24 K Single-Stage Coaxial Pulse Tube Cryocooler Without Double-Inlet Phase Shifter

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ABSTRACT

Several 40 K pulse tube cryocoolers (PTCs) have been developed to meet the demand of long wavelength infrared detectors. Traditionally, the multi-bypass or double-inlet arrangement is often employed to reach a the temperature below 40 K for the PTC. To minimize the complexity and guarantee the required long-term stability of the PTC, for our cooler design, the inertance tubes together with the reservoir become the only phase-shifter. At present, the cooler prototype has achieved a no-load temperature of 23.7 K and can typically provide 2.1 W cooling power at 40 K with 150 W electric input power rejecting at 293 K. The relative Carnot efficiency is up to 8.8% at 40 K. The key parameters and performance of the PTC are presented in detail.

INTRODUCTION

Space applications (weather monitoring, Earth observation, astronomy) require large format long wavelength infrared (LWIR) detector arrays in the range of 13–16 μm. The longer the wavelength of the electromagnetic wave, the lower the suitable working temperature of the infrared detector. For the LWIR detectors, the suitable working at temperature is around 40 K [1]. To meet the demand of a 40 K cryocooler, several 40 K pulse tube cryocoolers (PTCs) were designed. In order to get the lower temperature, the conventional phase-shifter arrangement of 40 K PTCs are multi-bypass and double-inlet. However, considering the strong need of low vibration, long life, simple structure for detectors, the single-stage PTCs using an inertance tube together with a gas reservoir as the only phase-shifter have become a research hotspot. In 1995, TRW Space & Electronics Group designed a single-stage PTC, this cooler produced 1 W at 35 K for 200 W of input power and reached a no-load temperature of around 29.2 K [2]. In 2011, J. Ren & W. Dai developed an in-line type single-stage pulse tube cryocooler driven by a linear compressor. This cryocooler has reached a no-load temperature below 34.2 K at 35.2 Hz without the double-inlet phase shifter. With an optimum double-inlet opening, the cryocooler has reached a lower no-load temperature of 24.7 K [3]. In the same year, H. Dang demonstrated an 860mW/40K single-stage coaxial PTC, which achieved a no-load temperature of 29.7 K using inertance tubes together with a gas reservoir as the only phase shifter [4]. In 2018, S. Liu designed a 35 K single-stage PTC, which reached a no-load temperature of 26.9 K and cooling power of 2 W at 35 K with electrical input power of 222 W. It only uses an inertance tube and reservoir as phase shifter also [5].

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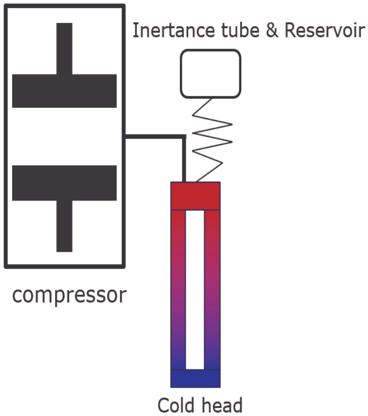

Figure 1. Schematic of the PTC.

For the above mentioned PTCs working below 40 K, the minimum temperature of a single-stage PTC is difficult to go below 25 K when the PTC is using inertance tube & reservoir as the phase-shifter. However, in order to meet the demand for single-stage 40 K PTCs with high reliability, the minimum temperature needs to be lower. Our group has conducted the research on 40 K PTCs for several years. Recently, a high efficiency 24 K single-stage coaxial PTC has been designed, manufactured and tested. In this paper, the main parameters and performance of the 24 K PTC are presented in detail and some experimental studies on parameter optimization of the phase shifter and hot-temperature were carried out.

CRYOCOOLER CONFIGURATION

As shown in Figure 1, a PTC mainly consists of a compressor, a cold finger and a phase shifter. The compressor of the 24 K PTC is our linear compressor design with a total swept volume of 11 cm^3. It has dual-opposed pistons driven by a moving-coil motor. The main structure parameters of the cold-finger are illustrated in Table 1. The length of the regenerator and pulse tube are 90 mm and 100 mm, respectively. In order to achieve sufficient heat exchange between the working fluid and the matrix, the regenerator is filled with #500 stainless steel screen. The cold finger is connected to the compressor by a 10 cm flexible copper tube, which is helpful for isolating the vibration of the compressor. Conventionally, the multi-bypass or double-inlet arrangement is often applied to get the cooling temperature below 40 K with the PTCs. However, the potential DC flow can induce instability to the PTC, which may seriously affect the performance of the PTC [6]. Thus, in our PTC design, only the inertance tube and reservoir are used as the phase shifter.

EXPERIMENTAL RESULTS

Optimization of Phase-Shifter

The phase shifter is a component that adjusts the phases of mass flow and the pressure wave. The phase angle between the mass flow and pressure wave determines the cooling performance of the PTC. According to primary research, three-segmented inertance tubes with different diameter

Table 1. The main parameters of the PTC (three copper tubes in series).

Components	Values
Length of REG	90 mm
Diameter of REG	25 mm
Length of PT	100 mm
Diameter of PT	10 mm
Mesh	#500 stainless steel screen
Connecting tube	10 cm long and an inner diameter of 4 mm

Table 2. The combinations of the phase-shifter.

Case	Combinations
Case 01	$\emptyset 2mm \times 0.5m + \emptyset 3mm \times 2.5m + \emptyset 4mm \times 2m$
Case 02	$\emptyset 2mm \times 1.0m + \emptyset 3mm \times 2.5m + \emptyset 4mm \times 2m$
Case 03	$\emptyset 2mm \times 1.5m + \emptyset 3mm \times 2.5m + \emptyset 4mm \times 2m$
Case 04	$\emptyset 2mm \times 0.5m + \emptyset 3mm \times 2.0m + \emptyset 4mm \times 2m$
Case 05	$\emptyset 2mm \times 0.5m + \emptyset 3mm \times 3.0m + \emptyset 4mm \times 2m$
Case 06	$\emptyset 2mm \times 0.5m + \emptyset 3mm \times 3.5m + \emptyset 4mm \times 2m$
Case 07	$\emptyset 2mm \times 0.5m + \emptyset 3mm \times 3.5m + \emptyset 4mm \times 3m$
Case 08	$\emptyset 2mm \times 0.5m + \emptyset 3mm \times 3.5m + \emptyset 4mm \times 1m$

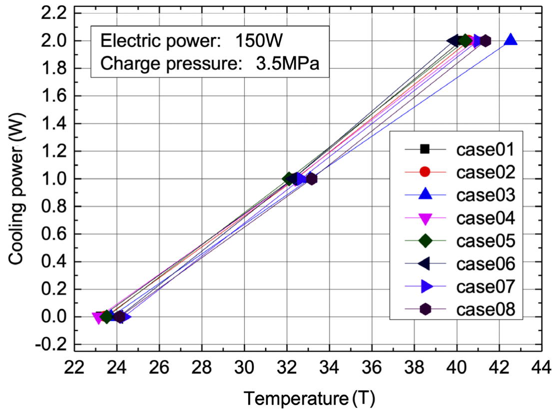

Figure 2. PTC performance for each case of phase shifter.

and length have a stronger ability of phase shifting [7]. Three copper tubes with diameters of 2 mm, 3 mm and 4 mm in series coupling with a gas reservoir are chosen to be the phase-shifter of our PTC design. Table 2 shows the 8 combinations of phase shifter, and Figure 2 shows the PTC performance for each case of phase shifter. The experimental results show that the cooling power of the PTC is different with a different phase shifter. In case 6, the PTC has the lowest cold-end temperature when the cooling load is 2.0 W. Therefore, the optimal phase shifter for the PTC is case 6, and the optimal frequency is 40 Hz.

Influence of Hot Temperature

The hot temperature of PTC has a significant impact on the cooling performance and no-load temperature. As shown in Figure 3, the difference in cooling performance of the PTC at hot-end

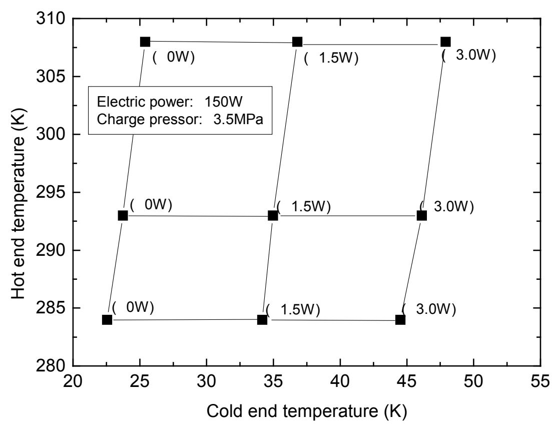

Figure 3. Experimental results of cooling performance with different hot temperatures.

Figure 4. The photo of 24K PTC.

Table 3. The key parameters of the PTC.

Key parameter	Values
Frequency	40Hz
Hot-end temperature	293K
No-load temperature	23.7K
Inertance tube	$\emptyset 2mm \times 0.5m + \emptyset 3mm \times 3.5m + \emptyset 4mm \times 2m$
Charge pressure	3.5MPa
Mass	12.7kg

temperature of 284 K, 293 K and 308 K are shown. As can be seen in Figure 3, when the hot-end temperatures decreases from 308K to 284K, the no-load temperature decreases from 25.4K to 22.5 K, and the cold tip temperature of a load of 3 W decreases from 48 to 44.5 K.

Cooling Performance of the PTC

Figure 4 is a photo of the 24 K pulse tube cryocooler. Part of the inertance tubes are placed in the gas reservoir to improve the compactness. Table 3 displays the main parameters of the optimal PTC, the frequency is 40 Hz, the charge pressure is 3.5M Pa, the weight of the PTC is 12.7 kg. When the rejecting temperature is 293 K, the PTC can reach a no-load temperature of 23.7 K.

Figure 5 shows the cooling performance of the PTC at input powers of 100 W and 150 W. It can be seen that the input power of the PTC has little effect on the minimum no-load temperature. Under 150 W and 100 W input power (hot end at 293 K and 278 K respectively), the no-load temperature of the PTC

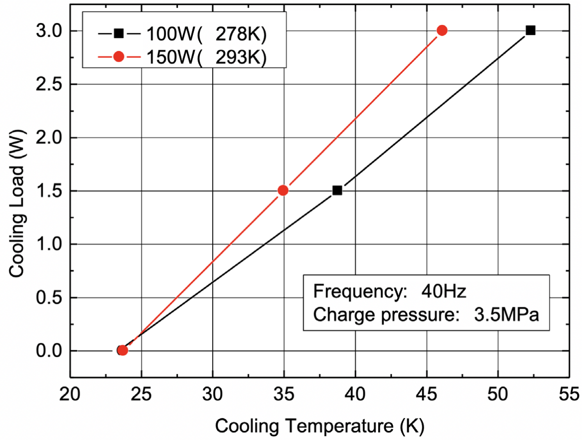

Figure 5. The cooling performance of PTC with different input powers.

Table 4. Cooling performance of PTC.

Compressor input power (W)	Cooling capacity	Hot-end Temperature (K)	rCOP(%)
100	0.5W@30K	278	4.1
	1.1W@35K	278	7.6
	1.6W@40K	278	9.5
150	0.8W@30K	293	4.6
	1.5W@35K	293	7.3
	2.1W@40K	293	8.8

is 23.7 K and 23.4 K, respectively. However, the cooling capacity of PTC varies greatly at different input powers. As shown in Table 4, the cooling power and relative Carnot efficiency at the cooling temperature of 30 K, 35 K and 40 K are presented in details when the electrical power of the PTC is 100 W and 150 W. The higher the cooling temperature, the more obvious the difference in cooling capacity. When the input power of the PTC is increased from 100 W to 150 W, the cooling capacity at 30 K is only increased by 0.3 W, while the cooling capacity at 40 K is increased by 0.5 W. In addition, when the cooling temperature is 30 K, the relative Carnot efficiency of the PTC with 150 W input power is higher than the relative Carnot efficiency of the PTC 100 W input power, while when the cooling temperature is 35 K and 40 K, the PTC shows the opposite trend. In general, the maximum relative Carnot efficiency of the PTC is up to 9.5% at 40 K, and the PTC typically provides a max cooling power of 2. 1 W at 40 K with an electric power of 150 W.

CONCLUSIONS

To meet the demand of 40 K high reliability PTCs, a coaxial single-stage PTC has been developed in our group. The phase shifting mechanism of the PTC only uses the inertance tubes together with a reservoir. The phase shifter was optimized and the impact of hot-end temperatures on the PTC performance was carried out. The experimental results show that the optimal frequency is 40 Hz, and the hot temperature of PTC has a significant impact on the cooling performance and no-load temperature. Finally, A coaxial single-stage PTC is built successfully with a no-load temperature of 23.7 K, it can typically provide 2.1 W cooling power at 40 K with 150 W electric power rejecting at 293 K.

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