Progress of the 4 K-class Vuilleumier type cryocooler and its further applications

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Abstract. Vuilleumier cycle was first patented in 1918. It was usually regard as the thermal-driven Stirling refrigeration cycle, which combined the low-frequency working pattern like Giffod-McMahon (GM) cryocooler and the compactness of Stirling-type cryocooler. With the continuous development in the past 100 years, the Vuilleumier-type (VM-type) cryocoolers have to been proved to generate cooling power from ambient temperature to liquid nitrogen temperature and even to liquid helium temperature. In recent decades, some efforts were made on traditional displacer-type VM cryocooler, Vuilleumier hybrid pulse tube cryocooler (VM-HPTC) and the VM-type pulse tube cryocooler (VM-type PTC) to obtain the liquid helium temperature. Successfully, not only the 4 K was obtained, but also the limit temperature of oscillating cryocooler by He4 was hit. This paper presents the progress of the 4 K-class VM-type cryocooler and analyzed the possible applications of 4 K class VM-type cryocooler.

1. Introduction
Small scale oscillating cryocoolers operating at liquid helium temperature are widely applied in cryogenic superconductor, physics and medicine science now. GM cryocooler and GM-type cryocoolers working at 4.2 K have been commercially applied form many years [1, 2]. However, the rather big bulk and oil in compressor hinder their applications in some fields, especially in space science. Recently, multi-stage Stirling pulse tube cryocooler working at liquid helium temperature is attracting more attention for its reliability and compactness. Many efforts and important improvements...
had been made in different institutes [3-5]. But it is relatively difficult to attain high efficiency at liquid helium temperature for large irreversible losses in regenerator.

Vuilleumier-type (VM-type) cryocooler based on the Vuilleumier cycle patented in 1918 is usually regarded as the Stirling-type cryocooler driven by thermal compressor. VM-type cryocooler mainly operates at low frequency and is suitable to be filled with larger dimensions of regenerative materials to reduce the pressure drop. Therefore, the study of VM-type has important significance on developing efficient cryocoolers operating at liquid helium temperature. Until now, some efforts were made on traditional displacer-type VM cryocooler, Vuilleumier hybrid pulse tube cryocooler (VM-HPTC) and the VM-type pulse tube cryocooler (VM-type PTC) and some of them successfully obtained the liquid helium temperature even the 2.2 K. For memorizing the relative researching process and the 101 birth of the Vuilleumier cycle, this paper was carried out to introduce the progress of the efforts on 4 K-class VM-type cryocooler and simply discuss the further applications of the 4 K-class VM-type cryocooler.

2. Efforts on 4 K VM-type cryocooler by Matsubara et al.

Matsubara et al. first reported a three-stage displacer-type VM cryocooler and tried to obtain 4K [6, 7], as shown in figure 1. This cooler was precooled by liquid nitrogen (LN2) at both cold end of the thermal compressor and the hot end of the first stage expansion space. The annular gap between the cylinder and the displacer was used as a regenerator in each stage. The lowest temperature at the coldest end was 7.7 K while the average pressure was 0.54 MPa and frequency was 1.17 Hz. The temperatures at other two other cold ends were about 13 K and 33 K. This cooler could provide a cooling power of 8mW at 8.3 K. Total LN2 consumption was 0.5 litter per hour maximally. After further optimization, it could obtained the lowest temperature of 6.5 K.

![Figure 1. The three-stage displacer-type VM cryocooler [6].](image-url)
To study the coldest section of VM cryocooler, Matsubara et al. made another VM cryocooler prototype \cite{6, 7}, as shown in Figure 2. In this prototype, a two-stage VM displacer-type cryocooler (pre-cooler) pre-cooled a single-stage VM displacer-type cryocooler (test cooler) below 20 K. Both pre-cooler and test cooler were precooled by LN\textsubscript{2}. After the pre-cooler provided a heat sink at 16.1 K under 1.0 Hz and 0.68 MPa, the test cooler obtained the lowest temperature of 5.4 K under 0.65 Hz and 0.25 MPa. Matsubara et al. estimated the energy relationship in this cryocooler and found that most of the cooling power was consumed by its own regenerator loss in the pre-cooler. This meant the pre-cooler could not provide a lower heat sink for the test cooler.

3. Efforts on 4 K VM-type pulse tube cryocooler by Dai et al.

3.1. VM-type pulse tube cryocooler with two pre-cooling source

Dai et al. presented a single stage VM-type PTC as shown in the left side of figure 3 \cite{8}. A GM pulse tube cryocooler was located in the dashed cycle of figure 3 and pre-cooled by LN\textsubscript{2}. The regenerator in VM-type PTC was pre-cooled by LN\textsubscript{2} at 77 K and the GM pulse tube cryocooler at 20 K. For introducing a hollow tube in the thermal compressor, the displacer of the thermal compressor could be arranged at ambient temperature. This was an important modification for VM cryocooler for cancelling all the moving parts in cryogenic temperature and improving the stability of the system. By optimizing the working parameters, a lowest temperature of 3.5 K was obtained under the average pressure of 2.1 MPa and frequency of 1 Hz. The pressure ratio of this system was about 1.3 and they indicated that if the pressure ratio became larger the 20 K heat sink provided by the GM pulse tube cryocooler could be cancelled. This was the first time for the VM-type pulse tube worked around the
liquid helium temperature and provided many inspirations to the further work of VM type cryocooler.

Figure 3. The single-stage VM-type pulse tube cryocooler designed by Dai et al [8].

3.2. VM-type pulse tube cryocooler with single pre-cooling source

Wang et al. reported a single stage VM-type PTC whose thermal compressor was driven by a low-frequency linear compressor (<5 Hz) [9, 10], as shown in figure 4. They replaced the LN$_2$ by a high-efficiency Stirling-type pulse tube cryocooler which contributed to a total cryogen-free VM-type cryocooler system. By optimizing the filling pattern of magnetic regenerative materials in regenerator of VM-type PTC and considering the coupling effect of the orifice valve and double inlet valve, the liquid nitrogen temperature was obtained in simulations. By reducing the pre-cooling temperature to
70.3 K, the relative experiments obtained the lowest temperature of 6.5 K under the frequency of 2.5 Hz and average pressure of 1.7 MPa.

4. Efforts on 4 K VM-type cryocooler by Zhou et al.

![Diagram of cryocooler](image)

**Figure 5.** The 4 K VM-type cryocooler in Zhou’s group [11-19].

4.1. Single-stage VM hybrid Simon expansion cryocooler

Inspired by Chills and Hogan’s work, Zhou et al. present the first single-stage displacer-type VM cryocooler precooled by LN$_2$ in China [11], as shown in figure 5(a). After coupling a Simon expansion refrigerator at the cold of this single-stage VM cryocooler, 40 mL liquid helium per hour could be obtained. This hybrid VM cryocooler realized commercial application in China for a period of time.

4.2. Single-stage VM hybrid pulse tube cryocooler
Zhou et al. analyzed theoretically that the VM cryocooler had the potential to obtain the no-load temperature of 2.3K using He4 as working fluid [12]. To realize Zhou’s prediction, Pan et al. first optimized Zhou’s previous single-stage VM displacer-type cryocooler to 7.3 K and then added a another pulse tube cryocooler on the cold end of this single-stage cooler[13, 14]. The novel structure cancelled the moving part at the coldest end and was called Vuilleumier hybrid pulse tube cryocooler (VM-HPTC), as shown in figure 5(b). The reservoir of the second stage pulse tube cryocooler was arranged at the ambient temperature, and an artificial DC flow was introduced into the system. After optimizing the phase shifter parameters and regenerator filling pattern, the lowest temperature of 4.4 K was successfully obtained under the frequency of 2.2 Hz and average pressure of 1.73 MPa.

Continually, Zhang et al. analyzed the arrangement of the second stage pulse tube cryocooler in VM-HPTC and pointed that the cold phase shifter thermal-coupled with the VM cold end would help the VM-HPTC to obtain lower temperature, as shown in figure 5(c). The experiments of modified VM-HPTC with cold phase shifter were carried out. The displacer stroke of the thermal compressor increased from 20 mm to 32 mm compared with the stroke in Pan’s experiment. The lowest temperature of 3.4 K obtained under frequency of 1.22 Hz and pressure of 1.5 MPa [15].

Wang and Zhang et al. further studies the optimal filing pattern of the regenerators in the VM-HPTC. And in experiments, the lowest temperature of 2.5 K was obtained under the frequency of 1.6 Hz and the average pressure of 1.4 MPa [16]. The cooling power was 36 mW at 4.2 K. At last, Wang et al. optimized the seal performance of cold end displacer in the VM-HPTC and finally obtained the lowest temperature below 2.2 K, which firstly hit the limit temperature of the Stirling-type cryocooler [17]. A cooling power of 10 mW can be provided at 3 K. The development of VM-HPTC shows that the VM-type cryocooler even Stirling-type cryocooler is potential to obtain the lowest temperature like GM-type cryocoolers.

4.3. Single-stage VM-type pulse tube cryocooler with multi-bypass

Multi-bypass was developed by Zhou in 1990s and had shown good capacity to reduce the lowest temperature in high-frequency Stirling-type pulse tube and GM-type pulse tube. Pan et al. designed a multi-bypass single stage pulse tube cryocooler driven by thermal compressor, which called VM-type multi-bypass pulse tube cryocooler (VM-MPTC) [18, 19], as shown in figure 5(d). Compared with common double inlet pulse tube cryocooler, the existence of multi-bypass could generate cooling power at the middle position at the pulse tube, which reduced the loss transferred to the coldest end of the pulse tube cryocooler. The LN2 pre-cooling bath in VM-HPTC was replaced by a mechanical cryocooler. The lowest temperature of 3.7 K was obtained under the frequency of 1.57 Hz and average pressure of 1.2 MPa. The cooling power of 14 mW can be supplied at 4.2 K.

4.4. Double-stage VM-type pulse tube cryocooler

To cancel cold end displacer in VM-HPTC, Wang et al. decided to use a thermal compressor to drive a double-stage pulse tube directly, so called VM-type double stage pulse tube cryocooler (VM-DPTC), as shown in figure 5(e). For no moving parts except thermal compressor, the stability of the VM-DPTC could be better than the previous VM-DPTC. Relative experiments were carrying out and the lowest temperature below 4 K has already obtained.
5. Future applications of 4 K-class VM-type cryocooler

The future application of 4 K VM-type cryocooler mainly concentrates on the precooling source of the mK-class refrigerator like ADR or DR. The demanded cooling power of ADR or DR is usually from 0.5 W-3 W at 4 K. The cooling power of the existing VM-type cryocooler should be stronger.

6. Conclusions

In this paper, an overall view of the progress of 4 K-class Vuilleumier-type cryocooler was presented, as can be summarized in table.1. The further development of the 4 K-class Vuilleumier-type cryocooler is for higher stability and lower vibration. These aims will promote the Vuilleumier-type pulse tube cryocooler to replace the traditional displacer-type Vuilleumier cryocooler in further applications.

table.1 The development of the 4 K-class Vuilleumier-type cryocooler.

| Time  | Nation | Structure | Precooling temperature | Lowest temperature | Cooling power       |
|-------|--------|-----------|------------------------|--------------------|---------------------|
| 1970s | China  | single stage VM a hybrid Simon expansion | 77 K               | 4.2 K              | -                   |
| 1980s | Japan  | three stage VM a | 77 K                  | 7.7 K              | 8 mW@8.3 K          |
| 1980s | Japan  | two stage VM a  | 77 K & 16 K           | 5.4 K              | 7 mW@6.4 K          |
| 2002  | China  | Single stage VM-PT b | 77 K & 20 K         | 3.5 K              | 12 mW@5.0 K         |
| 2016  | China  | single stage VM a hybrid pulse tube cryocooler | 77 K             | 4.4 K              | 50 mW@6.0 K         |
| 2018  | China  | single stage VM-PT b | 70.3 K              | 6.5 K              | -                   |
| 2018  | China  | single stage multi-bypass VM-PT b | 71 K              | 3.7 K              | 13 mW@4.2 K         |
| 2019  | China  | single stage VM a hybrid pulse tube cryocooler | 77 K            | 2.2 K              | 10 mW@3 K           |
| 2019  | China  | two-stage VM-PT b  | 70 K                | 3.9 K              | 4 mW@4.2 K          |

a VM: displacer-type Vuilleumier cryocooler
b VM-PT: Vuilleumier-type pulse tube cryocooler

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