Development of a 15 W at 80 K Coaxial Pulse Tube Cryocooler

N.Wang[1,2], M.Zhao[1,2], X.Liu[1,2], L.Wei[1], Q.Zhu[1], H.Chen[1,2], J.Liang[1,2]

[1]Key Laboratory of Space Energy Conversion Technologies, Technical
Institute of Physics and Chemistry, CAS, Beijing, 100190, China
[2]University of Chinese Academy of Sciences, Beijing 100190, China

ABSTRACT

To meet the demands of the high capacity cryocoolers used in space applications, the Technical Institute of Physics and Chemistry (TIPC) has successfully developed a high-capacity pulse tube cryocooler. The cryocooler is driven by a long-life linear compressor which consists of two dual-opposed pistons and a maximum swept volume of 10cc. In this paper, the operating frequency was optimized by adjusting the inertance tubes, and the performance of the pulse tube cryocooler has been tested over a wide range of electrical powers. When the operating frequency is 44 Hz and the mean working pressure is 4.0 MPa for helium gas, the high efficiency pulse tube cryocooler achieves a no-load temperature of about 32K. Its typical is cooling performance of 15W at 80K under an input electrical power of 230W and a reject temperature of 293K. When 100W of electrical power is provided, the PTC obtains a cooling power of 7.2W at 80K with a Carnot efficiency of 19%.

INTRODUCTION

Given that the pulse tube cryocooler (PTC) has no moving parts in its cold head, it demonstrates a greater reliability than the Stirling refrigerator in many space applications. In recent years, many PTCs have been sent to the space, and they all have been working well for years [1].

With the development of space technology, there are many aerospace applications which require very large cooling capacity cryocoolers. The optical components of large earth surveillance satellites have high heat loads, which must be cooled by high-capacity cryocoolers. To meet the current demands, in 2007, Sunpower Inc. developed a single-stage coaxial PTC, named CPT60, and it achieved 7.2W cooling power at 80K with 145W input power [2]. In the same year, Thales had developed and tested the LPT9710 coaxial pulse tube cooler which produced a cooling power of at least 15W at 80K [3-4]. In 2010, the Key Laboratory of Cryogenics, TIPC/CAS, developed a coaxial PTC named CPTC-10, which obtained a capacity of 10W power at 77K and a relative Carnot efficiency of 18.6% [5]. In 2012, Shanghai Institute of Technical Physics, CAS, developed a single-stage PTC for space-borne optics cooling, which typically provided a cooling power of 10W at 90K with an input power of 175.6W and the cryocooler achieved a 14% of Carnot efficiency at 90K [6]. After 5 years, they developed a 10W at 70K PTC for cooling infrared focal-plane array in a space mission, which achieved a 14.75% of the relative Carnot efficiency [7].

These exciting results indicate that the high capacity PTC is available. However, there still needs efforts to improve the COP, reduce the weight and increase the cooling power. The Key Laboratory

Cryocoolers 20, edited by S.D. Miller, R.G. Ross, Jr. and J.R. Raab

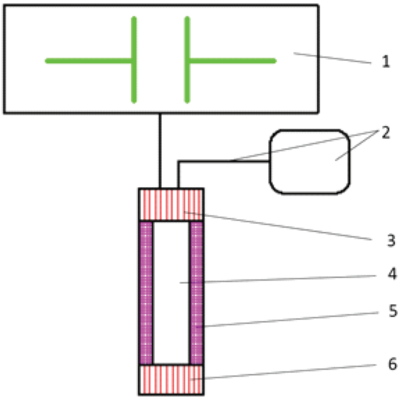

Figure 1. The schematic of the PTC: 1 Compressor, 2 Inertance tube and reservoir, 3 Hot-end exchanger, 4 Pulse tube, 5 Regenerator, 6 Cold-end exchanger

of Space Energy Conversion Technologies of TIPC, CAS has been conducting the research on coaxial PTCs for more than 20 years. Many coaxial PTCs were developed with the capacity varying from hundreds of milliwatts to greater than 15W at the cooling temperatures ranging from 20K to 180K. In recent years for the single-stage coaxial PTCs operating at 80K, much effort has been paid to increase the cooling capacity to meet the requirement of some large aerospace applications. In 2014, we developed a 9W at 80K coaxial PTC for superconductor research. In 2017, a 13W at 80K coaxial PTC was designed in our group with a corresponding electric power of 300W [8]. In this paper, a high efficiency coaxial single-stage PTC with a high cooling capacity of 15W at 80K is introduced. The optimization of the phase shifter and compressor is discussed in details. Moreover, the operating performance of the PTC is presented at the end of this paper.

OPTIMIZATIONS OF PTC

Figure 1 shows the schematic of the single-stage coaxial PTC. It uses a dual-opposed piston linear compressor with a maximum swept volume of 10 cc. The working gas is helium and the charge pressure is 4.0 MPa. Constant 500 mesh stainless steel stacked screens are used as the regenerator matrix. The cooler optimization is based on the above operating parameters.

Optimization of phase shifters

The purpose of the phase shifter is to shift the phases of mass flow and pressure wave. An optimal phase relationship means that the mass flow and the pressure wave in the midpoint of the regenerator are close in phase, and the phase range of the mass flow in the regenerator is not too large. According to primary research, a single inertance tube with a constant diameter has a great challenge in obtaining the desired phase relationship. Thus, a three-segment inertance tube with different diameters and lengths is selected to achieve a suitable phase shift.

Table 1 shows the combinations of inertance tubes. Figure 2 illustrates cooling performance of the PTC with these inertance tube configurations. The results show that when the cooling power is 10W, the PTC with Case 1 has the lowest cold-end temperature. Therefore, the Case 1 is the best combination of inertance tubes, and at this condition the optimal frequency of the PTC is tested to be 44Hz.

Optimization of compressor

Using advanced technologies, our group designed a new high efficiency compressor. The test results of the new compressor indicate that the efficiency of the newly designed compressor is up to 85%. As shown in Figure 3, 1# compersSor is the original compressor and 2# compressor is the new one. The cooling performance of the cold-finger coupled with 1# compressor as well as

Table 1. Combinations of inertance tubes

Case	Combinations of inertance tubes
Case 1	Φ2.5mm×0.5m+Φ3mm×2m+Φ4mm×2m
Case 2	Φ2.5mm×1m+Φ3mm×2m+Φ4mm×2m
Case 3	Φ2.5mm×0m+Φ3mm×2m+Φ4mm×2m
Case 4	Φ2.5mm×0.5m+Φ3mm×1m+Φ4mm×2m
Case 5	Φ2.5mm×0.5m+Φ3mm×2.5m+Φ4mm×2m
Case 6	Φ2.5mm×0.5m+Φ3mm×2m+Φ4mm×1m

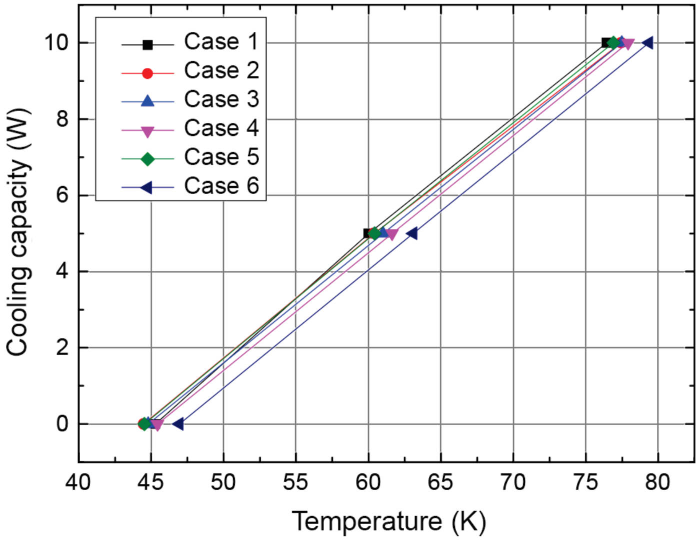

Figure 2. The cooling performance of the PTC with different inertance tubes

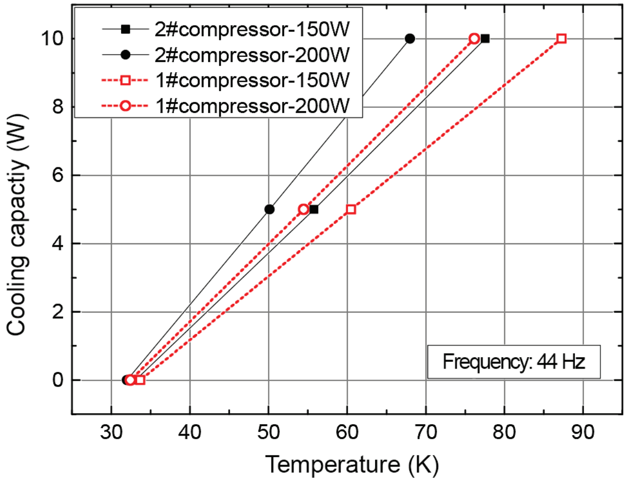

Figure 3. The performance of PTC with two compressors

2# comperssor is presented in Figure 3. Compared with the original compressor, we find that the cooling capacity of the PTC is raised substantially when the cold-finger is coupled with the new compressor. The reason is that the new compressor has a higher efficiency to convert the electric power into the PV power. Besides, the two PTCs have almost the same no-load temperature but the PTC with the new compressor has a much steeper slope in the graph. This result also indicates that the new compressor has a higher efficiency than the original one.

PERFORMANCE OF THE PTC

Figure 4 shows the PTC's cooling performance with 2# compressor. The limited experimental data is extrapolated in Figure 4 to generate predicted performance plots over a wide temperature and power range. The dotted lines in the graph represent the lines of constant specific power (the input electric power divided by the cooling power). The PTC was tested at an input electric power between 100W and 230W. The graph indicates that the constant specific power increases with the increment of input electric power, which illustrates that the efficiency of PTC deteriorates with the increase of the input power. It should be mentioned that the PTC achieves a cooling capacity of 15W at 80K when an electric power of 230W is provided. Besides, the PTC can obtain a remarkable high Carnot efficiency of 19% at 80K with an electrical power of 100W.

Figure 5 shows the Carnot efficiency of the PTC changing with the cooling temperature at different electric powers. As can be seen from Figure 5, all lines increase at first, and then they

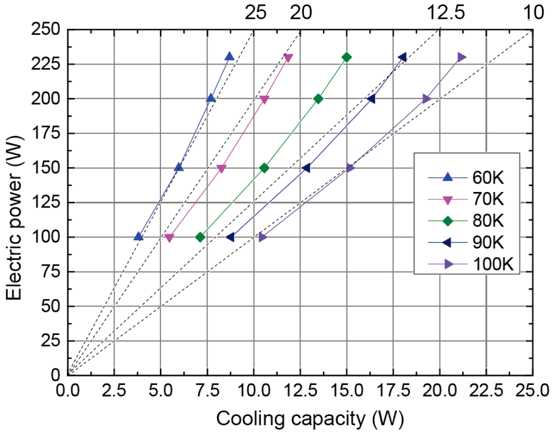

Figure 4. The cooling performance of the PTC with different cold-end temperature

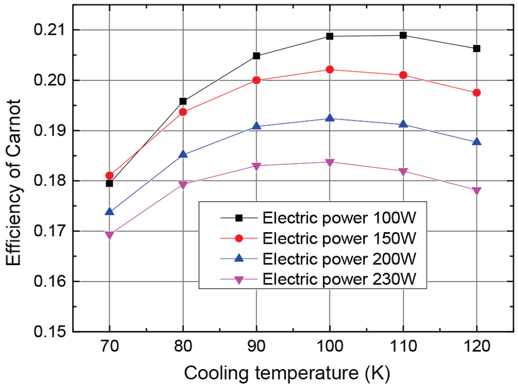

Figure 5. The Carnot efficiency of the PTC at different electric power.

reach a maximum value at the cooling temperature of 100K, and will decrease afterward. It could be concluded that the PTC has a best performance near the temperature of approximately 100K. The Carnot efficiencies of the PTC decrease with an increase of electric power when the electric power is over 100W.

CONCLUSIONS

A high-capacity coaxial PTC for aerospace applications has been developed and tested. A typical cooling capacity of 15W at 80K is obtained with 230W electric power and 293K reject temperature. A remarkable high Carnot efficiency of 19% at 80K also can be obtained with an electric power of 100W. The related experiments reveal that the combinations of three-segmented inertance tubes have significant influence on the performance of PTC. As there is a coupling mechanism of compressor and cold-finger, a new designed cold-finger should be coupled with a suitable compressor, to make full use of the cold finger's potential ability.

ACKNOWLEDGMENT

This work was financially supported by National Basic Research Program of China (grant number 613322) and National Key R&D Plan of China (grant number 2018YFB0504603)

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