Numerical study of a cryogen-free vuilleumier type pulse tube cryocooler operating below 10 K

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Abstract. This paper presents a numerical investigation on a Vuilleumier (VM) type pulse tube cooler. Different from previous systems that use liquid nitrogen, Stirling type pre-coolers are used to provide the cooling power for the thermal compressor, which leads to a convenient cryogen-free system and offers the flexibility of changing working temperature range of the thermal compressor to obtain an optimum efficiency. Firstly, main component dimensions were optimized with lowest no-load temperature as the target. Then the dependence of system performance on average pressure, frequency, displacer displacement amplitude and thermal compressor pre-cooling temperature were studied. Finally, the effect of pre-cooling temperature on overall cooling efficiency at 5 K was studied. A highest relative Carnot efficiency of 0.82 % was predicted with an average pressure of 2.5 MPa, a frequency of 3 Hz, a displacer displacement amplitude of 6.5 mm, ambient end temperature 300 K and pre-cooling temperature 65 K, respectively.

1.Introduction
Cryocoolers operating at around 4 K have been extensively applied in many fields, such as space exploration, medical service and physical research. G-M and G-M type pulse tube cryocooler (PTC) working at liquid helium temperature have been developed for many years and become quite matured. The coefficient of performance of these cryocoolers is still not satisfying. Newly investigated multi-stage Stirling type PTC for this temperature range has a poor efficiency and is still in the early stage of development. As an alternative, Vuilleumier (VM) type PTC is driven by a thermal compressor and has the potential advantages of compactness, long lifetime and a reasonable efficiency. Dai and Pan et al. [1-4] developed VM type pulse tube cryocoolers and lowest temperatures below 4 K were achieved. These systems all use liquid nitrogen to provide required cooling power for the thermal
compressor, which is not convenient. Furthermore, the pre-cooling temperature for the thermal compressor is fixed at around 80 K which may not be the best pre-cooling temperature for overall system efficiency.

Zhao et al. [5,6] proposed a modified system in which Stirling type pulse tube cryocoolers are used to provide the required cooling power for the thermal compressor. In this way, a cryogen-free system was built and working temperature difference of the thermal compressor can be easily adjusted. At present, a lowest no-load temperature below 10 K was obtained. Through numeric means, this paper further optimizes the system for liquid helium temperature. Dependence of system performance on average pressure, frequency, displacer displacement amplitude and thermal compressor pre-cooling temperature were studied. Most importantly, evaluation of the influence of pre-cooling temperature on overall cooling efficiency at 5 K is performed.

2. System configuration

The VM type pulse tube cryocooler consists of three subsystem: pre-cooler, thermal compressor and low temperature stage PTC. Figure 1 illustrates the basic configuration. The thermal compressor consists of ambient heat exchanger, regenerator, cold heat exchanger and displacer, which utilizes temperature difference between the ambient and the pre-cooler temperature to generate an oscillating pressure wave. Pre-cooler is thermally coupled with the cold end of the thermal compressor, providing the required cooling power. Low temperature stage PTC is driven by the thermal compressor, and is mainly composed of regenerator, cold head, U shape connecting tube, pulse tube and phase shifter. The orifice and the double-inlet are used at the pulse tube hot end to regulate the phase difference between the pressure wave and mass flow inside the regenerator. Compared with previous setup [6], the system has undergone some major revisions and details are listed in Table 1.

| Subsystem                      | Components         | Parameters                                                                 |
|-------------------------------|--------------------|----------------------------------------------------------------------------|
| Thermal compressor            | Ambient HX         | Diameter 40 mm, length 52 mm, finned type HX                              |
|                               | Cold heat exchanger| Diameter 18 mm, length 25 mm, finned type HX                              |
|                               | Regenerator I      | Diameter 30 mm, length 150 mm, 80# stainless steel screens               |
| Low temperature stage PTC     | Regenerator II (ErPr) | Inner diameter 16.5 mm, length 166 mm, 0.2 mm sphere diameter, with porosity of 0.36. |
|                               | Regenerator II (HoCu2) | Inner diameter 16.5 mm, length 80 mm, 0.15 mm sphere diameter, with porosity of 0.4. |
|                               | Pulse tube         | Inner diameter 12 mm, length 247.5 mm, wall thickness 0.15 mm            |
|                               | Reservoir          | Volume 1 L                                                                 |

Table 1. Main structure parameters of VM type pulse tube cryocooler
Figure 1. Schematic of the VM type pulse tube cryocooler.
1.Linear motor  2.Ambient HX I  3.Displacer  4. Regenerator I  5.Cold HX for thermal compressor  6.Thermal bridge  7.Regenerator II (ErPr)  8. Regenerator II (HoCu$_2$)  9. Cold head  10. U shape connecting tube  11. Flow straightener  12. Pulse tube  13. Ambient HX II  14. Double-inlet valve  15. Orifice valve  16. Reservoir

3. Simulation results and discussion
The simulation was conducted using the SAGE program [7]. In the simulation, helium is selected as working gas, and the ambient temperature is set at 300 K. In section 3.1, calculations are carried out to find optimum lowest no-load temperature through investigating the influence of the frequency, average pressure and displacer displacement amplitude for thermal compressor. In section 3.2, influence of the pre-cooling temperature on the overall cooling efficiency is investigated.

3.1. Influence of the operating parameters
Figure 2 shows the influence of the average pressure on lowest no-load temperature. With average pressure increasing from 1.5 MPa to 2.5 MPa, lowest no-load temperature decreases from 9.75 K to approximately 5.5 K. Figure 3 presents the dependence of pressure wave amplitude and volume flow rate at cold end of regenerator II on average pressure. A larger average pressure leads to a larger pressure wave amplitude, while volume flow rate decreases with the increase of average pressure. Meanwhile, the required cooling power for the thermal compressor as well as the acoustic power at the cold end of Regenerator II increase with the average pressure, as shown in Figure 4.
Figure 2. Dependence of lowest no-load temperature on average pressure, 3 Hz, 6.5 mm displacement, 90 K pre-cooling temperature.

Figure 3. Dependence of the pressure wave amplitude and volume flow rate at cold end of regenerator II on average pressure, 3 Hz, 6.5 mm displacement, 90 K pre-cooling temperature.
**Figure 4.** Dependence of the required cooling power for thermal compressor and acoustic power at cold end of regenerator II on average pressure, 3 Hz, 6.5 mm displacement, 90 K pre-cooling temperature.

Figure 5 demonstrates the dependence of lowest no-load temperature on frequency. The operating frequency has a large influence on the no-load temperature and the optimum frequency is around 5 Hz. The increment of the frequency leads to a larger acoustic power density, however, higher operating frequency will lead to a larger pressure drop and worsen heat transfer in regenerators. There is a trade-off between these factors.

![Graph](image)

**Figure 5.** Dependence of lowest no-load temperature on frequency, 2.5 MPa, 6.5 mm displacement, 90 K pre-cooling temperature.

Figure 6 presents the effect of the displacer displacement amplitude on lowest no-load temperature and pressure wave amplitude. Lowest temperature reduces from 6.33 K to 4.19 K and pressure wave amplitude rises from 2.67 bar to 4.23 bar when the displacer displacement amplitude increases from 5.5 mm to 9 mm. Increasing the displacer displacement amplitude can enlarge the swept volume and the pressure wave amplitude will increase, which means larger acoustic power provided to low temperature stage PTC, so the cryocooler can achieve a lower temperature. In practice, the displacement amplitude is limited by the mechanical driving mechanism of the displacer, and in our case, it is limited to 6.5 mm.

The dependence of lowest no-load temperature and required cooling power on the pre-cooling temperature for thermal compressor is shown in Figure 7. As seen in the figure, lowest no-load temperature decreases with decreasing of the pre-cooling temperature. This can be mainly attributed to following two factors: on one hand, a lower pre-cooling temperature increases the working temperature difference for thermal compressor, which is helpful to generating more acoustic power to drive low temperature stage PTC; on the other hand, the lower pre-cooling temperature means that the gas entering the regenerator II is lower in temperature. Meanwhile, the required pre-cooling power gets larger with the decrease of pre-cooling temperature.
5. Dependence of lowest no-load temperature and pressure wave amplitude on displacer displacement amplitude, 3Hz, 2.5MPa, 90 K pre-cooling temperature.

6. Dependence of lowest no-load temperature and pre-cooling power on pre-cooling temperature, 3Hz, 2.5 MPa, 6.5 mm displacement.

3.2. Overall efficiency evaluation with variable pre-cooling temperature

For practical systems, overall efficiency at a target temperature is more important than lowest no-load temperature. Based on the results in section 3.1, we select a cold end temperature of 5 K and modify the pre-cooling temperature for performance evaluation. According to figure 6, a lowest no-load temperature of 5.0 K is obtained when pre-cooling temperature for thermal compressor is 87 K. So the pre-cooling temperature here varies from 40 K to 87 K. The relative Carnot efficiency $\eta$ is defined as:

$$\eta = \frac{Q_c}{W_{in}} / \frac{T_c}{T_h - T_c}$$

Where $T_c=5$ K, $T_h=300$ K, $Q_c$ is the cooling power of the low temperature stage cold head at 5 K, $W_{in}$ is the total input power, including the electric power $W_1$ to drive the thermal compressor and an
estimated electric power $W_2$ to drive the pre-cooler to provide the pre-cooling power. Compared with $W_2$, $W_1$ is more than one order smaller in our experiments and neglected in the following calculation. $W_2$ is calculated with:

$$
W_2 = \frac{Q_{\text{pre}}}{\eta_{\text{pre}}} \frac{T_{\text{pre}}}{T_0 - T_{\text{pre}}}
$$

(2)

Where $T_{\text{pre}}$ and $Q_{\text{pre}}$ represent the pre-cooling temperature and required pre-cooling power respectively, $\eta_{\text{pre}}$ is pre-cooler relative Carnot efficiency at the responding pre-cooling temperature, which is estimated based on state of the art of cryocooler technology. In reference to the work in our lab [8], the relative Carnot efficiency at 40 K and 77 K is 14.8% and 25.9%, respectively. So the pre-cooler efficiency at other temperature is derived from a linear interpolation between the two values.

Figure 8 presents dependence of the relative Carnot efficiency and cooling power at 5 K on the pre-cooling temperature. The result shows that there is an optimal pre-cooling temperature to achieve the maximum efficiency. At a pre-cooling temperature of 65 K for the thermal compressor, the relative Carnot efficiency reaches to about 0.82%.

![Figure 8. Dependence of the relative Carnot efficiency and cooling power at 5 K on the pre-cooling temperature, 3 Hz, 2.5 MPa, 6.5 mm displacement.](image)

**4. Conclusion**

This paper numerically investigate a cryogen-free VM type pulse tube cryocooler. The analysis shows that frequency and average pressure have significant influences on the lowest no-load temperature, and there exists an optimum value for them in terms of lowest no-load temperature. Moreover, overall relative Carnot efficiency at 5 K can reach 0.82% when the pre-cooling temperature is 65 K. Optimum pre-cooling temperature in terms of overall system efficiency may depend on the exact system parameters, which needs further investigation. Although the overall efficiency here is not high, future optimization may give a better efficiency. Meanwhile, the cryogen-free VM type pulse tube cryocooler possesses advantages of long lifetime, high reliability, low vibration and compactness, which is beneficial to many important applications such as portable medical devices or cooling sensors for...
space applications.

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