A preliminary study of $^4$He convective heat switches

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Abstract. Heat switches are key components in sub-kelvin refrigeration. It is widely used in cryogenic systems, such as controlling thermodynamic cycle, coupling/decoupling redundant cryocoolers, accelerating the cooling of cryogenic components and so on. Convective heat switch features simple structure, no moving parts and great thermal conductance, which is mainly used to precool cryogenic components. In order to accelerate the pre-cooling of a test platform to 4K, the passive convective heat switch is investigated in this paper, which consists of a circuit comprising two identical stainless steel tubes and two copper cavities respectively connected to the cold and warm stages. The ON/OFF state of the switch is realized by the presence/absence of a gravity-driven convective helium–4 gas loop. Several convective heat switches with different cavity structures and charge pressures are designed and assembled. The preliminary experimental results on thermal conductance are presented. With a typical dimension of a cylindrical cavity with a diameter of 28mm and a height of 16.8mm, a stainless steel tube with a diameter of 9.6mm and a length of 72mm, thermal conductance of 40-50mW/K in ON state has been obtained.

1. Introduction

Sub-kelvin temperature is necessary for many scientific research fields[1]. It provides a low temperature environment for special physical phenomena, improves the resolution of detectors and reduces the background thermal noises of the system. Cryogenic heat switches are key components in sub-kelvin refrigerators[2-4]. As the name implies, heat switches are used to control the heat flow. It is widely used in cryogenic systems. One of the purposes is to control the thermodynamic cycle. A typical example is heat switches used in single-shot adiabatic demagnetization refrigerators[5]. Other purposes include to couple/decouple a redundant cryocooler[6], to produce adiabatic environments, to accelerate the cooling of cryogenic load and so on.

Based on different physical mechanisms, heat switches can be classified into several categories[7]. Among them, mechanical heat switches have complex structures such as a motor; Superconducting heat switches and magneto-resistive heat switches require additional magnetic fields; Gas-gap heat switches are compact and can be passively operated, but they can’t work at temperature below 0.2K.

In addition, there are convective heat switches, which can be used to precool cryogenic components. It typically consists of a circuit comprising two identical stainless steel tubes and two copper cavities respectively connected to the cold and warm stages shown in figure 1 [8]. According to whether there is an adsorbent bed and associated thermal control or not, it can be divided into active or passive convective heat switch (ACHS/PCHS). For active convective heat switch, ON/OFF state is controlled by heating or cooling the adsorbent bed. For passive heat switch, it is controlled by temperature...
difference. The heat transfer through the switch is provided by a convective gas loop. And convection is naturally activated by gravity when the top of the switch is colder than the bottom.

![Figure 1. Schematic of convective heat switches[8].](image)

There are a few studies on convective heat switches. In 1987, Torii and Maris [9] first proposed the concept of convective heat switch. They gave theoretical formulas for mass flow and thermal conductance. In 2019[8], May Andrew studied active/passive convective heat switch for the bolometric cryogenic system --- QUBIC project[10].

The twin-tube configurations have also been used in sorption coolers as well as miniature dilution coolers to accelerate the pre-cooling. A typical example is the warm start-up mode of the sorption cooler shown in figure 2 [11, 12]. In warm start-up mode, before the cryopump starts to function, there is gas remaining in the tubes and the evaporator's temperature is higher than the condenser. The existence of gravity triggers convective motion and increases the cool-down speed of the evaporator and the load connected with it. After that, in cooling mode, the cryopump is cooled and adsorbs the evaporated gas from the pot.

![Figure 2. Twin-tube heat switch used in single-stage sorption refrigerator.](image)

In-depth study of convective heat switches, such as numerical simulation, the comparison between experiments and simulations, has not been found. Based on the experimental study by May, we have conducted some preliminary experiments in our lab.

2. Theoretical analysis

In the OFF state, the heat leak of the switch is mainly caused by the stainless steel tube. In the ON state, although the contribution of conduction through the stainless steel still exists, the total thermal conductance is dominated by the contribution of convective heat transfer. For calculating the thermal conductance in the ON state, the effective model reported in Reference [9, 11] is introduced below.
The flow of gas in the tubes is considered as steady flow. Taking the continuity equation, it can be seen that the quantity \( \rho UA \) is constant for any “cut” through the circuit:

\[
\rho UA = \text{const}
\]  

(1)

where \( \rho \) is density, \( U \) is mean velocity and \( A \) is the cross-sectional area.

Under equilibrium state, the sum of the gravitational potentials of the convection loop is zero. In order to maintain the stability of the equilibrium condition, the total pressure increment in the circuit is equal to the total pressure loss.

It is assumed that the heat transfer between the fluid and the solid parts of the switch only occurs at the upper and bottom heat exchanger sections. And the fluid is divided into two discrete regimes: A and B. The outlet gas density of the two heat exchangers is set to \( \rho_1 \) and \( \rho_2 \), and the tube lengths of the two regimes are set to \( L_1 \) and \( L_2 \) respectively, as shown in figure 3.

**Figure 3.** The theoretical model of passive convective heat switch.

The total pressure increment from buoyancy forces around the circuit as:

\[
\Delta P_p = \Delta \rho gZ = (\rho_1 - \rho_2)gZ
\]  

(2)

where \( Z \) is the vertical distance between the two outlets. Because of dissipative force, internal viscosity will cause pressure loss when the fluid travels around the loop. The pressure loss in the flow caused by the dissipative force can be expressed by Darcy-Weisbach equation[13]. In the case of laminar flow, the pressure drop per unit length of tube in a circular pipe as:

\[
\frac{\Delta P_p}{L} = \frac{128}{\pi} \cdot \frac{\mu Q}{D^4}
\]  

(3)

where \( \mu \) is the dynamic viscosity of the fluid, \( Q \) is the volumetric flow rate, \( D \) is the diameter of the tube. The sum of the viscous losses (the total pressure loss) around the circuit is given by

\[
\Delta P_p = \Delta P_{p1} + \Delta P_{p2} = \frac{128}{\pi} \cdot \frac{\mu_1 Q L_1}{D^4} + \frac{128}{\pi} \cdot \frac{\mu_2 Q L_2}{D^4}
\]  

(4)

Given that

\[
Q = \frac{\dot{M}}{\rho}, L_1 = L_2, L = L_1 + L_2
\]  

(5)

where \( \dot{M} \) is the mass flow rate, \( L \) is the total length of the loop. So

\[
\Delta P_p = \frac{8ML}{\pi r^4} \cdot \left( \frac{\mu_1}{\rho_1} + \frac{\mu_2}{\rho_2} \right)
\]  

(6)

The sum of the potentials of the convection loop is zero, and therefore

\[
(\rho_1 - \rho_2)gZ = \frac{4ML}{\pi r^4} \cdot \left( \frac{\mu_1}{\rho_1} + \frac{\mu_2}{\rho_2} \right)
\]  

(7)
The mass flow rate \( \dot{M} \) is given by

\[
\dot{M} = \frac{\pi r^4}{4L} \cdot \frac{(\rho_1 - \rho_2)gZ}{\mu_1/\rho_1 + \mu_2/\rho_2}
\]

(8)

In the steady-state condition, the heat transferred from the hot exchanger to the switch is equal to the enthalpy difference between the gas flow out and back to the hot end (similarly for the heat rejected from the cold exchanger). Neglecting pressure loss through the heat exchangers, the heat transferred through the switch becomes

\[
\dot{Q} = \dot{M} \cdot \Delta h = \frac{\pi r^4}{4L} \cdot \frac{(\rho_1 - \rho_2)gZ}{\mu_1/\rho_1 + \mu_2/\rho_2} \cdot C_p(T_2 - T_1)
\]

(9)

where \( C_p \) is the specific heat capacity. In fact, the exit temperature of the fluid is close to but not equal to the temperature of the heat exchanger. So the model needs to be extended to include an experimentally determined efficiency factor to account for the imperfection of the heat exchanger. This model gives an ideal theoretical formula for mass flow and thermal conductance, and it cannot be used for the accurate calculation. Influences such as that of different cavity structures. In order to understand the convective heat transfer process more accurately, we are having Conducted 3-dimensional unsteady-state and steady-state numerical simulations. The simulation results will be introduced in another journal submission[14].

3. Experiment

Many factors, such as the shape and size of the heat exchanger, the temperature difference between the heat exchanger and the fluid, and the physical properties of the fluid affect the convective heat transfer. For the convective heat switch used in the temperature regime of 4K, helium 4 is chosen as the heat transfer fluid. We conducted a preliminary study of the charge pressure of the gas and structure of the cavity to investigate the effects of different factors on convective heat switches. Table 1 shows the key geometric dimensions of several convective heat switches used for experimental tests.

**Table 1.** Selected geometries for experimental study

| Main dimensions          | Unit | HS1       | HS2      | HS3       | HS4       |
|-------------------------|------|-----------|----------|-----------|-----------|
| Structure of the cavity |      | cylindrical | hemispherical | hemispherical | cylindrical |
| Diameter of cavity      | D (mm) | 26         | 28       | 26        | 28        |
| Height of cavity        | H (mm) | 20         | 16.8     | 20        | 16.8      |
| Diameter of tube        | d (mm) | 8          | 9.6      | 8         | 9.6       |
| Height of tube          | h (mm) | 80         | 72       | 80        | 72        |

**Figure 4.** Convective heat switches is connected to the 4K cold plate.

**Figure 5.** A passive convective heat switch (HS1).
In the experiments, we used a two-stage GM-type pulse tube cooler to cool the cold plate to 4K. One end of the heat switches are connected to the 4K cold plate and a heater is attached to the free end to apply different heating power (as shown in figure 4 and 5). Thermometers are attached to both ends of each switch to record the temperature. The experimental effects of the charge pressure, cavity structure on the performance of convective heat switches are presented individually.

3.1. Charge pressure

Figure 6 shows the thermal conductance of HS1 and HS2 with different charge pressures. When the charge pressure is higher, the ON thermal conductance of the switch is greater. These results can be explained that the density of the gas affects the heat flow of the heat switch, which is a function of temperature and charge pressure. The greater the charge pressure, the greater the gas density, so the more heat carried per unit mass and the better the convective heat transfer effect.

![Figure 6](image1)

**Figure 6.** The thermal conductance of HS1 (left) and HS2 (right) with different charge pressure.

However, the practical charge pressure is limited by both the mechanical limitation given by the structure in terms of the allowable charge pressure and the heat leak in the OFF state. In this experiment, the thickness of 0.5mm of the charge tube limits the charge pressure not to be greater than 15.5 bar. Then, based on meeting the requirements of thermal conductance in the ON state, the charge pressure should ensure that the heat leak in the OFF state is as small as possible. For passive convection heat switches, if the charge pressure is too high, when the heat switch is OFF, and there will be considerable heat leak caused by residual helium 4. So an active convective heat switch with an adsorbent bed can be chosen to achieve lower heat leak, which uses activated carbon to adsorb helium in the OFF state.

3.2. Structure of the cavity

In addition to the charge pressure, the structure of the cavity also affect the performance of heat switches. Figure 7 shows that the cylindrical structure of the cavity performs better than the hemispherical arch structure of the cavity with the same geometrical dimensions. The possible reason is that the cylindrical structure changes the moving direction of some gases, causing the gas currents disturb each other, thereby forming more recirculation zones, destroying the stable boundary layer area, and achieving the effect of enhancing heat transfer. The hemispherical arch structure has a good guiding effect on the gas flow, but reduces the recirculation area. We consider designing the structure of cavity into fin-shaped, zigzag-shaped and other irregular shapes to further explore the effects of the structure of cavity on the convective heat transfer.

With the increase of the temperature difference between the two ends, the thermal conductance of convective heat transfer also increases. Among them, the thermal conductance of the cylindrical HS2 is equivalent to the thermal conductance of a copper column with a diameter of 1.7mm and a length of 72mm.
Figure 7. The thermal conductance of heat switches with different structures of the cavity with a charge pressure of 15 bar. Left: HS1 and HS3; Right: HS2 and HS4.

4. Conclusion
Several $^4$He convective heat switches are studied. In preliminary experiments, we measured the thermal conductance of the convective heat switch when the cold end temperature is at 4K. The effects of charge pressure and the structure of the cavity on the thermal performance of convective heat switch are studied. The results show that for the same geometric dimensions and the structure of the cavity, the higher the charge pressure, the greater the thermal conductance of the heat switch. Different cavity structures have an impact on the performance of the heat switch, a rougher heat exchange surface will be designed. The geometric dimensions including the cavity height, tube diameter and tube height may affect the performance of the heat switch, which needs to be further optimized. Meanwhile the comparison between experiments and simulations need to be done.

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