Experimental study on a helium-4 sorption cryocooler

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Abstract. The sorption cooler is one of the commonly used Sub-Kelvin temperature refrigeration technologies, used in space exploration and ground experiments to provide a low temperature below 1 K. In this paper, a sorption cooler using helium-4 as the working gas has been developed. At a heat sink temperature of 3 K, the lowest no-load temperature of the developed sorption cooler is 843 mK and the hold time below 1 K is 4 hours. The effects of different sorption pump temperatures and sorption pump cooling rates on the refrigeration performance were studied through experiments. The test results show that during the condensation process, when the temperature of the sorption pump is higher than 45 K, the pump temperature has little effect on the liquefaction efficiency, and speeding up the cooling rate of the sorption pump is conducive to obtaining a lower refrigeration temperature.

1. Introduction

In recent years, space detection technology has developed rapidly. A low temperature environment below 1 K is required to reduce the background radiation and thermal noise of the detectors, and improve their sensitivity for some applications. Commonly used Sub-Kelvin technologies include adiabatic demagnetization refrigerators (ADR), dilution refrigerators (DR), and sorption cooler (SC). Among them, the ADR can achieve continuous cooling, but it has a large size and a complicated system due to the presence of magnetic fields. The dilution refrigerator can provide a low temperature of about 10 mK, but its operation relies on gravity and its application in space is limited. Compared with the former two, the sorption cooler has the simplest structure, small size and lightweight, and no moving parts and magnetic field, which is very suitable for ground and space experiments. The working principle of the sorption cooler is evaporative refrigeration. When helium-3 or helium-4 were used as working gas, the low temperatures of ~300 mK or ~800 mK can be obtained respectively [1-3].
In this paper, a single-stage sorption cooler using helium-4 as the working gas was designed and developed. The effects of different sorption pump temperatures and hold time during the condensation process on the lowest temperature and working time were studied by experiments. In addition, the effect of different cooling rates of the sorption pump on the refrigeration performance was analyzed by changing the internal gas pressure of the gas gap heat switch during the evaporation process.

2. The structure and operating parameters of the sorption cooler

The structure of the helium-4 sorption cooler is shown in figure 1. The system mainly includes a sorption pump, a pump tube, an evaporator/condenser, and two gas gap heat switches. The sorption cooler is pre-cooled by a 4 K-class GM refrigerator. The sorption pump with a volume of 117 cm$^3$ and is filled with 16 g of activated carbon with a specific surface area of 1164 m$^2$/g. The pump tube is made of stainless steel with an outer diameter of 6 mm and a wall thickness of 1 mm. The volume of the evaporator/condenser is 18.3 cm$^3$. The sorption system is filled with 4 MPa helium at 290 K (0.2 mol). The gas gap heat switches are connected to a vacuum system at room temperature to switch the working state, instead of using a built-in cryogenic sorption pump.

In the experiment, heat switches 1 and 2 were charged with 1 MPa and 0.125 MPa $^4$He at 290 K, respectively. The GM refrigerator was used to pre-cool the entire sorption cooler to about 3 K, then the heat switch connected to the sorption pump and heat sink was switch to OFF state and an electric heating device was used to increase the temperature of the sorption pump to 45 K. The adsorption capacity of activated carbon is reduced at high temperature, the desorbed helium gas is condensed into liquid in the condenser at a lower temperature (3 K), and then the sorption pump is cooled by the GM refrigerator. The activated carbon adsorbs a large amount of helium, prompting the liquid helium continuously evaporates to produce a low temperature.

The temperature change of the sorption cooler during the whole process is shown in figure 2. The cool down time required for the sorption pump from 45 K to about 4 K is less than 1 h, the lowest no-load temperature is 834 mK, and the hold time below 1 K is about 4 hours.
3. The effects of different parameters on the cooling performance

The sorption cooler is a kind of one-shot refrigerator. The main performance parameters include hold time, the lowest temperature and cooling capacity. The hold time of the one-shot refrigerators has a very important influence on its application. The main optimization direction for extending the refrigeration time is to improve the liquefaction efficiency and increase the amount of helium in the system. The previous research on the liquefaction efficiency and self-cooling loss results shows that for the helium-4 sorption cooler, the part of helium adsorbed and the amount of helium in the dead volume of the system are the main factors that affect the efficiency of liquefaction. It can be optimized by lowering the heat sink temperature (condensing temperature) and increasing the sorption pump temperature [4]. The lowest temperature and the cooling capacity that can be obtained are affected by the evaporation rate of liquid helium (the pump speed of the sorption pump) and the heat leakage of the system. In the evaporation stage, the cold capacity that the cooler can provide is the product of the liquid helium evaporation rate and the latent heat. Since the adsorption characteristics of porous materials are closely related to temperature, the pump speed of the sorption pump is related to the size of the pump tube and the cooling rate of the sorption pump.

The effects of different sorption pump temperature, helium mass and cooling rate on the cooling performance of the sorption cooler are studied through experiments.

3.1. The sorption pump temperature and hold time

Under the condition of the heat sink temperature at 3 K, the influence of different maximum temperatures of the sorption pump (maintain 30 min) on the hold time (the temperature is lower than 1 K) and the lowest temperature of the sorption cooler was analyzed by experiments, the results are shown in figure 3. It can be seen that when the temperature of the sorption pump is below 45 K, the hold time increase as the temperature rises, because a higher temperature is beneficial to improve the liquefaction efficiency, and when the temperature of the sorption pump is in the range of 45 K-50 K, the temperature has no significant effect on the hold time of the refrigerator, indicating that when the
activated carbon is lower than 45 K, the temperature has a greater influence on its adsorption capacity.

In addition, the lowest temperature that the sorption cooler can obtain shows a downward trend as the temperature of the sorption pump rises. One possible reason is that a higher sorption pump temperature helps to increase the pumping speed, thus a lower cooling temperature can be obtained under the same heat leakage.

Due to the poor thermal conductivity of the activated carbon, it needs to be maintained for a period when the temperature of the sorption pump is heated to 45 K to avoid a large temperature difference between the wall and the activated carbon during the condensation process. Under the condition that the heat sink temperature is 3 K and the maximum temperature of the sorption pump is 45 K, the performance of the sorption cooler with different maintenance times is analyzed, as shown in figure 4. It can be seen that the maintenance time has little effect on the hold time and lowest temperature of the sorption cooler, which are about 4.25 h and 845 mK, respectively. Therefore, for this system, the optimum temperature of the sorption pump during the condensation process is 45 K, and there is no need for a long heat preservation time.
3.2. System inflation pressure

The increase in the mass of helium in the sorption cooler can significantly increase the amount of liquid helium during the condensation process and extend the hold time. Figure 5 and figure 6 show that when the inflation pressure of helium at room temperature rises from 4 MPa to 7 MPa, the lowest temperature basically unchanged, about 860 mK, while the evaporation time of liquid helium has been prolonged about twice, up to 7.5 h. However, because the mass of the activated carbon in the sorption pump has not increased, the pump speed is insufficient, and the temperature of the liquid helium increase gradually, which shortens the hold time below 1 K.

![Figure 5](image1.png)

**Figure 5.** The influence of the inflation pressure on the lowest temperature.

![Figure 6](image2.png)

**Figure 6.** The influence of the inflation pressure on the hold time.

3.3. The cooling rate of the sorption pump

In the evaporation stage, the cooling rate of the sorption pump has a significant impact on its pump speed. The heat transfer performance is adjusted by changing the inflation pressure in the gas gap heat switch between the sorption pump and the GM refrigerator (the room temperature is 288 K). When the
inflation pressure increases from 52 kPa to 200 kPa, the time required for the sorption pump from 45 K to 5 K is shortened from 4.3 hours to 47 min. When the pressure increases to 308 kPa, the corresponding time is 39 min. As shown in figure 7, the higher the cooling rate of the sorption pump, the lower the cooling temperature. When the mass of liquid helium is constant, the hold time is reduced accordingly.

![Figure 7](image)

**Figure 7.** The effect of different cooling rates on the cooling performance.

3.4. Cooling capacity

When the maximum temperature of the sorption pump is 45 K and the heat sink temperature is 3 K, the cooling capacity of the sorption cooler is tested. The cooling temperature of the sorption cooler is 855 mK with a 39.6 μW heat load, and the working time is 2 h 46 min. When the temperature is 890 mK, it can provide 595 μW cooling capacity, and the hold time is 1 h 30 min. Based on the experimental results, the parasitic heat load and liquefaction efficiency are estimated to be 618 μW and 46.7% respectively.

4. Conclusions

The effects of sorption pump temperature, inflation pressure and cooling rate on the cooling performance of a self-developed sorption cooler are studied through experiments. The main conclusions are as follows:

(1) In the condensation stage, higher sorption pump temperature is beneficial to obtain a longer hold time and a lower temperature, but when the temperature is higher than 45 K, the temperature has no obvious influence on the adsorption capacity of activated carbon. Therefore, 45 K is a suitable temperature. In addition, the temperature difference between the wall of the adsorption pump and the activated carbon is small, so a long heat preservation time is not required. The increase in the amount of helium is also conducive to obtaining a longer cooling time, but it must be matched with the appropriate mass of activated carbon.

(2) In the evaporation stage, increasing the gas pressure in the heat switch can speed up the cooling rate of the sorption pump, which is beneficial to obtain a lower temperature, but as the pump speed increases, the hold time of the sorption cooler is reduced accordingly.

5. References

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