Helium gas-gap heat switch for Sub-Kelvin refrigeration system

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Abstract. The heat switch is an indispensable thermal control device in the low-temperature system. The helium gas-gap heat switch plays a key role in Sub-Kelvin sorption coolers and adiabatic demagnetization refrigerators, and its effective switching between thermal conducting (ON state) and insulating (OFF state) is achieved by changing the pressure of the gas in the gap. In this paper, a 4He gas-gap heat switch was designed. And the thermal characteristics at different cold block temperatures were experimentally tested, which provides a reference for the development of high-efficiency gas-gap heat switches.

1. Introduction
The heat switch is a key temperature control component widely used in low-temperature systems [1,2]. It realizes the switch of thermal conducting and insulating by changing the thermal resistance between the two components. There are many types of heat switches, which can be divided into mechanical heat switches, superconducting heat switches and gas gap heat switches, etc. The principle of mechanical heat switches is to achieve thermal connection through bringing two metals surfaces into mechanical contact. Its thermal resistance in the OFF state is close to infinity, which means that complete disconnection can be achieved, but its switching requires a large force. The superconducting heat switch is made according to the low thermal conductivity of the material in the superconducting state. Because there are no moving parts, the structure of this kind of heat switch is simple, but there is a magnetic field and the working temperature zone is limited, and it cannot be completely disconnected in the OFF state. The gas gap heat switch realizes the ON/OFF state by changing the pressure of the gas in the gap between
the cold and hot blocks through a sorption pump. Its structure is simple and light in weight [3].

The operation of the helium sorption cooler, which is one of the most commonly used Sub-Kelvin systems, is inseparable from the gas gap heat switches. In this paper, according to the operating parameters of the sorption cooler, a gas gap heat switch was developed. Its heat transfer performance at liquid helium temperature was tested through experiments, and the effect of different cold block temperatures on the ON/OFF performance of the heat switch was studied [4].

2. The structure and design parameters of the gas gap heat switch

Figure 1 shows the structure of the designed gas gap heat switch. The meaning of the numbers in the figure are as follows: 1-the hot block of the heat switch, 2-the thin-walled stainless steel support tube, 3-the cold block of the heat switch, 4-the gas hole connecting the sorption pump and the inflation tube (the sorption pump and the inflation tube are not shown in this figure), 5, 6-the holes for placing the temperature sensors. The cold and hot blocks of the heat switch are made of oxygen-free copper, and the end faces are designed with threaded holes for connection, the size of the gap between them is 0.1 mm. The outer diameter of the 304 stainless steel support tube is 11.7 mm, the wall thickness is 0.2 mm, and the length is 70 mm, which is mainly used for support and heat insulation. The sorption pump is filled with 20 mg of activated carbon with a specific surface area of 1164 m²/g, and the entire heat switch is filled with 110 kPa of ⁴He at room temperature.

![Figure 1. Schematic of the sorption cooler (a) and the gas gap heat switch (b).](image)

The cold block of the heat switch is fixed at the second-stage cold head of a Gifford-McMahon (GM) refrigerator. Constantan heating wires and Rhodium-Iron thermometers are respectively installed at the cold block, hot block and sorption pump for temperature control and recording. In the sorption cooler, the gas gap heat switch usually works in the temperature range of 4-45 K. Based on this, the performance of the gas gap heat switch was tested.

3. The temperature of sorption pump of heat switch (State switching)

The heat transfer characteristics of the gas gap heat switch are mainly affected by the thermal conductivity of the gas in the gap. According to the mean free path of the gas molecules $\lambda$ and the size of the gap $d$, there are three cases of the gas heat conduction: (1) The gas molecules are in the regime of
continuous ($\lambda$<<$d$). The heat conduction of the gas is largely independent of pressure. (2) The gas molecules are in the regime of free molecular ($\lambda$>>$d$). The heat flow increases with the increase of pressure. (3) When the $\lambda$ ≈ $d$, the gas is in the intermediate regime.

Generally, when the heat switch is in the ON state, the gas in the gap is in the continuous regime, and its heat transfer performance is mainly affected by the gas temperature. In the OFF state, the gas is in free molecular regime, and the pressure of the gas should be reduced as much as possible to weaken the heat flux. Since the adsorption capacity of the porous material is closely related to the temperature, changing the temperature of the sorption pump can change the gas pressure in the gap. Therefore, the switching temperature of the gas gap heat switch was first studied.

When the temperature of the cold block of the heat switch is 4 K, the effect of the sorption pump temperature on the thermal conductance of the heat switch when different powers were applied to the hot block is shown in figure 2. When 30 mW was applied to the hot block, it can be seen that when the temperature of the sorption pump is lower than 7.5 K, the heat switch is in the OFF state. In order to obtain the ON state, the temperature should be higher than 11 K. For 69 mW, the ON state can be obtained when the sorption pump temperature is higher than 13 K. The difference in the applied power of the hot block has a slight impact on the switching temperature. Therefore, in order to ensure that this gas gap heat switch obtains the ON state, the temperature of the sorption pump should not be less than 15 K, for the OFF state, maintaining the temperature of the sorption pump below 8 K helps to improve the thermal insulation performance.

![Figure 2. The effects of sorption pump temperatures on the thermal conductance.](image)

Under the condition that the applied power of the hot block is 30 mW, the effect of the sorption pump temperatures on the heat transfer performance of the heat switch under different cold block temperatures was also studied through experiments, as shown in figure 3 and figure 4. It can be seen that the change of the cold block temperature has little effect on the temperature range of the sorption pump that maintains the OFF or ON state.
4. The ON state of the gas gap heat switch

Based on the above experimental results, the sorption pump temperature was maintained at 15 K to obtain the ON state. Figure 5 shows the relationship between the temperature of the hot block and the thermal conductance of the heat switch at different cold block temperatures. It can be seen that for a certain cold block temperature, the thermal conductance of the switch increases as the temperature of the hot block increases, the reason is that the thermal conductivity of helium in the gap increases with the increase of temperature. In addition, the slopes of the curves in figure 5 gradually decrease. This phenomenon is caused by the slower growth rate of the helium thermal conductivity with increasing temperature.

When the temperature of the cold block of the heat switch changes in the range of 4-10 K, the relationship between the power applied at the hot block and the temperature difference between the hot
and cold blocks are shown in figure 6. It can be seen that the higher the cold block temperature, the smaller the temperature difference of the gas gap heat switch. This shows that the heat transfer characteristics of the gas gap heat switch are determined by the thermal conductivity of the helium in the gap. Increasing the temperature of the helium is beneficial to the enhance the heat transfer between the cold and hot blocks.

5. The OFF state of the gas gap heat switch

In addition to providing better heat transfer in the ON state, another key function of the heat switch is heat insulation. In the sorption cooler, the heat insulation performance between the evaporator and the heat sink directly affects the lowest temperature and the cooling capacity. The test of the gas gap heat switch in the OFF state was performed by maintaining the temperature of the sorption pump below 8 K.

The results are shown in figure 7 and figure 8. When the cold block temperature is constant, the thermal conductance increases with the increase of the hot block temperature. This is because the performance of the gas gap heat switch in the OFF state mainly depends on the outer thin-walled stainless steel tube. Its thermal conductivity is small, but it increases with the increase of temperature. Therefore, the increase of the hot block temperature results in a deterioration of the thermal insulation performance of the heat switch. For a lower cold block temperature, the temperature difference between the two blocks under the same power should be greater, which means that the thermal resistance should be greater, but the experimental results failed to obtain this conclusion. The thermal conductance of the heat switch is significantly greater than that of the stainless steel tube (from 45 K to 4 K, the thermal conductance of the stainless steel tube is about 0.35 mW/K) in the OFF state. One possible reason is that the heat switch performance may be deteriorated due to the contact between these components during assembly or welding due to the gap between the two copper cylinders and the inner wall of the stainless steel tube and the copper cylinder in the design is only 0.1 mm and 0.3 mm.

![Figure 7](image1.png)  ![Figure 8](image2.png)

**Figure 7.** The relationship between the hot block temperature and the thermal conductance at different cold block temperatures.

**Figure 8.** The relationship between the power and temperature difference at different cold block temperature.

6. Conclusions

In this paper, a gas gap heat switch is developed for the sorption cooler, and its heat transfer performance
in the ON/OFF state is studied through experiments. The main conclusions are as follows:

(1) With a certain mass of helium (110 kPa) and the porous material in the sorption pump (20 mg), the temperature of the sorption pump required for the gas gap heat switch to be ON or OFF is not affected by the temperature of the hot or cold blocks, and is higher than 12 K or lower than 8 K, respectively.

(2) ON state: when the temperature of the cold block of the gas gap heat switch is constant, its thermal conductance increases with the increase of the temperature of the hot block, because the thermal conductivity of helium increases with the increase of temperature. The thermal resistance between the blocks can be reduced by increasing the temperature of the gas.

(3) OFF state: The greater the temperature difference between the hot and cold blocks of the heat switch, the greater the thermal conductance. However, the experimental test value is much larger than the calculated value of solid heat conduction between the cold and hot blocks. One possible reason is that there is contact between the two blocks.

7. References

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