Numerical study of a novel single-stage Vuilleumier type pulse tube cryocooler

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1. Introduction

The Vuilleumier cryocooler (VMC) is a novel kind of Stirling cryocooler driven by thermal compressor. To realize no moving parts at the cold end of VMC, this paper presents a study of the single stage Vuilleumier-type pulse tube (VM-PTC) cryocooler driven by thermal compressor. First, the structure and numerical model of VM-PTC are introduced. Then, the operating mechanism and performance of cold phase shifter including capillary tubes and double-inlets are studied. At last, a preliminary experiment is carried out to know about the practical performance of the single-stage VM-PTC. It can obtained no-load temperature of 12.1 K and 0.7 W cooling power at 20 K by using 46 W precooling power at 77 K.
compressor at 77 K [9]. Until now, their system can already obtain the lowest temperature below 6 K [10]. Pan et al. studied the multi-bypass type VM-PTC recent and successfully obtained 4.9 K [11].

In this paper, a VM-PTC driven by a thermal compressor is studied numerically and experimentally. The detailed introduction of single-stage VM-PTC’s structure and working principle and a numerical study of cold phase shifter of VM-PTC are all presented. From the numerical results, the VM-PTC can show similar relative Carnot efficiency with the VMC reported in reference [4]. At last, a preliminary experiment of VM-PTC precooled by a GM cryocooler at 77 K is presented, and under the precooling power of 46 W at 77 K, the VM-PTC could obtain the lowest temperature of 12.1 K and the cooling power of 0.7 W@20 K.

2. Physical parameters and simulation models
The schematic structure of the single-stage VM-PTC is showed in Figure 1. The thermal compressor is driven by crank case, and mainly uses the temperature difference between the ambient temperature and 77 K to generate pressure wave and acoustic power for the pulse tube cryocooler. The diameter and stroke of displacer in thermal compressor are 95 mm and 20 mm respectively. The regenerator is filled with 200 mesh steel screen, lead sphere (0.4-0.45 mm) and Er3Ni sphere (0.2-0.25 mm) from the hot end to cold end. The length of each segment is 40 mm. The outer diameters of the regenerator and the pulse tube are 26.4 mm and 11.7 mm respectively. The phase shifter is composed of a capillary tube and a gas reservoir. The cold phase shifter means the capillary tube and gas reservoir work around 77 K.

![Figure 1](image1.jpg)

**Figure 1** The schematic diagram of the single-stage VM-PTC

![Figure 2](image2.jpg)

**Figure 2** The numerical model of VM-PTC by sage software
The numerical model of the single-stage VM-PTC made by Sage software is shown in Figure 2. The numerical model mainly contains three parts, the thermal compressor, the pulse tube cryocooler and the cold phase shifter. The hot end and the cold end of the thermal compressor are kept at 300 K and 77 K respectively. The working frequency and mean pressure are 2 Hz and 1.4 MPa respectively.

3. Numerical study of the cold shifter of VM-PTC

3.1. Capillary tube in VM-PTC

The capillary tube is the basic phase shifter in VM-PTC. As the numerical results shown in Figure 3(a), the acoustic power into the regenerator will decrease if the length of capillary tube increases. This is mainly because the mass flow rate into regenerator will decrease and the phase angle of volume flow rate at the regenerator’s cold end will be more ahead of the phase angle of pressure wave. However, as the capillary grows longer, the pressure ratio in pulse tube grows higher. Figure 3(b) shows the phase angle at the inlet and the outlet of the regenerator and the pulse tube respectively. The inlet and outlet phase angle of the regenerator are 54.52 and 39.56 degrees while the inlet and outlet phase angle of the pulse tube are 34.96 and 2.35 degrees. It can be inferred that the combination of capillary tube and reservoir is more similar to the orifice and reservoir, no obvious inertial effect.

Figure 3 The impact of capillary tube on inner process
(a) The influence of capillary tube’s length on acoustic power and pressure ratio
(b) The P-U phase angle distribution in VM-PTC

Figure 4 The influence of capillary tube geometry on cooling power at 20 K
As can be seen in Figure 4, as the inner diameter of capillary tube grows from 0.9 mm to 1.2 mm, the optimal length of the 1.2 mm capillary tube grow 3 times longer than 0.9 mm capillary tube. This phenomenon indicates that the optimal capillary length is very sensitive to the inner diameter of the capillary tube. Also, at the optimal length, the thinner tube diameter could adjust the VM-PTC to provide larger cooling power when only capillary tube and reservoir are applied in VM-PTC.

3.2. Double inlet in VM-PTC

The function of double inlet in VM-PTC is shown in Figure 5(a). The phase angle at the regenerator’s cold end becomes smaller as the double inlet opening grows bigger, which proves that the double inlet can play the role of adjusting the phase angle. Also, the pressure ratio in pulse tube will becoming larger with larger double inlet opening. The DC flow rate in the regenerator increases sharply with the increasing of the double inlet opening, which will impact the cooling performance negatively.

Figure 5 The influence of double inlet opening VM-PTC
(a) The influence of double inlet opening on phase angle and DC flow
(b) The influence of double inlet on the cooling power at 20K

Figure 5(b) shows the influence of the double inlet on the cooling power at 20 K. Using the double inlet can improve the cooling power at 20 K. The geometries of the four capillary tubes in Figure 5(b) are the optimal length of diameters from 0.9 to 1.2 mm respectively. At the optimal combination of capillary tube and double inlet, the VM-PTC can provide cooling power about 1.6 W at 20 K, and the relative Carnot efficiency is about 3 %, which is similar to the result in reference [7]. It can be inferred that the VM-PTC can get it maximum performance when and double inlet is optimized under a certain capillary tube. So, the double inlet is imperative to be used in the VM-PTC.

4. Preliminary experimental result

Refer to the simulation parameters, a preliminary experiment was carried out, as seen in Figure 6. A GM cryocooler precools the VM-PTC through a thermal bridge. The two piece of capillary tubes are used (inner diameter*length: $\Phi 0.6*120$ mm+$\Phi 1*3.5$ m) and the double inlet opening diameter is 0.7 mm. The lowest temperature of the cold end is 12.1 K, and the cooling power at 20 K is 0.7 W. The precooling power at 77 K is 46 W.

5. Conclusion

This paper studied a novel single-stage Vuilleumier type pulse tube cryocooler (VM-PTC) by using numerical method. The effects of geometry of cold phase shifter on acoustic power, pressure ratio, phase angle, DC flow rate and cooling power at 20 K are studied. Numerical results show that the cooling power at 20 K of the present VM-PTC can reach 1.6 W, and the relative Carnot efficiency at 20 K can
reach 3 %. At last, a preliminary experiment based on the simulation parameter was built, and the lowest temperature of 12.6 K and the cooling power of 0.7 W at 20 K were obtained. The relative Carnot efficiency at 20 K is about 2.1 % in this experiment.

![Cooling down curve of preliminary experiment](image)

**Figure 6** The cooling down curve of preliminary experiment

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### Acknowledgement

This research is supported by National Key R&D Program of China (No. 2018YFB0504603), the National Natural Science Foundation of China (No. 51706233, 51427806, U1831203), Strategic Pilot Projects in Space Science of China (No. XDA15010400), National Postdoctoral Program for Innovative Talents (Foundation No. BX201600173) and Supported by Key Research Program of Frontier Sciences, CAS, Grant No. QYZDY-SSW-JSC028.