Development of the 3.5 W at 80 K high-frequency pulse tube cryocooler

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This paper reports a 3.5 W at 80 K high-frequency pulse tube cryocooler (PTC), which is developed in the Cryogenic Laboratory of the Chinese Academy of Sciences (CL/CAS). The U-shaped configuration is adopted for the pulse tube refrigerator. Up to now, the high-frequency PTC has reached the lowest temperature of 38.8 K and the cooling capacity is about 3.58 W at 80 K, with the input power of 200 W of the linear motor, and the optimal frequency is about 40 Hz. And also, this paper introduces the necessary analysis on the performance and discusses the approaches to improve the performance. The research is still on the way.

INTRODUCTION

In recent years, the pulse tube cryocoolers (PTCs) have experienced a rapid development with the goal to eventually replace Stirling- and GM-coolers in various applications of cryoelectronics [1]. An emerging market for highly reliable cryocoolers, either Stirling-coolers or Stirling-type PTCs, can be expected in wireless communication, where the use of high-temperature superconductor devices (e.g. high-quality microwave receiver filters) is moving forwards to commercial applications [2, 3, 4].

In order to meet the different requirements in space and military applications, a Stirling-type high-frequency PTC has been developed in the CL/CAS. The PTC has the advantage of operating with no moving displacer at the cold end and nearly no mechanical vibration. The PTC can be used to cool electronic devices and high-temperature superconductor devices in mobile communications and to keep a low temperature for far infrared devices in space applications.

This paper reports three aspects of the PTC mentioned above: the description of the PTC, the experimental data and the result analysis, so as to improve the performance of the PTC.

DESCRIPTION OF THE PTC

The PTC is driven by a commercial linear compressor, the Leybold Polar SC7, with a maximum swept volume of 10 cm^3.The U-shaped configuration, which allows easy access to the cold tip, is adopted to design the pulse tube cold tip, as shown in Figure 1. And also, the cold tip configuration of this PTC is designed to be readily adaptable to meet different requirements, such as temperature and cooling capacity. The regenerator and the pulse tube are made of thin-wall stainless steel tubes. A stack of stainless steel screens of mesh No. 400 server as the regenerator matrix. Phase shifting is adjusted by use of an orifice valve at the warm end of the pulse tube and a double-inlet valve between the warm end of the pulse tube and the inlet of regenerator. Moreover, the inertance tube has been used as flow impedance. The input power of the compressor can be adjusted from 0 W to 250 W, and its frequency can be changed between 30 Hz and 60 Hz.

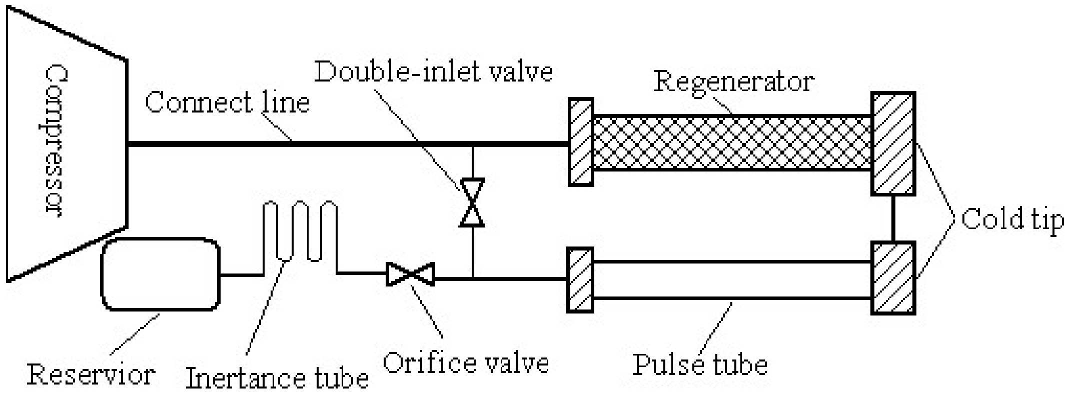

Figure 1 Schematic diagram of the Stirling–type PTC with U-shaped configuration

EXPERIMENTAL RESULT

The experimental data are shown in Figures 2-5 to describe the PTC performances clearly. All the test results are obtained at the frequency between 33 Hz and 40 Hz, the helium mean pressure is between 2.0 MPa and 3.0 MPa, as the optimum operating parameters are found in the ranges mentioned above.

Figure 2 shows the curve of the cold tip temperature in a typical process, while the mean pressure is 2.8 MPa and the operating frequency is 33 Hz. From step“1” to step “4”, the input power of the compressor has changed from 100 W to 200 W, the water cooling and the double-inlet valve are taken to operate in the process. Finally, a lowest temperature of 38.8 K is available, as seen in Figure 2 (Point A).

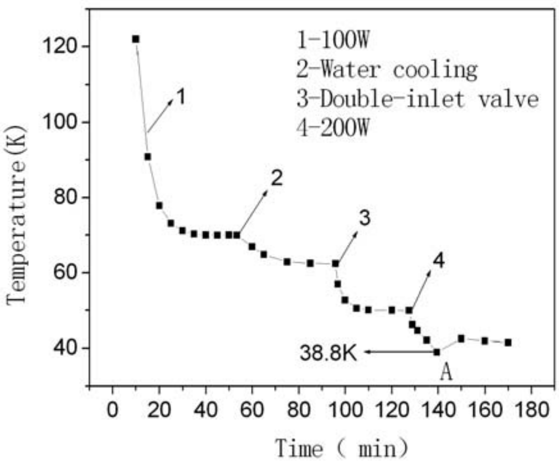

Figure 2 Curve of the cold tip temperature

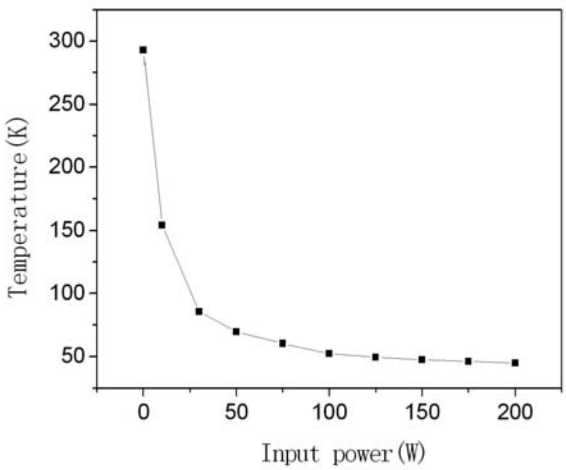

Figure 3 Lowest temperatures of the PTC at different input powers

Figure 3 shows the lowest temperature of the PTC at different input powers to the compressor, while the mean pressure is 2.8 MPa and the operating frequency is 33 Hz. At 100 W to the compressor, the lowest temperature is 53 K, the lowest temperature is 47 K with input power of 150 W, the lowest temperature is 45 K with input power of 200 W. However, as the input power increases from 150 W to 200 W, the decrease of the lowest temperature is just 2 K, this is because that the efficiency of the compressor is not in the optimal case.

Figure 4 shows the cooling capacity versus the temperature of the cold tip for the U-shaped PTC at different input power of the compressor, while the mean pressure is 2.8 MPa and the operating frequency is 40 Hz. After optimization position of value, the PTC provides a cooling capacity of 3.58 W at 80 K with the input power of 200 W, and the cooling capacity of 4.25 W at 80 K with the input power of 250 W. The cooling capacity changes linearly with the cold tip temperature.

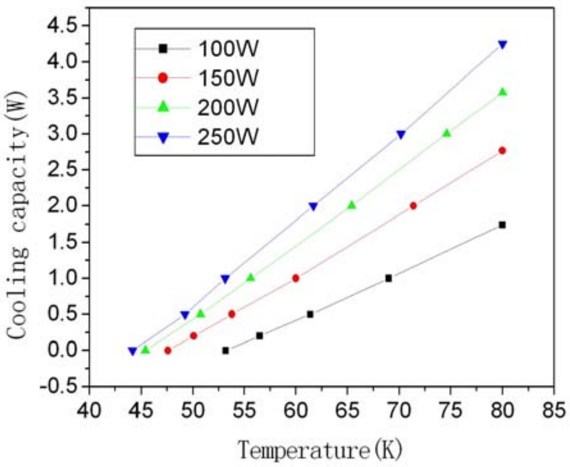

Figure 4 Cooling capacity versus the cold tip temperature at different input powers to the compressor

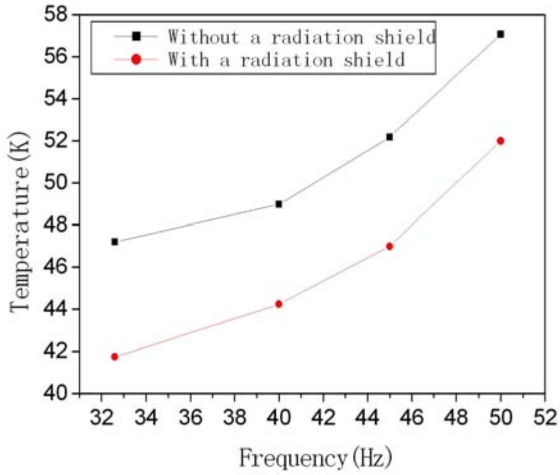

Figure 5 Temperature of the cold tip at different frequencies, Operation with and without a radiation shield

For improving the performance of the PTC, the radiation shield has been taken to decrease the heat loss. While the mean pressure is 2.8 MPa and the input power is 200 W, the temperature of the cold tip with the radiation shield is lower than that without the shield, the temperature difference is nearly 5 K, as shown in Figure 5.

RESULT ANALYSIS

In this paper, the compressor efficiency η_1 is defined as the ratio of the output PV power W_1 to the input power W_2 (W_2 includes W_1, Joule heat loss and friction loss), that is: $\eta_1 = W_1/W_2$; the cold tip efficiency η_2 is defined as the ratio of the cooling capacity P to the output PV power W_1, that is: $\eta_2 = P/W_1$; the PTC efficiency is denoted as the COP, which includes the compressor efficiency η_1 and the cold tip efficiency η_2, that is: $COP = \eta_1 * \eta_2$ [5]. While the mean pressure is 2.8 MPa, the COPs of the PTC at different frequencies are shown in Table 1.

Table 1 The COPs of the PTC at different frequencies

Frequency (Hz)	Input power W_2 (W)	Cooling capacity P at 80 K (W)	η_1	η_2	COP
33	200	3.45	53.3%	3.24%	1.73%
40	200	3.58	66.5%	2.7%	1.79%
46	200	3.00	63.2%	2.37%	1.5%

As shown in Table 1, the optimal COP of the PTC is 1.79% with 40 Hz of the operating frequency. The optimal η_1 is 63.2% with 46 Hz of the operating frequency and the optimal η_2 is 3.24% with 33 Hz of the operating frequency. That is, when the operating frequency decreasing from 40 Hz, the compressor efficiency and the cold tip efficiency will be improved respectively.

CONCLUSIONS

The present work demonstrates a Stirling-type high-frequency PTC with a U-shaped cold tip. The lowest temperature of 38.8 K and the cooling capacity of 3.58 W at 80 K have been achieved with the optimal frequency of 40 Hz and the input power of 200 W.

Based on the analysis, the better matching between the compressor and the cold tip, and the reduction of heat loss of the PTC and friction loss of the compressor can lead to an improvement of the PTC efficiency. The further work on the optimization of the PTC performance can be expected.

ACKNOWLEDGEMENTS

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