Numerical investigation on parameter influence in double-stage Vuilleumier type pulse tube cryocooler (VM-DPTC)

J Wang¹, ², C Z Pan³, X T Xi¹, ², L B Chen¹, ²*, Y Zhou¹, ² and J J Wang¹, ²*

¹ CAS Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry (TIPC.CAS), Beijing 100190, China
² University of Chinese Academy of Science, Beijing 100049, China
³ Laboratoire national de métrologie Et d’essais-Conservatoire national des arts et métiers (LNE-Cnam), F-93210 La Plaine, France
*Corresponding author: wangjunjie@mail.ipc.ac.cn & chenliubiao@mail.ipc.ac.cn

Abstract. The double stage Vuilleumier type pulse tube cryocooler (VM-DPTC) is a modified 4 K-class pulse tube cryocooler form the Vuilleumier hybrid pulse tube cryocooler in TIPC, CAS. Besides its compact size and low-frequency working pattern eliminating the moving parts in cryogenic temperature (<77 K) will improve the working stability and reduce the inherited losses. To design a proper double stage pulse tube cryocooler under a certain thermal compressor to work below 5 K, a numerical model based on Sage 10 software was established and the geometry of phase shifter was optimized firstly. Then the influence of working parameters on no-load temperature, cooling power and the heat rejection of the thermal compressor were studied.

1. Introduction
The demand of 4 K cryocooler increases in physical science and medicine science recently. The Gifford-McMahon (GM) cryocooler and GM-type pulse tube cryocooler are very powerful in liquid helium temperature. They have realized commercial application for many years [1, 2]. They can provide 0.1 W to 2 W cooling power at 4.2 K and a fast cooling from ambient temperature to no-load temperature within 1 to 2 hours. However, the big bulk of the compressor and very long connecting tube (>10 m) usually make them not suitable application with strict volume and weight limitation. Another cryocooler with more compact size called multi-stage Stirling type pulse tube cryocooler is becoming more and more popular. It is expected to be a compensation for such application which not suitable for GM-type cryocooler now. Some efforts have been made on this cryocooler and proved it to be a 4 K cryocooler [3-5]. At present, obtaining liquid helium temperature range efficiently by high frequency (>20 Hz) pulse tube cryocooler is still a challenge [6].
Vuilleumier-type cryocooler (VMC) driven by thermal compressor is usually regarded as a thermal-driven Stirling-type cryocooler, which has the advantages of both low-frequency work pattern of GM-type cryocooler and the compactness of the Stirling cryocooler. It has been proved experimentally that the VMC including Vuilleumier-type single stage pulse tube (VM-SPTC) and Vuilleumier hybrid pulse tube cryocooler (VM-HPTC) were both capable to work at liquid helium temperature. The VM-HPTC could even hit the lambda line of the He-4 [7-13]. The double-stage Vuilleumier type pulse tube (VM-DPTC) is modified form the previous VM-HPTC of TIPC and expected to have the similar superior performance like VM-HPTC. The first step is to verify the VM-DPTC has the ability to obtain liquid helium temperature. In this paper, a numerical work concerning on the parameter’s influence on VM-DPTC is carried out. The influence of average pressure, working frequency and precooling temperature on the lowest temperature, cooling power and heat rejection of thermal compressor are discussed.

2. Simulated model and main parameters

Figure 1. The schematic diagram and Sage model of VM-DPTC (Reg: regenerator; CT: capillary tube; DI: double inlet; PT: pulse tube; 1: first stage; 2: second stage).
The schematic diagram of the VM-DPTC is shown in the left side of the figure 1. It contains three main parts: thermal compressor, first stage pulse tube cryocooler and second stage cryocooler. The simulation model is shown in the right side of the figure 1. The thermal compressor is driven by the temperature difference between 320 K and 77 K. The initial working frequency is set at 2 Hz and the initial working pressure is set at 0.9 MPa. The basic simulated parameters are shown in Table 1. The initial length of capillary tube and opening diameter of double inlet are first optimized by the optimization function of Sage10 software itself. The relative values are shown in table 2. The temperatures of first stage and second stage cold end are 4.28 K and 27.17 K this time.

### Table 1. The simulation parameters of the VM-DPTC in Sage model.

| Equipment           | Component             | Parameter      | Value            |
|---------------------|-----------------------|----------------|------------------|
| Thermal compressor  | Cylinder              | Diameter       | 95 mm            |
|                     | Displacer             | Stroke         | 20 mm            |
| First stage pulse   | Regenerator (Reg1)    | Diameter       | 30 mm/12.5 mm    |
| tube cryocooler (1st PTC) | Packing1             |                | 200 mesh steel screen*60 mm |
|                     | Packing2              |                | Lead sphere (0.45 mm)*60 mm |
|                     | Pulse tube (PT1)      | Diameter       | 12.1 mm          |
| First stage phase   | Capillary tube 1 (CT1)| Diameter       | 0.6 mm           |
| shifter             | Reservoir 1           | Volume         | 500 mL           |
|                     | Double inlet 1 (DI1)  | Opening diameter | 0-0.5 mm        |
| Second stage pulse  | Regenerator (Reg2)    | Diameter       | 18 mm/8.9 mm     |
| tube cryocooler (2nd PTC) | Packing1             |                | Er₃Ni sphere (0.25 mm)*30 mm |
|                     | Packing2              |                | HoCu₂ sphere (0.25 mm)*30 mm |
|                     | Pulse tube (PT2)      | Diameter       | 12.1 mm          |
| First stage phase   | Capillary tube 2 (CT2)| Diameter       | 0.6 mm           |
| shifter             | Reservoir 2           | Volume         | 100 mL           |
|                     | Double inlet 2 (DI2)  | Opening diameter | 0-1.5 mm        |

### Table 2. The optimized parameters of capillary tube and double inlet optimized by Sage10 software.

| Frequency | Pressure | CT1 length | CT2 length | DI1 opening diameter | DI2 opening diameter |
|-----------|----------|------------|------------|----------------------|----------------------|
| 2 Hz      | 0.9 MPa  | 2.8 m      | 1.9 m      | 0.3 mm               | 1.0 mm               |

### 3. Simulation results and discussion

#### 3.1. Heat rejection analysis

Figure 2 shows that the negative PV work in cold cavity, solid conduction loss and shuttle loss contributes most to the heat rejection in this thermal compressor. In the present case, the negative PV work in cold cavity, total solid conduction loss and shuttle loss are 21.5 W, 14.9 W and 8.8 W
respectively. The conduction loss and shuttle loss are two kinds of parasitic loss. These losses hinder a practical thermal compressor to reach the ideal Stirling power cycle efficiency, which equals to 1. However, the optimization of the structure parameters will provide some helps to reduce these parasitic losses.

![Diagram showing heat rejection at the cold end of the thermal compressor](image)

**Figure 2.** The compositions of the heat rejection at the cold end of the thermal compressor.

### 3.2. Average pressure’s influence

As can be seen from the figure 3, the increase of the average pressure will make the first stage temperature grow up while the second stage temperature has a minimum value below 4.3 K. Although the increasing pressure will make more gas expending at the cold end, the enthalpy loss of the regenerator will increase together. Meanwhile, the precooling temperature of the second stage will also increase. The optimal average pressure in the present case for the lowest temperature is about from 0.65 to 0.85 MPa. The pressure ratio in system is about 1.5.

![Graph showing influence of average pressure on two stage cooling temperature](image)

**Figure 3.** The influence of average pressure on two stage cooling temperature.

In figure 4, the increase of the average pressure will make the negative PV work in cold cavity grow up while the cooling power of the second stage cold end at 5 K has a minimum value. The reason of this result is also that the enhancement of the cooling power by increasing the pressure can not always
compensate the growing loss. The optimal average pressure of the cooling power at 5 K is about from 0.8 MPa to 0.9 MPa, which is almost in the same range of the optimal average pressure of the lowest temperature.

![Graph showing the influence of average pressure on cooling power and PV work.](image)

**Figure 4.** The influence of average pressure on cooling power and PV work.

### 3.3. work frequency’s influence

As shown in figure 5, the increase of the working frequency will make the first stage temperature decrease while the second stage temperature has a minimum value. The increasing frequency will improve the ideal cooling power but also reduce the regenerator performance, especially the enthalpy loss caused by imperfect heat exchange. The optimal working frequency for lowest temperature is about from 2.2 to 2.4 Hz in the present case. Higher frequency means higher resistance in the capillary tube, so a shorter capillary may be more suitable for higher frequency.

![Graph showing the influence of work frequency on two stage cooling temperature.](image)

**Figure 5.** The influence of work frequency on two stage cooling temperature.

In figure 6, the increase of the working frequency will make the negative PV work in cold cavity grow up. The cooling power of the second stage cold end at 5 K has a maximum value. The optimal working frequency of the cooling power at 5 K is about from 2.0 to 2.2 Hz, which has little difference when compared with the optimal working frequency of the lowest temperature.
3.4. precooling temperature’s influence
As shown in figure 7, the decrease of precooling temperature reduces the first stage temperature. This is quite similar with the single stage VM cryocooler. However, for the VM-DPTC, the decrease of the precooling temperature will not always reduce the temperature of the second stage cold end. It has a minimum value. The main reason is the precooling temperature will also affect the impedance of the second stage pulse tube cryocooler. The structure and working parameters of VM-DPTC have to be redesigned if the precooling temperature has changed.

4. Conclusions
The parameter effects on a 4 K-class VM-DPTC was numerically studied in this paper. For both average pressure and working frequency, there were optimal values for the second stage temperature and the cooling power at 5 K. The increase of the average pressure and the working frequency would enlarge the heat rejection of the thermal compressor. Increasing or decreasing the precooling from the initial point (77K) would both worse the lowest temperature, which was quite different from the effect in single
stage thermal driven pulse tube cryocooler. The main loss in the thermal compressor were solid conduction loss and shuttle loss between the cylinder and the displacer in this case. Due to these parasitic losses, the practical efficiency of the thermal compressor was not able to reach the ideal efficiency of a Stirling power cycle.

5. References

[1] Wang C, Sun L, Lichtenwalter B, Zerkle B and Okada Y 2016 Compact, ultra-low vibration, closed-cycle helium recycler for uninterrupted operation of MEG with SQUID magnetometers *Cryogenics* 76 16-22

[2] Wang C, Lichtenwalter B, Friebel A and Tang H X 2014 A closed-cycle 1 K refrigeration cryostat *Cryogenics* 64 5-9

[3] Qiu L M, Cao Q, Zhi X Q, Han L, Gan Z H, Yu Y B, Liu Y, Zhang X J and Pfotenhauer J M 2012 Operating characteristics of a three-stage Stirling pulse tube cryocooler operating around 5 K *Cryogenics* 52 382-88

[4] Zhi X Q, Han L, Dietrich M, Gan Z H, Qiu L M and Thummes G 2013 A three-stage Stirling pulse tube cryocooler reached 4.26 K with He-4 working fluid *Cryogenics* 58 93-6

[5] Chen L B, Wu X L, Wang J, Liu X M, Pan C Z, Jin H, Cui W, Zhou Y and Wang J J 2018 Study on a high frequency pulse tube cryocooler capable of achieving temperatures below 4 K by helium-4 *Cryogenics* 94 103-9

[6] Wang B and Gan Z H 2013 A critical review of liquid helium temperature high frequency pulse tube cryocoolers for space applications *Progress in Aerospace Sciences* 61 43-70

[7] Dai W, Matsubara Y and Kobayashi H 2002 Experimental results on V-M type pulse tube refrigerator *Cryogenics* 42 433-7

[8] Pan C Z, Zhang T, Zhou Y and Wang J J 2016 A novel coupled VM-PT cryocooler operation at liquid helium temperature *Cryogenics* 77 20-24

[9] Zhang T, Pan C, Zhou Y and Wang J J 2016 Numerical investigation and experimental development on VM-PT cryocooler operating below 4 K *Cryogenics* 80 138-46

[10] Wang J, Pan C Z, Zhang T, Luo K Q, Zhou Y and Wang J J 2018 A novel method to hit the limit temperature of Stirling-type cryocooler *Journal of Applied Physics* 123 (063901) 1-6

[11] Wang J, Pan C Z, Zhang T, Luo K Q, Xi X T, Wu X L, Zheng J P, Chen L B, Wang J J, Zhou Y, Jin H and Cui W 2019 First Stirling-type cryocooler reaching lambda point He4 (2.17 K) and its prospect in Chinese HUBS satellite project *Science Bulletin* 64 219-21

[12] Pan C Z, Wang J, Luo K Q, Wang J J and Zhou Y 2017 Progress on a novel VM-type pulse tube cryocooler for 4 K *Cryogenics* 88 66-9

[13] Pan C Z, Wang J, Luo K Q, Chen L B, Jin H, Cui W, Wang J J and Zhou Y 2019 Numerical and experimental study of VM type pulse tube cryocooler with multi-bypass operating below 4 K. *Cryogenics* 98 71-9
Acknowledgments
This research is supported by the National Natural Science Foundation of China (No.51706233, 51427806, U1831203), Strategic Pilot Projects in Space Science of China (No.XDA15010400), Key Research Program of Frontier Sciences, CAS, Grant (No.QYZDY-SSW-JSC028), CAS Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry (No.CRYOQN201706).