

Table 3. Conversion efficiency.

Power /W	Frequency /Hz	Operating pressure /MPa	Cooling capacity	Precooling power/W	Conversion first-stage input power /W	Conversion total input power/W	Conversion relative Carnot efficiency
10	56	1	13.6 K	10	115	125	-
10	52	1	0.5 W@25.8 K	10.5	121	131	4.25%
20	60	1.5	13 K	20	230	250	-
20	56	1.5	0.5 W@22.2 K	20.5	236	256	2.44%
20	52	1.5	1 W@28.2 K	21	242	262	3.68%

4. Conclusion

The present paper sets forth the design of a micro single-stage coaxial PTC that is capable of direct operation within the 80 K temperature range. The cryocooler is powered by liquid nitrogen precooling in conjunction with a linear compressor, resulting in a total mass of 2.6 kg. The device utilises an inertance tube and gas reservoir as phase shifters. The cold finger has a diameter of 14 mm and a fill length of 55 mm. Preliminary experiments yielded the following results: at an operating frequency of 60 Hz, an input power of 20 W, a hot end temperature of 80 K, and an operating pressure of 1.5 MPa, the minimum no-load temperature achieved was recorded at 13 K. Additionally, a cooling capacity of 1 W was obtained at a temperature of 28.2 K when operated at 52 Hz.

Acknowledgments

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