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Influence of the structure of multi-bypass configuration regenerator on the performance of Pulse Tube Cryocooler

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Abstract. As the fundamental component of the pulse tube cryocooler, the functionality of the regenerator exerts a direct influence on the overall performance of the cryocooler. In the design of a pulse tube cryocooler, two principal structural options for the regenerator are available, contingent on the specific requirements. One option is a non-variable cross-section structure, while the other is a variable cross-section structure. The advantage of the variable cross-section structure is that it allows the pulse tube cryocooler to increase the cold end heat exchanger at the variable cross-section for cooling, thereby enabling the cryocooler to operate in different temperature zones. Furthermore, a multi-bypass configuration can be added at the variable cross-section region of the regenerator to enhance the phase modulation capacity of the inertance tube. Consequently, the mass of gas entering the cold end heat exchanger is reduced, which in turn diminishes the cooling capacity. The variable section structure presented in this paper is based on the design and processing experience of the single-stage pulse tube cryocooler. The design parameters are as follows: The diameter of the primary regenerator is 16 mm, with a filling length of 40 mm; the diameter of the secondary regenerator is 10 mm, with a length of 30 mm; and the packing of the regenerator is comprised of #500 and #635 stainless steel screens. The cryocooler was subjected to testing under varying operating pressures. At an input power of 100 W, an operating pressure of 4.2 MPa, a hot end temperature of 300 K, and an operating frequency of 92 Hz, a no-load temperature of 32.16 K and a cooling capacity of 1 W at 44.44 K can be achieved.

Keywords: multi-bypass · regenerator · cold end heat exchanger · 4.2 MPa · 92 Hz

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1. Introduction

In the contemporary era of relentless scientific and technological advancement, cryogenic technology has emerged as a pivotal supporting discipline, finding application in diverse fields such as space exploration, low-temperature quantum science, the industry of superconductor applications, and the domain of low-temperature medicine. Moreover, it has become an indispensable component in various aspects of daily production and life. The development of space technology, as the core technology, has attained a position of paramount importance in determining the scientific and technological prowess of nations, and is also a crucial metric in gauging a nation's overall strength. The absence of moving components in the low-temperature end of the pulse tube cryocooler (PTC) ensures that the PTC exhibits low vibration, low interference, no wear, a long service life, high performance, and high efficiency. These significant advantages position the PTC as an ideal choice for space cryocoolers in recent years. The PTC's design offers two primary structural options, depending on the specific requirements: the first option involves the use of a non-variable cross-section structure, while the second option employs a variable cross-section structure (see model diagram in Figure 1). The advantage of the variable cross-section structure is that it allows the PTC to increase the cold end heat exchanger in the variable cross-section; that is, the structure of the variable cross-section can realise the PTC in different temperature zones. At the same time, the structure of the variable cross-section can increase the multi-channel structure at the variable cross-section area of the regenerator to strengthen the phase modulation capability of the inertance tube. Consequently, the mass of gas entering the cold end heat exchanger is reduced, thereby diminishing the cooling capacity.

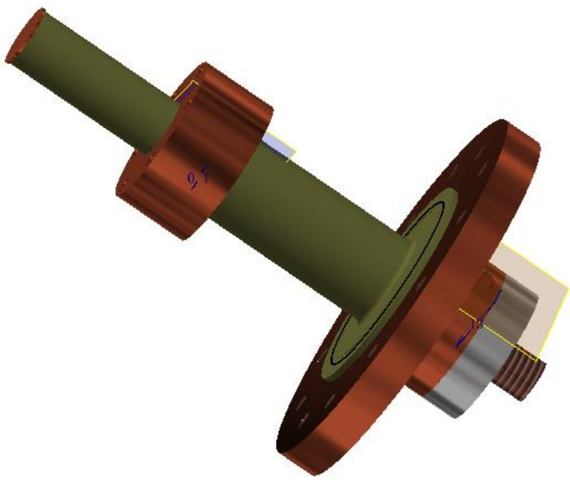

Figure 1. Single-stage multi-bypass PTC.

The multi-bypass structure has attracted considerable scholarly attention since the early days of the field. In 1995, C. Wang et al. conducted experiments on a multi-bypass PTC to study the effect of the intermediate bypass valve on the PTC performance and determine the minimum cooling temperature. The experimental results of the multi-bypass structure and the dual-entry structure verify that the former can achieve lower temperatures than the latter [1]. In 1996, Chao Wang et al. investigated the impact of the intermediate bypass valve on the performance of a multi-bypass pulse tube refrigerator (MPTR) through numerical analysis and experimentation. Their numerical predictions revealed the energy transfer and two cooling processes occurring in the MPTR. The comparison results demonstrated that the multi-bypass structure enhances the performance of the PTC in the low-temperature range. The MPTR, equipped with two intermediate bypass tubes, was constructed, and a temperature of 24 K was successfully attained [2]. In 1998, Y. L. Ju et al. investigated the instantaneous velocity and pressure in an MPTR, observing direct current (DC) flow. The paper goes on to explain how the multi-bypass structure enhances the performance of the PTC. In 1999, Yang Luwei et al. proposed a mechanism for reducing the temperature of a PTC with dual air intakes by analysing the phase relationship between the dual-pass multi-bypass pressure and the flow characteristics, and they subsequently suggested replacing the low-temperature multi-pass valve. Through experimentation, the efficacy of this multi-double inlet structure in reducing the cooling temperature is substantiated, and the experimental setup utilises two double inlet valves to attain a no-load temperature of 37 K and a single double inlet valve to achieve a no-load temperature of 50 K [4]. In 2001, L.W. Yang et al. introduced a multi-bypass PTC, and experiments showed that multiple bypass channels can improve performance, and the function of the multi-bypass is more similar to the dual inlet than the first stage of a multistage cooler [5]. In 2013, Chen Liubiao et al. developed a single-stage high-frequency multi-bypass coaxial PTC for physical experiments. Employing the cooperative phase adjustment method of multi-bypass and double inlet, the PTC attained a temperature of 18.6 K when the electrical input power was 268 W [6]. In 2015, Qiang Zhou et al. adopted a coaxial configuration of dual entry and multi-bypass to enhance performance. Utilising the Er_3Ni ball at the cold end of the regenerator, the PTC can attain a no-load temperature of 13.9 K with an input power of 250 W [7]. In 2019, Changzhao Pan and colleagues conducted a numerical study on the multi-bypass mechanism. This study comprehensively investigates the interaction of multi-bypass and double entrances and optimises it through experimental means. Additionally, it explores the effects of orifice, operating frequency and average pressure on the multi-bypass. The experimental results, conducted under optimal operating conditions, demonstrate that a no-load temperature of 3.7 K is attained [8].

The variable section structure presented in this paper has been derived from the design and processing experience of a single-stage PTC. The design parameters are specified as follows: a primary regenerator with a diameter of 16 mm and a length of 40 mm; a secondary regenerator with a diameter of 10 mm and a length of 30 mm; and #500 and #635 stainless steel screens utilised for the regenerator packing. The cryocooler was subjected to testing under a range of operating pressures. It was established that, at an input power of 100 W, an operating pressure of 4.2 MPa, in conjunction with a hot end temperature of 300 K, could be attained at an operating frequency of 92 Hz. Furthermore, the system attained a no-load temperature of 32.16 K while delivering a cooling capacity of 1 W at 44.44 K.

2. Experimental system design

The experimental system incorporates a vacuum system, a cooling water circulation system, a charge system, a data measurement and acquisition system, and a cryocooler system. The PTC is composed primarily of a linear compressor, a cold finger, and phase shifters. The compressor employs a double-piston opposed configuration, driven by a linear motor. The cold finger features a coaxial design and utilizes #500 and #635 stainless steel screens as regenerator material, while the phase shifters incorporate an inertance tube and a gas reservoir. The cold end temperature was measured using a PT100 thermometer.

Table 1 presents the phase shifters employed in the single-stage multi-bypass PTC.

Table 1. Combination of different inertance tubes.

Case	Combination
Case01	Φ2 mm×1 m +Φ3 mm×1 m+Φ4 mm×1 m +200 cc
Case02	Φ1.4 mm×0.2 m+Φ2 mm×1 m+Φ3 mm×1 m +Φ4 mm×1 m+200 cc
Case03	Φ1.4 mm×0.3 m+Φ2 mm×1 m+Φ3 mm×1 m +Φ4 mm×1 m+200 cc
Case04	Φ1.4 mm×0.4 m+Φ2 mm×1 m+Φ3 mm×1 m +Φ4 mm×1 m+200 cc

3. Experimental results and discussion

Figure 2 shows the influence of the combination of four groups of inertance tubes on the performance of the PTC. None of the four groups of phase shifters adopts the multi-bypass structure, at the same time, the input power of the PTC is 100 W and the operating pressure is 5 MPa. It can be seen from the figure that the four groups of inertance tubes have little difference on the performance of the PTC; however, the difference in the operating frequency of the PTC is obvious, which is successively 94 Hz, 86 Hz, 82 Hz, and 80 Hz. Correspondingly, the no-load temperatures recorded are 40.92 K, 41.21 K, 41.71 K, and 41.31 K. Conversely, when the cooling capacity is 2 W, the corresponding no-load temperatures are 62.56 K, 62.67 K, 63.93 K, and 62.95 K, respectively. A comparison of the performance of the PTC with that of the single-stage non-variable cross-section PTC reveals a significant decrease in performance (when the input power of the PTC is 100 W and the cooling capacity is 2 W, the temperature at the cold end of the PTC is 54.72 K). Given that the operating frequency of the PTC in this study is approximately 100 Hz, the inertance tube combination Case01 is selected as the optimized phase shifter combination.

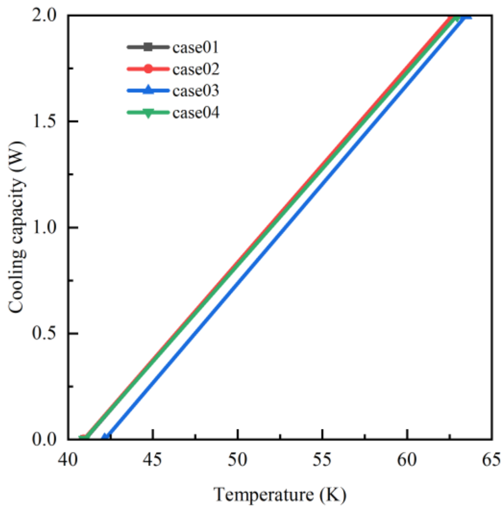

Figure 2. The influence of different inertance tube combinations on the performance of PTC.

The Case01 inertance tube combination was utilised to construct a 0.5 mm micro-hole in the cold end heat exchanger at the variable section, with the objective of adjusting the phase difference between the pressure wave and the mass flow inside the PTC system. The schematic diagram with a 0.5 mm bypass hole is shown in Figure 3. As illustrated in Case01* of Figure 4, the

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performance diagram of the PTC following the implementation of the 0.5 mm micro-hole demonstrates a notable enhancement. It is evident from Figure 4 that the incorporation of the bypass hole results in a reduction of the no-load temperature of the PTC from 40.92 K to 34 K when the input power of the PTC is set at 100 W. Furthermore, when the cooling capacity of the cold end of the PTC is 2 W, the corresponding temperature is reduced from 62.56 K to 59.54 K, thereby enhancing the performance of the PTC. At the same time, it can also be observed that when the cooling capacity at the cold end of the PTC increases to 3 W, the performance of the PTC with a bypass hole structure deteriorates. The analysis suggests that the main reason for this problem lies in the fact that as the cooling capacity at the cold end and the cooling temperature range increase, the mass flow rate of the working medium required at the cold end heat exchanger increases. Due to the introduction of the bypass hole, a portion of the gas output by the compressor of the PTC flows into the pulse tube through the built-in small hole in the first-stage cold end heat exchanger at the variable cross-section of the regenerator, resulting in a reduction in the gas flow rate at the second-stage cold end heat exchanger and a decrease in the PV power at the cold end.

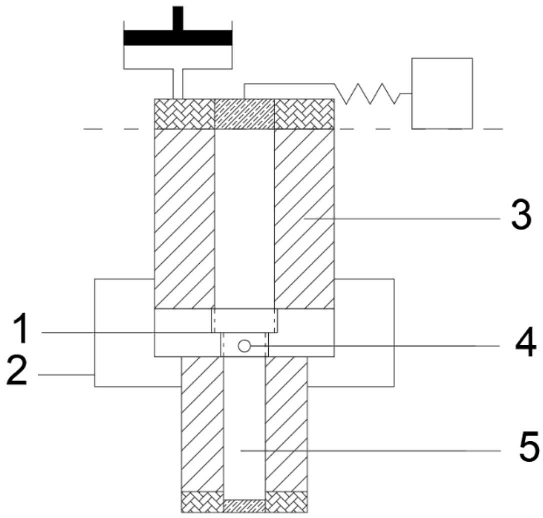

Figure 3. The position of the 0.5 mm bypass hole.

1.The channel connecting the pulse tube;
2. Adapter flange; 3. Regenerator; 4. Bypass hole; 5. Pulse tube.

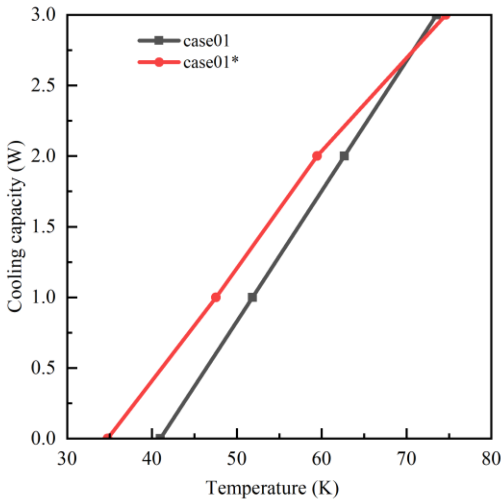

Figure 4. Influence of bypass hole on PTC performance.

As demonstrated in Figure 5, the performance of the PTC is influenced by the operating pressure. Figure 5a illustrates the variation of the no-load temperature of the PTC with frequency when the input power is 60 W. It is evident that as the operating pressure diminishes, the optimum operating frequency corresponding to the no-load temperature of the PTC also decreases. Furthermore, as the operating pressure decreases, the no-load temperature of the PTC gradually declines. When the operating pressure is reduced from 6.0 MPa to 3.5 MPa, the optimum operating frequency is reduced from 94 Hz to 90 Hz, and the no-load temperature is reduced from 38.75 K to 35.68 K. As illustrated in Figure 5b, the performance curve for the system is shown when the input power is 100 W. It is evident that as the operating pressure is reduced, the lowest temperatures are 34.76 K, 34.43 K, 32.16 K, and 31.83 K, respectively. When the cooling capacity is 1 W, the corresponding temperatures are 47.53 K, 47.10 K, 44.44 K, and 46.83 K. The optimal operating pressure of the varied-section multi-bypass PTC is thus determined to be 4.2 MPa. A detailed analysis of the data reveals a direct correlation between the required operating pressure and the cooling capacity, with optimal performance observed at pressures ranging from 3.5 MPa to 4.2 MPa within the temperature range of 40 K. As demonstrated in Figure 6, the performance of the PTC at an operating pressure of 4.2 MPa and an input power of 200 W is optimal, with a no-load temperature of 30.54 K being achieved. It is noteworthy that when the cooling capacity is reduced to 1.0 W, the no-load temperature increases to 39.3 K.

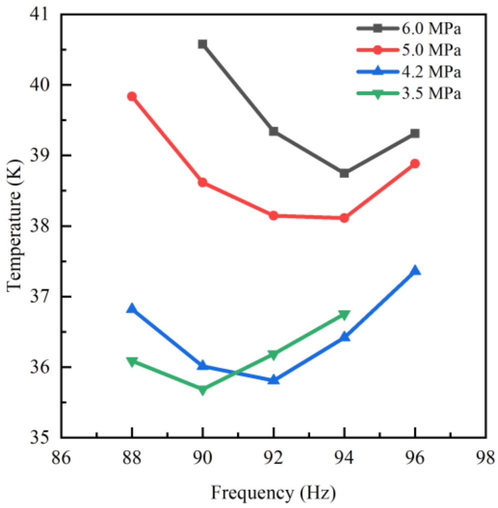

Figure 5a. The influence of operating pressure on the no-load temperature at an input power of 60 W.

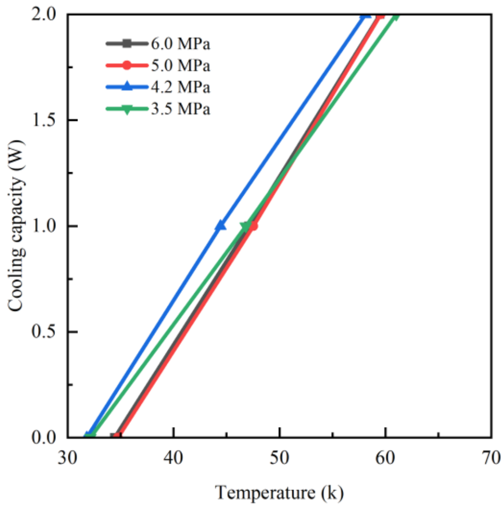

Figure 5b. The influence of operating pressure at the optimal frequency on PTC performance.

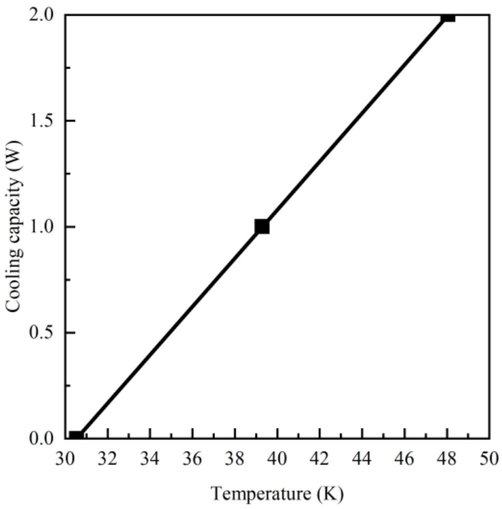

Figure 6. Performance curve of the PTC.

4. Conclusions

The multi-bypass structure PTC proposed in this paper has been shown to be capable of achieving a no-load temperature of 32.16 K and a cooling capacity of 1 W at 44.44 K when the input power is 100 W, the operating pressure is 4.2 MPa, the hot end temperature is 300 K, and the operating frequency is 92 Hz.

Acknowledgments
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