1.5W@47.7K high frequency lightweight coaxial Pulse Tube Cryocooler

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Abstract

Human space exploration is becoming more frequent with the rapid development of modern space technology. The pulse tube cryocooler is an indispensable part of the space probe, but the cost of launching space probes restricts their volume and weight. Therefore, it is particularly important to improve the performance of the pulse tube cryocooler under the premise of limited volume and weight. This paper develops on a single-stage, high frequency, lightweight coaxial pulse tube cryocooler. This cryocooler is driven by a linear compressor with a total mass of 2.5 kg, using the inertance tube and gas reservoir as phase shifters. The cold finger has a diameter of 14 mm and a length of 55 mm. At an operating frequency of 102 Hz, an input power of 100 W, a hot end temperature of 293 K and a charge pressure of 6 MPa, a minimum temperature of 31.7 K and a cooling capacity of 1.5 W at 47.7 K can be achieved. In this paper, the related parameters that affect the performance of the cryocooler are introduced in detail, which are mainly charge pressure, hot end temperature and cold finger direction.

Introduction

This paper develops on a single-stage, high frequency, lightweight coaxial PTC. This cryocooler is driven by a linear compressor with a total mass of 2.5 kg, using the inertance tube and gas reservoir as phase shifters. The cold finger has a diameter of 14 mm and a length of 55 mm. Miniaturisation reduces the mass of the working medium, which in turn reduces the cooling capacity and efficiency of the PTC. Research indicates that increasing the frequency can enhance the energy flux density of the PTC. Additionally, higher charge pressure and a smaller hydraulic diameter of the regenerator packing can compensate for the decrease in efficiency caused by the reduction of the PTC volume. This PTC can achieve a minimum temperature of 31.7 K and a cooling capacity of 1.5 W at 47.7 K by increasing the frequency and charge pressure. The results are obtained under specific conditions: operating frequency of 102 Hz, input power of 100 W, hot end temperature of 293 K, and charge pressure of 6 MPa. This paper mainly presents the relevant parameters of the PTC and details the operating performance at different charge pressures, hot end temperatures, cold finger directions and input powers.

Experimental apparatus

The cryocooler system comprises a linear compressor with a length of 150 mm, a diameter of 60 mm, and a piston diameter of 15 mm, as illustrated in Fig. 2. The cold finger has a coaxial structure, measuring 55 mm in length and 14 mm in diameter. The regenerator is filled with a combination of #635 and #500 stainless steel screen. The phase shifters comprise an inertance tube and a gas reservoir. The inertance tube has a total length of 2.5 m, consisting of three tubes with different lengths and diameters. The first tube is 0.5 m long and has a diameter of 2 mm. The second tube is 1 m long and has a diameter of 3 mm. The third tube is 1 m long and has a diameter of 4 mm. The gas reservoir has a volume of 200 cc.

Table 1. Main parameters of this PTC

Component	Parameter
Compressor	60 mm in diameter and 150 mm in length
Piston	15 mm in diameter
Cold Finger	14 mm in diameter and 55 mm in length
Regenerator	#635 and #500 stainless steel screen
Inertance Tube	A total length of 2.5 m, Φ2*0.5+Φ3*1+Φ4*1
Reservoir	200 cc in volume
Charge Pressure	4MPa，5MPa，6MPa

Experimental results and discussion

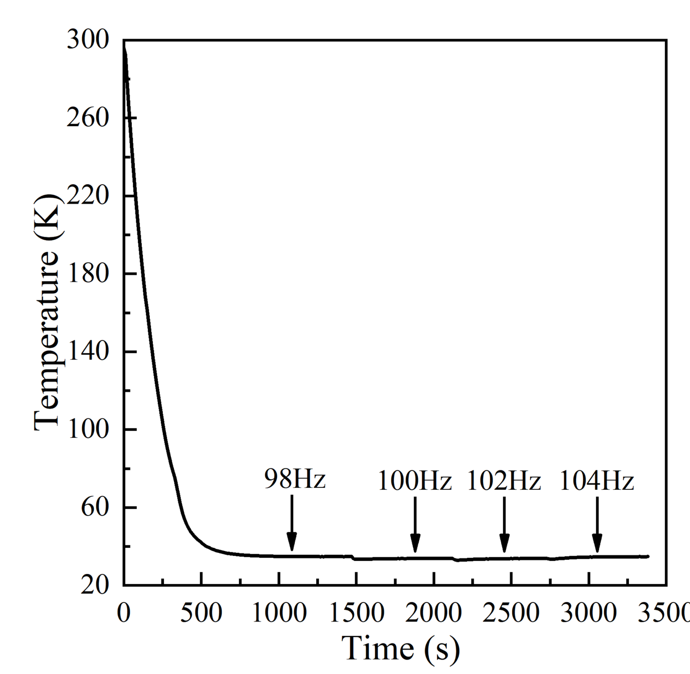


Fig. 1 . The no-load cooling curve

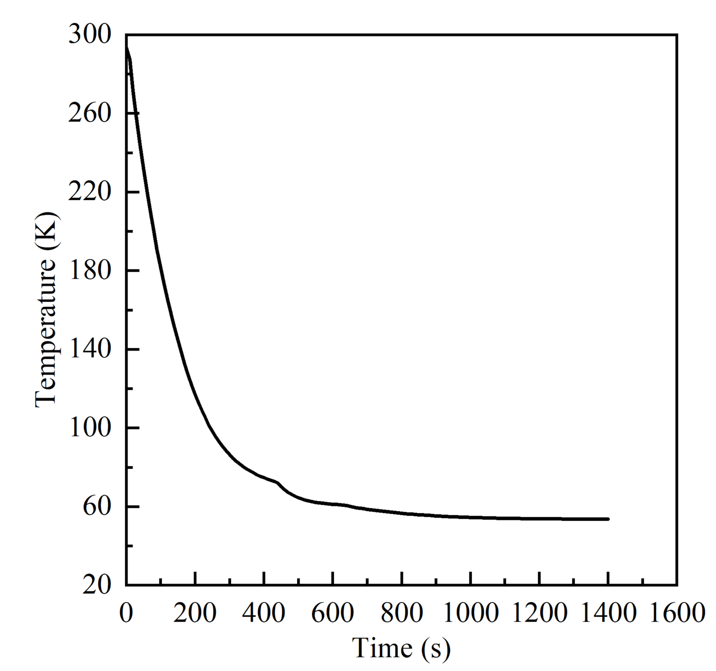


Fig. 2. The cooling curve of a 1.5 W load

1.Experimental study of operating frequency

Fig. 1 shows that at an operating frequency of 98 Hz, the cold head temperature of the PTC takes approximately 300 s to decrease from 293 K to 80 K, and around 500 s to decrease to 40 K. At an operating frequency of 102 Hz, the minimum cold head temperature is 31.7 K and remains relatively stable. Therefore, 102 Hz is the optimal operating frequency for the PTC.

Fig. 2 displays the cooling curve of a 1.5 W load when the cold finger of this PTC is placed horizontally. The experimental conditions are 80 W input power, 6 MPa charge pressure, 293 K temperature at the hot end of the cold finger, and 102 Hz operating frequency. The cooling head temperature drops from 293 K to 80 K in approximately 340 s and then to 60 K in approximately 650 s. The minimum cool head temperature recorded is 52.2 K.

2.Effect of different hot end temperatures on the performance of PTC

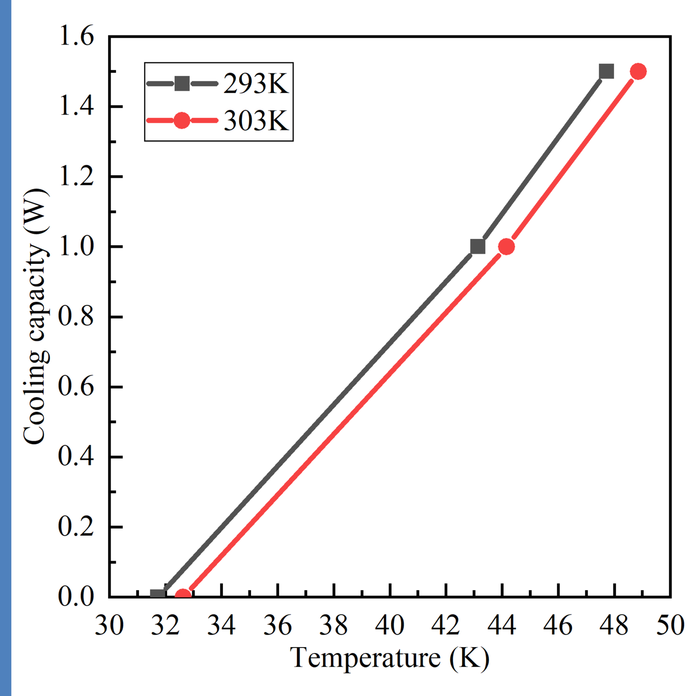


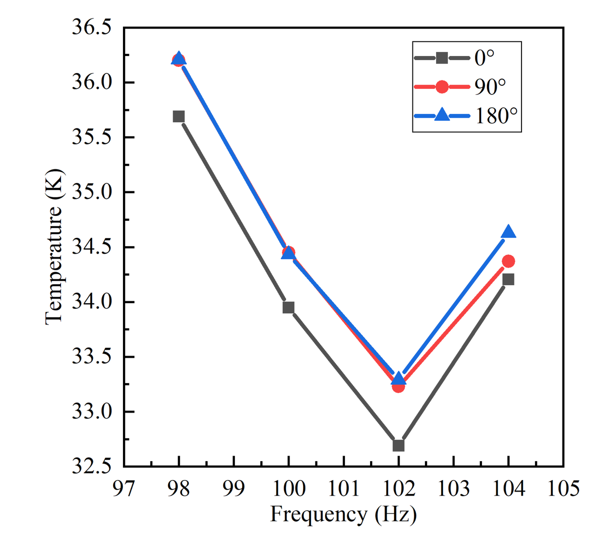
Fig.3. Effect of hot end temperature on cooling capacity

Two different hot end temperatures, 293 K and 303 K, were tested for the cooling capacity of the PTC. Fig. 5 illustrates the relationship between cooling capacity and hot end temperature at an input power of 100 W, operating frequency of 102 Hz, and charge pressure of 6 MPa. Fig. 3 demonstrates that an increase in the hot end temperature results in a corresponding increase in the cold head temperature, while maintaining the same cooling capacity. Specifically, when the hot end temperature rises from 293 K to 303 K, the cold head temperature increases by 1 K.

3. Effect of cold finger direction on the performance of PTC

Fig. 4 illustrates the cold finger direction has little influence on the PTC's optimal operating frequency. However, the minimum no-load temperature is 0.7 K lower when the cold end of the cold finger is facing downwards (i.e. when θ=0°) under the same power.

Fig. 5 illustrates the relationship between the cooling capacity and the direction of the cold finger of this PTC, with an input power of 100 W, a hot end temperature of 293 K, an operating frequency of 102 Hz, and a charge pressure of 6 MPa. When the cold end of the cold finger faces downwards (i.e. θ=0°), the same cooling capacity can be achieved at a lower temperature. The temperature is 0.5 K lower at 0 W and 0.4 K lower at 1.5 W. In this case, a cooling capacity of 1.5 W can be achieved at 47.4 K.



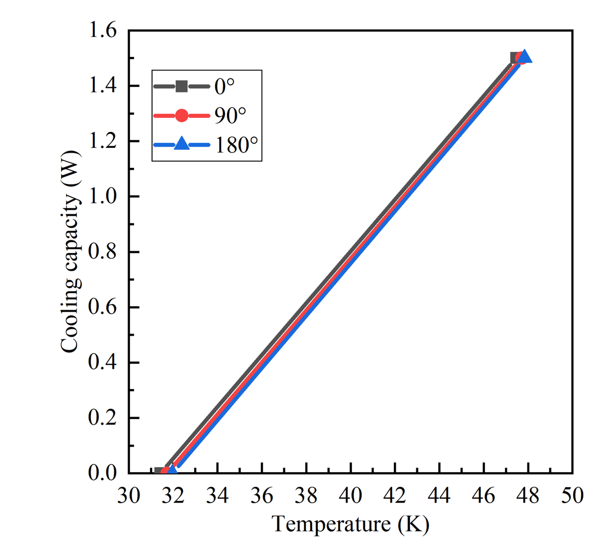


Fig. 4. Fig. 5. Effect of changing the direction of the cold finger on the performance of PTC

4 Effect of different charge pressures on the performance of PTC

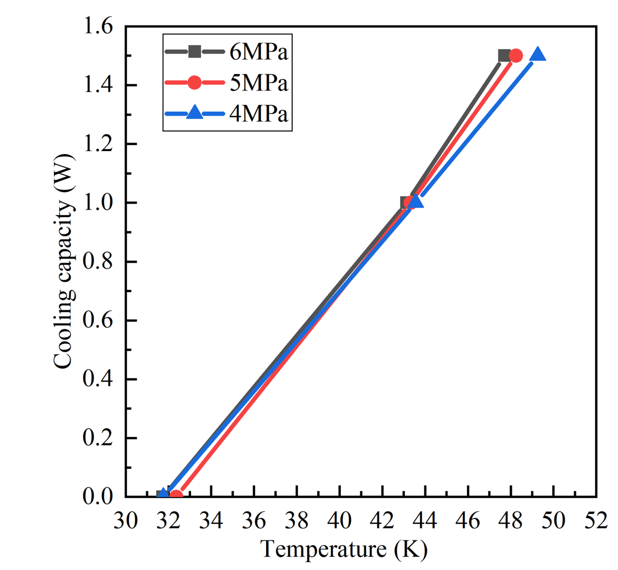


Fig. 6 Effect of charge pressure on cooling capacity

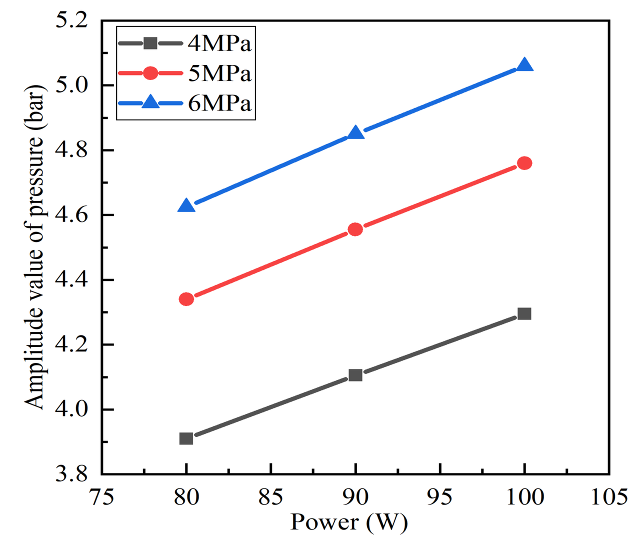


Fig. 7 Effect of charge pressure on the amplitude value of pressure

Fig. 6 illustrates the cooling capacity of this PTC under varying charge pressures, with an input power of 100 W, a hot end temperature of 293 K, and an operating frequency of 102 Hz. Under a charge pressure of 6 MPa, this PTC reaches a minimum temperature of 31.7 K. Varying charge pressures affect the cooling temperature at 1 W cooling capacity. This PTC can achieve 1 W cooling capacity at 43.3 K, with a relative Carnot efficiency of 5.8% (defined as the ratio of the actual efficiency of the PTC to the Carnot efficiency). At a charge pressure of 6 MPa, this PTC can achieve a cooling capacity of 1.5 W at 47.7 K, with a relative Carnot efficiency of 7.7%..

Fig. 7illustrates the relationship between the amplitude value of pressure and different charge pressures of this PTC. The experiment was conducted using input powers of 80 W, 90 W, and 100 W, a hot end temperature of 293 K, and an operating frequency of 102 Hz. The amplitude value of pressure increases with the charge pressure at the same power. For instance, when the input power is 100 W and the charge pressure increases from 4 MPa to 6 MPa, the amplitude value of pressure increases from 4.29 bar to 5.06 bar.

Conclusion

In order to meet the demand of high frequency lightweight in the 50K temperature zone in space infrared detection, this paper investigates an experimental study on the effects of charge pressure, hot end temperature, and cold finger direction on the cooling capacity of the PTC. Finally, a PTC with a weight of 2.5 kg and a cooling temperature zone of 47.7 K is developed. Under the given conditions of 100 W input power, 293 K hot end temperature, 102 Hz operating frequency, and 6 MPa charge pressure, a minimum temperature of 31.7 K and a cooling capacity of 1.5 W at 47.7 K can be achieved. The relative Carnot efficiency is 7.7%. This is the lightest hundred Hertz PTC known to operate near the 50K temperature zone.