

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, the structure of the variable cross-section must incorporate a multi-bypass configuration at the variable cross-section region of the regenerator, with the objective of enhancing 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 charge pressures. At an input power of 100 W, a charge pressure of 4.2 MPa, a hot end temperature of 300 K, and an operating frequency of 92 Hz, a minimum temperature of 32.16 K and a cooling capacity of 1 W at 44.44 K can be achieved.

Introduction

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 minimum temperature of 32.16 K while delivering a cooling capacity of 1 W at 44.44 K.

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

Experimental results and discussion

Figure 1 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 minimum temperature recorded is 40.92 K, 41.21 K, 41.71 K, and 41.31 K. Conversely, when the cooling capacity is 2 W, the corresponding minimum 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.

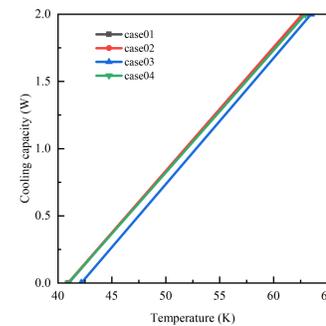


Figure 1. The influence of different inertance tube combinations on the performance of PTC.

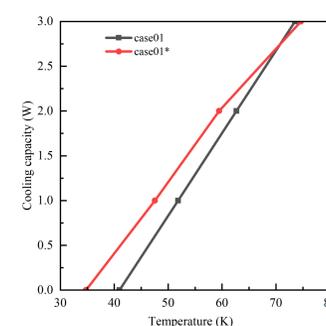


Figure 2. Influence of bypass hole on PTC performance.

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. As illustrated in case01 of Figure 2, the performance diagram of the PTC following the implementation of the 0.5 mm micro-hole demonstrates a notable enhancement. It is evident from Figure 2 that the incorporation of the bypass hole results in a reduction of the minimum 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. Conversely, it can be observed that when the cooling capacity of the cold end of the PTC is increased to 3 W, the performance of the PTC with the bypass hole structure deteriorates. The analysis indicates that the primary cause of this problem is the increase in the mass flow of the working medium required by the cold end heat exchanger, which occurs as the cooling capacity and cooling temperature zone are enhanced. Consequently, a proportion of the gas output from the compressor of the PTC enters the pulse tube situated at the inner opening of the primary cold-end heat exchanger at the variable section of the regenerator. This phenomenon leads to a decline in gas flow at the secondary cold-end heat exchanger, consequently resulting in a reduction in cold-end PV power. This, in turn, leads to a deterioration in the performance of the PTC. This phenomenon is a primary factor contributing to the utilisation of single-stage PTC in temperature ranges exceeding 80 K.

As demonstrated in Figure 3, the performance of the PTC is influenced by the operating pressure. Figure 3a illustrates the variation of the minimum 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 minimum temperature of the PTC also decreases. Furthermore, as the operating pressure decreases, the minimum 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 minimum temperature is reduced from 38.75 K to 35.68 K. As illustrated in Figure 3b, 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 4, the performance of the PTC at an operating pressure of 4.2 MPa and an input power of 200 W is optimal, with a minimum temperature of 30.54 K being achieved. It is noteworthy that when the cooling capacity is reduced to 1.0 W, the minimum temperature increases to 39.3 K.

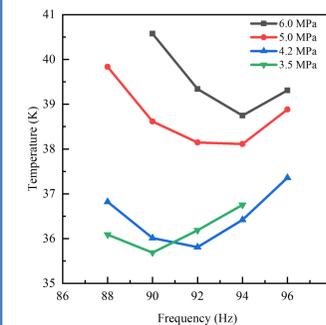


Figure 3a. The influence of operating pressure on the minimum temperature.

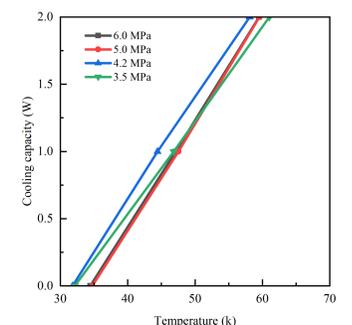


Figure 3b. The influence of operating pressure on PTC performance.

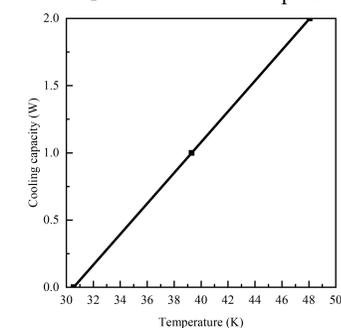


Figure 4. Performance curve of the PTC.

In comparison with non-variable cross-section PTC, the performance of variable cross-section PTC with multi-bypass structure does not reach the performance index of 40 K@1.5 W. The primary reasons for this are as follows: Firstly, the phase shifters adopt a non-variable cross-section structure, which has not been optimised in detail, and only the first section of the inertance tube is optimised in this experiment, but this has little impact on the performance of the PTC. Secondly, the overall size of the regenerator is not optimized when compared with the 20 K PTC in the laboratory. Thirdly, the regenerator is of a reduced size overall, and the filling mode and flow distribution are not optimized by the built-in bypass hole. These factors are identified as the primary contributors to the suboptimal performance of the PTC.

Conclusion

The multi-bypass structure PTC proposed in this paper has been shown to be capable of achieving a minimum 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.