Experimental Investigation of a Helium Sorption Cooler Operating below 1 K

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Abstract. With advancements in space exploration and condensed matter physics, the demand for ultra-low temperature (mK) technology is on the rise. Sorption coolers, known for their extended service life, absence of moving parts, low vibration, high reliability, and immunity to electromagnetic interference, stand out as a crucial refrigeration technology for the future. In this study, we successfully developed a prototype single-stage sorption cooler, utilizing helium-4 as the working gas. Research findings demonstrate that our prototype sorption cooler can achieve a minimum temperature of 827 mK, with a hold time of 19 hours under no load conditions. To meet the demands for prolonged operation, our unit is actively involved in the development of a continuous sorption cooler.

1. Introduction

Cryogenic conditions play an indispensable role in scientific research and engineering applications. Their necessity is evident in various fields, including the in-depth study of material properties, extensive practical applications in cryogenic engineering, advancements in quantum computing[1] and information processing, efficient energy storage and transmission, and deep exploration in astronomical observations[2,3]. Various refrigeration systems have been developed to meet the needs of quantum voltage standards and quantum computers. Common ultra-low temperature refrigeration technologies in the sub-Kelvin range include dilution refrigeration[4], adsorption refrigeration, and adiabatic demagnetization refrigeration. Among these, adsorption refrigeration, as a closed-cycle refrigeration method, offers advantages such as independence from gravity and scarce helium-3, compactness, high efficiency, no electromagnetic interference, vibration-free operation, and long lifespan. Adsorption refrigerators operate based on the varying adsorption capacity of adsorbents at different temperatures, creating a pressure differential by adsorbing the working fluid at lower temperatures, leading to throttling or evaporative cooling of the fluid.

In 2009, a cryogenic adsorption refrigerator was deployed in space for the first time aboard the Herschel satellite, using helium-3 as the working fluid and achieving a minimum temperature of approximately 300 mK[5]. Since the initial design of the single-stage helium adsorption refrigerator, numerous advancements have been reported, including coolers utilizing 4He to reach 1 K and serial coolers with a single-stage 4He precooling stage.

Over the past two years, the Shanghai Institute of Technical Physics has conducted several studies on adsorption refrigeration. Our laboratory focuses on providing long-lifespan, low-vibration, and high-efficiency cooling for space applications, with extensive experience in designing and manufacturing Stirling cryocoolers and pulse tube cryocoolers[6]. Several typical Stirling and pulse tube refrigerators, coupled with Joule-Thomson (JT) refrigerators, have been designed and manufactured, serving as precooling stages for adsorption refrigerators.

In the design of refrigerators, thin-walled stainless steel tubes are typically used as the pump tubes connecting to the evaporator. Due to the low thermal conductivity of stainless steel at cryogenic temperatures, this design generally meets the requirements. However, existing designs lack an analysis of the impact of pump tube parameters on the overall performance of the refrigerator. Therefore, this paper conducts an analysis of the parameters related to pump tubes and components in the flow path.

2. Structure of the Helium Adsorption Refrigerator

The structure of the helium adsorption refrigerator includes an adsorption pump, condenser, evaporator, and superfluid suppressor. The adsorption pump is filled with high-performance activated carbon (3500 m^2/g). The condenser of the adsorption refrigerator is coupled with the second-stage cold head of the GM cryocooler and tested in a vacuum chamber. A photo of the cold head is shown in the figure 1.

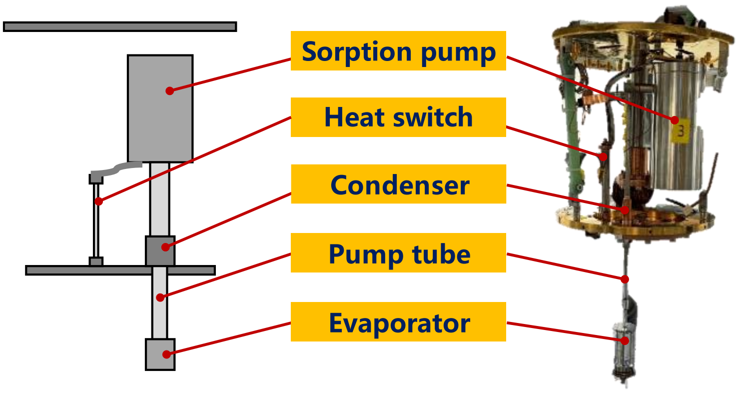

Figure 1. Photo of the SPR helium adsorption refrigerator.

The adsorption pump exchanges heat through fins and activated carbon, with diode temperature sensors on the fins for temperature measurement. The temperature of the adsorption pump is controlled by a thermal switch and a heating element. The volume of the adsorption pump is approximately 170 cc, and it is filled at room temperature with a filling pressure of about 40 bar. The developed thermal switch has a diameter of 6 mm and a filling pressure of 1 bar at room temperature. The thermal switch's adsorption pump is connected to the GM cryocooler's cold head via copper wires. The adsorption pump and thermal switch are placed outside the second-stage cold shield to minimize radiative heat leakage to the evaporator and second-stage cold shield. Inside the second-stage cold shield, only the evaporator and pump tube are present. The evaporator is connected to the condenser via the pump tube, which is made of titanium alloy to significantly reduce heat transfer at low temperatures. Heat transfer from the condenser to the evaporator is achieved through convection of the working fluid within the pump tube. A small hole to suppress superfluid helium film crawling is located at the upper end of the evaporator. All components are sealed by brazing. There are also supporting systems, such as the vacuum system, power supply, and data acquisition system.

3. Results

To achieve a larger cooling capacity and longer holding time for the adsorption refrigerator, a numerical model was established and simulation analysis was conducted. The study focused on the effects of condenser temperature and pump tube diameter on the overall system performance, as well as a comparative analysis of different design schemes.

Figure 2 illustrates the variation of liquid helium mass in the evaporator with respect to the condenser temperature. It can be observed that as the condenser temperature increases, the obtained liquid helium mass decreases. The computational model indicates that it becomes challenging to obtain a sufficient amount of liquid helium for refrigeration when the condenser temperature exceeds 5K. The green portion represents the portion consumed during the cooling process from 4K to 0.8K, while the blue portion represents the remaining part. These results demonstrate the necessity of minimizing the condenser temperature to enhance the liquid helium mass in the evaporator, thereby improving the cooling capacity and holding time.

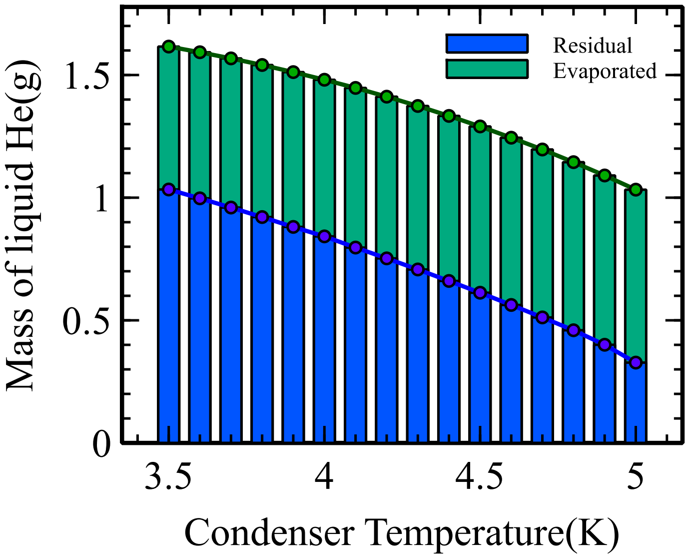

Figure 2. Relationship Between Liquid Helium Evaporation Rate, Remaining Quantity, and Condenser Temperature.

Figure 3 presents a comparison between the heat switch (HS) scheme and the pump tube (Pipe) scheme. When using the pump tube as a precooling scheme, the adsorption refrigerator experiences a significant deterioration in condensation performance when the evaporator heat load exceeds 40 μW. Moreover, when the heat load surpasses 130 μW, the pump tube fails to reduce the evaporator temperature below the condensation temperature of liquid helium (5.2 K).

Under these conditions, liquid helium cannot condense within the evaporator, rendering the adsorption refrigerator inoperable.

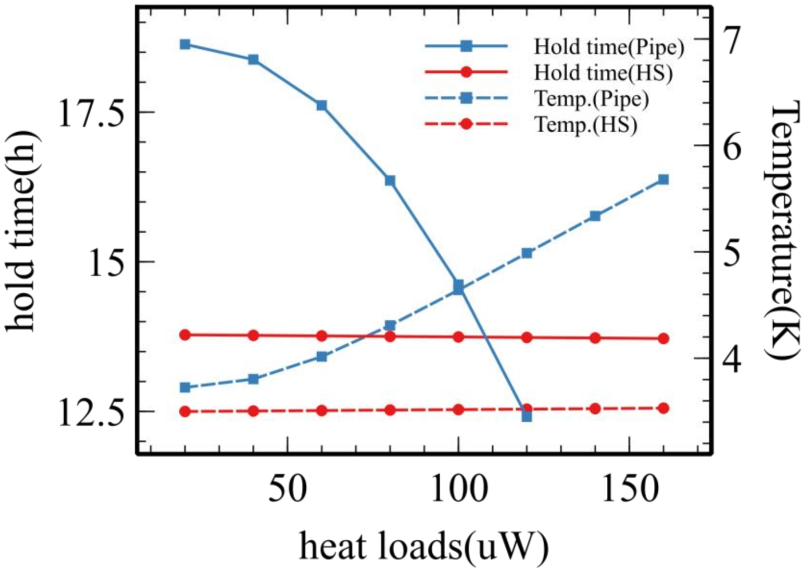

Figure 3. Performance Comparison of Different Structural Schemes.

Figure 4 illustrates the temperature variation of the evaporator during the experiment. The results demonstrate that the developed adsorption refrigerator can complete condensation within 1 hour and reach the 1 K temperature zone approximately 40 minutes after initiating cooling. The evaporator temperature stabilizes at 0.82 K and exhibits a slight increase towards the end of the cooling process, resulting in a total holding time of 19 hours.

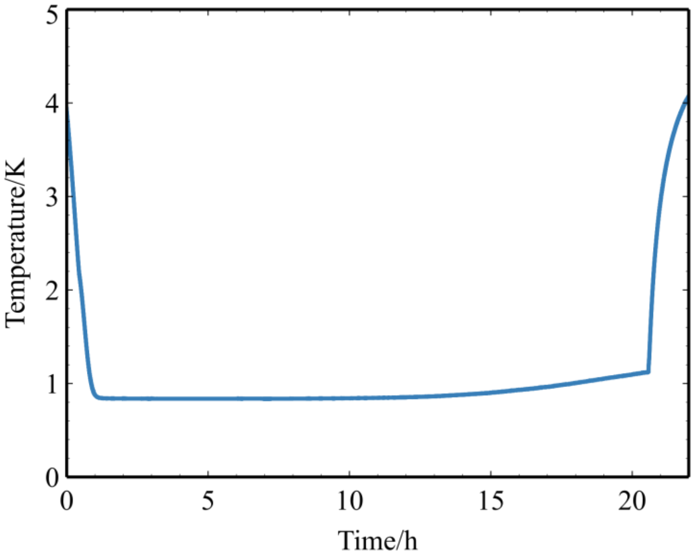

Figure 4. Temperature of the evaporator.

Figure 5 illustrates the relationship between cooling power and cold head temperature. The figure reveals that, following the application of a heat load to the cold head, there is an initial step increase in the cold head temperature, which then shows a linear relationship with the heat load. At a cold head temperature of 1 K, the system is capable of providing a maximum cooling power of approximately 350 μW.

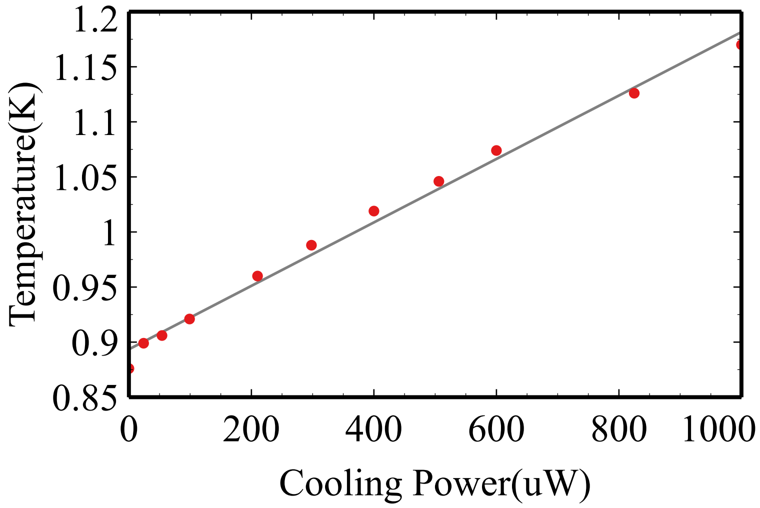

Figure 5. The relationship between evaporator temperature and thermal load.

The cooling capacity of the adsorption refrigerator closely matches the model calculation results, with the cooling power approaching the design target. The temperature of the cold head remains very stable during the cooling process, which is advantageous for components such as quantum detectors that are mounted on the system, as it enhances detection accuracy. The cooling time of the cold head exceeds the time required for both the condensation process and the cooling down process, thereby providing a necessary condition for the next step in developing a continuous adsorption refrigerator.

4. Conclusions

The adsorption refrigerator provides a low-vibration, stable temperature environment at cryogenic temperatures. This paper analyzes the impact of key parameters on the overall performance of the system and selects appropriate parameters based on target specifications. Four adsorption refrigerators have been manufactured in our laboratory, each capable of delivering 13.23 J of cooling. The required precooling refrigerator has a cooling capacity of 200 mW at 4 K. Each unit has a hold time of 19 hours and can provide a maximum cooling power of 350 μW at 1 K.

Additionally, in future work, the heat exchanger of the evaporator will be optimized to further lower the temperature.

Acknowledgments. This work is supported by the Hundred Talents Program of the Chinese Academy of Sciences, the National Natural Science Foundation Projects (51806231), the Strategic Priority Research Program of Chinese Academy of Sciences (XDB35000000).

References

[1] Kwon D, Bae J, Jeong S. Development of the integrated sorption cooler for an adiabatic demagnetization refrigerator (ADR)[J]. Cryogenics, 2022, 122: 103421.

[2] Miki S, Fujiwara M, Sasaki M, et al. Development of SNSPD System With Gifford-McMahon Cryocooler[J]. IEEE Transactions on Applied Superconductivity, 2009, 19(3): 332-335.

[3] De Wit M, Gottardi L, Taralli E, et al. High aspect ratio transition edge sensors for x-ray spectrometry[J]. Journal of Applied Physics, 2020, 128(22).

[4] May A, Chapron C, Coppi G, et al. Thermal architecture for the QUBIC cryogenic receiver[C]. Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX, 2018: 897-910.

[5] Duband L, Clerc L, Ercolani E, et al. Herschel flight models sorption coolers[J]. Cryogenics, 2008, 48(3): 95-105.

[6] Zhang A, Wu Y, Liu S, et al. High-efficiency 3 W/40 K single-stage pulse tube cryocooler for space application[J]. Cryogenics, 2018, 90: 41-46.