Experimental study on a one-stage Vuilleumier cryocooler with large pressure ratio

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Abstract. A detailed experimental results of one-stage VM cryocooler with larger pressure ratio is presented and discussed in this paper. By increasing the stroke distance of hot displacer from 20 mm to 32 mm, the pressure ratio raised to 1.8 at the terminal temperature. Besides, TFL-spring combined with labyrinth sealing was used on cold displacer. Finally, a no-load temperature of 7.55 K was attained and the cooling capacity is 1.98 W@15 K. Although the terminal temperature was not apparently improved, it still showed great potential to reach liquid helium temperature when adding an extra stage.

1. Introduction

Vuilleumier (VM) cryocooler is one kind of Stirling cryocooler, which is driven by thermal compressor. VM cryocooler is first patented by Vuilleumier in 1918 [1]. Chellis et al. developed this kind of cryocooler and attained a terminal temperature of 15 K by using liquid nitrogen in 1964 [2]. Zhou et al. optimized the main parameters of Chellis’s proto and obtained a no-load temperature of 10.7 K and a cooling power of 1.7 W@15 K [3]. Pan et al. analyzed the pressure drop loss of cold regenerator and establish an numerical program of one-stage VM cryocooler operating below 10 K[4-5]. Recently, they obtained a terminal temperature of 7.35 K on a one-stage VM cryocooler by improving sealing method and using magnetic materials on cold regenerator, but the cooling capacity was smaller than Zhou’s work [6]. Generally, compared with GM cryocooler, the pressure ratio of these VM cryocoolers is small, which greatly affects their performance.

In this paper, a detailed experimental investigation of a one-stage VM cryocooler with larger pressure ratio is introduced. Based on a VM cryocooler which could achieve a terminal temperature of 9 K, we reduced the length of hot displacer and increased its stroke distance from 20 mm to 32 mm.
Initial experimental results showed that its pressure ratio raised from 1.5~1.8 to 1.8~2.1. Based on this, this paper will show a series of experimental results and corresponding discussions. Meanwhile, the comparison with former experimental results in our laboratory will also be presented.

2. Experimental setup and procedures

Figure 1 (a) shows the schematic of experimental apparatus and Figure 1 (b) shows the structure of one-stage VM cryocooler. The main parameters are listed in Table 1. VM cryocooler generally includes three cavities and two displacers that reciprocate in a cylinder. The hot cavity is kept at a constant temperature (about 325 K) by a chiller and the middle cavity is cooled by liquid nitrogen. A motor drives the crankshaft leading a motion of two displacers and a proper phase angle difference between them. In this proto, it was 90° and the cold displacer moves ahead the hot displacer. Regenerators are placed inside the displacers for compactness.

| Hot displacer | Diameter 95 mm, length 165 mm, stroke distance 32 mm |
| Hot regenerator | Ring structure, inner diameter 23.6 mm, out diameter 45 mm, length 128 mm |
| Cold displacer | Diameter 26 mm, length 190 mm, stroke distance 20 mm |
| Cold regenerator | Inner diameter 23.6 mm, length 128 mm |

The cryocooler was placed in a vacuum chamber. The radiation heat loss of the cold end was reduced by installed a radiation shield attached onto the liquid nitrogen tank. A calibrated Rh-Fe resistance thermometer with 0.1 K accuracy was used to measure the cold end temperature and three Pt100 thermometers were used to monitor the temperatures of the liquid nitrogen tank, the bottom and middle part of the cold cylinder, respectively. An electrical heater was attached to the cold end to measure the cooling capacity. Two pressure sensors were installed in the hot cavity and crank chamber respectively. The working gas was helium-4 and the charge pressure was about 1.8 MPa in the room temperature. The pressure ratio was near 1.8 and the mean pressure was about 1 MPa at the terminal temperature. The working frequency could be adjusted from 0.4 Hz to 2 Hz.
3. Experimental results and discussions

3.1 The optimization of regenerative materials of cold regenerator

In order to attain lower temperature, the cold regenerator which has significant influence on the performance of VM cryocooler should be optimized on regenerative materials. Besides specific heat capacity, flow resistance, thermal conductivity and thermal penetration depth should be comprehensively considered when selecting regenerative materials. Figure 2 (a) and Figure 2 (b) show the volumetric heat capacities and thermal penetration depths (operating at 2 Hz) of several main regenerative materials and helium-4, respectively. Based on this, a series of experiments with different regenerative materials had been carried out.

![Figure 2](image.png)

**Figure 2.** Properties of materials and helium-4 (a) specific heat (b) thermal penetration depth

Figure 3 shows the filling pattern of the cold regenerator and the total filling length is 125 mm. Generally, the filling length of cold regenerator was divided into three parts. Based on previous experimental results, the best filling pattern of the bottom part is about 45 mm 200# stainless steel screens. So the filling pattern of this part was fixed in the following experiments. Length A and B were filled with different kinds and diameters of regenerative materials, whose filling rate was about 64%. The adjacent parts were separated by rectificated parts, which were made up of one piece of felt mat on both sides and six pieces of 200# stainless steel screens in the middle. The thickness of rectificated part was about 1mm. Table 2 shows the results of these experiments.

![Figure 3](image.png)

**Figure 3.** The filling pattern of cold regenerator

Compared Case 1 and Case 2 we could find that when changing the diameter of lead from 0.4-0.45 mm to 0.2-0.25 mm on the top 40 mm, the terminal temperature rose from 8.37 K to 9.16 K. This was mainly caused by the increasing pressure drop when using smaller lead sphere. Figure 2 (a)
indicates that the specific heat of lead decreases rapidly below 10 K, so it is necessary to use magnetic materials to attain lower temperature. Case 3-5 shows the experimental results which filled different lengths of $\text{Er}_3\text{Ni}$ (diameter 0.2-0.25 mm) and a no-load temperature of 7.68 K was obtained in Case 4. Later, in order to reduce the pressure drop, a larger diameter of $\text{Er}_3\text{Ni}$ (diameter 0.3-0.355 mm) was used. However, the terminal temperature rose to 7.95 K, seen in Case 6. This is mainly caused by incomplete heat transfer between helium and regenerative materials. Figure 2 (b) shows that although the diameter of $\text{Er}_3\text{Ni}$ was smaller than its thermal penetration depth, the size of gas space formed by the materials was still bigger than the thermal penetration depth of helium-4, which could cause the loss due to incomplete heat transfer. So the optimal value of the diameter of regenerative materials should be experimental studied. Finally, the regenerator volume was filled up with HoCu$_2$ to replace $\text{Er}_3\text{Ni}$ based on Case4, the no-load temperature rose to 8.22 K since the specific heat capacity of HoCu$_2$ which has two peaks on this temperature zone is not complete larger than that of $\text{Er}_3\text{Ni}$.

### Table 2. Experimental results of various filling pattern of cold regenerator

| Case | A(mm) | B(mm) | Material 1 (diameter, mm) | Material 2 (diameter, mm) | Terminal temperature (K) |
|------|-------|-------|--------------------------|--------------------------|--------------------------|
| Case 1 | 80    | —     | Lead(0.4-0.45)           | —                        | 8.37                     |
| Case 2 | 40    | 40    | Lead(0.4-0.45)           | Lead(0.2-0.25)           | 9.16                     |
| Case 3 | 60    | 20    | Lead(0.4-0.45)           | $\text{Er}_3\text{Ni}(0.2-0.25)$ | 8.25                     |
| Case 4 | 50    | 30    | Lead(0.4-0.45)           | $\text{Er}_3\text{Ni}(0.2-0.25)$ | 7.68                     |
| Case 5 | 40    | 40    | Lead(0.4-0.45)           | $\text{Er}_3\text{Ni}(0.2-0.25)$ | 7.84                     |
| Case 6 | 50    | 30    | Lead(0.4-0.45)           | $\text{Er}_3\text{Ni}(0.3-0.355)$ | 7.95                     |
| Case 7 | 50    | 30    | Lead(0.4-0.45)           | HoCu$_2(0.2-0.25)$       | 8.22                     |

3.2 The labyrinth sealing of cold displacer

Traditional VM cryocooler used C-shaped seal ring on the cold displacer. Pan et al. adopted TFL spring-sealing on the cold displacer and verified its advantage. However, this seal ring is hardened at a low temperature and the gas is likely to leak. In order to improve the sealing performance, a method of TFL spring-sealing combined with labyrinth sealing on cold displacer was used in this cryocooler. Fig.4 (a) and Fig.4 (b) show the schematic of cold displacer and its sealing pattern.

It is known that labyrinth sealing have some influence on the performance of cryocooler. Based on previous work [6], the shape of the groove slightly affected the performance of cryocooler. Therefore rectangle groove was used in the following experiments for its simple manufacturing. Limited to the experiment conditions, only the influences of depth and quantity were tested. The clearance between displacer and cylinder was 0.07 mm and the width of groove is 1 mm. The filling pattern of cold regenerator was same as Case4.

### Table 3. Experimental results of labyrinth sealing of cold displacer

| Case | Depth(mm) | Spacing(mm) | Terminal temperature (K) | Cooling capacity |
|------|-----------|-------------|--------------------------|-----------------|
| Case A | —         | —           | 7.59                     | 1.67 W@15 K     |
| Case B | 0.3       | 15          | 7.68                     | 1.68 W@15 K     |
| Case C | 0.6       | 15          | 7.71                     | 1.73 W@15 K     |
| Case D | 0.6       | 7.5         | 7.55                     | 1.98 W@15 K     |
Table 3 shows the experimental results of different labyrinth sealing parameters. All the terminal temperatures were attained at an operating frequency of 0.6 Hz and the cooling capacities were measured at an operating frequency of 2 Hz. It is found that the depth of groove slightly affect the performance of cryocooler. When increasing the quantities of grooves, a terminal temperature of 7.55 K was attained and the cooling capacity at 15 K increased about 20%. Figure 5 (a) and Figure 5 (b) show the typical cooling down curve and the cooling capacities operating at different frequencies, respectively.

3.3 Advantage and potential

Recently, Pan et al. attained a terminal temperature of 7.35 K by using $\text{Er}_{0.6}\text{Pr}_{0.4}$ instead of lead. However, the poor mechanical property and weak oxidation resistance of $\text{Er}_{0.6}\text{Pr}_{0.4}$ limit its application.
So it was not used in this apparatus. Comparing with the former experimental results we could find that the cooling capacity is much larger when increasing the pressure ratio. In this proto, the cryocooler was limited to establish enough temperature gradient to attain lower temperature for its parameters of cold regenerator. Nevertheless, this VM cryocooler has great potential to reach liquid helium temperature after adding an extra stage.

4. Conclusion
The pressure ratio of Vuilleumier (VM) cryocooler is generally smaller than that of GM cryocooler, which is considered to be one of the most significant factors that affect its performance. In this paper, an experimental study on a VM cryocooler with larger pressure ratio is introduced. By increasing the hot displacer’s stroke distance and reducing its length on the original experimental system which could achieve a no-load temperature of 9 K, the pressure ratio raised from 1.5~1.8 to 1.8~2.1. By optimizing the regenerator materials of the cold regenerator and adopting labyrinth sealing cold displacer, a no-load temperature of 7.55 K has been achieved. The cooling power at 15 K is 1.98 W with a pressure ratio near 1.8 and a mean pressure of 1.0 MPa. Comparing with the former experimental results, it shows great potential to reach liquid helium temperature after coupling an extra stage of displacer or pulse tube cryocooler.

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