Design and performance evaluation of a closed-cycle single-shot ^{3}He sorption cooler

Xiang Fan[1,2,3], Juan Wang[1,2*], Shubao Zhao[1,2,3], Yilin Lei[4], Lingjiao Wei[1,2], Yuexue Ma[1,2] and Miguang Zhao[1,2]

[1] Technical Institute of Physics and Chemistry, Chinese Academy of Science, Beijing, China
[2] State Key Laboratory of Cryogenic Science and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China
[3] University of Chinese Academy of Sciences, Beijing, China
[4] Department of Mechanical Engineering, Michigan State University, Michigan, USA

*E-mail: wangjuan@mail.ipc.ac.cn

Abstract. Sub-Kelvin technology plays a crucial role in both ground-based experiments and space exploration. ^{3}He sorption cooling is one of the few methods capable of achieving temperatures below 500 mK. The sorption cooler is based on the principle of liquid helium evaporation refrigeration, and the adsorption and desorption of helium gas are realized by periodically cooling and heating activated carbon. Due to its advantages, including compact size, light weight, absence of vibration and electromagnetic interference, and simple operation, it offers strong competitiveness in the field of space extreme low temperature refrigeration. In this paper, we present the design and performance evaluation of a closed-cycle single-shot ^{3}He sorption cooler, which incorporates a sorption pump filled with activated carbon granules. The ^{3}He sorption cooler, pre-cooled by a two-stage GM type pulse tube refrigerator and a superfluid helium bath, achieves a minimum temperature of 393.6 mK and provides a net cooling power of 200 μW at 486 mK. At a charge of 2 STP L ^{3}He, a single cycle can be maintained at temperatures below 400 mK for about 6 hours. The ^{3}He sorption cooler needs further optimization and is expected to be used for pre-cooling of the adiabatic demagnetization refrigerator in the future.

1. Introduction

Cryogenic technology is pivotal for advancing ground experiments and space exploration. While the evaporation of liquid ^{4}He via mechanical pump decompression can achieve temperatures of 1.0–1.2 K, achieving temperatures below this range poses significant challenges. The helium sorption coolers addresses this limitation by replacing mechanical pumps with sorption pumps, enabling operation at sub-Kelvin temperatures (below 1 K). A key advantage of sorption pumps lies in the elimination of external pumping systems [1]. Through meticulously optimized adsorbent configurations, these coolers not only achieve efficient pumping speeds but also enhance the system's stability and reliability. Owing to the simplicity, compact design, and absence of moving parts, helium sorption coolers have been used in the field of astronomy. The integration of sorption pump technology facilitates miniaturization and automation, while the reliance on static components minimizes operational complexity—only low-current heaters are required during cycling [2, 3].

A typical operating temperature for a sorption cooler utilizing ^{4}He as the working fluid is 800 mK, whereas for one using ^{3}He, it is 300 mK [2]. There are two main reasons for the temperature difference: firstly, at identical temperature, ^{3}He exhibits a higher saturated vapor pressure than ^{4}He [3], so when a sorption pump attains the same pressure, the corresponding saturation temperature for ^{3}He becomes markedly lower than that of ^{4}He. Secondly, when the temperature drops below 2.17 K, liquid ^{4}He transitions into a superfluid state, and the superfluid helium film evaporates directly in the pump tube [4, 5]. This does not produce an effective cooling effect and directly leads to a loss of cooling capacity and a reduction in the duration of continuous refrigeration for the sorption cooler. Additionally, the superfluid helium film adhering to the pump tube intensifies the heat conduction between the pump tube and the evaporator, greatly increasing the parasitic load of the evaporator. Therefore, to achieve an operating temperature below 500 mK, it is necessary to use ^{3}He as the circulating working fluid. In this paper we design and manufacture a laboratory prototype of a ^{3}He sorption cooler and conducts experimental tests.

2. Structural design and system introduction

2.1 Structure and working process of ^{3}He sorption cooler

The ^{3}He sorption cooler operates intermittently, characterized by its ability to provide cooling effects during specific periods. Once the liquid in the evaporator has completely evaporated, the system must restart the cycle. Despite this, the overall operating time of the sorption cooler appears quite long compared to the time needed for regeneration. A typical ^{3}He sorption cooler structure is shown in Figure 1, consisting of a sorption pump, a pump tube divided into three sections, a condenser, an evaporator, and a gas-gap heat switch. Its working cycle can be divided into two stages:

(1) Condensation stage: During this stage, the heat switch is OFF, and the sorption pump is heated to approximately 40 K (the desorption temperature). The ^{3}He gas condenses into a liquid state in the condenser (below the critical temperature of 3.2 K) and flows towards the evaporator due to gravity;

(2) Evaporation stage: After the condensation stage is over, the heat switch is ON, and the sorption pump is cooled to about 5 K (a strong adsorption state). The liquid ^{3}He in the evaporator evaporates under low pressure and absorbs heat, achieving cooling within the target temperature range.

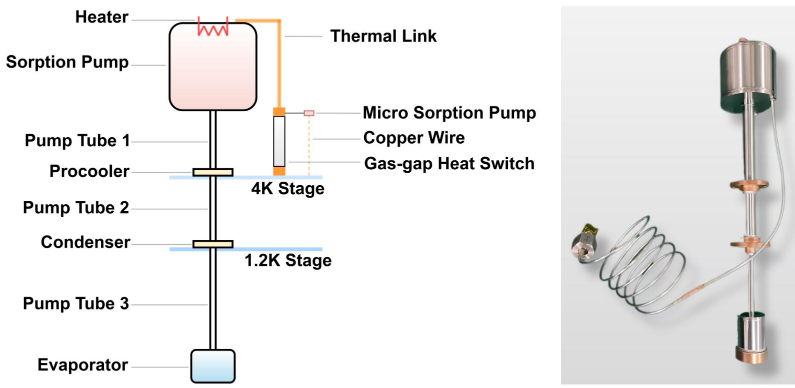

Figure 1. Schematic diagram and actual picture of the ^{3}He sorption cooler. The curved tube is the gas charging tube of the ^{3}He sorption cooler.

Table 1. A part of structural parameters of the prototype ^{3}He sorption cooler.

Pump tubes	Inner diameter (mm)	Wall thickness (mm)	Length (mm)
Sorption pump side wall	48	2	47
Pump tube 1	11.5	0.25	75
Pump tube 2	11.5	0.25	40
Pump tube 3	6.4	0.1	60
Evaporator side wall	22	1	35

The size of the pump tube must consider both flow rate and thermal conductivity [6]. To minimize heat leakage along the axial direction of the pump tube, a low thermal conductivity TC4 alloy was utilized, and the wall thickness was reduced to the minimum necessary to ensure adequate strength for withstanding gas pressure. The structural dimensions of ^{3}He sorption cooler used in the experiment are shown in Table 1. Before filling the sorption pump, the activated carbon granules need to be vacuum-baked, heating the activated carbon to 150 °C and maintaining it for over 12 hours. The sorption pump of ^{3}He sorption cooler used in the experiment was filled with 23 g activated carbon. The micro-sorption pump of the heat switch is connected to the 4 K cold plate through a thin copper wire, used to cool the heat switch micro-sorption pump. However, turning ON the heat switch necessitates heating the micro-sorption pump, which in turn increases heat dissipation to the 4 K cold plate.

2.2 Experimental system

Figure 2 illustrates a schematic diagram of the experimental system. A two-stage GM type pulse tube refrigerator is used to provide pre-cooling, and soft copper braids are used to connect the first and second stage cold heads and cold plates to minimize the impact of vibration on the sorption cooler. Additionally, a ^{4}He bath depressurized by a mechanical dry pump is employed to provide a condensation temperature as low as 1.2 K, allowing the ^{3}He gas to condense at the condenser and flow into the evaporator under the force of gravity.

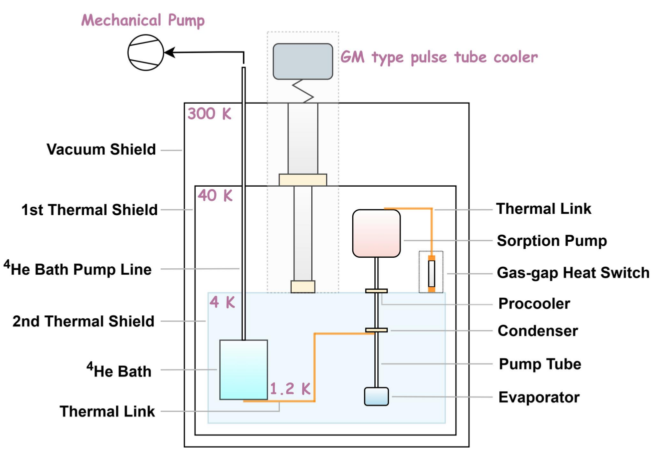

Figure 2. Schematic diagram of the experimental system, including cryostat and the ^{3}He sorption cooler.

2.3 Gas charging system

Considering the scarcity and high cost of ^{3}He, recycling of ^{3}He gas is required. In this experiment, the ^{3}He sorption cooler adopts low temperature depressurization, meaning the sorption pump is cooled to approximately 5 K, at which point the activated carbon is in a state of strong adsorption [7]. Consequently, the ^{3}He gas in the gas tank can flow into the sorption pump. To account for the possible existence of impurity gas in the gas tank, a liquid nitrogen cold trap was set up, with the spiral coil immersed in liquid nitrogen, aiming to condense these impurity gases. After the experiment test, the ^{3}He gas in the sorption cooler can be recovered to the gas tank through the circulating pump in the system. The gas charging system is depicted in Figure 3.

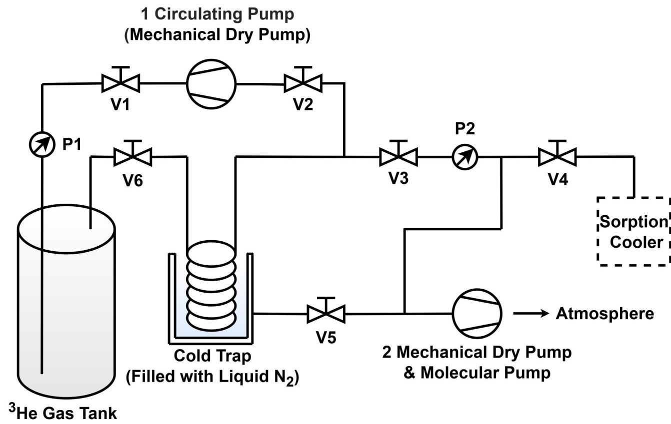

Figure 3. Schematic diagram of gas charging system. Valves are represented by *V*, and pressure gauges are represented by *P*.

3. Experimental results and discussion

3.1 Gas charging at low temperature

Before inflation, the ^{3}He sorption cooler needs to undergo gas flushing - filling with ^{4}He gas and evacuating, repeating this process multiple times. During the flushing procedure, the sorption pump must be heated to activate the activated carbon particles. All valves in the inflation system are closed. After the gas flushing process is completed, the GM type pulse tube refrigerator is started to pre-cool the whole experimental system until the first and second cold plates reach the expected temperature of about 40 K and 4 K respectively. Then, turn ON the heat switch to cool the activated carbon. The micro-sorption pump of the heat switch is heated to 24 K (the heating power is about 20 mW), the temperature of the sorption pump gradually decreases, and finally stabilizes at about 5 K. The temperature of the second cold plate will increase during the cooling period of the sorption pump.

Add liquid nitrogen to the cold trap, open valves 6 and 3, and then close valve 6 once the pressure gauge 2 stabilizes (near pressure gauge 1). Next, open valve 4. Only the ^{3}He gas between valve 6 and valve 4 will enter the sorption cooler, causing pressure gauge 2 to decrease. After the pressure is stable, repeat the above operation and inflate several times. The purpose of this small amount of inflation is to ensure that the ^{3}He gas is fully pre-cooled by liquid nitrogen and prevent the impurity gas from blocking the inflation tube. After each small amount of inflation, the temperature of the sorption pump rises first and then drops. The temperature increase can be attributed to two factors: firstly, the higher temperature of the ^{3}He gas entering the sorption pump; and secondly, the exothermic nature of the activated carbon adsorption process for ^{3}He gas [8]. By observing the temperature changes of the sorption pump during the inflation process, it becomes evident that the temperature rise diminishes, suggesting that the activated carbon's adsorption capacity is gradually reaching saturation. Finally, the ^{3}He gas charging volume is approximately 2 STP L in the experiment. The temperature variations of the sorption pump throughout the gas charging process are depicted in Figure 4.

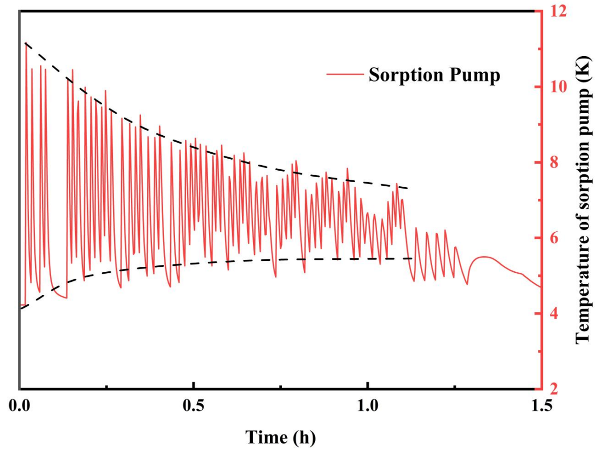

Figure 4. The temperature variations of the sorption pump during gas charging.

3.2 Condensation

After inflation, prepare for condensation of ^{3}He gas in the sorption cooler. At this stage, turn OFF the heat switch, turn off the heater to close the heat switch. When the temperature of the micro-sorption pump drops to 10 K, the heat switch is gradually disconnected. Once the sorption pump temperature is stable, heat the sorption pump to gradually increase and stabilize the temperature at about 40 K. At the beginning, 76 mW is applied to the sorption pump, causing a rapid temperature increase. After half an hour, reduce the heating to 30 mW. As the temperature rises, the ^{3}He gas begins to desorb from the activated carbon, causing the internal pressure of the sorption cooler to gradually increase. When the pressure reaches the saturated vapor pressure corresponding to the condenser temperature (1.2 K, provided by the superfluid ^{4}He bath), the ^{3}He gas starts to liquefy and flows into the evaporator due to gravity.

Notably, the evaporator temperature remains high when the ^{3}He gas does not condense. This is because the pump tube 3 has a very thin wall thickness (0.1 mm), making it challenging for the condenser's cooling capacity to transfer from the pump tube to the evaporator. However, as more and more ^{3}He gas is desorbed from the activated carbon, the internal pressure of the sorption cooler rises, leading to a convection effect between the evaporator and the condenser. Acting as a heat transfer medium, the ^{3}He gas causes the evaporator's temperature to gradually decrease. When the ^{3}He gas condenses into a liquid, the evaporator temperature drops rapidly. Once condensation ceases, the evaporator temperature becomes essentially the same as the condenser temperature.

3.3 Evaporation cooling

Once the evaporator's temperature stabilizes, the adsorption and evaporation cooling process commences. Stop heating the sorption pump; when the heat switch is turned ON, the temperature of the sorption pump gradually decreases, and the activated carbon enters the strong adsorption phase. Liquid ^{3}He starts to evaporate, producing cooling and lowering the evaporator temperature. When the sorption pump temperature stabilizes at approximately 5 K, the evaporation temperature also reaches its lowest point. The experiment achieved a minimum temperature of 393.6 mK, maintaining it below 400 mK for 6 hours without any load. Once the liquid ^{3}He is completely evaporated, the evaporator temperature rises rapidly and returns to the temperature of about 8 K before the condensation stage begins. Figure 5 illustrates the temperature variation over time for the evaporator and sorption pump. In another experiment, to simulate the thermal load, 200 μW of heat was applied to the bottom of the evaporator, causing the temperature to rise to 486 mK, which was sustained for about 2 hours. It can be expected that if the amount of ^{3}He gas is increased, the hold time will also increase.

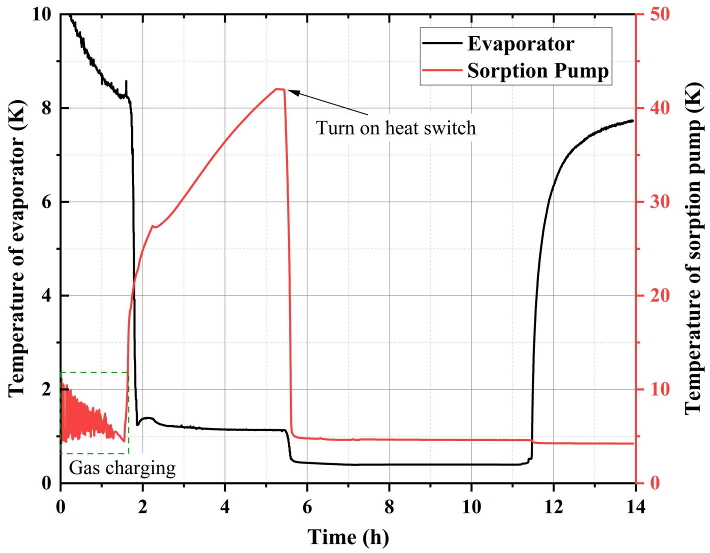

Figure 5. Time versus temperature plot.

4. Conclusion

This paper presents the design and performance of a prototype single-shot ^{3}He sorption cooler, achieving a minimum cooling temperature of 393.6 mK under no load with a 6-hour hold time. Additionally, it can provide a cooling capacity of 200 μW below 486 mK. The performance of the prototype still requires optimization, with a primary focus on the sorption pump structure. Since the temperature measurement point of the sorption pump is outside, the internal temperature of the activated carbon granules cannot be determined. It is possible that due to the non-optimized design of the sorption pump structure, the activated carbon has not been adequately cooled, leading to a decline in adsorption performance. The next research plan aims to optimize the prototype for use in pre-cooling within an adiabatic demagnetization refrigerator. This work is currently being adjusted and ongoing.

Acknowledgments
This work was supported by the Innovation Program for Quantum Science and Technology (No. 2023ZD0300100).

References

[1] Torre JP, Chanin G. Miniature liquid-^{3}He refrigerator. Rev Sci Instrum 1985;56:318–20. https://doi.org/10.1063/1.1138350.
[2] Xi X, Wang J, Chen L, Zhou Y, Wang J. Progress and challenges of sub-kelvin sorption cooler and its prospects for space application. J Low Temp Phys 2020;199:1363–81. https://doi.org/10.1007/s10909-020-02442-1.
[3] L. Piccirillo, G. Coppi, A. May. Miniature sorption coolers – theory and application. CRC Press; 2018.
[4] May AJ, Coppi G, Haynes V, Melhuish S, Piccirillo L, Sarmento T, et al. A highly effective superfluid film breaker for high heat-lift 1 K sorption coolers. Cryogenics 2019;102:45–9. https://doi.org/10.1016/j.cryogenics.2019.07.007.
[5] Lei Y, Hong G, Quan J, Zhao Y, Li R, Wang G, et al. Design and development of a ^{4}He sub-Kelvin sorption cooler. Cryogenics 2024;141:103876. https://doi.org/10.1016/j.cryogenics.2024.103876.
[6] Masi S, Aquilini E, Cardoni P, De Bernardis P, Martinis L, Scaramuzzi F, et al. A self-contained ^{3}He refrigerator suitable for long duration balloon experiments. Cryogenics 1998;38:319–24. https://doi.org/10.1016/S0011-2275(97)00174-4.
[7] Li Z, Deng W. Investigation on the adsorption characteristics of activated carbons in the sub-kelvin ^{4}He sorption cooler. Cryogenics 2024;140:103861. https://doi.org/10.1016/j.cryogenics.2024.103861.
[8] Pobell F. Matter and methods at low temperatures. 3rd, revised and expanded ed. Berlin: Springer; 2007.