Design and test of a 80 K miniature pulse tube cryocooler

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A 80 K miniature pulse tube cryocooler has been designed, fabricated and tested. The pulse tube cryocooler is designed to provide 0.5 W of cooling power at 80 K with input electrical power less than 40 W. The cryocooler system incorporates a compressor with U-shaped pulse tube configuration. A computer simulation program based on the theory of thermodynamic non-symmetry is developed for performance predictions, optimizations, and as a guide for system design. Dimensions of the pulse tube and the regenerator are optimized further by experimental methods. The double inlet valve and the inertance tube are both used for phase shifting. The lowest temperature of 59.3 K is achieved.

INTRODUCTION

The pulse tube cryocooler (PTC) was originally described in 1964, and is now called the basic pulse tube cryocooler. The performance of the PTC has been greatly improved by introducing an orifice and a buffer volume added to the hot end of the pulse tube in 1984, and this is now called the orifice pulse tube cryocooler. The double inlet pulse tube cryocooler was introduced in 1990, which greatly increased the performance of the PTC. And the inertance pulse tube cryocooler was investigated in 1994.

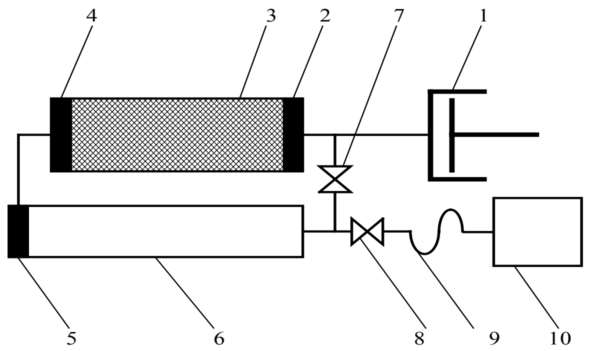
Because of the absence of moving parts at low temperature, the PTC driven by a linear compressor has the potential to achieve high reliability and very long lifetime. With the technical development of the PTC, the performance of the PTC in high frequency operation can now compare with the Stirling cryocooler in some cases.

Here we report on the state of development of a 80 K miniature pulse tube cryocooler. Compactness, low cost, lightweight, high performance and high reliability are required. Based on the demands, U-shaped miniature PTCs were designed, fabricated and tested. The design and the test results of the PTCs are presented.

DESIGN OF PULSE TUBE CRYOCOOLER

A computer simulation program based on the theory of thermodynamic non-symmetry is developed for performance prediction, optimization, and as a guide for system design. Three samples of miniature PTCs were designed by the simulation program, and then fabricated and tested. The PTCs use U-shaped configuration. In principle the U-shaped pulse tube configuration has better performance than that of the co-axial configuration, and is more convenient to get cryogenic cooling from the pulse tube cold head than the in-line configuration.

A schematic diagram of the PTC is shown in Figure 1. The cryocooler system incorporates a compressor with a U-shaped pulse tube configuration and a reservoir. The compressor is made in our laboratory with a linear motor supported by flexure springs. Maximum swept volume of the compressor is 2 cm^3, which leads to a lightweight cryocooler. Double inlet valve and inertance tube are used for phase shifting.



1-compressor 2-heat exchanger 3-regenerator 4-heat exchanger
5-heat exchanger 6-pulse tube 7-double inlet 8-orfice
9-inertance tube 10-reservior

Figure 1 Schematic diagram of the U-shaped pulse tube cryocooler

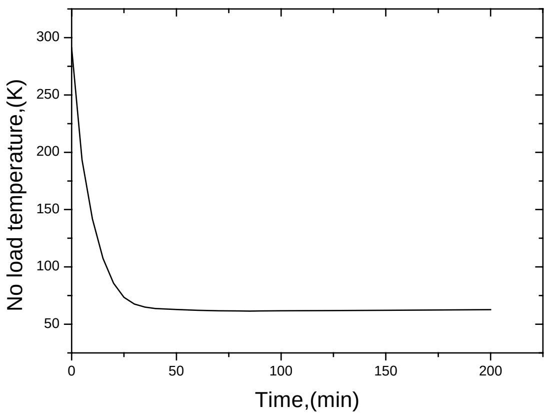


Figure 2 Cool down profile with no heating load

The phase difference between of the mass flow and pressure wave of the regenerator is measured with our dynamic experimental apparatus. By the measurement of phase, we can optimize dimensions of the pulse tube, regenerator and inertance tube more effectively.

ANALYSIS

Enthalpy Flow Theory shows that if the flow and pressure are sinusoidal functions of time, the time–average enthalpy flow rate can be written as:

$$< \dot{H} >=< P_d \dot{V} >= (1/2)\,|P||\dot{V}|\cos\theta = (1/2) R T_0 \,|\dot{m}|\,(|P|/P_0)\cos\theta$$

where P_d is dynamic pressure, $\dot{V}$ is volume flow rate. P is sinusoidal pressure oscillation, θ is phase angle between flow and the pressure, R is gas constant per unit mass, $\dot{m}$ is sinusoidal mass flow rate and P_0 is average pressure. We can use it for qualitative analysis.

Effect of operational frequency on cooling capacity

To predict the cooling capacity, the mass flow rate, the ratio between the pressure and average pressure, and the phase between the pressure and the mass flow rate are needed. The pressure reduces with the rising of operational frequency, which will lead the pressure ratio reduction. The mass flow rate and the phase between the pressure and the mass flow rate will be reduced too. Therefore, the cooling capacity of the cooler will increase with lowing of operational frequency.

Effect of average pressure and input electrical power

According to an analysis as before, the mass flow rate and the phase between pressure and mass flow rate increase with an increase of average pressure. And the pressure ratio first increases then decreases with the pressure rising. The cooling capacity increases then decreases by the average pressure increasing, it exists an optimum average pressure.

With the input electrical power increasing, the pressure and the mass flow rate increase. While the phase between the pressure and the mass flow rate increases with the input electrical power increasing. So the cooling capacity increases then decreases with the input electrical power increasing. It also exists an optimum input electrical power.

TEST OF PULSE TUBE CRYOCOOLER

Figure 2 is a typical cool-down profile of the PTC. The cooler can obtain the lowest temperature of 61.5 K within 40 minutes with no load. The experiments are operated at an average pressure of 4.0 MPa and an operational frequency of 35 Hz with 45.5 W of input electrical power. In the experiments, double inlet and inertance tube are both used to shift the phase. The length of the inertance tube is 2.4 m and the inner diameter of the inertance tube is 1mm.

Figure 3 shows the effect of different average pressures on the lowest temperature of the PTC. The lower temperature goes down with an increasing of average pressure. The temperature of the cold head changes little when the average pressure is higher than 3.5 MPa.

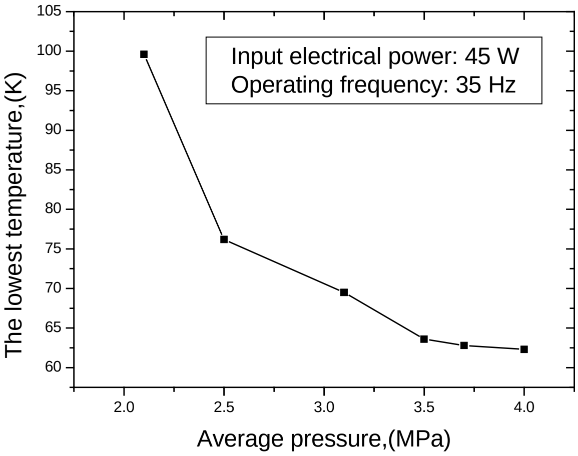


Figure 3 Effect of average pressure on the lowest temperature

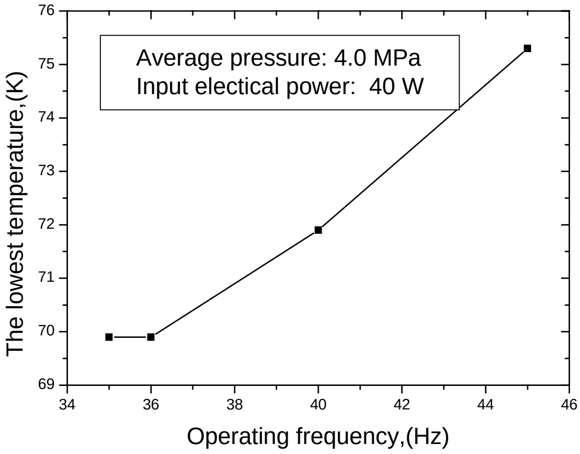


Figure 4 Relationships between the lowest temperature and operating frequency

Figure 4 shows the effect of different frequencies on the lowest temperature. The lowest temperature varies with frequency, and 35 Hz is the optimal frequency for the lowest temperature of the PTC.

The cooling capacity of the PTC with different input electrical power is shown in Figure 5. The average pressure is 4.0 MPa and operating frequency is 35 Hz. The lowest temperature is 59.3 K when the input electrical power is 54.3 W. The lowest temperature of 66.3 K was got with 40 W of electrical power with no load.

Figure 6 shows the cooling capacity of different input electrical power. The PTC can provide 0.5 W of cooling capacity at 80 K with 54.3 W of input electrical power. But only 0.25 W of cooling capacity is got at 80 K with 40 W of input electrical power. The ratio between cooling capacity and input electrical power increases with an increase of input electrical power. The measurements shows, there is a large pressure difference between the warm end and the cold tip of the regenerator, which causes the mass flow rate to decrease. On the other hand, the pressure difference is smaller in the cold tip. These two effects cause the cooling capacity of the PTC to reduce, and we can conclude the flow resistance in the regenerator is too large. It shows that the performance of the PTC is not in its optimum situation.

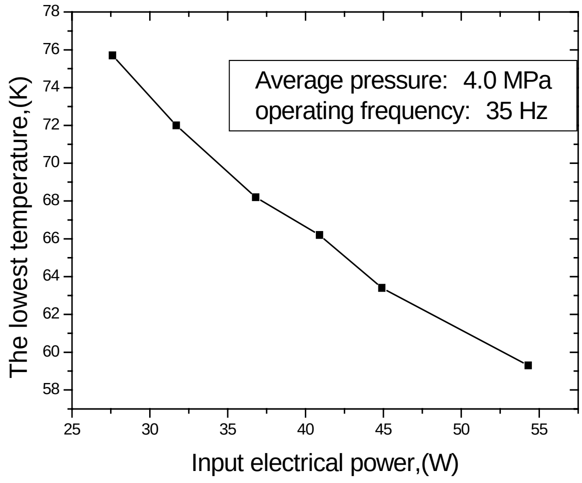


Figure 5 Effect of input electrical power on the lowest temperature.

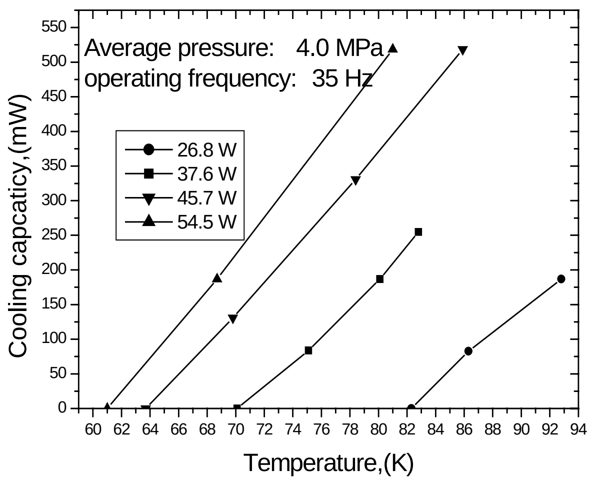


Figure 6 Cooling capacities as a function of cold end temperature with different input electrical power

By analyzing the above test results of the PTC we have designed, the dimensions of the pulse tube and the regenerator geometry can be optimized in further.

CONCLUSION

The lowest temperature of 59.3 K has been achieved and the PTC can provide a cooling capacity of 0.5 W at 80 K with an input electric power of 54.3 W. But the cooling capacity at 80 K with 40 W of input electrical power is not sufficient. Because this PTC was adjusted for lower temperature, it is not in the best performance at a temperature of 80 K. The next step is to optimize the dimensions of the PTC and experimental apparatus of the PTC system.

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