IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012013 doi:10.1088/1757-899X/1344/1/012013

Optimization of a 2.9W@80K miniature coaxial pulse tube cryocooler with a mass of merely 1.6kg

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Abstract. Lightweight pulse tube cryocooler holds significant potential for cooling infrared detectors in various applications. Previous research on Lightweight pulse tube cryocoolers has been reviewed in this work, and a theoretical analysis of key parameters for achieving lightweighting has been conducted. Meanwhile, experimental investigations were carried out to optimize the phase shifter (inertance tube) and charging pressure. Various combinations of inertance tubes were tested, and the charging pressure was systematically varied. The optimized cryocooler can obtain 2.9W of cooling capacity at 80K under the input power of 60W and an optimal frequency of 104 Hz, with a relative Carnot efficiency of 13.07% and a weight of only 1.6kg, and the specific mass reached 1.81 W/kg, which is at a high level among the 80K miniature pulse tube cryocoolers reported so far.

1. Introduction

Since the cold head does not have any moving parts, the Pulse Tube Cryocoolers (PTCs) has the advantages of compact structure, low mechanical vibration, high reliability and long lifetime [1]. PTCs have been widely utilized in the field of space infrared technology to provide stable cooling power for infrared detectors [1]. However, with detector technology complexity development, there is an emerging need for higher cooling capacities. Unfortunately, increasing cooling power often leads to an increase of the weight of PTC, which presents challenges due to the restricted payload capacity of aerospace equipment. Therefore, the development of lightweight cryocoolers that can provide enhanced cooling capacity within the constraints of weight limitations is of utmost importance. Prior research indicates that increasing the operating frequency of PTCs can effectively reduce their size and mass since higher operating frequencies can enhance energy density [2]. Numerous studies on high-frequency pulse tube cryocoolers are currently in progress.

In 2007, Northrop Grumman Space Technology (NGST) introduced a miniaturized coaxial pulse tube cryocooler with a frequency of 100 Hz. The PTC has a total mass of 782 g and is capable of achieving a cooling capacity of 1.1 W at 77 K[3]. Shortly afterwards, NGST developed a coaxial PTC operating at 124 Hz, the PTC achieved a minimum temperature of 47 K, with a cooling capacity of 1.3 W at 77 K and the weight of the whole cryocooler was 857 g. This corresponds to a relative Carnot efficiency of 7.68% and a specific mass (cooling power per kilogram) of 1.52 W/kg[4]. In 2012, the Shanghai Institute of Technology (SITP) developed a 2.2 kg coaxial PTC with an operating frequency of 75 Hz. This PTC demonstrated a cooling capacity of 2.5 W at 80 K when the input electric power was 80 W, resulting in a relative Carnot efficiency of 8.59% and a specific mass of 1.14 W/kg[5]. SITP subsequently reported a 1.22 kg coaxial miniature pulse tube cryocooler (MPTC) that, when operating at 120 Hz, achieved a no-load temperature of 53.5 K with a charging pressure of 3.8MPa. It also achieved a cooling power of 2 W at 80 K with an input electric power of 55 W, corresponding to a relative Carnot efficiency of 9.68% and a specific mass of 1.64 W/kg[6].The Technical Institute of Physics and Chemistry (TIPC, CAS) has been engaged in the development of micro pulse tube cryocoolers since 2010. In 2017, they successfully developed a pulse tube cryocooler that weighed 1.6 kg and operated at a frequency of 100 Hz. This cryocooler was capable of achieving a cooling capacity of 2.1 W at 80 K, under an electric power input of 45 W[7]. Subsequent to this, through the optimization of the cold finger, a cooling capacity of 2.2 W was achieved. The specific mass of this PTC was 1.38 W/kg, and it demonstrated a relative Carnot efficiency of 13.4%[8].In 2024,TIPC has developed a novel and lightweight single-stage coaxial pulse tube cryocooler, which achieves a cooling capacity of 11 W at 80 K while maintaining a relatively low mass of 4.4 kg with an operating frequency of 102 Hz.This results in a specific mass of 2.5 W/kg[9].

In this work, a method to achieve PTC lightweighting with guaranteed little efficiency loss is presented. The phase shifter and charging pressure of a miniature pulse tube cryocooler are experimentally optimized in order to operate at higher frequencies while guaranteeing its cooling performance. Subsequently, the cooling performance of this miniature pulse tube cryocooler was tested at different compressor input electrical powers.

2. Specific mass

The lightness of a cryocooler can be measured in terms of its specific mass. The specific mass of a PTC can be defined as the ratio of its mass to its cooling capacity, as shown in Eq. (1)[10].

$$\beta_{PTC} = \frac{Q_{cPTC}}{M_{PTC}} = \frac{\eta_{cf}}{M_{comp} + M_{cf}} \pi f P_0 V_{sv} \cos\theta \frac{P_r - 1}{P_r + 1} \propto \eta_{cf} f P_0 \quad (1)$$

The term M_{PTC} is the PTC mass, Q_{cPTC} is the cooling capacity, η_{cf} is the efficiency of the cold finger, W_{PV} is the PV power, M_{comp} is the compressor mass, M_{cf} is the cold finger and phase shifter mass, f is the frequency, P_0 is the charge pressure, V_{sv} is the amplitudes of sinusoidal volume, θ is the phase angle by which the volume flow leads the pressure, and P_r is the pressure ratio.

As shown in Eq. (1),The weight of both the compressor and the cold finger is inversely proportional to the frequency. According to this equation, the specific mass of the PTC mainly depends on the cold finger efficiency, frequency, and charge pressure. Given that improving cooling efficiency in a short period is challenging due to the limitations of current research. Thus, the key to achieving the lightness of the PTC is to increase the operating frequency and charge pressure while maintaining the efficiency of the PTC.

3. Experimental apparatus

The experimental setup mainly includes the cooling water circulation system, vacuum system, data acquisition system, and cryocooler system. The role of the cooling water circulation system is to maintain a target temperature of around 300 K at the hot end of the cold finger. The vacuum system serves dual purposes: firstly, to provide an optimal vacuum environment for the cryocooler system prior to operation, and secondly, to maintain the external vacuum environment of the cold finger. Data from the cold head temperature and the corresponding operating parameters of the compressor are collected via the data acquisition system. The pulse tube cryocooler mainly consists of a linear compressor, coaxial cold finger, and a phase shifter (comprising inertance tubes and gas reservoir). The experimental pulse tube cryocooler is shown in Figure. 1.

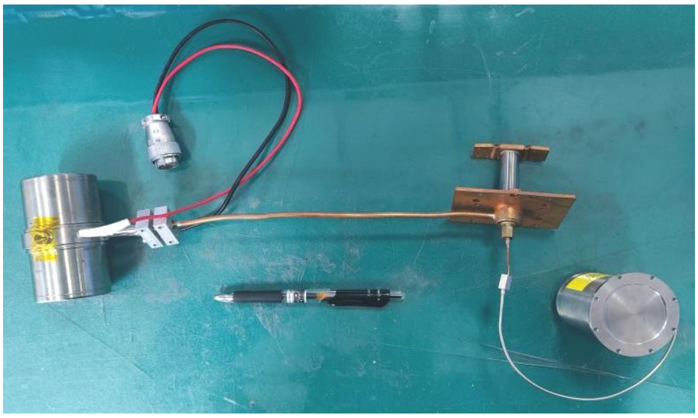

Figure 1. Experimental pulse tube cryocooler (PTC).

4. Experimental Results and Discussion

4.1 Optimization of operating frequency

The inertance tube as a phase shifter of a PTC, mainly used to adjust the phase relationship between the pressure wave and the mass flow. Changing the combination of inertance tubes can optimize the operating frequency of PTCs. In this study, experiments were conducted to test the frequency, compressor characteristics, and cooling performance across six distinct inertance tube combinations.These combinations are detailed in Table 1.

Table 1. Combination of different inertance tubes.

Serial No.	Combination
case 1	ϕ1.4mm*0.4m+ϕ2mm*1m+ϕ3mm*1m
case 2	ϕ1.4mm*0.3m+ϕ2mm*1m+ϕ3mm*1m
case 3	ϕ1.4mm*0.2m+ϕ2mm*1m+ϕ3mm*1m
case 4	ϕ1.4mm*0.2m+ϕ2mm*0.8m+ϕ3mm*1m
case 5	ϕ2mm*1m+ϕ3mm*1m
case 6	ϕ2mm*0.8m+ϕ3mm*1m
case 7	ϕ1.4mm*0.3m+ϕ2mm*0.6m+ϕ3mm*0.6m

The inertance tube combinations listed in Table 1 were selected based on the baseline configuration of the existing cryocooler. Systematic adjustments were made to this baseline to facilitate a clear investigation into the effects of geometry on operating frequency and cooling performance.

The experimental testing of the no-load lowest temperature and its corresponding optimal frequency under each combination reveals that the optimal frequency fluctuates with the adjustment of the inertance tube, as depicted in Figure 2. To ensure the displacement of the compressor remains within a safe range, simultaneous monitoring of the compressor's displacement and its lowest achievable temperature was conducted under two distinct input powers and heat loads. The results, as shown in Figure 3, demonstrate that increasing frequency reduces the compressor's displacement—a beneficial effect. However, this also leads to a rise in load temperature with higher frequencies, which is disadvantageous. Therefore, It is crucial to

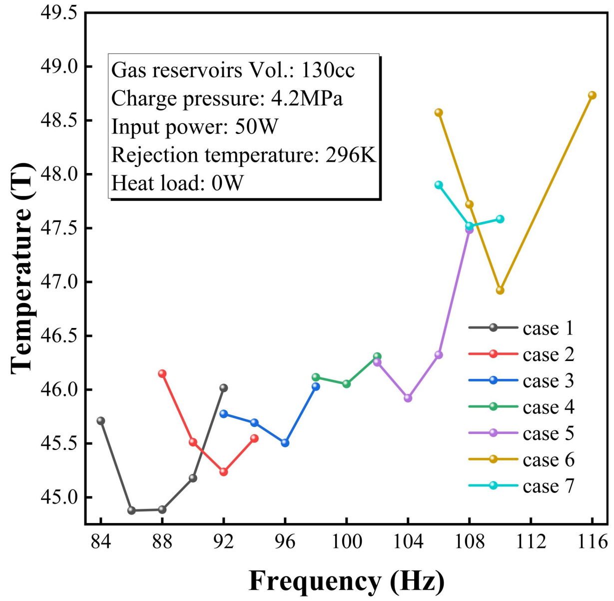

Figure 2. No-load temperature achieved by different inertance tubes at the optimal frequency.

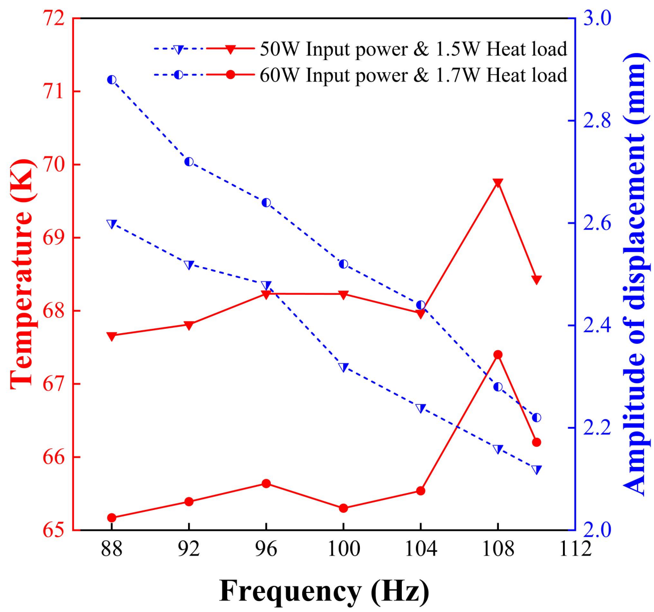

Figure 3. Temperature and compressor displacement at different input powers and heat loads.

find the best balance between these two parameters. Given the requirements of practical applications, case 5 was selected as the inertance tube combination for this miniature cryocooler, which has a gas reservoir volume of 130 cc. This combination operates at an optimal frequency of 104 Hz, achieving a no-load lowest temperature of 45.9 K, with the compressor displacement remaining below 2.5 mm. Under these conditions, the efficiency of the compressor is approximately 78.07%.

4.2 Optimization of charging pressure

As previously noted in Section 2, an increase in charging pressure is one method to achieve lightweighting. However, alterations in the charging pressure can affect the performance of the pulse tube cryocooler. Consequently, following the selection of the optimal inertance tube configuration (Case 5) from the initial screening phase, the charging pressure was optimized specifically for this final design to maximize its cooling performance. An experimental study was conducted to examine its cooling performance under charging pressures of 3.8 MPa, 4.2 MPa, 4.6 MPa, and 5.0 MPa, with cold-end loads of 1.5 W, 2.0 W, and 2.5 W. The experimental results are depicted in Figure 4. From this figure, it is evident that under identical loading conditions, the lowest achievable temperature gradually decreases as the charging pressure increases. For instance, at a load of 2.5 W, the stabilized temperature at a charging pressure of 3.8 MPa is 82.9 K, whereas at a charging pressure of 5.0 MPa, the stabilized temperature is 81.2 K. Given the potential safety risks associated with higher charging pressures, a charging pressure of 5.0 MPa was ultimately selected for the operation of this pulse tube cryocooler.

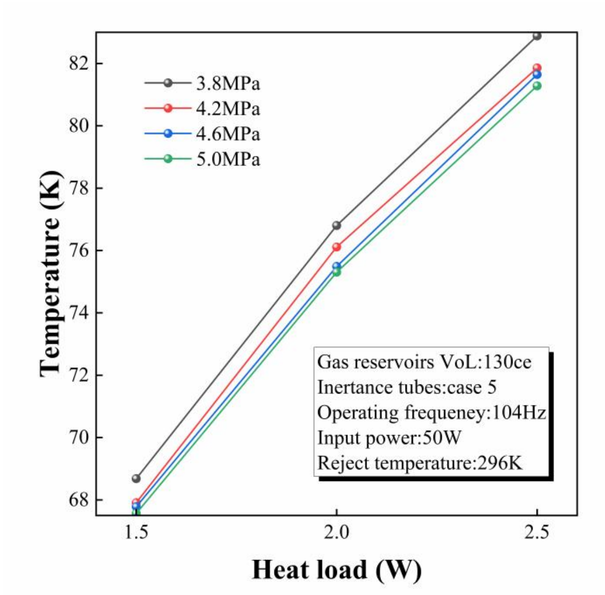

Figure 4. Cooling performance at different charging pressures.

4.3 Performance of pulse tube cryocooler

The cooling performance of the pulse tube cryocooler was ultimately experimental tested. The tests were conducted under specific conditions: using case 5 inertance tube combination, a gas reservoir volume of 130 cc, and a charging pressure of 5.0 MPa. The cooling performance was tested against varying input powers and different cold end loads. Figure 5 illustrates the results of these experiments.The results indicate that under the same loading conditions, the no-load lowest temperature decreases as input power increases. With an optimal frequency of 104 Hz and a compressor input power of 60 W, the cryocooler can achieve a cooling capacity of 2.9 W at 80 K. This corresponds to a relative Carnot efficiency of 13.07%. Notably, the total weight of the PTC is only 1.6 kg.

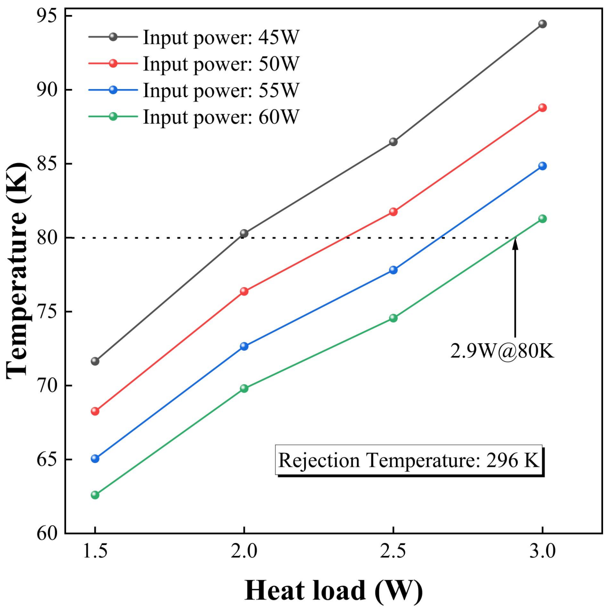

Figure 5. Cooling performance at different input powers and heat loads.

5. Conclusion

An experimental study was conducted on a miniature pulse tube cryocooler utilizing inertance tubes as phase shifters to achieve high efficiency and reduce weight. The focus is mainly on two key parameters: operating frequency and charging pressure. The optimization of the frequency was accomplished by modifying the combination of inertance tubes and cooling performance was tested at different charging pressures. The results show that the cryocooler achieves a cooling capacity of 2.9 W at 80 K with an input power of 60 W and an optimal frequency of 104 Hz, yielding a relative Carnot efficiency of 13.07%. With a total weight of just 1.6 kg, the PTC achieves a specific mass of 1.81 W/kg.The miniature pulse tube cryocooler demonstrates high energy density while maintaining high efficiency..

Acknowledgments

This work is supported by the Strategic Priority Research Program of Chinese Academy of Sciences（XDB0800202）.

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