Design of a two-stage gas-coupled high-frequency pulse tube cryocooler working around 4 K

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Abstract. High-frequency pulse tube cryocooler have unique advantages for aerospace and ground applications. However, it is difficult to obtain lower cooling temperature: to obtain the liquid helium temperature, three-stage or four-stage structure by thermal coupling are currently used. In order to further improve the compactness, a two-stage gas-coupled high-frequency multi-bypass coaxial pulse tube cryocooler has been designed. The simulation results indicate that the designed cryocooler can provide a cooling capacity of 25 mW@4.2 K with 416 W input electrical work. The interaction between structural parameters and operating conditions, as well as some preliminary test results will be presented in this paper.

1. Introduction

With the development and advancement of cryogenic technology, the liquid helium temperature zone has become a prerequisite for the operation of many advanced scientific instruments and equipment. In recent years, in the fields of space detection, low-temperature superconductivity, cryogenic biology and medicine [1], there has been a strong demand for small cryogenic cryocoolers working around liquid helium temperature. Moreover, the liquid helium temperature zone is not only the working temperature zone of many instruments and equipment in the above-mentioned fields, but also some cryocoolers working below liquid helium temperature [2], such as throttling, dilution and adiabatic demagnetization refrigerators, also require liquid helium temperature zone cryocoolers to provide pre-cooling. The high-frequency pulse tube cryocooler without moving parts in cold tip and with higher energy flow density, has many advantages such as low vibration, stable operation and compact structure, especially suitable for the development of the space field, and has become a research hot spot in the cryogenic field [3].

Pulse tube cryocoolers tend to cause larger regenerator losses when the operating frequency is higher, and it is difficult to obtain lower temperatures due to real gas effects, low matrix heat capacity and difficulties of phase shifting with a small acoustic power [4]. In order to obtain the liquid helium temperature, the high-frequency pulse tube cryocooler often adopts a complicated thermal-coupled structure [5], that is, using an additional refrigerator or cryogenic liquid to pre-cool the regenerator or phase modulation mechanism of the high-frequency pulse tube cryocooler. The more pre-cooling stages are, the more it is helpful to get lower temperatures. However, the thermal-coupled multi-stage structures inevitably require the use of thermal bridges, so that the heat transfer loss is inevitable and the cooling efficiency will be also reduced.
Compared with thermal-coupled structure, the gas-coupled high-frequency pulse tube cryocooler adjusts the temperature distribution and working ability of each stage by directly adjusting the gas distribution between the stages, without additional cryocoolers or cryogenic liquid pre-cooling, without additional thermal bridge connection, with a more compact structure. Therefore, the gas-coupled high-frequency pulse tube cryocooler is more suitable for the demand for lightweight devices in more and more fields. Designing a gas-coupled high-frequency pulse tube cryocooler which can operate around 4 K, is significant for space and ground applications.

Therefore, this paper designs a two-stage gas-coupled high-frequency multi-bypass coaxial pulse tube cryocooler operating around 4 K based on the professional numerical simulation software SAGE. Firstly, the influence of phase modulation mechanisms and operating conditions on the refrigeration performance of the model is numerically analyzed. Then, some preliminary experiments are also carried out.

2. Numerical simulation model
This paper uses SAGE as a simulation calculation tool. Compared to other softwares, SAGE has a visual interface, which can be used to model each component of the cryocooler, including geometry parameters and materials. Each component is connected by mass flow, pressure wave and energy flow, and then the simulation of the whole system is realized by inputting operating parameters. In addition, a large number of empirical parameters are used in the calculation process, and various actual losses such as the actual gas effect of the working gas at low temperature and radiation heat leakage can also be considered. Therefore, it has strong guidance for the design and experiment of the cryocooler.

However, SAGE is only a one-dimensional numerical calculation software. A large number of empirical formulas are also used in the calculation process, most of which come from stable flow. In order to satisfy alternating flow of the working gas, some correction factors are added, so there is a certain error in the calculation accuracy. In addition, some components are simplified during the modeling process, such as simplifying a spiral inertance tube into a straight tube, directly ignoring its inductive reactance. These all have an impact on the accuracy of the calculation. Therefore, the simulation results cannot be completely consistent with the experimental results. But for the design and experiment of the cryocooler, SAGE is still the best simulation tool. Figure 1 shows the structure of the designed cryocooler.

![Figure 1](image)

**Figure 1.** Schematic of the designed cryocooler, (Reg: regenerator, PT: pulse tube, IT: inertance tube, Res: reservoir, T₁: temperature of first-stage cold end, Tᵐ: temperature of multi-bypass, T₂: temperature of second-stage cold end).

3. Simulation results and discussion

3.1 Effects of structural parameters on refrigeration performance
It can be seen from Figure 2 that the length of first-stage and second-stage inertance tubes has different effects on the refrigeration performance of two stages. It can be seen from Fig. 2(a) that when the length of first-stage inertance tube increases from 1 m to 2 m, under 3 MPa charge pressure, 27 Hz operating
frequency and 6 A current amplitude input, the temperature of first-stage cold head is reduced from 122.1 K to 109.5 K, while the temperature of second-stage cold head first decreases and then increases. When the length of the first-stage inerter tube is 1.4 m, $T_2$ is reduced to a minimum of 3.26 K. It can be seen from Fig. 2(b) that under the same working conditions, as the second-stage inerter tube increases from 0.75 m to 0.9 m, $T_2$ and $T_1$ are both monotonously decreasing. Specifically, the no-load temperature of $T_2$ is reduced from 4.68 K to 3.26 K, and the temperature of $T_1$ is reduced from 115.4 K to 113.4 K. Generally, despite reducing $T_1$ by about 13 K, the length change of the first-stage inerter tube has a small influence on $T_2$ due to the existence of multi-bypass, the change of which in the whole calculation range does not exceed 0.17 K. The length change of the second-stage inerter tube is beneficial to lower the temperature of the second-stage cold head. In the variation range of 0.15 m, $T_2$ is reduced by about 1.4 K.

![Figure 2](image)

**Figure 2.** The variations of refrigeration temperature with different lengths of inerter tubes.

It can be seen from Fig. 3 that the change of multi-bypass opening has a great influence on the performance of two stages, but the specific influence is also different. Specifically, keeping the first-stage and second-stage inerter tube lengths of 1.4 m and 0.9 m respectively, when the multi-bypass opening is increased from 0.6 mm$^2$ to 1.8 mm$^2$, $T_2$ is reduced from 13.52 K to 3.26 K, and $T_1$ is increased from 105.9 K to 113.4 K. We analysed the working mechanism of multi-bypass in the previous article. When the multi-bypass opening is small, its working mechanism is similar to that of double-inlet, which can improve the phase distribution; when the multi-bypass opening is large, its working mechanism is similar to the multi-stage gas-coupled structure, which can further reduce the cooling temperature of the coldest-stage.
3.2 Effects of operating parameters on refrigeration performance

It can be seen from Fig. 4 that keeping the multi-bypass opening 1.8 mm², when the operating frequency is near 26 Hz, T₂ is reduced to a minimum of 3.44 K. As the frequency rises from 23 Hz to 27 Hz, T₁ decreases monotonically from 124.7 K to 111.7 K. There are different optimal operating frequencies in first-stage and second-stage. This also reflects that it is difficult for the gas-coupled high-frequency pulse tube cryocooler to make each stage simultaneously work at the optimal state. Similar conclusions can be also drawn from Figure 5. Under 23 Hz operating frequency, when the input current amplitude increases from 5 A to 7 A, the corresponding input electric power increases from 220 W to 440 W, T₂ decreases from 5.14 K to 4.43 K, while T₁ decreases first and then increases, and the lowest value of 123.7 K is obtained near 380 W. It also shows that there is different optimal input power in first-stage and second-stage.

Figure 4. The variations of refrigeration temperature with operating frequency.

It can be seen from Fig. 6(a) that by optimization, under 416 W input electric power, 3 MPa charge pressure and 26.5 Hz frequency, keeping the lengths of first-stage and second-stage inerter tubes 1.5 m and 0.94 m respectively, as well as multi-bypass opening 1.81 mm², the system obtains the optimal cooling performance, the no-load temperature of T₂ is reduced to 3.10 K, and the cooling capacity of 25 mW is provided at 4.2 K, or 50 mW is provided at 5.2 K. At the same time, the temperature of T₁ is basically stable at 113 K. It can be seen from Fig. 6(b) that when the first-stage cold head outputs 1.5 W of cooling capacity, the temperature of T₁ increases from the initial 113 K to 120 K, and the temperature of T₂ remains stable at 3.1 K. In other words, when the first-stage cold head outputs a certain amount of cooling, it has little effect on the performance of the second stage. As mentioned above, the multi-bypass has similar multi-stage gas-coupled working mechanism at a certain opening, and when the temperature of second-stage hot end rises (the temperature of T₁ increases from 113 K to 120 K), the working gas at
multi-bypass produces a cooling effect, causing the temperature in the middle of second-stage regenerator does not rise too much (the temperature of $T_m$ increases from 39.3 K to 42.2 K), so that $T_2$ is not significantly deteriorated, as shown in Fig.6(c) and (d).

![Figure 5. The variations of refrigeration temperature with input electric power.](image)

![Figure 6. Mutual influence of temperatures between two stages of the designed cryocooler.](image)

4. Experimental verifications
Based on the numerical calculation model, a two-stage gas-coupled high-frequency pulse tube cryocooler prototype is built. The physical photo is shown in Figure 7, and related verification
experiments are carried out. 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.

![Physical photo of the developed cryocooler prototype.](image1)

**Figure 7.** Physical photo of the developed cryocooler prototype.

![Cooling time of the developed cryocooler prototype.](image2)

**Figure 8.** Cooling time of the developed cryocooler prototype.

![Temperature of second-stage cold head under different operating frequency.](image3)

**Figure 9.** Temperature of second-stage cold head under different operating frequency.

It can be seen from Fig. 8 that with 6A input current amplitude (about 405 W input electric power), 27 Hz operating frequency, and 3 MPa charge pressure, the no-load temperature of second-stage cold
head drops 8.25 K. At the same time, the corresponding first-stage cold head temperature is stable around 160 K. Moreover, it can be seen from Fig. 9 that with 26 Hz operating frequency, the temperature of second-stage cold head is further reduced to 8.21 K.

5. Conclusion
Based on the SAGE simulation software, this paper designs a two-stage gas-coupled high-frequency pulse tube cryocooler operating around 4 K. By optimization of the phase modulation mechanism and operating conditions, the model obtains a no-load temperature of 3.10 K. With 416 W input electric power, it can provide 25 mW cooling capacity at 4.2 K or 50 mW cooling capacity at 5.2 K. Then, an experimental prototype is developed. Through preliminary experiments, a no-load temperature of 8.21 K is obtained with 405 W electric power input.

6. References
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