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High efficiency 40 K single-stage Stirling-type pulse tube cryocooler

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Abstract. A high efficiency single-stage Stirling-type coaxial pulse tube cryocooler (SPTC) operating at around 40 K has been designed, built and tested. The double-inlet and the inertance tubes together with the gas reservoir were adopted as the phase shifters. Under the conditions of 2.5 MPa charging pressure and 30 Hz operating frequency, the prototype has achieved a no-load temperature of 23.8 K with 330 W of electric input power at a rejection temperature of 279 K. When the input power increases to 400 W, it can achieve a cooling capacity of 4.7 W/40 K while rejecting heat at 279 K yielding an efficiency of 7.02% relative to Carnot. It achieves a cooling capacity of 5 W/40 K with an input power of 450 W. It takes 10 minutes for the SPTC to cool to its no-load temperature of 40 K from 295 K.

1. Introduction

Stirling-type pulse tube cryocoolers (SPTC) have the advantages of compactness, low vibration, long lifetime, and no moving parts in the cold head. They have been widely used in high-temperature superconducting applications, physics based experimental research, space applications, and other fields. At present, SPTC working at around 80 K can achieve a relative Carnot efficiency larger than 20% [1]. For example, Wang has developed a SPTC which has achieved a cooling capacity of 26.4 W/80 K with an input power of 290 W. At lower temperatures, the efficiency of the SPTC is much lower, it usually can achieve a cooling capacity of 0.2-1 W at 35 K with 300 W of input power [2-7]. For example, Yang has reported a SPTC that reaches the lowest temperature of 26.1 K using a double-inlet and can provide a cooling capacity of 0.5W /35 K with an input power of 200 W [3]. Dang has reported a SPTC that reaches 29.7 K by use of standard regenerator matrix consisting of 3 segments and can provide a cooling capacity of 0.86 W/40 K with an input power of 200 W [4]. A multi-bypass type SPTC can achieve a higher cooling performance, for example, Chen has developed a multi-bypass type SPTC with a no-load temperature of 15.5 K and a cooling capacity of 2.5 W/35 K with 240 W input power [5], and the no-load temperature reduced to 13.9 K further when part of the regenerator matrix was replaced by Er_3Ni, which is the lowest temperature record for single-stage SPTC [6].

In this paper, a single-stage SPTC driven by a linear dual-opposed compressor aiming for providing 5 W cooling capacity at 40 K has been developed. The structure of the cryocooler and the experimental results will be introduced.

2. Design of the cryocooler

A SPTC driven by a linear dual-opposed compressor was designed and fabricated to meet the cooling capacity of 5 W/40 K. Figure 1 shows the schematic of the developed SPTC. Optimization of the SPTC configuration is done by Sage software [8]. The design parameters of the SPTC are summarized in Table 1. The regenerator is filled with 300 mesh, 400 mesh and 500 mesh stainless steel screens and the parameters are optimized by Sage software. The flow straighteners at the hot and ends of pulse tube are made from 80 mesh and 200 mesh copper screens, respectively. Double-inlet value, inertance tube together with gas reservoir are adopted as phase shifters. A radiation shield is adopted to reduce the radiation heat loss from the regenerator to vacuum shield. The temperatures were measured by means of Rh-Fe resistance sensors (calibration range: 2-300 K). The cooling capacity was measured by means of thermal heat balance method. The temperature of the hot end of cryocooler is controlled by a chiller. The temperature of the hot end is controlled at 279 K. The detail parameters of the linear compressor are listed in Table 2. The linear compressor is dual-opposed configuration to reduce vibration. The diameter of the piston is 34 mm and the maximum amplitude is 6 mm. The compressor works at a charging pressure of 2.0~3.0 MPa and an operating frequency of 24~32 Hz.

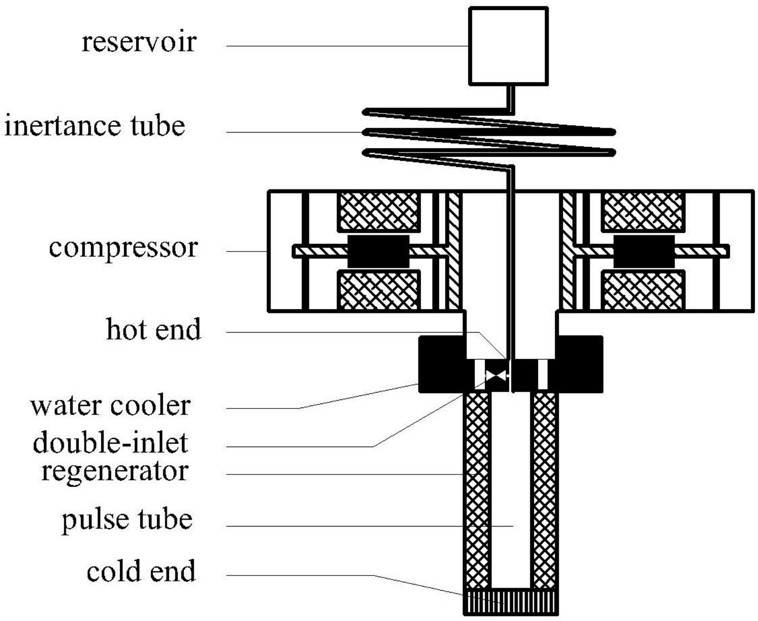

Figure 1. The schematic of the single-stage pulse tube cryocooler.

Table 1. Parameters of the cold tip.

Parameters	Values (mm)
Regenerator	Φ26*91
Pulse tube	Φ12.5*104
Inertance tube	Φ2*1400+Φ3*1800+Φ4*2200
Gas reservoir	600 cc

3. Experimental results and discussion

Figure 2 shows a typical cooling curve of the developed cryocooler. A no-load temperature of 23.8 K can be achieved with a charge pressure of 2.5 MPa, an operating frequency of 30 Hz and an input power of 330 W. It takes about 10 minutes for the SPTC to lower its no-load temperature at the cold head from 295 K to 40 K. The cooling rate decreases when the temperature goes to below 40 K. One reason is that the regenerative capacity of stainless steel screen at lower temperatures is much lower than that at higher temperatures. It takes an hour to lower the temperature to 23.8 K.

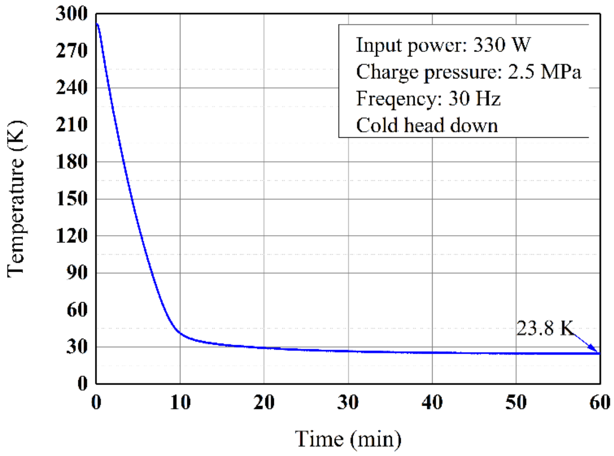

Figure 2. The cooling curve of the developed cryocooler.

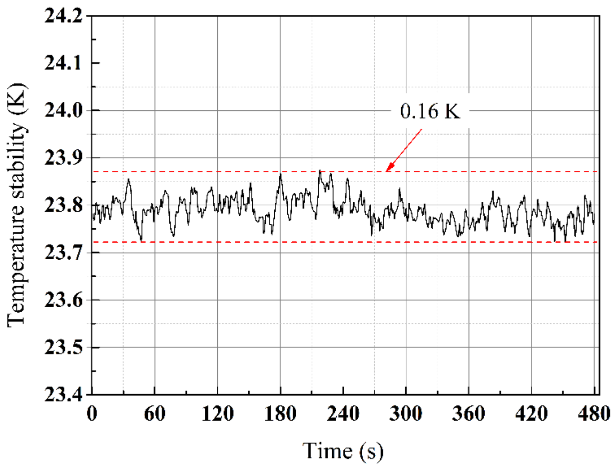

Figure 3. Temperature stability of the cold head of SPTC.

Figure 3 shows the temperature fluctuations of the cold head of the SPTC within 8 min. The temperature fluctuation amplitude without any control is less than ±0.08 K.

The influence of operating frequency on the performance of the cryocooler has been investigated as shown in Figure 4. The optimum operating frequency for the SPTC is around 30 Hz with a charge pressure of 2.5 MPa and an input power of 330 W.

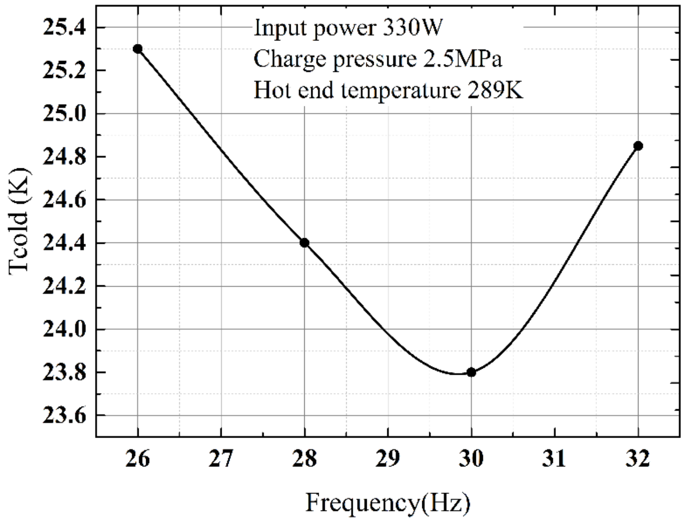

Figure 4. Effect of operating frequency on the temperature of cold head.

Figure 5 shows the cooling capacity of the developed SPTC. It can be found that a no-load temperature of 23.8 K and a cooling capacity of 1.5 W/29 K when rejecting at 279 K can be achieved at a charge pressure of 2.5 MPa and an input power of 330 W. When the input power increases to 400 W, it can achieve a cooling capacity of 4.7 W/40 K and an efficiency of 7.02% relative to Carnot. At present, the relative Carnot efficiency of SPTC working at around 40 K is generally less than 6.5% [2-7]. It achieves a cooling capacity of 5 W/40 K with an input power of 450 W.

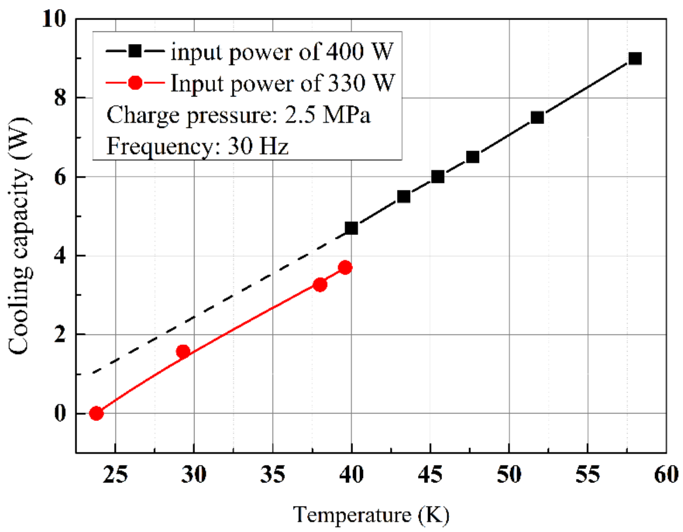

Figure 5. Cooling capacity of the developed SPTC.

Figure 6 shows the influence of hot end temperature, which is controlled by a chiller, on the cold head temperature. It can be found that the temperature of cold head varies linearly with the temperature of the hot end. The temperature of cold head increases 1.4 K when the temperature of hot end increases from 6 °C to 16 °C.

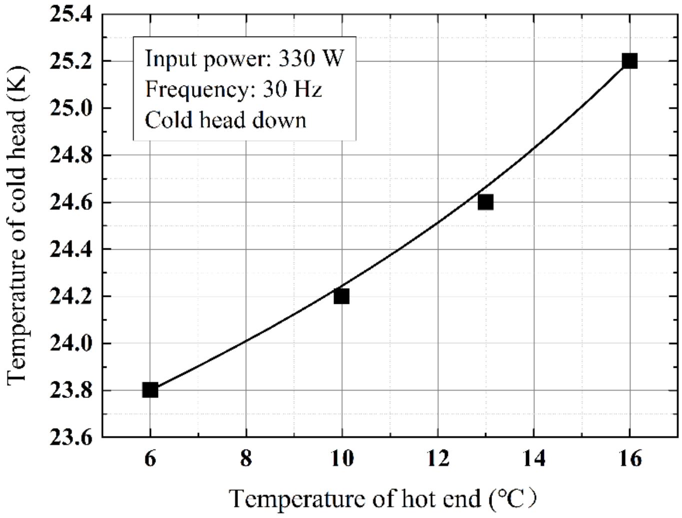

Figure 6. Effect of the hot end temperature on the cold head.

4. Conclusions

A high efficiency single-stage Stirling-type coaxial pulse tube cryocooler driven by a linear dual-opposed compressor has been designed, manufactured and tested. It takes 10 minutes for the SPTC to lower its no-load temperature at the cold head from 295 K to 40 K. A no-load temperature of 23.8 K and a cooling capacity of 1.5 W/29 K at a rejection temperature of 279 K can be achieved with a charge pressure of 2.5 MPa and an input power of 330 W. When the input power increases to 400 W, it can achieve a cooling capacity of 4.7 W/40 K and an efficiency of 7.02% relative to Carnot which is higher than most of the SPTCs working in this temperature range. It achieves a cooling capacity of 5 W/40 K with an input power of 450 W. Test results show that the cold head temperature is sensitive to the temperature of the hot end. It increases 1.4 K when the temperature of the hot end increases 10 K.

5. Reference

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