Numerical study of a VM type multi-bypass pulse tube cryocooler operating at 4K

Changzhao Pan¹, Tong Zhang¹,², Jue Wang¹,², Liubiao Chen¹, Chen Cui¹, Junjie Wang¹,², Yuan Zhou¹

1 CAS Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Beijing, 100049, China
2 University of Chinese Academy of Sciences, Beijing, 100049, China

zhouyuan@mail.ipc.ac.cn

Abstract. VM cryocooler is one kind of Stirling type cryocooler working at low frequency. At present, we have obtained the liquid helium temperature by using a two-stage VM/pulse tube hybrid cryocooler. As a new kind of 4K cryocooler, there are many aspects need to be studied and optimized in detail. In order to reducing the vibration and improving the stability of this cryocooler, a pulse tube cryocooler was designed to get rid of the displacer in the first stage. This paper presents a detail numerical investigation on this pulse tube cryocooler by using the SAGE software. The low temperature phase shifters were adopted in this cryocooler, which were low temperature gas reservoir, low temperature double-inlet and multi-bypass. After optimizing, the structure parameters and the best diameters of orifice, multi-bypass and double-inlet were obtained. With the pressure ratio of about 1.6 and operating frequency 2Hz, this cryocooler could supply above 40mW cooling power at 4.2K, and the total input power needs no more than 60W at 77K. Based on the highest efficiency of 77K high capacity cryocooler, the overall efficiency of this VM type pulse tube cryocooler is above 0.5% relative Carnot efficient.

1. Introduction

Small scale and high efficiency 4 K cryocooler has many important applications in fields of superconductive electronics, aerospace exploration, medical science and etc. GM cryocooler and GM type pulse tube cryocooler (GPTC) are the only commercial 4K cryocooler, but the efficiency of this type cryocooler is relatively low due to the low efficiency of its GM compressor. The large bulk and oil filtering system of the GM compressor also limit its applications in many fields. In recent years multi-stage 4K Stirling pulse tube cryocooler (SPTC) [1] [2] [3] develops rapitly because of its compact, long-life, and low vibrations. This type of cryocooler is driven by the linear compressor which normally works at the frequency above 20Hz. However, the rare earth material, such as Er₃Ni and HoCu₂, need to be used to increase the volume heat capacity of regenerator below 10 K. Due to mechanical reasons, this type material is difficult to be processed into screen meshes and the shape of sphere is always used. Compared with the low frequency cryocooler, the high frequency oscillating flow would result in a higher pressure drop in regenerator and lower efficiency of regenerator. Therefore, it is necessary to develop the high efficiency 4K SPTC operating at low frequency.
Vuilleumier (VM) cryocooler is one kind of closed-cycle Stirling type cryocooler driven by a thermal compressor. VM cryocooler normally works at low frequency, so it has potential for working with high efficiency at 4K. Combining thermal compressor with the pulse tube, it would to be a new type of high efficiency, compact, long-life, low vibration VM type 4K cryocooler (VM-PTC). Dai et al. [4] have introduced the concept of VM-PTC and built a this type cryocooler, which obtained the lowest temperature of 3.5 K by using 77 K and 20 K pre-coolers. This work also demonstrated its capacity of obtaining liquid helium temperature. Matsubara et al. [5] also presented the concept of thermally actuated He-3 PTC. In his cryocooler, the TCP worked between the temperatures of 300 K and 40 K. Nowadays, Wang et al. [6] developed a 15 K single-stage VM-PTC by using an 80 K Stirling type PTC as pre-cooler.

In our previous works [7] [8], a VM/PT hybrid cryocooler has been built and successfully obtained the temperature below 4K. In order to reducing the vibration and improve the stability of this cryocooler, a pulse tube cryocooler was designed to get rid of the displacer in the first stage. This paper built a numerical model of VM-PTC by using the SAGE software. The double-inlet, multi-bypass and cold gas reservoir were used as its phase relationship shifter. After optimizing, this cryocooler could supply above 40mW cooling power at 4.2K, and the total input power needs no more than 60W at 77K.

2. Physical and mathematical model

Table 1 System configuration parameters

|                  | Thermal compressor | Pulse tube                  |
|------------------|--------------------|-----------------------------|
| Diameter         | 95mm               | D=12.5mm, L=100mm           |
| Stroke           | 20mm               | D=8.9mm, L=80mm             |
| 300K heat exchanger | D=5mm, L=200mm         | D_{in}=12.5mm, D_{out}=20mm |
| 77K heat exchanger | D=3mm, L=200mm         | Regenerator I               |
|                  | D_{in}=26mm, D_{out}=44mm | 40mm 200# SS screen         |
| Regenerator      | 80# SS screen      | 50mm 0.4–0.45mm lead sphere |
|                  | L=120mm            | D_{in}=8.9mm, D_{out}=18mm   |

2.1. Physical model

Figure 1 showed the schematic diagram of VM-PTC. It mainly contains a thermal compressor and a multi-bypass pulse tube. The displacer moves back and forth in the cylinder of thermal compressor to
generate a pressure wave. To obtain the liquid helium temperature, a multi-bypass configuration was adopted in this VM-PTC. The multi-bypass was invented by Zhou et al [9] and has been experimentally proven to be effective way to improve the performance of PTC. Figure 1 also shows the structure diagram of multi-bypass. For practical reasons, the coaxial arrangement is adopted in our design.

In our design, the orifice, cold gas reservoir and cold double-inlet were used as the phase relationship shifters of PTC. The phase shifters of PTC and cold cavity of thermal compressor were located at low temperature 77K. For the regenerators of PTC, the layered structure was adopted. The Stainless Steel Screen was used at the 77K end, and the lead sphere, Er₃Ni, and HoCu₂ were used at the cold end. The detail structural parameters are listed in the Table 1.

![Fig. 2 Numerical model of VM-PTC in the SAGE software](image)

2.2. Mathematical model

The numerical simulation was conducted by using SAGE software, a 1D simulation program based on thermal and fluid dynamic equations [10]. The software provides a series of modules to simulate different components of cryocooler. All the modules are connected by energy flow, mass flow and pressure wave. So it is convenient to connect different modules to build different cryocoolers. Besides, this software also has a function of optimization. The structural parameters could be optimized automatically.

Figure 2 showed the numerical model in the SAGE software. The radial heat transfer of pulse tube and regenerator was considered to simulate the coaxial structure PTC. The double-inlet, multi-bypass and the orifice were calculated by using the module of capillary tube. The double-inlet, orifice and gas reservoir kept at the constant temperature 77K. The cold end kept at the temperature 4.2 to calculate its cooling power.

3. Simulation results and discussion

3.1. Double-inlet working at low frequency

Figure 3 showed the pressure ratio of cold end and the PV power in the middle cavity changed with the opening of double-inlet. With the opening of double-inlet, the pressure ratio of cold end would be increased, and the PV power in the middle cavity would be decreased. This showed that the double-inlet will increase the cooling capacity of cold end and decrease the power consumption. An appropriate double-inlet would increase the efficiency of the cryocooler.
Figure 4 showed the cooling power of cold end (at 4.2K) changing with the opening of double-inlet. With the increasing of the diameter of double-inlet, the cooling capability of cold end would increase and then the cooling power would increase. But with the opening of double-inlet, the DC flow rate will increase at the same time. The DC flow will directly flow through the regenerator, which will add the thermal loss in the regenerator. So when the double-inlet opened too large, the cooling power will decrease because of the DC flow. Figure 4 also showed the influence of multi-bypass on the cooling power. With the different multi-bypass, there is a corresponding optimal double-inlet. For this case, the optimal multi-bypass is about 0.4mm, and the corresponding optimal double-inlet is about 0.95mm. The cooling power is about 42mW@4.2K at this condition.

Figure 5 showed the influence of double-inlet on the T1 and DC flow. With opening of double-inlet, the DC flow rate will increase, which has been discussed in the last paragraph. The double-inlet will make the T1 decrease at first. When the DC flow rate is too large, the T1 will increase then.
3.2. Acoustic power and thermal efficiency

Figure 6 showed the distribution of acoustic power in the regenerator and pulse tube. The axial structure was adopted in the simulation, so the direction of regenerator and pulse tube were opposite. The negative acoustic power in the pulse tube meant its direction was negative. The acoustic power was about 13W at inlet of regenerator. It was consumed about 7W in the regenerator I. Through the multi-bypass, a little acoustic power flowed into pulse tube. At the inlet of regenerator II, the acoustic power was about 5W, and it was consumed about 4W in the regenerator II. The pulse tube barely consumed the acoustic power because the pressure drop in the pulse tube was very small. At the hot end of pulse tube, the acoustic power increased sharply because of the double-inlet. There was about 1W acoustic power flow through the double-inlet and consumed in the orifice.

For this case, the largest cooling power at 4.2K was about 42mW. The PV power consumption in the middle cavity was about 25W. And the heat loss (including the shutter loss, heat conduction loss leakage gas loss and et al.) was about 35W. So the total heat consumption at 77K was about 60W. According to the highest efficiency 77K cryocooler, its relative Carnot efficiency is above 28\%\textsuperscript{[11]}\textsuperscript{[11]}. Its input power could keep below 600W to supply 60W cooling power at 77K. So the overall efficiency of this VM type pulse tube cryocooler is above 0.5\% relative Carnot efficient.
4. Preliminary experimental result

Based on the simulation result, the experiment system has been built. Figure 7 showed the preliminary result of this VM type pulse tube cryocooler. At present, the opening of multi-bypass was 0.38mm, and the opening of double-inlet was 0.75mm. The lowest temperature of cold end was 6.1K; the temperature of multi-bypass was 48.9K. The operating frequency was 2Hz, and the average pressure was 1.8MPa. The multi-bypass and double-inlet should be optimized in the next works.

5. Conclusion

This paper studied a new type 4K cryocooler, VM type multi-bypass pulse tube cryocooler, by using numerical method. By using the optimization function of Sage software, the structure parameter of this cryocooler was obtained. The influence of double-inlet on the pressure ratio, PV work consumption, cooling power and DC flow rate was studied. The acoustic power and thermal efficiency of this cryocooler was also analyzed. At last, an experiment based on the simulation results was built, and a preliminary temperature 6.1K was obtained.

Acknowledgments

This work was supported by the National Postdoctoral Program for Innovative Talents (Foundation No. BX201600173).

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