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A high frequency lightweight coaxial pulse tube cryocooler operating at 70 K

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Abstract. An infrared detector represents a crucial instrument for human exploration of the universe. The pulse tube cryocooler is a widely utilized technology for the cooling of various types of infrared detectors. At present, the development of pulse tube cryocoolers, which can operate at lower temperatures and have higher cooling capacity, has become an important development direction in this field. In order to achieve this objective, a pulse tube cryocooler with a substantial cooling capacity in the lower temperature zone has been developed, in this study, a high-frequency pulse tube cryocooler operating at 70 K with a total weight of 4.7 kg, a cold finger diameter of 25.6 mm, and a length of 51 mm. The regenerator is filled with #600 and #500 stainless steel screens. Under the conditions of input power 200 W, hot end temperature 300 K, operating frequency 106 Hz, and charge pressure 6MPa, the minimum temperature is 32.4 K, and the cooling capacity of 10 W can be obtained at 70.75 K, the relative Carnot efficiency is 16.35%.

Keywords. pulse tube cryocooler·10 W@70.75 K·106 Hz·lightweight

1. Introduction

The exploration of space has constituted a perennial pursuit of humankind, with space infrared detection equipment serving as an indispensable instrument for observing the cosmos. Currently, to ensure optimal performance, the majority of space infrared equipment necessitates cryogenic cooling via a cryocooler[1]. Among the various mechanical cryocoolers employed in space-based applications, the pulse tube cryocooler (PTC) has gained considerable traction in the domain of space infrared technology. This is largely attributed to the inherent advantages of the PTC, including a straightforward structural design, high reliability, minimal vibration, extended operational lifespan, and the absence of moving components within the cold head. These attributes collectively enable the PTC to deliver a stable cooling power supply for infrared detectors[2]. As space exploration continues to develop, there is a need for PTC to provide greater cooling capacity at lower temperatures. Nevertheless, augmenting the cooling capacity of PTC frequently gives rise to an expansion in its volume and weight, which can consequently precipitate augmented launch costs for space probes. Accordingly, the development of PTC that can operate at lower temperatures with greater cooling capacity while maintaining the constraints of volume and weight is currently a topic of significant research interest. Radebaugh's research indicates that by simultaneously increasing frequency and optimizing charge pressure and cold finger structures, the volume and weight of PTC can be reduced while maintaining a higher operating efficiency and cooling capacity [3]. It thus follows that research into high-frequency lightweight PTC has become a principal focus within this field of study. In recent years, there has been a considerable amount of research conducted on the miniaturization and utilization of high-frequency PTC.

In 2007, the NGAS reported a 100 Hz miniature coaxial pulse tube cryocooler. The cryocooler has a total mass of 782 g and can achieve a cooling capacity of 1.1 W at 77 K[4]. Later, the NGAS made improvements to it, increasing the maximum frequency to 144 Hz. When operating at a frequency of 100 Hz and an input electrical power of 49 W, the cryocooler's lowest temperature can reach 47 K, and it can achieve a cooling capacity of 1.3 W at 77 K[5]. In 2009, Zhejiang University developed a Stirling-type PTC weighing approximately 11 kg, with an operating frequency of 120 Hz. At 500 W input power, the PTC's no-load temperature was 47.8 K, and it provided a cooling capacity of 8.0 W at 78.6 K[6]. The Shanghai Institute of Technology Physics (SITP) has developed a 2.2 kg coaxial PTC with an operating frequency of 75 Hz. When the input electric power was 80 W, the PTC had a cooling capacity of 2.5 W at 80 K[7]. In 2017, Huiqin Yu and others designed a 1.22 kg coaxial micro-pulse tube cryocooler. The geometric parameters of the regenerator, pulse tube, and phase shifter were optimized. At a frequency of 120 Hz, a charge pressure of 3.8 MPa, and an input power of 55 W, the no-load temperature of the PTC was 53.5 K, the cooling capacity was 2 W@80 K, and the relative Carnot efficiency was 9.68%[8].

The Technical Institute of Physics and Chemistry of Chinese Academy of Sciences has been involved in the research of micro-pulse tube cryocooler since 2010. In 2017, we developed a pulse tube cryocooler weighing 1.6 kg with a working frequency of 100 Hz. With an electrical power input of 45 W, the cryocooler can achieve a cooling capacity of 2.1 W at 80 K[9]. A lightweight pulse tube cryocooler, weighing 2.7 kg and operating at a frequency of 126 Hz, is achieved through the optimization of factors that influence the efficiency of the cryocooler, including the phase shifter and charge pressure. The cooling capacity of 10 W can be obtained at 80 K when the electric power input is 250 W, and the relative Carnot efficiency of the pulse tube cryocooler is 10.9%[10]. In 2024, Nailiang Wang et al. developed a new lightweight single-stage coaxial PTC. The PTC has a total weight of 4.4 kg, an optimal operating frequency of 102 Hz, and a cooling capacity of 11 W at 80 K when the input power is 200 W[11].

2. Setup of the PTC

The single-stage coaxial PTC schematic is shown in Figure 1. The cryocooler is composed of three main parts: the compressor, the cold finger, and the phase shifter. The compressor generates oscillating pressure waves. It uses flexible springs to support the piston, and its main advantages are almost frictionless operation and the need for no lubrication, which greatly improves the reliability and lifespan of the cryocooler. The cold finger can receive the pressure waves and then generate a cooling effect at the cold head. The phase shifter is the key component for manipulating the phase angle of the pressure waves and mass flow within the cryocooler.

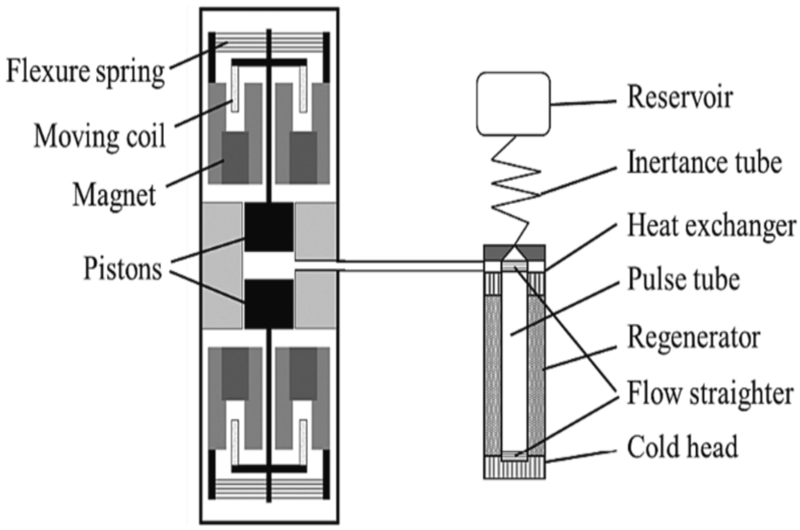

Figure 1. Schematic of the coaxial PTC.

The key parameters of the PTC are shown in Table 1. The diameter and length of the regenerator are 25.6 mm and 51 mm, respectively. The #600 and #500 stainless steel screen are filled in the regenerator, and the compressor has a diameter of 77 mm and a length of 182 mm.

Table 1. Main parameters of this PTC Table 1.

Parameters	Value
Diameter of piston	Ø17mm
Length of compressor	182mm
Diameter of compressor	Ø77mm
Filling length of regenerator	51mm
Diameter of regenerator	Ø25.6mm
Diameter of pulse tube	Ø11.6mm
Length of pulse tube	65mm
Mesh	#600 and #500 mesh stainless
Phase shifter	inertance tube and gas

3. Experimental results and discussion

3.1 Optimize the phase shifter of the PTC and experimental study of operating frequency

The phase shifter is the key component for controlling the phase angle of the pressure waves and mass flow within the cryocooler. The choice of an inertance tube and a gas reservoir as the phase shifter in this article is based on their simple and reliable structure and the ability to adjust the phase over a wide range[12,13]. We can adjust the optimal operating frequency of the PTC by adjusting the combination of the inertance tube and gas reservoir, on the basis of achieving lightweighting at high frequency, have better cooling capacity. Table 2 lists the combinations of inertance tubes with different inner diameters.

Table 2. Combinations of different inertance tubes.

Serial number	Combination
Case 1	Ø4mm*1m+ Ø5mm*1m
Case 2	Ø4mm*0.85m+ Ø5mm*1m
Case 3	Ø4mm*0.75m+ Ø5mm*1m
Case 4	Ø4mm*0.5m+ Ø5mm*1m

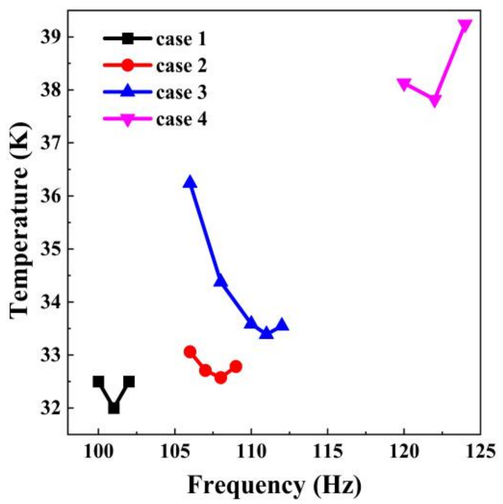

Figure 2. The variation of the no-load temperature of the PTC with frequency under different inertance tube combinations.

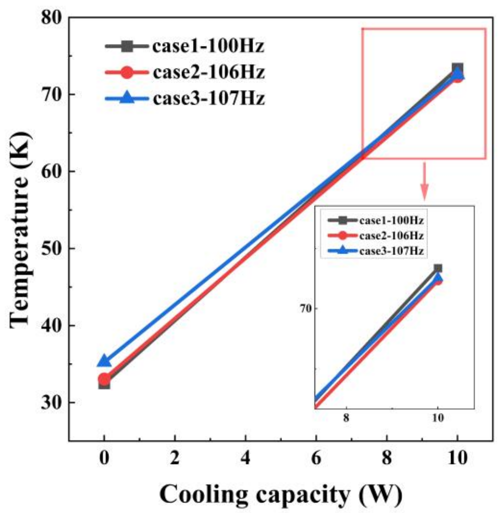

Figure 3. Performance of the PTC under different inertance tube combinations.

Figure 2 shows the influence of four different inertance tube configurations on the minimum temperature of PTC, with the electrical power input to PTC being 200 W at this time. The four different inertance tubes primarily differ in the length of the inertance tubes with a nominal inner diameter of 4 mm. The experimental data indicate that as the length of the inertance tubes with an inner diameter of 4 mm increases, the optimal operating frequency of PTC decreases. Within the range of 0.5 m to 1.0 m, the optimal operating frequencies for PTC are 122 Hz, 111 Hz, 108 Hz, and 101 Hz, respectively, with corresponding minimum temperatures of 37.82 K, 33.38 K, 32.57 K, and 32.01 K at these frequencies. It can be seen that, although case 4 has a higher frequency, the excessive frequency resulted in a decrease in the efficiency of the cold finger, leading to an increase in the minimum temperature reached by the cold finger. Therefore, from the perspective of achieving an optimal frequency that is high and the goal of reaching the lowest possible temperature, the combination of inertance tubes in case 1, case 2, and case 3 perform well.

Figure 3 shows the performance of the three inertance tube combinations in case 1, case 2, and case 3 under a heating load of 10 W at their respective optimal frequencies. It can be seen that the three are not significantly different, but case 2 exhibits a better slope and temperature. Under a 10 W load condition, the corresponding temperatures for case 1, case 2, and case 3 are 73.35 K, 72.32 K, and 72.55 K, respectively.

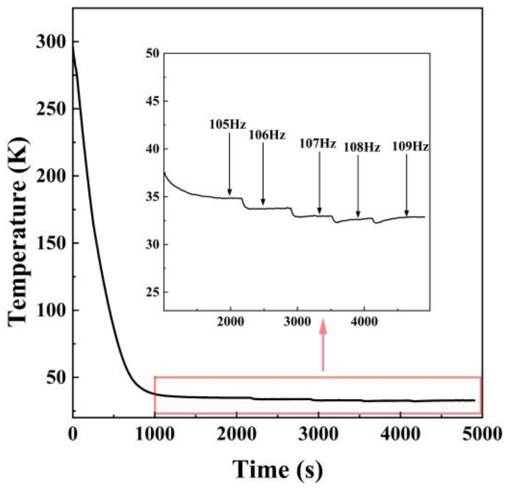

Figure 4. The no-load cooling curve.

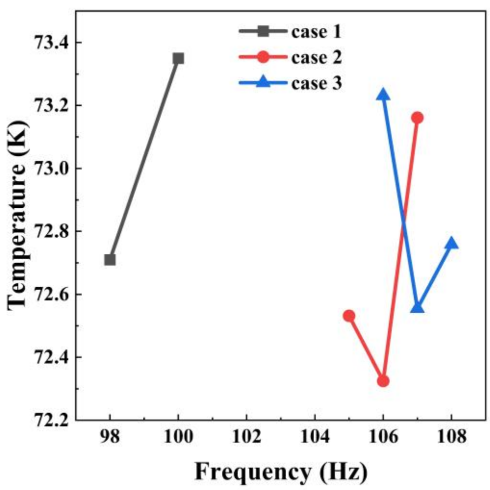

Figure 5. The variation of the 10 W load of the PTC with frequency under different inertance tube combinations.

Figure 4 shows the no-load cooling curve of PTC, the experimental conditions are as follows: the input power is 200 W, the temperature of the cold finger hot end is 300 K, the charge pressure is 6 MPa, and the frequency is increased from 105 Hz to 109 Hz. It can be seen that at an operating frequency of 108 Hz, the minimum cold head temperature is 32.57 K and remains relatively stable. Therefore, 108 Hz is the optimal operating frequency for the PTC.

Figure 5 presents the temperatures of the three inertance tube combinations (case 1, case 2, and case 3) under a 10 W load at different frequencies. It is evident that case 2 performs better. At this point, its optimal frequency is 106 Hz, which is slightly different from the optimal frequency without load, which is 108 Hz. This is a common phenomenon in experiments, where the frequency shift is due to the different temperature zones, causing a shift in the optimal frequency of the PTC operation. Finally, we used the inertance tube combination of case 2 and determined the optimal frequency for the PTC under 10 W load conditions to be 106 Hz.

3.2 Effect of different charge pressures on the performance of PTC

Charge pressure can significantly affect the performance of PTC, so we chose case2 and case3, two inertance tube combinations that are more suitable than the other two combinations, to test the performance difference of PTC under different charge pressures. The following text analyzes the impact of different charge pressures on the performance of the PTC under the conditions of an input power of 200 W and a frequency of 106 Hz.

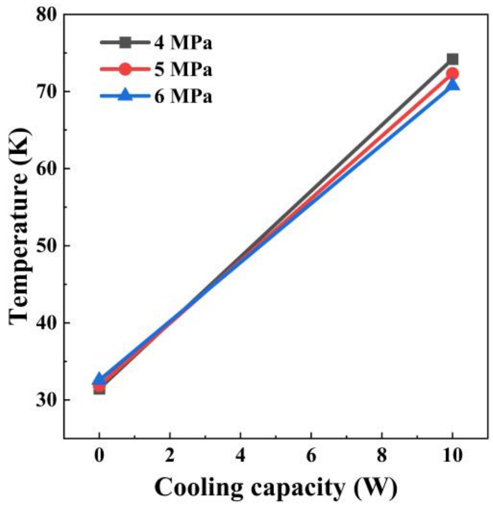

Figure 6. Effect of different charge pressure on the performance of PTC with case2.

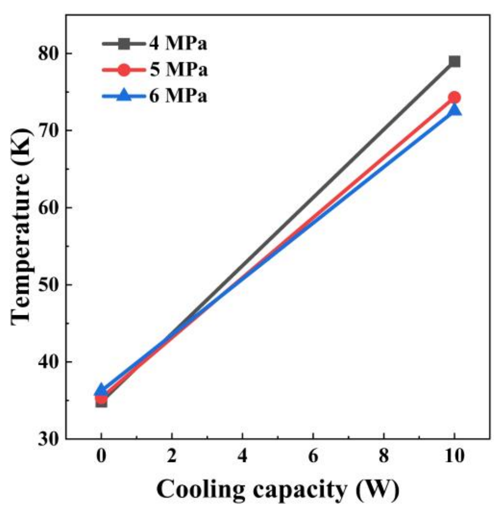

Figure 7. Effect of different charge pressure on the performance of PTC with case3.

As shown in Figure 6, for case2, as the charge pressure increases from 4 MPa to 6 MPa, the lowest temperature without load rises to 31.47 K, 31.87 K, and 32.57 K, respectively. However, under a 10 W load condition, the lowest temperature reached by the PTC decreases to 74.21 K, 72.32 K, and 70.75 K, respectively. As can be seen from Figure 7, the Case3 combination exhibits the same variation, with the corresponding PTC minimum temperatures of 34.85 K, 35.36 K, and 36.32 K as the charge pressure increases from 4 to 6 MPa, while the lowest temperatures at 10 W load are 78.97 K, 74.29 K, and 72.55 K, respectively. Although the increase in charge pressure results in a slight increase in the no-load minimum temperature, it has the beneficial effect of significantly increasing the cooling capacity, making a higher charge pressure the more advantageous option.

Figure 8 shows a comparison of the relative Carnot efficiency of PTC under different charge pressures. It can be seen that the relative Carnot efficiency of case 2 is greater than that of case 3 at the same charge pressure. For case 2, when the charge pressure increased from 4 MPa to 6 MPa, the relative Carnot efficiency of PTC was 15.42%, 15.86%, and 16.35%, respectively, and gradually increased. Therefore, the cooling performance of PTC was significantly improved by the increase of charge pressure, but considering the burden of high pressure on the structural strength of PTC, the performance of PTC under higher charge pressure was not tested for experimental safety reasons.

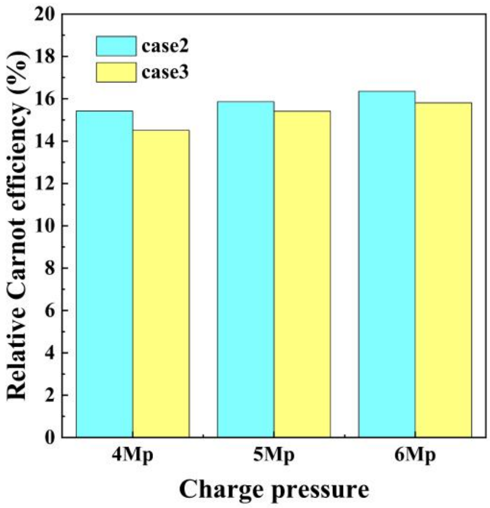

Figure 8. Effect of charge pressure on the relative Carnot efficiency of PTC.

4. Conclusion

This paper presents the findings of an experimental investigation into the optimization of PTC phase shifters, with the objective of identifying the most effective inertance tube combination. The research involved an analysis of the impact of charge pressure on the performance of pulse tube cryocoolers, with the charge pressure of the pulse tube cryocooler determined to be 6 MPa. As a result, a high frequency lightweight coaxial pulse tube cryocooler with a total weight of 4.7 kg and an operating frequency of 106 Hz has been obtained. Under the input power of 200 W and the temperature of 70.75 K, the cooling capacity of the cryocooler is 10 W, and the relative Carnot efficiency is 16.35%.

Acknowledgments

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