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Design and analysis of a pulse tube cryocooler for low temperature fridge

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Abstract. The low temperature fridge is used for doing some experiments and storing some special products at the temperature of $-80^{\circ}\text{C} \sim -150^{\circ}\text{C}$. Compared with the conventional cascade fridge, the pulse tube cryocooler has the advantages of reliability, compactness, green refrigerant and large range of temperature, which has been considered as an ideal cryocooler for low temperature fridge. In order to design a PTC used in the temperature range of $-80^{\circ}\text{C} \sim -150^{\circ}\text{C}$, a numerical model of coaxial PTC is built by using the SAGE. Based on this model, the influence of regenerator length and regenerator diameter on optimal cold-end temperature are analyzed and the key parameters of cold finger are optimized to promote the COP. A single-stage coaxial PTC has been manufactured and tested in our laboratory. And some experiments are conducted to promote the performance of PTC by optimizing the frequency, phase shifter and mesh. Finally, the performance of the coaxial PTC are presented at different electrical powers. This PTC typically provides a cooling power of 31 W at 160K with a corresponding electric power of 200W.

1. Introduction

The low temperature fridge is mainly used to provide cooling capacity at the temperature lower than -80°C for storing products in the field of medicine, science and pharmacology. The cascade fridges are widely used in the traditional low temperature fridges. However, the cascade fridges have complicated structures, large weight, big noise and low reliability. Compared with the cascade fridges, the pulse tube cryocoolers that are used in low temperature fridges have many advantages: compactness, light-weight, quiet, green refrigerant and long-life. Besides, the pulse tube cryocoolers choosing helium as its working gas, it can provide stable cooling power and realize temperature control at -200°C to -20°C [1-2]. Therefore, the pulse tube cryocoolers have big attraction in low temperature fridges. At present, only a few researches focus on the low temperature fridge using pulse tube cryocooler and the cooling efficiency of the PTCs are still low. In 2013, Liu et al [3] designed a coaxial PTC with the cooling power of 20W@170K and the electrical power was 140W. In 2014, NGAS [4] built a PTC operating at 290W input power which achieved 35W@150K corresponding to a specific cooling power at 150K



of 8.25W/W. In 2014, Wen et al. [5] designed a coaxial PTC for an aerospace low temperature fridge, which provided a cooling power larger than 30W at 160K with 250W input power.

The PTC is the cooling source of the low temperature fridge, therefore it is the core part of the low temperature fridge system. Generally speaking, the PTCs are mostly designed to provide cooling power at the temperature lower than 100K and the study about this temperature range are really mature. However, the research of the PTC on the cooling temperature during -200°C to -20°C is still insufficient. Thus, in this paper, we introduce a method to design a high efficiency PTC used for low temperature fridge. Firstly, for a more deep understanding of the high temperature PTC, an analytical model of PTC is built by SAGE software. Based on the model, the relationship between high temperature PTC and traditional low temperature PTC are analyzed, the length of regenerator also is optimized. Then, some experimental optimization on the phase shifter, operating frequency and input electrical power are presented. At last, the typical performance of the PTC is introduced.

2. Design of the PTC

The numerical simulation of the coaxial PTC is based on SAGE 10. The SAGE is a software designed by Gedeon Associates, the Pulse-tube Model Class of SAGE has been widely used by researchers to design PTCs [6-7].

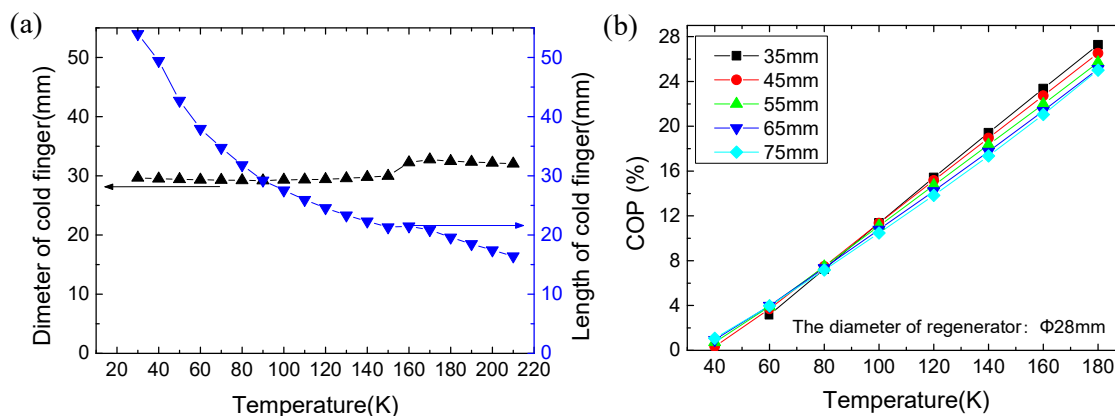


Figure 1. The simulation results of the optimal diameter and length of cold fingers at different cold end temperature (a) and the COP (cooling power/PV power) of PTC with different length of regenerators at different cold end temperature (b)

Based on this model, the diameter and length of cold fingers at different cold end temperatures are optimized. The analytical results are labelled in figure 1 (a). During the optimization, the phase shifter, mesh and the frequency are optimized together when the cold end temperature is determined, the input PV power is kept at 200W by adjusting the stroke of piston. As shown in figure 1 (a), it should be mentioned that the optimal diameter of cold finger almost remains constant at different cold end temperatures, but the length of cold finger decreases as the cold end temperature increases. It is because the PV power is same, the mass flow in the cold finger changes a little, thus the diameter of cold finger does not change a lot. As well known, the temperature distribution along the cold finger is nearly linear. When the cold end temperature increases, it is not necessary to keep a large temperature difference between hot end and cold end. Therefore, the optimal length of cold finger becomes shorter when the temperature increases. Based on these results and our previous coaxial PTC used at 80K [8], an analysis on the COP of PTC with different lengths of regenerator at different cold end temperature was carried out. As can be seen from figure 1 (b), the COP at the temperature lower than 80K decreases with the decreasing of length of regenerator, whereas, the COP at the temperature higher than 120K increases with the decreasing of length of regenerator, which illustrates that choosing short length regenerator will contribute to the performance of high temperature PTC.

3. Experimental optimization of the PTC

The schematic of the single-stage 60K coaxial PTC is shown in figure 2. The table 1 displays the key parameters of the high temperature PTC. The length of regenerator are chosen to be 35mm for a good cooling performance at the high temperature. The Diameter of regenerator is 28mm, just the same with the regenerator's diameter of the PTC used in 80K [8]. The phase shifter contains three-segmented inertance tubes and a gas reservoir, which is one type of the phase shifters that is simple, reliable and widely used in PTCs. The linear compressor is designed by our group working with two dual-opposed pistons and it has a maximum swept volume of 10cc.

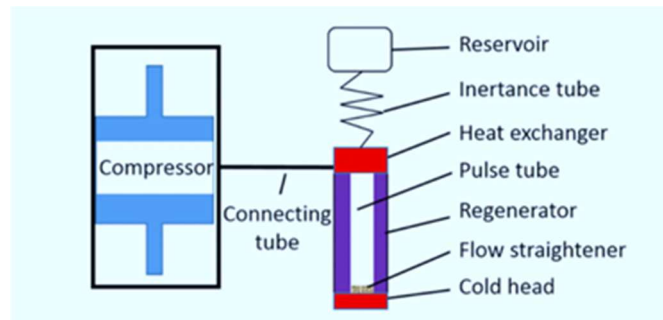


Figure 2. Schematic of the single-stage coaxial PTC

Table 1. Key parameters of the high temperature PTC

Parameters	Values
Length of REG	35mm
Diameter of REG	28mm
Mesh	#400Ǵ stainless steel screens
Connecting tube	100mm long and an inner diameter of 4mm
Maximum swept volume of compressor	10cc
Volume of gas reservoir	350cc

3.1. Experimental optimization of inertance tubes

The inertance tube is a slim tube, it can shift the phase between the mass flow and pressure wave in regenerator. An optimal phase relationship means that the phase of mass flow and pressure wave in the midpoint of the regenerator is very close. Usually the optimal phase relationship of one newly designed PTC can be obtained by adjusting the length of inertance tubes. Table 2 shows the parameters of different combinations of inertance tubes. The small diameter tubes are closer to the pulse tube.

Table 2. The combinations of inertance tubes (mm)

No.	Inertance tubes
Case 1	$\Phi 3 \times 1500 + \Phi 4 \times 500$
Case 2	$\Phi 3 \times 1000 + \Phi 4 \times 500$
Case 3	$\Phi 2 \times 500 + \Phi 3 \times 1000 + \Phi 4 \times 500$
Case 4	$\Phi 2 \times 500 + \Phi 3 \times 500 + \Phi 4 \times 500$
Case 5	$\Phi 2 \times 500 + \Phi 3 \times 1000$

Figure 3 gives the cooling performance of the PTC with different inertance tubes. It can be seen that the PTC with the inertance tubes of case 3 has the lowest no-load temperature and the biggest cooling capacity at every temperature. Therefore, case 3 is the best combination of inertance tubes, the corresponding optimal frequency is 64Hz.

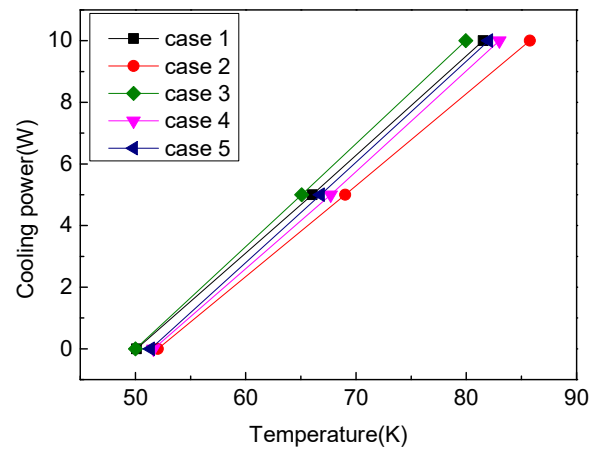


Figure 3. The cooling performance of the PTC with different inertance tubes

3.2. Experimental optimization of meshes

The meshes, the regenerative material, are filled into the regenerator. Generally speaking, the performance of regenerator is mainly determined by the heat capacity and the conduction loss of meshes, the heat exchange between helium gas and meshes and the pressure drop of the helium gas flow through the meshes. However, some of them are conflict. Therefore, in order to promote the performance of the PTC, the meshes are optimized in the experiments. The stainless steel screens is the most widely used mesh in regenerator of PTC, thus the #400, #500 and #600 stainless steel screens are chosen to optimize the performance of the PTC.

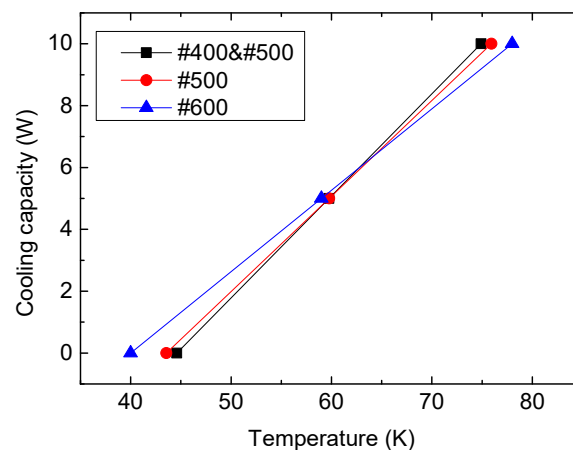


Figure 4. The cooling performance of the PTC with different meshes

Figure 4 displays the cooling performance of the PTC with different filling proportions of mixed meshes. As we can see from this figure, although the PTC with #600 meshes has the lowest no-load temperature, it has the lowest cooling capacity at higher temperature. For the reason that when the cold-end temperature is low, the #600 meshes has a better heat transfer between helium gas and meshes. While, when the cold-end temperature is high, the #600 meshes has smaller pore and causes a higher pressure drop in regenerator, which deteriorates the performance of PTC. Taken together, the PTC filling with #400Ǵ mixed meshes has a steeper line of cooling of about 3K/W, while the PTC filling with #600 meshes has a line of cooling of about 3.8K/W. Therefore, in the higher temperature region, the regenerator with #400Ǵ mixed meshes will make a very positive contribution to enhance the performance of PTC.

4. Experimental performance of the high temperature PTC

The cooling map of the PTC is measured for heat load of 10-30W with input electric power from 100W to 200W, as labeled in figure 5. The PTC reaches a maximum cooling power of 31W@160K with an electric power of 200W. It should be mentioned that the PTC can obtain a relative Carnot efficiency of 14.7% at 160K with an electrical power of 100W corresponding to a specific cooling power of 5.6W/W.

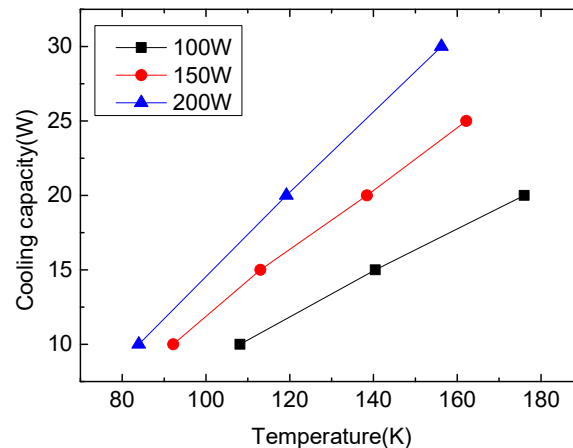


Figure 5. The cooling performance of the PTC at different electric power

5. Conclusions

In order to design a pulse tube cryocooler used for space low temperature fridge, we proposed a simple method to turn the traditional PTC into a high temperature PTC—shortening the length of regenerator. Some experiments were carried out, the results of experiments proved that this method was effective. Finally, we built a high temperature PTC, which had a cooling power of 17.7W at 160K with an input power of 100W at 293K reject temperature and it had a specific cooling power at 160K of 5.6W/W. The highest cooling capacity of 31W@160K can also be achieved when the corresponding input power of 200W were provided.

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Acknowledgement

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