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Design and experiments of a 1 K superfluid ^{4}He system for precooling the ultra-low temperature refrigerators

Jiarun Zou[1,2#]; Ziyao Liu[1#]; Zijie Pan[1*]; Lingjiao Wei[1]; Maowen Zheng[1*]; Haowen Guo[1,2]; Houlei Chen[1]; Jingtao Liang[1,2]

[1] Key Laboratory of Cryogenic Science and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Science, Beijing 100190, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China

[*]E-mail: panzijie@mail.ipc.ac.cn; zhengmaowen@mail.ipc.ac.cn

Abstract. With the development of the frontier domains such as quantum computing, condensed matter physics and space exploration, there is an urgent need for the multi-stage ultra-low temperature refrigerators to reduce the internal thermal noise and external thermal interference of the equipment. The superfluid ^{4}He system is a key component of the 1 K stage of ultra-low temperature refrigerators. Its cooling capacity depends on the throttling, liquefaction and evaporation process which are affected by the impedance. In this paper, a superfluid ^{4}He system is used to precool a space dilution refrigerator. To balance the thermal load of the helium isotopes, the influences of the impedance parameters, the flow rates and the heat exchange modes on the performance of the superfluid ^{4}He system are researched. A capillary which can provide a pressure drop of 1 bar is selected as the impedance by calculation, with the inner diameter of 100 μm and the length of 1 m. The superfluid ^{4}He system can reach a lowest temperature of 1.06 K, with the cooling power of 30 mW@1.41 K. It can meet the precooling requirement of the ultra-low temperature refrigerators in the start-up and operation processes.

1. Introduction

Sub-Kelvin technology means the cryogenic technology which operates in the temperature below 1 K [1]. Many quantum bit effects require the sub-Kelvin environment to reduce the thermal noise and ensure the stability of quantum states. With the high-speed development of quantum technology and space science, it puts forward more and more requirements for sub-Kelvin cryogenic technology. The sub-Kelvin refrigerators including adsorption refrigeration, adiabatic nuclear demagnetization refrigeration, and dilution refrigeration, are all overlapping cryogenic systems that require the 1 K pre-cooling stage to meet the start-up requirement. Superfluid ^{4}He system is one of the common 1 K precooling equipment for sub-Kelvin refrigerators, which utilize throttling, liquefaction, and depressurized evaporation processes to achieve the temperature of 1 K [2,3]. It has been widely applied in international precision equipment such as superconducting single photon detectors, large hadron colliders, quantum computers and muon colliders by research institutes such as CERN [4–7]. In the superfluid ^{4}He system, the flow impedance is a key component which directly affect the throttling and liquefaction process.

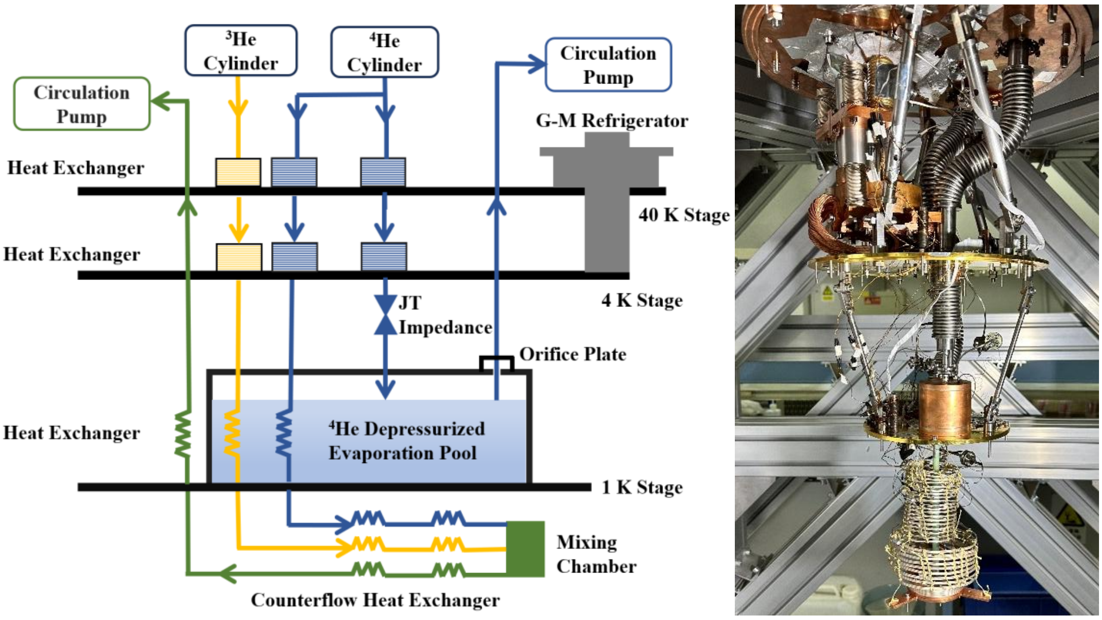

Figure 1. Structure and working process of the superfluid ^{4}He system

In this paper, a 1 K superfluid helium liquid pool system is developed, including the key components such as capillary flow impedance, evaporation liquid pool, and orifice plate to inhibit the superfluid crawling membrane. The ^{4}He cycle is driven by a scroll pump, and a G-M refrigerator is equipped for 4 K-stage precooling. Different designs of the 1 K superfluid ^{4}He pools are researched and their impedance characteristics are obtained. Finally, an appropriate structure of the superfluid ^{4}He pool is selected, and it can provide a precooling temperature of 1.1 K, which meets the start-up requirement of the space dilution experiment.

2. The principle of the 1K superfluid ^{4}He pool

2.1 System structure and working process

The refrigeration principle of the superfluid ^{4}He pool is derived from the throttling, liquefaction, and evaporation of ^{4}He. The structure and working process of the superfluid ^{4}He pool is shown in Figure 1. In this experiment, the cooling capacity of the superfluid ^{4}He pool is used to cool a space dilution refrigerator, so the two are thermally coupled, and the heat exchange takes place at the 1 K plate. The cold plate and inner vacuum cover are constructed of oxygen-free copper with gold-plated surfaces in order to minimize radiant heat leakage. The pool operates at the temperature around 1.1 K. When the system is in operation, ^{4}He gas is injected at ambient temperature and pressure, and is cooled by the GM refrigerator to 4 K. ^{4}He throttles through the flow impedance, and a part of the gas is liquefied, the enthalpy is constant before and after the throttling process. The circulating pump extracts the throttled ^{4}He and the liquid temperature decreases to the superfluid region as the pressure decreases. Mechanical pumping leads to the evaporation of liquid ^{4}He, and the gas can be returned to the system inlet again. The space dilution unit is cooled to around 1.4 K by the superfluid ^{4}He pool, and further cooled by the counterflow heat exchanger. Finally, dilution refrigeration occurs in the mixing chamber, completing the startup process. The cooling power of the superfluid ^{4}He system originates from the latent heat of ^{4}He evaporation, it can be expressed as Eq (1):

$$Q_{JTpol} = \dot{m}q_{lat} \tag{1}$$

Where q_{lat} is the latent heat of evaporation of ^{4}He, which is about 22 J/g; $\dot{m}$ is the mass flow rate of ^{4}He. The heat load of the space dilution unit is about 10mW, it requires the mass flow rate of about 0.11 mmol/s. Define $\dot{V}_p$ as the pumping speed, ρ_p as the density of ^{4}He in the inlet of pump. We neglect the pressure differential along the pipe, $\dot{m}$ can be expressed from Eq (2):

$$\dot{m} = \rho_p \dot{V}_p \tag{2}$$

Based on the required mass flow rate, we select an Agilent TS-600 mechanical pump with a maximum pumping speed of 30 m^3/h in this system.

2.2 Capillary flow impedance

The flow impedance is a key component of the superfluid ^{4}He pool, which is used to control the liquid helium liquefaction rate and to maintain the pressure difference between the inlet and outlet of the pool, in order to achieve a balance between liquid helium evaporation and replenishment. This system uses a capillary flow impedance, which is able to adjust the impedance value by changing its length. Since the vapor temperature of ^{4}He is exponentially related to the saturated vapor pressure as shown in Figure 2, if the superfluid ^{4}He pool needs to operate below the temperature of 1.4 K, the saturated vapor pressure should be lower than 287 Pa. Assuming the inlet pressure is ambient, the system requires the flow impedance to provide a pressure difference of around 1 bar. Therefore, the design of the flow impedance is important for the cooling capacity of the superfluid ^{4}He pool. The impedance value Z can be calculated from Eq (3):

$$Z = 128l / \pi d^4 \tag{3}$$

Where l and d are the length and inner diameter of the capillary. Based on the principle of throttling refrigeration, if the flow impedance gets smaller, the ^{4}He flow rate will be larger, which can increase the cooling power of the superfluid ^{4}He pool. However, in practice, too small

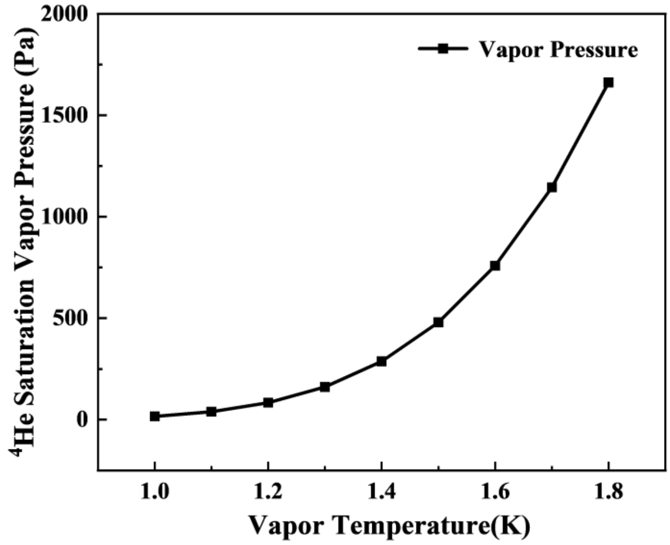

Figure 2. The correspondence between the saturation vapor pressure and vapor temperature of ^{4}He from 1 K to 1.8 K

impedance value will adversely affect the throttling and liquefaction process because it reduces the pressure drop of ^{4}He, making it difficult for the pool to reach a lower temperature [8]. In the circular pipe, the pressure difference of constant flow can be calculated from the friction coefficient *f*, which can be calculated based on its flow state. Substituting the mass flow rate $\dot{m}$, the Reynolds number of the fluid can be simplified to Eq (4):

$$\mathrm{Re} = \frac{\rho v d}{\mu} = \frac{\dot{m} d}{s \mu} = \frac{4\dot{m}}{\pi d \mu} \tag{4}$$

Where ρ is the density of ^{4}He; s is the cross-sectional area of capillary; v is the flow velocity; μ is the viscosity coefficient of ^{4}He. If Re≤2300, the fluid is laminar flow, the friction coefficent is calculated by Eq (5):

$$f = \frac{64}{\mathrm{Re}} \tag{5}$$

If Re>2300, the fluid is turbulent flow, the friction coefficent is calculated by Eq (6):

$$f = 0.316\,\mathrm{Re}^{-\frac{1}{4}} \tag{6}$$

Then the pressure difference Δp can be calculated from Eq (7):

$$\Delta p = f \frac{l}{d} \frac{\rho v^2}{2} \tag{7}$$

We consider a series of capillaries with the inner diameter of 80 μm, 100 μm, and 120 μm as the impedance. The pressure difference provided by the capillary at these inner diameters and different lengths can be obtained from calculation, as shown in Figure 3. Based on the designed pressure drop, a copper-nickel capillaries with the inner diameter of 100 μm and the length of 1 m is selected as the impedance. For the selected capillary, the Reynolds number of the fluid is 7242, corresponding to turbulent flow state. The impedance value is 4.07×10^{11} cm^{-3}.

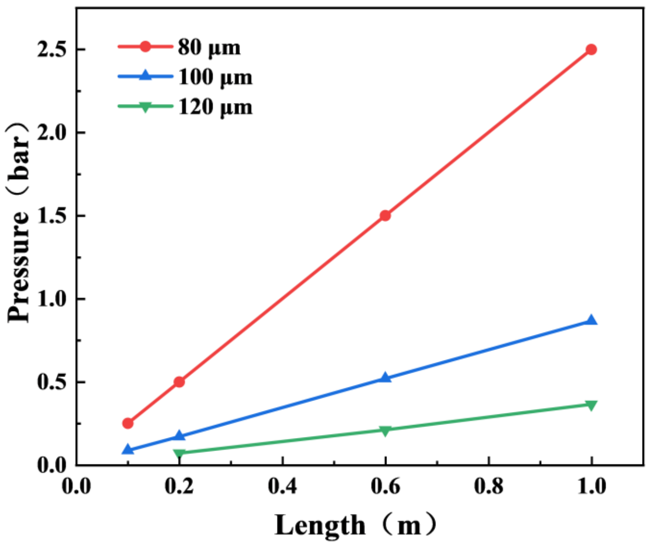

Figure 3. The pressure difference of the impedance with different diameters and lengths

Figure 4. The orifice plate structure in the system to inhibit the superfluid helium crawling membrane

2.3 Structure for suppressing superfluid helium crawling membrane

Superfluid helium crawling membrane leads to one of the key heat leakages in the superfluid ^{4}He pool. The superfluid ^{4}He has a very small viscosity and is likely to produce a crawling membrane on the wall. The crawling membrane of superfluid helium reaches a higher temperature and evaporates rapidly, causing a significant increase in temperature and pressure of the pool, which ultimately limits the refrigeration performance. The thermal conductivity of superfluid helium is good, so heat will also be introduced through the membrane from the high-temperature region to the pool.

Therefore, the orifice plate structure shown as Figure 4 is introduced in the system to inhibit the superfluid helium crawling membrane rate. The thickness of the orifice plate is 0.5 mm, and 7 holes with the diameter of 1 mm are machined on the plate. In practice, the orifice plate that is too thick or too thin will also limit pumping performance, and will ultimately affect the lowest temperature. From the experiments, this structure can limit the heat leakage of the crawling membrane to within 3 mW.

2.4 Depressurized evaporation

In the superfluid ^{4}He system, the throttled ^{4}He evaporates because of pumping. The liquid pool is constructed of oxygen-free copper to enhance heat transfer effect. As the evaporation cooling capacity of this system is sufficient and the membrane climbing is effectively inhibited, the heat leakage in the evaporation pool can be ignored. Therefore, the evaporation cooling capacity of the ^{4}He pool only includes the latent heat of vaporization of ^{4}He, which can be calculated from Eq (1). Considering the dryness of ^{4}He after throttling, the theoretical cooling capacity of the pool is calculated to be 47 mW@1.4 K and 6.4 mW@1.1 K.

3. Experimental results and analysis

The superfluid ^{4}He pool is coupled with a space dilution unit to verify its cooling performance. The required start-up temperature for space dilution refrigerator is less than 1.6 K [9], for the isotope to further generate phase interface droplets in the capillary, and then undergo osmotic dilution process [10].

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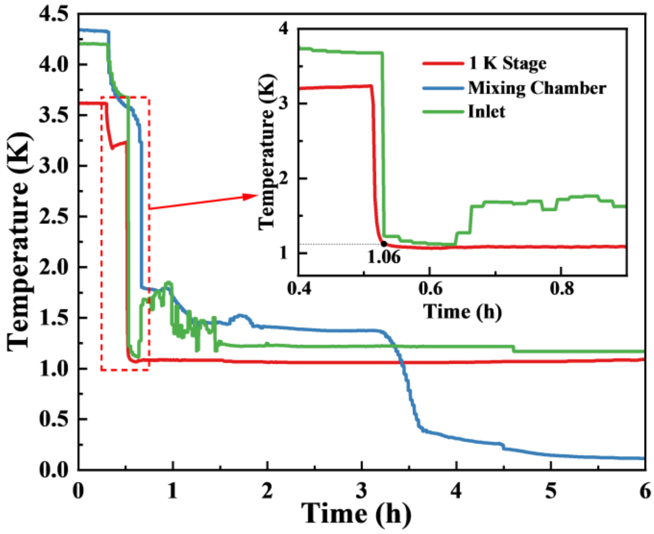

Figure 5. Cooling process of the superfluid ^{4}He pool and the space dilution unit

Early experiments show that immersing the 1 K dilution pipe in the superfluid ^{4}He pool will improve the precooling efficiency because of the increase in heat transfer area. Figure 5 shows the cooling process of the space dilution refrigeration system. It demonstrates that when the system is precooled sufficiently, the temperature reaches 3.7 K before throttling. After injecting ^{4}He and starting the circulation pump, the 1 K stage can be cooled quickly to 1.06 K in several minutes, causing the inlet of dilution unit cooling down together. When the helium isotope is injected in the dilution pipe, the inlet shows small temperature fluctuations but eventually stabilizes at 1.2 K,

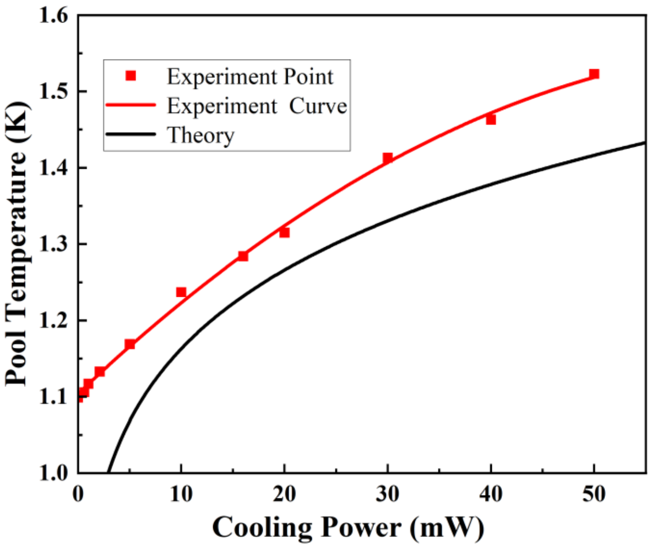

Figure 6. The heating experiment curve of the superfluid ^{4}He pool system

with the 1 K plate temperature maintains stability. It indicates that the cooling capacity is sufficient to balance the heat flow from the helium isotope with the maximum flow rate of 149 μmol/s in the experiment. As the superfluid ^{4}He pool cools the whole dilution unit down to less than 1.4 K, space dilution refrigeration with capillary forces occurs and causes a large temperature drop in the mixing chamber. Eventually it reaches the temperature of 91 mK.

The cooling capacity of the superfluid ^{4}He pool is tested from heating experiment as shown in Figure 6. The average temperature of the experimental system is 0.1 K higher compared to theory, presumably due to heat leakage and viscous temperature rise. The superfluid ^{4}He pool can reach the cooling power of 30 mW@1.41 K, which is sufficient for the startup requirements of space ultra-low temperature refrigerators. We plan to further transform the superfluid ^{4}He pool into a space Joule-Thomson refrigerator for gravity-free operation.

4. Conclusion

Ultra-low temperature refrigerators are all multi-stage cryogenic systems, and the precooling of the 1 K stage is important for their startup process. Based on the principle of throttling refrigeration, we build a superfluid ^{4}He pool system and conduct research on the structural parameters, flow rate, and heat exchange means of its flow impedance. A copper-nickel capillary with the inner diameter of 100 μm and the length of 1 m is selected as the flow impedance for this system. The pumps used in the experiment are able to meet the requirements for the designed flow rate of the pool, and the superfluid helium crawling membrane is effectively suppressed by the orifice plate structure. After optimization, the cooling capacity of the superfluid ^{4}He pool in the experiment can reach 1.06 K, and the cooling power is 30 mW@1.4 K. It can meet the startup requirements of the ultra-low temperature cryogenic refrigerators, and the space dilution refrigerator in the experiment finally reaches the temperature of 91 mK. In the future, a further evolution into a Joule-Thomson refrigerator will be conduct for the precooling of space cryogenic refrigerators in the gravity-free environment.

Acknowledgments

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