Optimization of a 2.9W@80K Miniature Coaxial Pulse Tube Cryocooler with a Weight of Merely 1.6kg

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ID:C1Po1B-08

Abstract

This paper is centered on the optimization of miniature coaxial pulse tube cryocoolers. While these cryocoolers offer distinct advantages, they encounter significant challenges in fulfilling increased cooling capacity demands while preserving their lightweight nature. This paper reviews previous research on high-frequency pulse tube cryocoolers. Theoretical analysis of key parameters to achieve lightweighting. 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 higher than the 80K miniature pulse tube cryocooler reported so far.

Introduction

- PTCs have found extensive application in space-based infrared technology, providing stable cooling power for infrared detectors. However, as detector technology continues to evolve, there is an increasing demand for higher cooling capacities. Unfortunately, enhancing cooling power often results in an increased weight of the PTC, posing challenges due to the limited payload capacity of aerospace equipment. Consequently, there is an urgent need to develop lightweight cryocoolers capable of providing superior cooling capacity within weight constraints.
- Prior research indicates that increasing the operational frequency of PTCs can effectively reduce their size and mass since higher operating frequencies can augment energy density.
- This paper furthers research on lightweight, high-capacity pulse tube cryocoolers utilizing the Laboratory's established space cooler development technology.

Miniature Pulse Tube Cryocooler

Theoretical analysis

- Method of loss weight

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).

$$\beta_{PTC}=\frac{Q_{cPTC}}{M_{PTC}}=\frac{\eta_{cf}}{M_{comp}+M_{cf}}\pi f P_0 V_{sv}\cos\theta\frac{P_r-1}{P_r+1}\propto\eta_{cf}fP_0 \quad (1)$$

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.

Acknowledgments

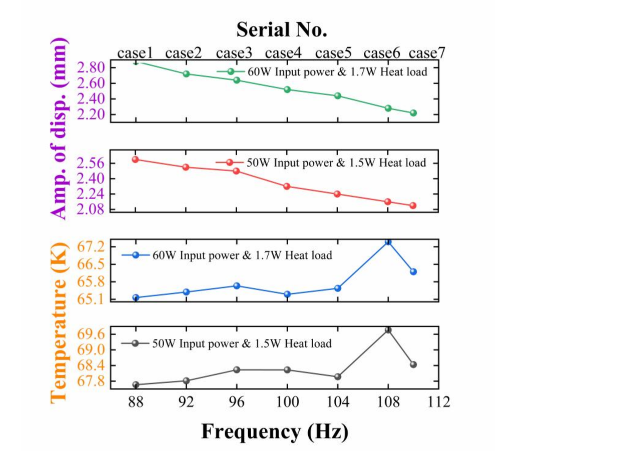
This work is supported by the Strategic Priority Research Program of Chinese Academy of Sciences (XDB0800202).

Experimental results and analysis

- Optimization of operating frequency

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

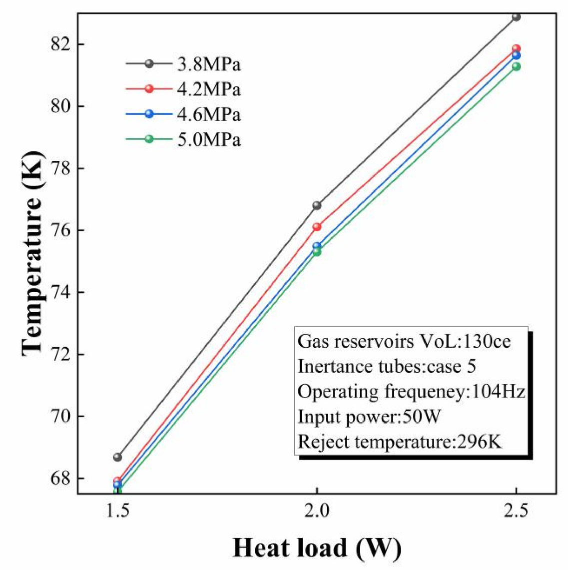


Temperature and compressor displacement at different input powers and heat loads.

Case 5 is finally chosen as the inertance tube combination for this miniature cryocooler with a gas reservoir volume of 130 cc, which has an optimal frequency of **104 Hz**, achieves a no-load minimum temperature of **45.9 K**, and compressor displacement is less than **2.5 mm**, and the compressor efficiency under this combination is about 78.07%.

- Optimization of charging pressure

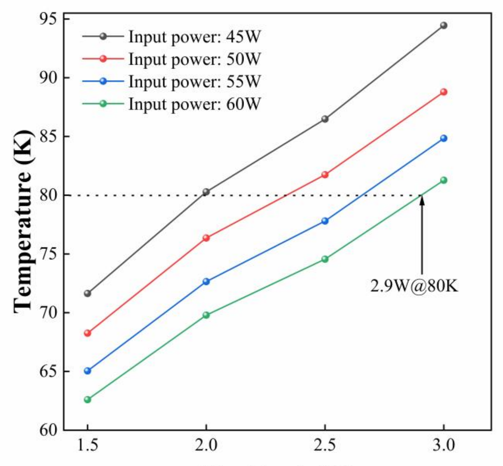
From the figure, it can be seen that under the same loading conditions, the lowest temperature it can realize gradually decreases with the increase of charging pressure. Considering that there is a safety risk at higher charging pressures, **5.0 MPa** was finally adopted as the charging pressure for the operation of this pulse tube cryocooler.



Cooling performance at different charging pressures.

- Performance of Pulse Tube cryocooler

Under the condition that the inertia tube combination is **case 5**, the volume of the gas reservoir is **130 cc**, and the charging pressure is **5.0 MPa**.At a compressor input power of **60 W** and an optimal frequency of **104 Hz**, the cryocooler is able to obtain a cooling capacity of **2.9 W** at **80 K**, with a relative Carnot efficiency of **13.07%**. In addition, its overall weight is only **1.6 kg**.



Cooling performance at different input powers and heat loads.

Conclusions

This paper presents an experimental investigation of a miniature pulse tube cryocooler that employs inertance tubes as phase shifters. The focus is primarily on two key parameters: operating frequency and charging pressure. The results indicate that with an input power of 60 W and an optimal frequency of 104 Hz, the cryocooler can achieve a cooling capacity of 2.9 W at 80 K. This corresponds to a relative Carnot efficiency of 13.07%, a weight of only 1.6 kg, and a specific mass of **1.81 W/kg.** Thus, **a high energy density is achieved while ensuring high efficiency.**