Experimental study on a 20W/80K high frequency pulse tube cryocooler

Xuming Liu¹ ², Liubiao Chen¹ *, Xianlin Wu¹ ², Jue Wang¹ ², Yuan Zhou¹ ², Junjie Wang¹ ² *

¹ Chinese Academy of Sciences Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, China
² University of Chinese Academy of Sciences, China

Corresponding Author: chenliubiao@mail.ipc.ac.cn; wangjunjie@mail.ipc.ac.cn

Abstract. The cryocoolers working around the liquid nitrogen temperature have important applications in high temperature superconducting, infrared detectors and gas liquefaction. A cryocooler sometimes needs to work in different temperatures. For the high-frequency pulse tube cryocooler operating around the liquid hydrogen temperature, due to the limitation of the length of the regenerator, it is often impossible to simultaneously have higher performance around the liquid nitrogen temperature. Therefore, this paper enhances its performance around the liquid nitrogen temperature based on a high-frequency pulse tube cryocooler working around the liquid hydrogen temperature, by changing the effective length of the regenerator with filling different lengths of copper mesh. Firstly, the effect of filling different lengths and meshes of copper mesh on its 80 K refrigeration performance is simulated. Finally, the experimental verification is also carried out. Moreover, by further optimizing the phase modulation mechanism and operating parameters including working frequency and charge pressure, the cryocooler can provide 20 W cooling capacity at 78 K under the input electric power of 420 W. The relative Carnot efficiency is increased from the initial 9.8 % to 13.56 %.

1. Introduction

With the development and advancement of cryogenic technology, the cryocoolers working around liquid nitrogen temperature have important applications in high temperature superconducting, infrared device cooling, gas liquefaction and other fields [1]. Due to the absence of moving parts in the cold tip and higher energy flow density, the high-frequency pulse tube cryocooler has the advantages of low vibration and compact structure [2], attracting more and more attention. High-frequency pulse tube cryocoolers often adopt a single-stage structure around the liquid nitrogen temperature, and the technology is relatively mature. For example, Dai Wei and Wang Xiaotao developed a high-frequency pulse tube cryocooler, which can provide a 26.4 W cooling power at 80 K under 290 W electric power input, through the use of active phase modulation at the hot end of the pulse tube. The relative Carnot efficiency reached 24.2 % [3].

As the core component of the pulse tube cryocooler, the regenerator is not only a heat exchanger, but also realizes the function of work heat conversion, and therein its loss greatly affects the performance of the cryocooler [4]. In addition to the filling method of regenerator materials, the regenerator loss is also determined by the length of the regenerator. Specifically, lengthening the regenerator, which helps
to reduce the incomplete heat exchange loss between the regenerator materials and the working gas at lower temperature, is beneficial to obtain a lower cooling temperature. Shortening the regenerator, which helps to reduce the flow resistance loss of the working gas at higher temperature, is conducive to obtaining a larger cooling capacity. However, depending on actual application requirements, a cryocooler sometimes needs to work in different temperatures. For a high-frequency pulse tube cryocooler operating around the liquid hydrogen temperature, has often a longer regenerator. If it works around the liquid nitrogen temperature, its refrigeration performance will be limited due to its longer regenerator.

Therefore, this paper improves its refrigeration performance around the liquid nitrogen temperature, based on a high-frequency pulse tube cryocooler working around the liquid hydrogen temperature, with iner-tance tube and gas reservoir as the phase modulation structure, by shortening the effective length of the regenerator with filling different lengths of copper mesh. Firstly, the following is a numerical simulation analysis of the influence of filling different lengths and meshes of copper mesh on the 80 K cooling capacity of the refrigerator. Next, the experimental verification is also carried out.

2. Numerical simulation model
This paper uses SAGE as a simulation calculation tool. Compared with other tools, SAGE can simulate the whole system by inputting the operating conditions of the system and the structural parameters of each component. It can also consider the actual gas effect of the working gas and the actual loss of each component. Simultaneously, the compressor electric module can be added to the calculation model to better reflect the real working condition of the whole system.

However, because SAGE is only one-dimensional numerical calculation software, some components will be simplified during the simulation process, and a large number of empirical parameters are also used, the simulation results cannot be completely consistent with the experimental results. But for the design of the cryocoolers and the qualitative explanation of some experimental phenomena, SAGE is still the best simulation tool. Figure 1 shows the diagram of the program calculation, and Figure 2 shows the structure of the cryocooler.

![Figure 1. Numerical calculation diagram.](image-url)
3. Simulation results and discussion

Base on the existing liquid hydrogen temperature zone cryocooler, a numerical calculation model is built. The regenerator is initially filled with 400 # stainless steel wire mesh. The effective length of different inherent length regenerator is changed by additionally filling different lengths and meshes of the copper mesh, then exploring its influence on the 80 K cooling power of the system. The rhombic and grey curve in Fig. 3 indicates that the length of the regenerator is directly changed without filling copper mesh. The square, circular and triangular curves indicate that the inherent length of the regenerator is 120 mm, 90 mm, 60 mm, respectively. The solid, hollow and half-and-half curves indicate that the filled copper mesh is 80 #, 200 #, 400 #, respectively. The abscissa indicates the filling length of the stainless steel wire mesh, that is, the effective length of the regenerator, and the inherent length of the regenerator minus the filling length of the stainless steel wire mesh is the filling length of the copper mesh. It can be seen from the rhombic and grey curve that under the corresponding working conditions, when the length of the regenerator is 55 mm, the system performance is optimal, and a 20.55 W cooling power can be obtained at 80 K. When the inherent length of the regenerator is 120 mm, which has seriously deviated from the optimal value, the corresponding cooling capacity is only 9.64 W. By filling 50 mm 400 # stainless steel mesh and 70 mm 80 # copper mesh, the cooling capacity can be increased to 13.44 W. When the inherent length of the regenerator is 90 mm, the corresponding cooling capacity is 15.49 W. By filling a 40 mm 400 # stainless steel wire mesh and 50 mm 200 # copper mesh, the cooling capacity can be increased to 17.83 W. When the inherent length of the regenerator is 60 mm, which is almost the same with the optimal length, filling the copper mesh is not conducive to the improvement of system performance. Therefore, the filling of the copper mesh can help improve its performance when the cryocooler works around the liquid nitrogen temperature with a relatively longer regenerator. Specifically, when the regenerator is much longer than the optimal value, filling the copper mesh with low mesh, or when the regenerator is slightly longer, filling the copper mesh with high mesh, both cases can better improve the performance around the liquid nitrogen temperature. This is because when the regenerator is too long, the high mesh is likely to generate a larger resistance loss, and when the regenerator is slightly longer, the low mesh is likely to easily generate a larger empty volume, which are both not conducive to the improvement of system performance. It is worth noting that the impedance distribution characteristics of the system after filling the copper mesh are changed, and the system performance can be further improved by optimizing the phase modulation mechanism and operating conditions.
4. Experimental verifications

Figure 4 shows a physical photograph of the liquid hydrogen temperature zone cryocooler. The regenerator has an inherent length of 90 mm, with 400 # stainless steel wire mesh filling. Under 2.5 MPa charge pressure, 30 Hz operating frequency, a no-load temperature of 23.6 K is obtained. With 400 W electric power input, the cryocooler prototype can only provide a 13.9 W cooling capacity at 80 K. From the above numerical analysis, it can be seen that for the regenerator with an inherent length of 90 mm, by filling the 40 mm 400 # stainless steel wire mesh and the 50 mm 200 # copper mesh, the 80 K refrigeration performance can reach optimal. Moreover, by filling 60 mm 400 # stainless steel wire mesh and 30 mm 80 # copper mesh, the system still achieves a good cooling performance at 80 K. Therefore, the experimental process was only verified and analyzed in the following four cases, as shown in Table 1. During the experiment, the operating temperature was tested with a calibrated Rhodium-iron thermometer with an accuracy of ±0.1 K in the temperature range of 1.3 K to 295 K. The cooling capacity was tested by electric heating with an accuracy of ±1 mW.

Figure 4. Physical photo of the cryocooler prototype.
Table 1.

| Case | 400 # SS mesh filling length / mm | 80 # copper mesh filling length / mm |
|------|-----------------------------------|-------------------------------------|
| 1    | 90                                | 0                                   |
| 2    | 80                                | 10                                  |
| 3    | 70                                | 20                                  |
| 4    | 60                                | 30                                  |

It can be seen from Fig. 5 that when the 90 mm regenerator is fully filled with 400 # stainless steel wire mesh, although the no-load temperature of 23.6 K is obtained by optimizing the inertance tube and operating conditions, the cryocooler can only provide cooling capacity of 13.9 W at 80 K with 400 W electric power input. Under keeping length and diameter of the inertance tube as well as operating conditions unchanged, the effective length of the regenerator is shortened to 80 mm by filling 10 mm copper mesh, and the 80 K cooling capacity with 400 W electric power input is increased to 14.9 W. When filling 20 mm copper mesh and 70 mm stainless steel mesh, the corresponding cooling capacity is increased to 15.13 W. Finally, the effective length of the regenerator is shortened to 60 mm, that is, the copper mesh of 30 mm 80 # and the stainless steel mesh of 60 mm 400 # are simultaneously filled. Under the input of 400 W electric power, the 80 K cooling capacity of the cryocooler is increased to 15.81 W. In addition, it can be seen from the figure 5 that the variation trend of experimental values under different filling modes are basically consistent with that of simulated values.

Figure 5. Cooling capacity of the developed prototype working at 80K under different filling modes.

As mentioned above, the changes of the operating temperature and the effective length of the regenerator will affect the impedance distribution characteristics of the whole system. Therefore, inertance tubes and operating conditions need to be optimized again. In the case of filling 30 mm copper mesh and 60 mm stainless steel wire mesh in the regenerator, the system performance is further improved by re-optimizing lengths and diameters of inertance tubes as well as operating conditions, including frequency and charge pressure. It can be seen from Fig. 6 that under the input of 220 W electric power, the cryocooler can provide 10 W cooling capacity at 78 K, or under 420 W electric power input, it can provide a 20 W/78 K cooling capacity. Compared with the initial cooling capacity of 13.9 W at 80 K, the system's relative Carnot efficiency increased from 9.8 % to 13.56 %.
5. Conclusions

Based on a single-stage high-frequency pulse tube cryocooler operating around the liquid hydrogen temperature, by filling different lengths of copper mesh in the regenerator to reduce its effective length, the refrigeration performance of the cryocooler operating around the liquid nitrogen temperature is improved. Firstly, the influence of filling different lengths and meshes of copper mesh on the performance of the system with different inherent length regenerator is analyzed in numerical calculation. Finally, the verification experiment is also carried out. Under the optimal working condition, the initial cryocooler can only provide 13.9 W cooling capacity at 80 K with 400 W electric power input, and the relative Carnot efficiency is only 9.8 %. By filling 30 mm 80 # copper mesh in the regenerator, the effective length of the regenerator is reduced from the initial 90 mm to 60 mm. Under 420 W electric power input, the optimized cryocooler can provide 20 W cooling capacity at 78 K, and the relative Carnot efficiency is increased to 13.56 %.

6. References

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