Research of a High Capacity Coaxial Pulse Tube Cryocooler Working at 170 K

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ABSTRACT

A high cooling capacity coaxial pulse tube cryocooler (PTC) which works at 170 K is presented in this paper. The outer diameter and the length of the regenerator of the designed cold finger are 40 mm and 32 mm, respectively. As the cold finger structure is short and thick, the jet flow from the inertance tube can obviously affect the velocity field in the pulse tube, thus influencing the cooling performance of the cold finger. A two-dimensional axisymmetric CFD model was built using FLUENT software to prove the importance of the flow straightener on weakening the jet flow. In addition, experiments have been carried out to investigate the cooling performance of the manufactured PTC and study the influence of mesh number of the flow straightener on the cooling capacity. The experimental results show that when a 100 # copper wire mesh is applied in the hot-side flow straightener, the PTC achieves the best performance compared with using 80 # and 120 # copper mesh. With an electric power of 200 W added to the compressor, the PTC obtains a temperature of 59 K with no heat load and a cooling power of 45 W at 170 K, and the system efficiency can reach 22.5%.

INTRODUCTION

In recent years, due to the advantages of small vibration, compact structure, high reliability, the coaxial pulse tube cryocooler (PTC) have been widely used in infrared detection, low temperature optics, superconducting technology, and other fields. The PTC can be specially designed according to the required temperature as well as the cooling capacity. In the field of low-temperature biomedical application, small-scale low-temperature refrigerator, infrared observation, the PTC working at medium temperature from 130 K to 200 K have received much attention.

The research of PTC in medium temperature region is mainly divided into two directions: one is to improve the cooling capacity as well as the efficiency of PTC; the other is to realize the lightweight of PTC by increasing the working frequency. Wang designed a PTC which provided a cooling power of 31 W at 160 K with an input electric power of 200 W and was used for low temperature refrigeration[1]. Deng developed a 150 K-200 K pulse tube cooler for infrared detector, which can achieve a cooling performance of 50 W and specified Carnot efficiency of 16% at 170 K with 230 W electrical power input [2]. Durand developed an efficient high capacity space microcooler which weighs only 900 g [3]. However, it could provide nearly 5 W of cooling at 150 K. Chassaing built a 150

K-200 K miniature pulse tube cooler to cool infrared detectors for micro-satellite missions [4]. The cooling power is 1 W to 3 W with a total electric power less than 20 W. In the future, the research of PTC at medium temperature will still be focused on improving work efficiency and optimizing compact structures.

In order to further develop the application of PTCs in low-temperature refrigerator, a coaxial PTC working at the temperature range of 130 K-170 K is designed in this paper. The structure of the cold finger was designed using SAGE [5] software based on the operation parameters of the compressor made by our lab. To analyze the influence of the hot-side flow straightener on the velocity field inside the pulse tube and the performance of the refrigerator, a two-dimensional axi-symmetric model of the cold finger was established by using FLUENT [6] software. The cooling performance of the developed PTC was experimentally tested, and the influence of the copper mesh in the straightener on the performance of the refrigerator was analyzed.

DESIGN OF PTC

For the purpose of medium operation temperature and large cooling capacity, a coaxial pulse tube cold finger was designed to be coupled with the compressor developed by our lab using Sage software [5]. The key parameters of the PTC are listed in Table 1. The maximum swept volume of the compressor is 10 cc. The gas reservoir and inertance tubes were chosen as the phase shifter. According to the numerical optimization results, the length and the outer diameter of the regenerator are 32 mm and 40 mm, respectively. The theoretical cooling performance of the PTC is shown in Fig. 1. It is indicated that the designed PTC obtains 50 W cooling capacity with an input PV power of 200 W.

Table 1. Main structural parameters of the PTC

Parameters	Values
Diameter of piston	25 mm
Maximum swept volume of compressor	10 cc
Length of regenerator	32 mm
Outer diameter of regenerator	40 mm
Inner diameter of regenerator	20 mm
Inertance tubes	Φ3 mm ×1 m+Φ4 mm×1 m
Volume of gas reservoir	250 cc

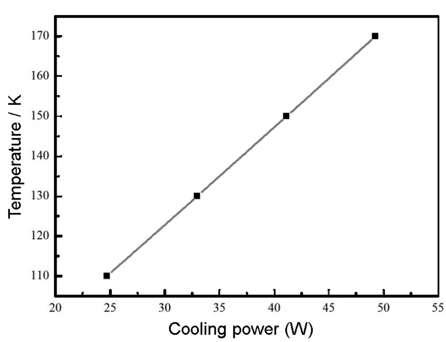

Figure 1. Cooling performance of the PTC with an input PV power of 200W

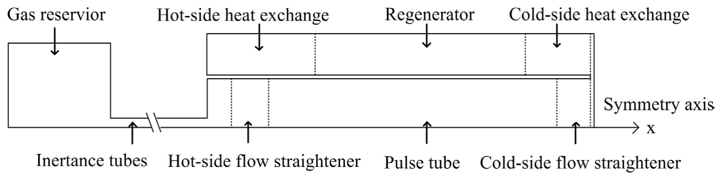

Figure 2. Two-dimensional axisymmetric model of the coaxial PTC

As the structure of the designed cold finger has the characteristics of short and thick, the influence of the jet flow from the inertance tube on the velocity field and temperature field of the pulse tube becomes more significant. The jet flow can enhance the mixing of cold and hot working fluids in the pulse tube and, as a result, increase the heat leakage at the cold end of the pulse tube. Therefore, the cooling performance can be greatly affected by the jet flow. However, Sage, as a one-dimensional design software, cannot accurately analyze the two-dimensional flow field and temperature field in the pulse tube, so the jet flow effect is not considered in the calculation. In order to analyze the influence of jet flow and hot-side flow straightener on the thermal performance of the PTC, it is necessary to analyze the flow field in the whole zone of the cold finger.

ANALYSIS OF THE JET FLOW

In order to analyze the influence of jet flow from the entrance of the inertance tube on the velocity field and temperature field in the pulse tube zone, a two-dimensional axisymmetric model was built using FLUENT [6] software, as shown in Figure 2. The modeled system included a cold finger, inertial tubes and a gas reservoir. The pressure boundary condition was adopted at the inlet of the heat exchanger at the hot side of the regenerator. The average pressure was 3.5 MPa, the fluctuation amplitude was 0.4 MPa, and the frequency was 50 Hz. 500 # stainless steel mesh was filled in the regenerator. Copper wire mesh is a common material to be stacked at the cold and hot ends of the pulse tube to perform the function of fluid diversion. When modeling, the cold end adopts 80 # copper wire mesh, and the hot end uses 80 # or 100 # copper wire mesh as the guide wire mesh. The thickness of the hot flow straightener is 5 mm. The parameters of the two meshes are shown in Table 2 [7].

As shown in Figure 3, if the hot-side flow straightener is not used, the impact of the jet flow can lead to higher velocity in the pulse tube. The mixing of cold and hot fluids will result in the failure to establish a large temperature gradient in the pulse tube, especially for the designed short size pulse tube. However, when a 5 mm thickness flow straightener is adopted, the jet flow is effectively restrained. As shown in Figure 4, the flow velocity inside the straightener zone is lower and the flow field is more uniform.

Table 2. Calculation parameters of the 80# /100# Cu mesh [7]

Mesh	80	100
Wire diameter /mm	0.15	0.18
Porosity	0.60	0.69
Viscous resistance /m^{-2}	7.435×10^{8}	1.94×10^{9}
Inertial resistance /m^{-1}	8.147×10^{3}	1.15×10^{4}

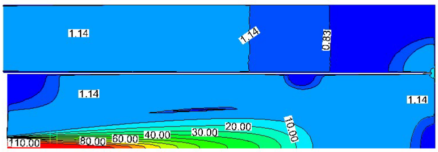

Figure 3. Influence of the jet flow on the velocity field inside the pulse tube without flow straightener

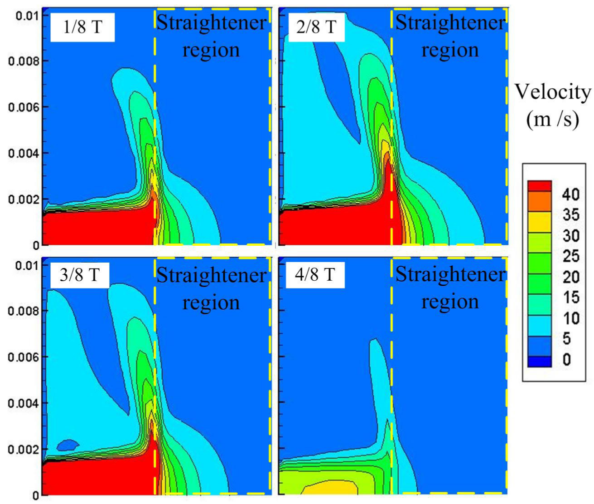

Figure 4. Effect of the hot-side flow straightener on the jet flow

Figure 5 shows the velocity distribution in the radial direction at the cold-end section, middle section and hot-end section of the pulse tube with 80 # or 100 # copper wire mesh flow straightener at the hot side of the pulse tube. It can be seen from the figure that compared with the middle and cold end of the pulse tube, the velocity at the hot end of the pulse tube is not uniform indicated by the higher velocity at the central point. In addition, the velocity for the 100 # case is lower than that of the 80 # case at the same location in the pulse tube zone. Therefore, it can be concluded from the calculation results that the 100 mesh is more effective than the 80 mesh in reducing the influence of jet flow on the pulse tube flow field.

Figure 6 shows the periodic variation of temperature field in the pulse tube with 100 # copper wire mesh. The temperature at the cold head is 170 K. It can be seen that the stability of the temperature field is determined by the stability of the flow field, especially when a large temperature gradient is established at a short distance. With a 100 mesh flow straightener, the flow field is more uniform and the refrigeration performance is better.

EXPERIMENTAL RESULTS

As shown in Figure 7, an experimental system was built to test the cooling performance of the developed cold finger. The input power of the compressor was 200 W, the charge pressure was

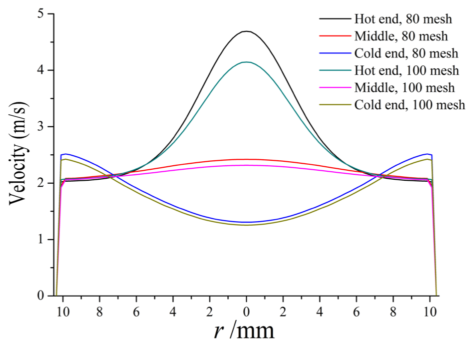

Figure 5. Velocity distribution in the pulse tube for 80/100 mesh straightener

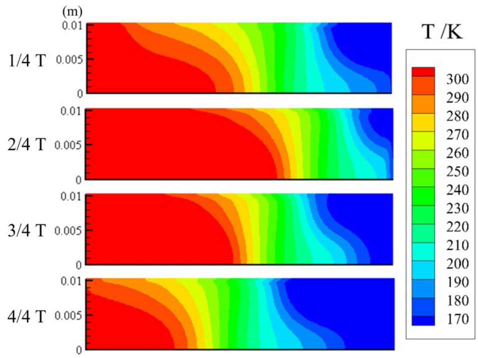

Figure 6. Periodic variation of the temperature field in the pulse tube

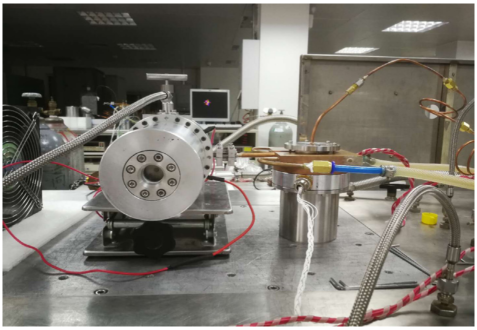

Figure 7. The experimental set-up of the PTC

3.5 MPa, the operation frequency was 50 Hz, and the reject temperature was 283 ± 1 K. Platinum resistance was used as the heater at the cold head, and PT100 column thermometer was used for temperature measurement. The length of the flow straightener was designed as 5 mm. Three kinds of copper wire mesh (80#, 100 #, 120 #) were chosen as the flow straightener filler. The cooling performance of the PTC is shown in Figure 8. It is clearly seen that when using the 100 # copper mesh at the hot side, the PTC achieves the highest cooling capacity compared with 80 # and 120 # copper mesh. The higher the mesh number, the better the diversion effect. However, the flow resistance also increases with the mesh number, which results in higher PV power loss at the hot end of the pulse tube. Therefore, using the 100 # copper mesh can achieve a balance between the flow diversion and

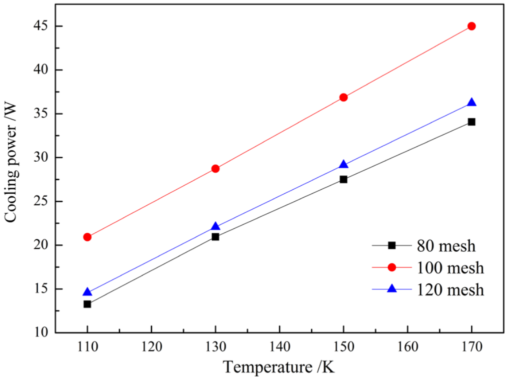

Figure 8. Cooling performance of PTC at different mesh number of the hot-side straightener

flow resistance. The lowest temperature can reach 59 K. The cooling capacity is 45 W at 170 K, and the work efficiency of the PTC is 22.5%.

CONCLUSIONS

A coaxial PTC which operates at 130 K-170 K is introduced in this paper. The cold finger has the characteristics of short and thick, which makes the hot-side flow straightener important for weakening the effect of jet flow on the velocity field inside the pulse tube. The influence of the copper wire mesh number of the hot-side flow straightener on the thermal performance of the PTC was theoretically and experimentally studied. The results show that using 100 # copper mesh as the filler of the flow straightener achieves a good flow guiding effect. With an input electric power of 200 W, the PTC achieves a cooling power of 45 W at 170 K, and the work efficiency of the PTC reaches 22.5%.

ACKNOWLEDGMENT

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