IOP Conf. Series: Materials Science and Engineering **278** (2017) 012044 doi:10.1088/1757-899X/278/1/012044

Experimental progress of a 4K VM/PT hybrid cryocooler for pre-cooling 1K sorption cooler

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Abstract. Sub-kelvin refrigerator has many applications in space detector and manned space station, such as for the transition-edge superconducting (TES) bolometers operated in the 50 mK range. In order to meet the requirement of space applications, the high efficient, vibration free and high stability refrigerator need to be designed. VM/PT hybrid cryocooler is a new type cryocooler capable of attaining temperature below 4K. As a low frequency Stirling type cryocooler, it has the advantages of high stability and high efficiency. Combined with the vibration free sorption cooler and ADR refrigerator, a novel sub-kelvin cooling chain can be designed for the TES bolometer. This paper presents the recent experimental progress of the 4K VM/PT hybrid cryocooler in our laboratory. By optimizing of regenerators, phase shifters and heat exchangers, a lowest temperature of 2.6K was attained. Based on this cryocooler, a preliminary sorption cooler could be designed.

1. Introduction

Sub-kelvin refrigerator has many applications in space detector and manned space station, such as for the transition-edge superconducting (TES) bolometers operated in the 50 mK range. At present, a 4K mechanical cryocooler combined with an adiabatic demagnetization refrigerator (ADR) were the common used in space [1] [2]. For the 4K mechanical cryocooler, the J-T cryocooler was always used. This type of cryocooler needs another mechanical cryocooler to precool, so it showed the disadvantage of complex. Besides, some impurities in helium may choke the JT valve and making the whole cooling system failure.

Alternative 4K mechanical cryocooler is the pulse tube cryocooler (PTC). In recent years multi-stage 4K Stirling pulse tube cryocooler (SPTC) [3] [4] [5] develops raptly because of its compact, long-life, and low vibrations. This type of cryocooler is driven by the linear compressor which normally works at the frequency above 20Hz. However, the rare earth material, such as Er_3Ni and $HoCu_2$, need to be used to increase the volume heat capacity of regenerator below 10 K. Due to mechanical reasons, this type material is difficult to be processed into screen meshes and the shape of sphere is always used. Compared with the low frequency cryocooler, the high frequency oscillating flow will generate a higher pressure drop in regenerator. Therefore, it is necessary to develop the high efficiency 4K SPTC operating at low frequency.

Vuilleumier (VM) cryocooler is known as a heat driven cryocooler. It is one kind of Stirling cryocooler driven by a thermal compressor. The thermal compressor is always operating at the frequency below 5Hz. Therefore, combining with a displacer or pulse tube, it could be a now type 4K cryocooler. Dai et al. [6] have introduced the concept of VM-PTC and built a this type cryocooler, which obtained the lowest temperature of 3.5 K by using 77 K and 20 K pre-coolers. This work also demonstrated its capacity of obtaining liquid helium temperature. Matsubara et al. [7] also presented the concept of thermally actuated He-3 PTC. In his cryocooler, the TCP worked between the temperatures of 300 K and 40 K. Nowadays, Wang et al. [8] developed a 15 K single-stage VM-PTC by using an 80 K Stirling type PTC as pre-cooler.

In our previous works [9] [10] [11], a VM/PT hybrid cryocooler has been built and successfully obtained the temperature around 3.4K. This paper presents the recent experimental progress of the 4K VM/PT hybrid cryocooler in our laboratory. By optimizing of regenerators, phase shifters and heat exchangers, a lowest temperature around 2.6K was attained. Based on present result, a 1K sorption cooler could be designed.

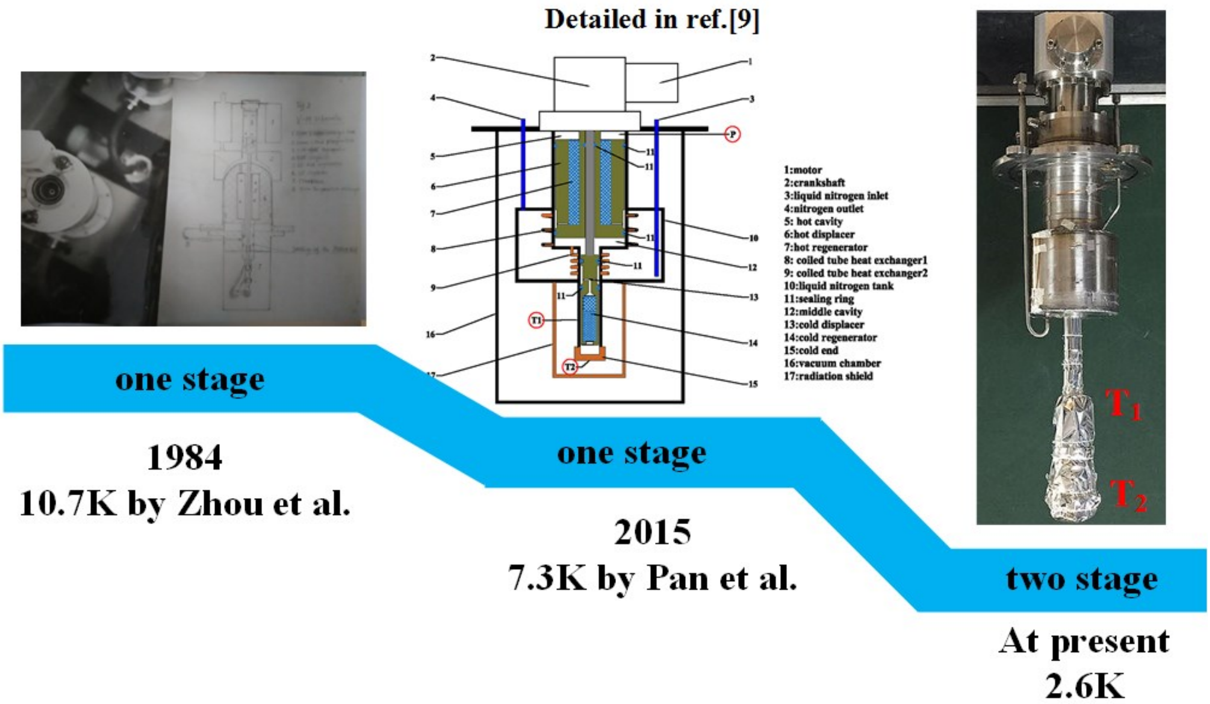

Fig1. Development history of VM cryocoolers in our Lab.

2. System configurations

Figure 1 showed the development history of VM cryocooler in our laboratory. The first generation was developed by Zhou et al. in the 1984. The lowest temperature of 10.7K was obtained by using lead sphere. In the 2015, we had obtained the lowest temperature of 7.35K by using the rare earth materials. For the two-stage VM cryocooler, we have considered three different configurations in our design. The first configuration was used two displacers, but the simulation results showed its performance affected largely by the sealing. So it is difficult to build this structure because of technical reasons. The second configuration was VM/PT hybrid cryocooler using a room temperature gas reservoir. In our previous works [10], this configuration has the ability to obtain the liquid helium temperature. But the room temperature gas reservoir would bring a large heat loss to the cold end of first stage. So the performance of this cryocooler is not very well. Therefore, the main optimization works of this paper were focus on the third configuration, which is VM/PT hybrid cryocooler using a cold gas reservoir.

The main geometrical parameters were list in Table 1. The regenerator of second stage and capillary tube were optimized in the experiment.

Table 1 Structural parameters of VM/PT hybrid cryocooler using cold gas reservoir.

	Components	Parameters
First stage	displacer	Diameter of 26 mm, length of 190 mm, stroke distance of 20 mm
	regenerator	Diameter of 23.6 mm, length of 125 mm, layer 1 filling 45 mm200# SS with porosity of 70.7%, layer 2 filling 50 mm Lead sphere(diameter of 0.4–0.45 mm) with porosity of 36%, layer 3 filling 30 mm Er_3Ni sphere(diameter of 0.4–0.45 mm) with porosity of 36%
Second stage	Regenerator	Annular structure, inner diameter of 8.9 mm, outer diameter of 18 mm, layer 1 filling 30mm Er_3Ni sphere (diameter of 0.2–0.25 mm) with porosity of 36%, layer 2 filling 40mm $HoCu_2$ sphere (diameter of 0.2–0.25 mm) with porosity of 36%,
	Pulse tube	Diameter of 8.5 mm, length of 70 mm
	Capillary tubes	0.4 mm*80 mm + 0.8 mm*0.2 m, connecting PTC hot end and cold reservoir
	Reservoir	Volume of 1 L

3. Experimental results and discussion

3.1. Phase shifters

In our previous simulation results [11], the phase relationship of the pulse tube showed that the function of capillary tube in this cryocooler was similar to a orifice. So the resistance of capillary tubes was very important for the performance of PTC. Table 2 showed the experimental results with different capillary tubes. The diameters of capillary tube in the case 1#~4# were all 0.4mm. And the resistances were adjusted by changing its length. With the increasing of its resistance, the mass flow rate flowed into the second stage decreased, and the working gas stay in the first stage would increase. So the temperature of the first stage would decrease but the temperature of the second stage had its optimal value because of the performance of regenerator. The optimal operating frequency was influenced by the resistance of capillary tubes. With the increasing of the resistance of capillary tube, the optimal operating frequency would decrease.

Table 2. Experimental results with different parameters of capillary tubes

Case	Parameters /mm	T1 /K	T2 /K	Opt. Frequency
1#	Φ0.4*200+Φ0.8*200	4.68	15.0	1.06
2#	Φ0.4*150+Φ0.8*200	4.55	15.8	1.38
3#	Φ0.4*120+Φ0.8*200	4.21	16.3	1.53
4#	Φ0.4*100+Φ0.8*200	4.41	18.0	1.61

3.2. Regenerators

Regenerator is one of the most important parts in the cryocooler, especially for the 4K cryocooler. In order to improving the performance of VM/PT cryocooler, the regenerator in the second stage was optimized. The mainly studies was focus on the layered structure filling method. For the regenerator of the first stage (R1), SS screen, lead sphere and Er_3Ni sphere were used. For the regenerator of the second stage (R2), Er_3Ni and $HoCu_2$ sphere were used.

Figure 2 showed the lowest temperature of second stage changed with the increasing of the length of Er_3Ni in the R1.The lowest temperature appeared its optimal value at the 40mm length of Er_3Ni. It is because that the volume heat capacity of Er_3Ni is larger than the lead at the temperature below 20K.

When the filling amount of Er_3Ni is too large, it may work at the temperature above 20K. So the filling length of Er_3Ni in the R1 has an optimal value.

Figure 3 showed the lowest temperature of second stage changed with the increasing of the length of $HoCu_2$ in the R2.The volume heat capacity of $HoCu_2$ shows its advantage at the temperature below 7K. A suitable filling amount of $HoCu_2$ could improve the performance of R2. The optimal length was about 60mm, and the lowest temperature of 3.06K was obtained.

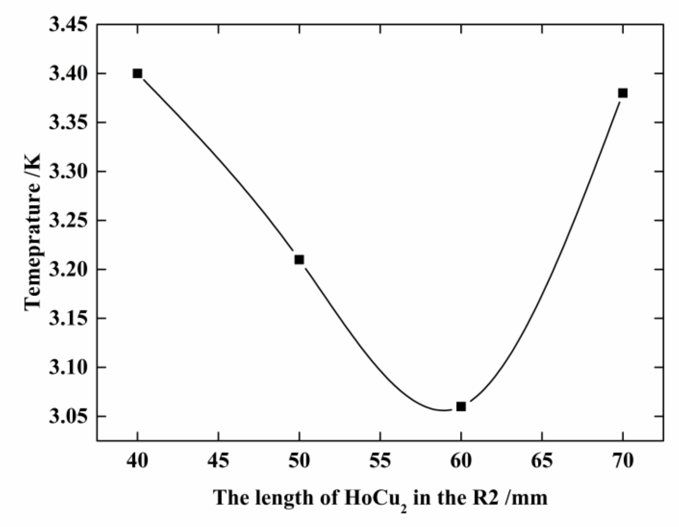

Figure 2. The lowest temperature of second stage changed with the increasing of the length of Er_3Ni in the R1

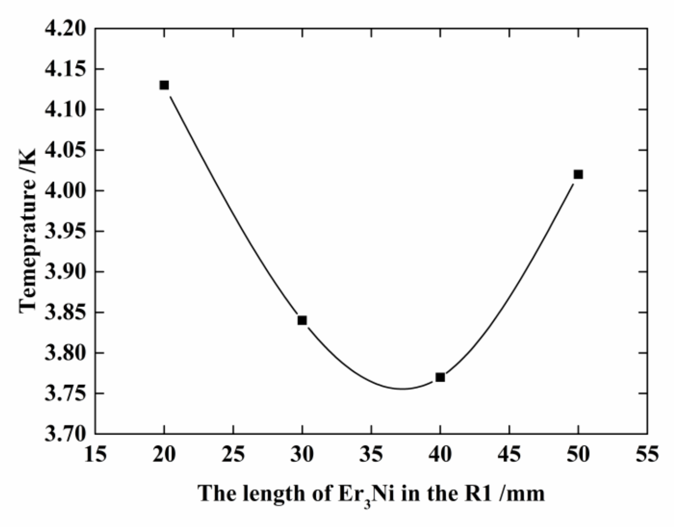

Figure 3. The lowest temperature of second stage changed with the increasing of the length of $HoCu_2$ in the R2

3.3. Operating pressure

The operating pressure is another important factor for the performance of VM/PT cryocooler. With the decreasing of the temperature of cold end, the average pressure would decrease. The initial charging pressure of this cryocooler was about 1.8MPa. When the temperature cooled down to the temperature around 5K, its average pressure would decrease to 0.6MPa. With so small average pressure, the input acoustic power of cooler was too small to overcome the heat losses in the regenerator, so the performance of cryocooler was not very well. Increasing of the operating pressure in the system would increase the input acoustic power and obtain a lower coldest temperature in the cold end. On the other hand, too large operating pressure would worsen the performance of regenerator and worsen the performance of cryocooler. Figure 4 showed the influence of average pressure on the lowest temperature. It can be seen that the optimal operating pressure was about 1.3MPa for this cryocooler.

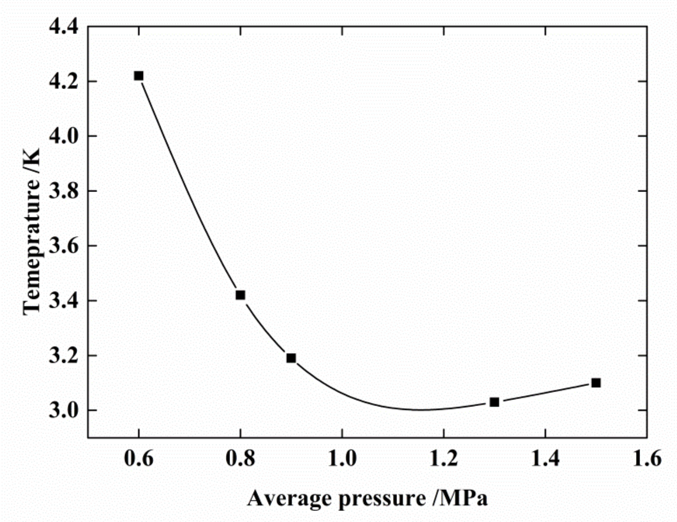

Figure 4. The influence of operating pressure on the lowest temperature

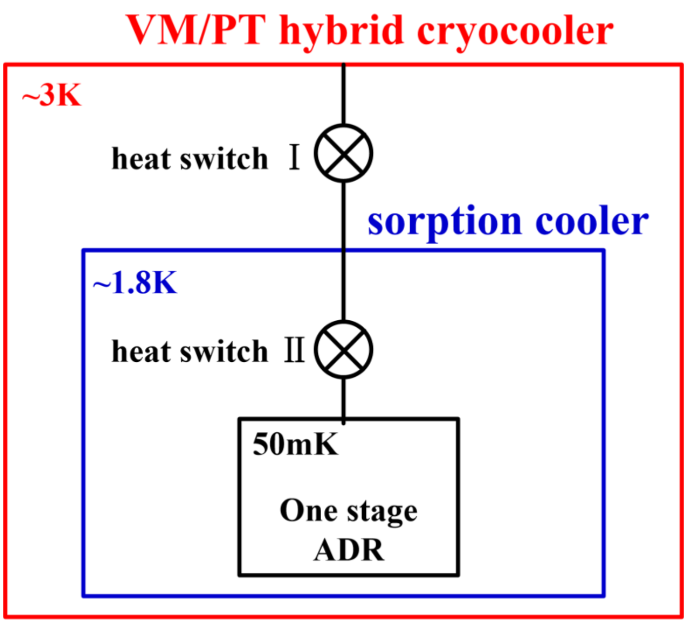

Figure 5. An alternative cooling method for TES

3.4. Further Development

In order to satisfy the requirements of TES, an ultra-low temperature refrigerator, such as adiabatic demagnetization refrigerator (ADR), need to be used. The precooling temperature of ADR should reach around 2K. Therefore, the next researches will focus on the method to obtain the lower temperature in VM/PT cryocooler. At present, by optimizing on the diameter of $HoCu_2$ in the R2, a lowest temperature of 2.6K was obtained in this cryocooler. We have also optimized the heat exchanger of cold end, but it hasn't showed any good results.

Based on the present experimental results, an alternative cooling method is combining with a sorption cooler to precool the ADR. Figure 5showed the schematic diagram of this cooling method.

By using this VM/PT cryocooler to precool a sorption cooler, the temperature around 1.8K could be obtained by using He-4. And then using a one stage ADR, the temperature below 50mK could be obtained. This cooling chain could be another chooses for TES because of its compact and low-power consumption.

4. Conclusion

This paper presented the experimental progress of the 4K VM/PT hybrid cryocooler in our laboratory. By optimizing the phase shifter (capillary tubes), regenerators (layered structures) and the operating pressure, a no-load temperature 2.6K was obtained. The optimal operating pressure was about 1.2MPa and the optimal operating frequency was about 1.5Hz. Based on this experimental result, we proposed a novel compact and low-power consumption cooling chain for TES.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (No. 2016YFB0901403) and National Postdoctoral Program for Innovative Talents (Foundation No. BX201600173)

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