Development of a Passive Helium Heat Switch for Fast Cool Down by Two-Stage Cryocooler

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ABSTRACT

A new type of thermal heat switch has been designed and analyzed using a numerical approach. A passive helium heat switch using adsorption of helium on activated charcoal is expected to facilitate the rapid cool down of the second stage of a two-stage cryocooler. The heat switch contains vertical fins in a staggered array, an activated charcoal bed, and helium gas. Those components are isolated from the outside by a thin-walled cylinder. The heat switch thermally connects the first and the second stage of a two-stage cryocooler at high temperature in order to utilize the larger refrigeration capacity of the first stage for the initial second-stage cooling. When the second stage reaches a certain low temperature, the heat switch opens and thermally isolates the second stage from the first. The thermal connection between the first and second stages is determined by the pressure of the helium gas in the switch, which is the function of activated charcoal bed temperature.

In this paper, the cooling time of the second stage is calculated by a heat transfer analysis that takes into account the helium gas adsorption on the activated charcoal, the various flow regimes in a vacuum environment, and an energy balance. The calculated heat transfer rate between the fins shows that the thermal resistance of the designed heat switch can be changed passively with the variation of the temperature, and a thermal resistance ratio of more than 2000 can be achieved. Moreover, the numerical results indicate that the cooling time for a 9 kg copper block using the two-stage cryocooler (RDK-415D) with the heat switch will be reduced by 71 %.

INTRODUCTION

A gas-gap heat switch is a device which thermally connects (ON state) and disconnects (OFF state) two objects for a specific purpose. As early as 1973, researchers began introducing the concept of a gas-gap heat switch in order to improve the lifetime of cooling systems for the electronic equipment in spacecraft. An article by R.P. Bywaters and R.A. Griffin[1] describes the prototype of a gas-gap heat switch. The experimental results of this prototype indicate that the thermal resistance can be changed by more than a factor of 500 by varying the helium pressure in the switch gaps. However, in order to change the ON to the OFF state, the prototype needs to be evacuated by a vacuum pump. P.J. Shirron et al.[2] introduced passive gas-gap heat switches for adiabatic demagnetization refrigerators. The heat switches passively turn off (OFF state) near 1 K or 4 K, relying on the temperature dependence of the vapor pressure of ^{4}He adsorbed onto neon or copper substrates, respectively.

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A gas-gap heat switch also can be applied to a two-stage cryocooler. For example, superconducting magnets are typically cooled by two-stage cryocoolers. This kind of superconducting magnet without using liquid helium for its cooling has received significant attention in recent years.[3-7] The conduction-cooled systems are easy to operate and do not require any liquid cryogens. However, it generally takes a very long time to cool down the superconducting magnet by the second stage of a two-stage cryocooler. For instance, the cryogenic cooling system using a two-stage cryocooler (RDK415D, Sumitomo) for a superconducting magnet developed by Y. S. Choi et al.[7] requires about 14 hours of cool down time for initial operation.

In order to achieve a fast cool-down rate by a two-stage cryocooler, many researchers[8-10] have developed cryogenic thermosiphones where the two-phase fluid plays a very efficient heat transfer role based on its boiling and condensation phenomena inside the thermosiphon. The thermosiphon has higher thermal conductance than pure copper during its ON-state and its conductance can be turned off when its working fluid freezes due to the low temperature of the 2nd stage of cryocooler. A cryogenic thermosiphon charged with the proper fluid and installed between the first and the second stages of a cryocooler can be regarded as a thermal diode and greatly reduces the cooldown time of the object that is attached to the second stage.

On the other hand, instead of using a two-phase fluid heat switch such as a thermosiphon, H. Chang and H. Kim[11] developed a gas-gap heat switch. The heat switch employs nitrogen gas and connects the first and the second stages of a two-stage cryocooler to take advantage of the large cooling capacity at the first stage. The main merit of the heat switch is that the OFF state can be achieved without any external actuation because the nitrogen gas is frozen, and the corresponding vapor pressure inside of the heat switch is greatly decreased. On the other hand, if the gap of the conductive surfaces is very small, the frost of nitrogen can stick to the surfaces and cause additional heat conduction during the OFF state. Since the spacing of the conductive surfaces significantly affects the thermal conduction of the gas, solidification of nitrogen gas makes it technically difficult to reduce the gap in order to improve thermal conduction of the heat switch.

Helium gas has been employed as the thermal conductor inside gas-gap heat switches by many previous researchers[1, 2, 12, 13] because of its high thermal conductance and adequacy of its operating temperature. In order to utilize a helium heat switch for a two-stage cryocooler, we need an efficient method to turn off the helium heat switch passively above 4 K. D. Martins[13] developed a helium heat switch which uses a sorption pump as the actuating device. The sorption pump consists of an activated charcoal bed in order to adsorb and desorb the helium gas depending on the temperature of the activated charcoal. In this case, the sorption pump needs to be cooled and heated by the cryocooler and a heater, respectively. If the temperature of the activated charcoal bed changes without any additional device, a helium heat switch can passively switch the ON and OFF stages.

This paper introduces a new type of passive helium heat switch for fast cool down of cryogenic systems using a two-stage cryocooler. The heat switch is designed to change the ON to OFF state at a temperature of around 50 K. The performance of the heat switch is analyzed by numerical calculation. Furthermore, the cooling time of a copper block using a two-stage cryocooler with the heat switch is calculated and compared to that without the heat switch. The main parameters which affect the performance of the heat switch are discussed in this paper.

DESIGN SCHEMES

Correlation of Isotherms

Figure 1 provides a schematic illustration of the heat switch. The heat switch is a closed container and consists of upper copper fins, lower copper fins, activated charcoal bed, and thin-walled stainless steel tube. The gap between upper and lower copper fins has been filled with helium gas. When the heat switch is cooled, the gas pressure decreases by adsorption of helium gas on the activated charcoal bed. The mass of the adsorbed helium gas can be determined by the correlation of absorption isotherms.

L. Duband et al.[15] have proposed the following correlation for adsorption isotherms of helium on activated charcoal for the pressure range from 100 kPa to 3 MPa.

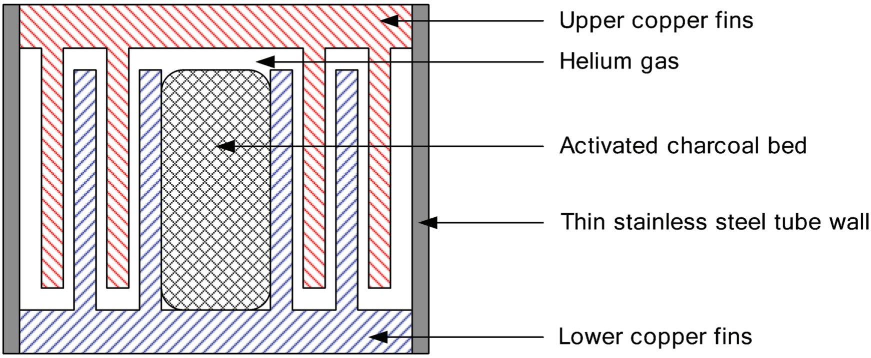

Figure 1. The helium gas heat switch using a activated charcoal bed.

$$C = f(T,P) = 0.1358 \cdot \exp(-0.1359\,x) \quad where \quad x = 0.0975 \cdot T\,(5.2 - \frac{22.728}{T} - \ln P) \tag{1}$$

Here, C is the mass of helium gas adsorbed per unit mass of charcoal. This correlation is valid for a temperature range from 15 K to 70 K. Since the helium gas pressure in the heat switch is lower than 100 kPa, the correlation has to be compared with experimental results in the low pressure range. D. Martins et al.[14] have measured adsorption isotherms for helium gas and their results are compared with the correlation in Fig. 2. We observe that this correlation is fairly consistent with the experimental data in the low pressure range from 0.01 kPa to 100 kPa. If we know the mass ($m_{charcoal}$) of activated charcoal bed and the volume of helium gas (V), the gas pressure is then determined using the following ideal gas equation.

$$P(T) = \frac{(m_{init} - C \cdot m_{charcoal})}{V} RT_{LM} \tag{2}$$

where m_{init} is the initial mass of the helium gas; R is universal gas constant; and T_{LM} is the log mean temperature between the upper and the lower copper fins. In this paper, however, the software REFPROP (NIST) version 9.1 is employed to calculate gas pressure instead of using the ideal gas equation for more precise results.

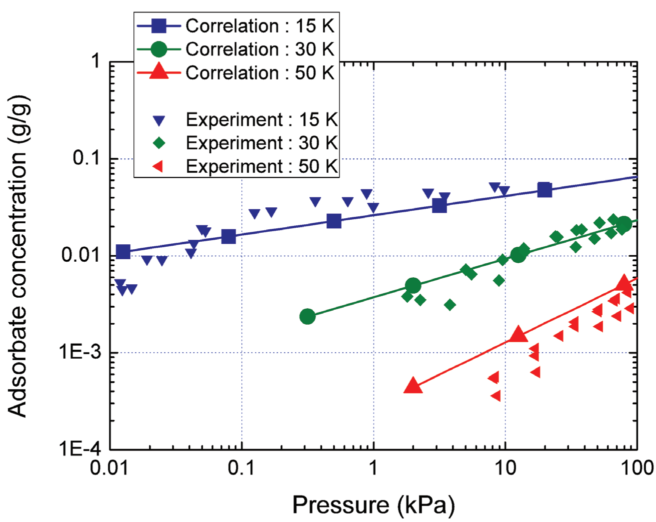

Figure 2. Adsorption isotherms for the helium gas[14] and the correlation developed by L. Duband et al.[15]

Heat Transfer Coefficient

In order to determine the representative heat transfer coefficient between the upper and lower fins, the flow regimes in the heat switch have to be estimated. The flow regime is a main factor to determine the state (ON or OFF) of the heat switch and can be deduced in terms of the Knudsen number as follows[16]:

1. Continuum flow, Kn < 0.01
2. Mixed flow, 0.01 < Kn < 0.3
3. Free-molecular flow, 0.3 < Kn

$$Kn \equiv \frac{\lambda}{\delta} \tag{3}$$

where Kn, λ, and δ are the Knudsen number, the gas mean free path, and the gas gap between the lower and upper copper fins respectively. In the continuum flow regime, because the gas gap is very small compared to length of the fins, the heat transfer coefficient between the fins can be calculated by thermal conductivity of the gas (k_g).

$$h(T) \approx \frac{k_g(T)}{\delta} \tag{4}$$

In the free-molecular flow regime, the gas molecules rarely strike each other.[16] Therefore, individual gas molecules directly transfer energy from one heat-switch surface to another. The equation for the heat transfer between two parallel surfaces[11, 17] is expressed as

$$h(T) \approx \alpha \frac{\gamma+1}{\gamma-1}\sqrt{\frac{R}{8\pi M}}\frac{P(T)}{\sqrt{T_{LM}}} \tag{5}$$

where α, γ, and M are accommodation coefficient, the ratio of specific heats, and the molecular weight of the gas, respectively. The accommodation coefficient is taken as 0.5, which is valid for helium gas [14]. As a result, Equations (1-5) show that the heat transfer coefficient between the fins is a function of the temperature.

Cooling Time Calculation

The overall cooling time is calculated by considering an energy balance. A schematic diagram of the cooling system using a two-stage cryocooler is illustrated in Fig.3. Each stage of the two-stage cryocooler cools down the copper block with the mass of m_{1st}, m_{2nd}. The heat switch is

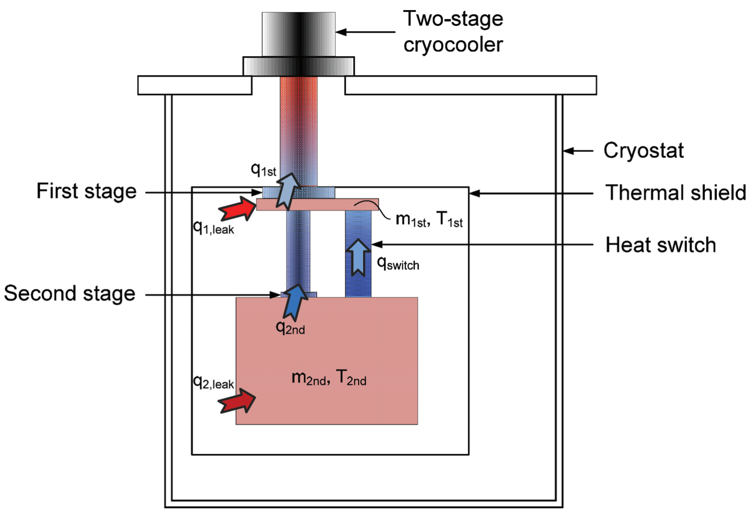

Figure 3. Schematic representation of a conduction cooled system by a two-stage cryocooler

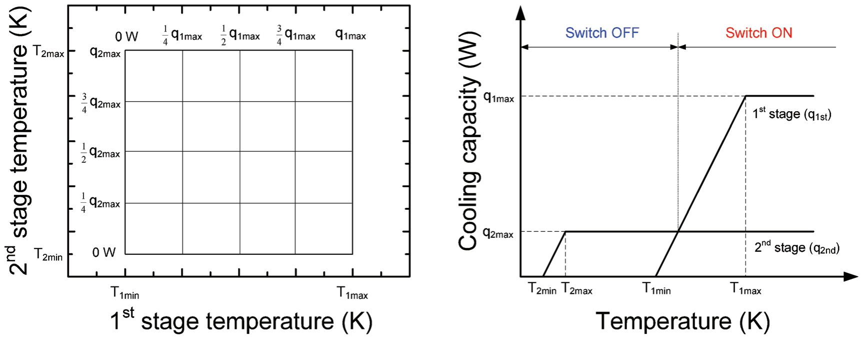

Figure 4. Schematic diagram of simplified cooling capacity of a two-stage cryocooler.

mechanically connected between the first and the second stages and stays thermally active (ON state) at high temperatures and inactive (OFF state) at low temperatures. The cooling capacities of each stage (q_{1st}, q_{2nd}) are simplified as shown in Fig. 4. In this paper, q_{1max}, q_{2max}, T_{1max}, T_{1min}, T_{2max}, and T_{2min}, are set to 80 W, 20 W, 90 K, 30 K, 14 K, and 3 K, respectively, to represent the two-stage cryocooler model RDK-415D manufactured by Sumitomo Cryogenics Group.[18] Although the actual variation of cooling capacities with time is indeed different, simplification will facilitate the analysis of the heat switch effect on cooling time. The heat transfer rate of the heat switch (q_{switch}) includes wall conduction (q_{wall}) and the heat transfer rate through fins and the helium gas (q_{fin}).

The thermal conductivity of the copper block or copper fins is assumed to be infinite.

$$q_{switch}(t) = q_{wall}(t) + q_{fin}(t) \tag{6}$$

$$q_{wall}(t) = \frac{A_{wall}}{L_{wall}} \int_{T_1(t)}^{T_2(t)} k_{wall} dT \tag{7}$$

$$q_{fin}(t) = hA_{HT}(T_2(t) - T_1(t)) \tag{8}$$

The temperatures of each stage are estimated by the following energy balance equations. The masses of the designed upper and the lower fins of the heat switch are 0.195 kg and 0.232 kg, respectively. They are included in the first (m_{1st}) and the second (m_{2nd}) stage copper block's masses, respectively, in the numerical calculations. We assume that the thermal masses of the charcoal bed and thin-walled stainless steel tube are negligible compared to the copper blocks.

$$T_1(t+\Delta t) = T_1(t) - \frac{q_{1st} - q_{switch} - q_{1,leak}}{m_{1st} c_{v,1st}} \Delta t \tag{9}$$

$$T_2(t+\Delta t) = T_2(t) - \frac{q_{2nd} + q_{switch} - q_{2,leak}}{m_{2nd} c_{v,2nd}} \Delta t \tag{10}$$

The specific heat of the copper block is calculated by Debye theory [14].

$$c_v = 3R\left(\frac{T}{310}\right)^3 D\left(\frac{T}{310}\right) \quad where \ T > \frac{310}{12} K \tag{11}$$

$$c_v = \frac{233.78RT^3}{310^3} \quad where \ T < \frac{310}{12} K \tag{12}$$

The software MATLAB version R2013a was used to calculate the temperature variation of the first and second stages with time. The cooling time is defined as the time required for the first and second-stage temperatures to achieve steady state. The initial conditions and dimensions of the heat switch for the analysis are specified in Table 1. Figure 5 shows the schematic configuration of the designed heat switch.

Table 1. Dimensions and initial parameters of the cooling system with the heat switch.

Length of the heat switch	60 mm	Mass of the activated charcoal	4.76 g
Diameter of the heat switch	40 mm	Volume of the helium gas	$1.6 \cdot 10^{-6}$ m^3
Length of fins	48 mm	Initial pressure of the helium gas	18 kPa
Gap of the fins	1 mm	Mass of the first stage copper block	1 kg
Thickness of the wall	0.4 mm	Mass of the second stage copper block	9 kg
Thickness of a fin	2 mm	Mass of the upper copper fins	0.23 kg
Heat transfer area of the fins	0.0145 m^2	Mass of the lower copper fins	0.20 kg

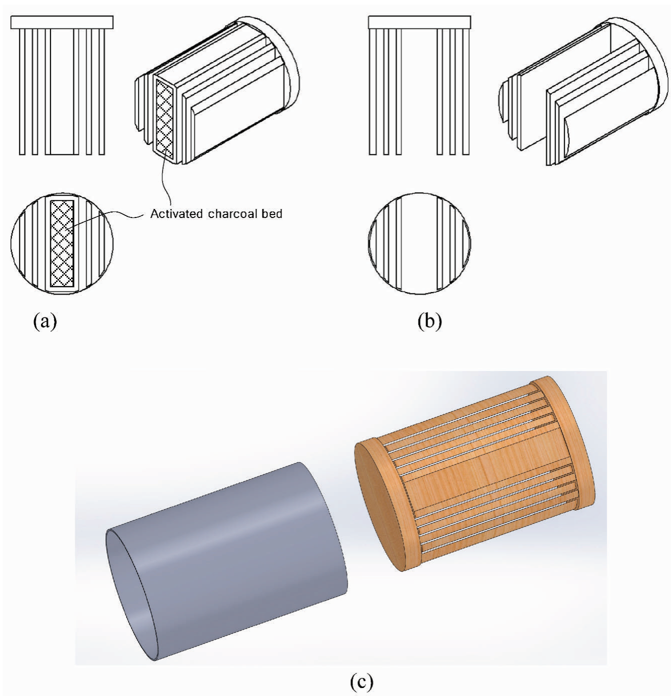

Figure 5. Configuration of the designed heat switch: (a) the lower copper fins with activated charcoal bed, (b) the upper copper fins, and (c) the assembly of heat switch.

RESULTS AND DISCUSSION

Heat Transfer Coefficient

The heat transfer coefficient between upper and lower fins is depicted in Fig. 6(a). In the continuum flow regime, since the thermal conductivity of the helium gas depends on temperature, the heat transfer coefficient decreases according to the temperature. Furthermore, if we set the gap of the fins smaller than the value specified in Table 1, the heat transfer coefficient will increase inversely proportional to the gap of the fins in the continuum flow regime. Dwelling in a mixed flow regime has to be minimized in order to achieve a rapid change from ON to OFF state.

Figure 6(b) illustrates the relation between the volume of helium gas and the temperature span of the mixed flow regime (ΔT) during the transition. The temperature span increases with the volume of helium gas inside the heat switch. Moreover, a precise regulation of the initial pressure

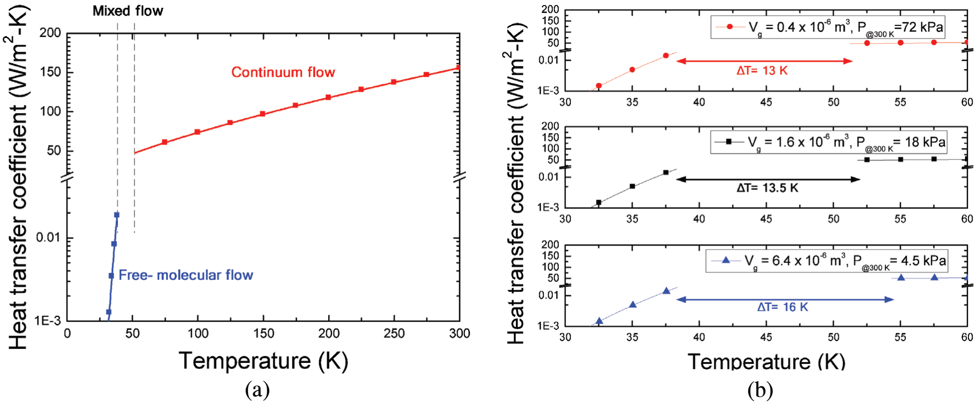

Figure 6. Heat transfer coefficient as a function of temperature with the gap of 1 mm (a) and mixed flow region with the volume of the heat switch (b).

($P_{@\,300\,K}$) of the helium fill gas is needed when the heat switch has a large gas volume. If the volume of helium gas increases, the pressure change of the helium gas due to adsorption of the activated charcoal bed will decrease. Therefore, the initial pressure should be set slightly higher than the pressure for the mixed flow regime. For these reasons, any unnecessary helium gas volume should be removed when one develops a helium gas heat switch with an activated charcoal bed. The heat transfer coefficient in the mixed flow regime is estimated by the two asymptotes between the continuum flow and the free-molecular flow regime. It should be noted that the heat transfer rate of rarefied gas exponentially decreases when the temperature of the heat switch decreases lower than 38 K. The calculation of the heat transfer coefficient with temperature shows that the thermal resistance of the helium heat switch can be modulated by more than a factor of 2000.

Cooling Time Calculation

Figure 7(a) shows a comparison of the cooling time with and without the heat switch. The external heat leaks to the first and the second stage are neglected in the cooling time calculation. The cooling system with the heat switch has a small temperature difference between the first and the second stages. This is because the heat switch facilitates the first stage to cool down the cooling load attached at the second stage and thus reduces the cooling time. When the heat switch reaches the temperature where free-molecular flow initiates, the heat transfer coefficient rapidly decreases and causes thermal isolation. As a result, the second stage becomes solely responsible for further cooling of the copper block to achieve its target temperature. In the case of a cooling system without the heat switch, the temperature of the second stage decreases slowly because the second stage cannot take advantage of the higher cooling capacity of the first stage at all.

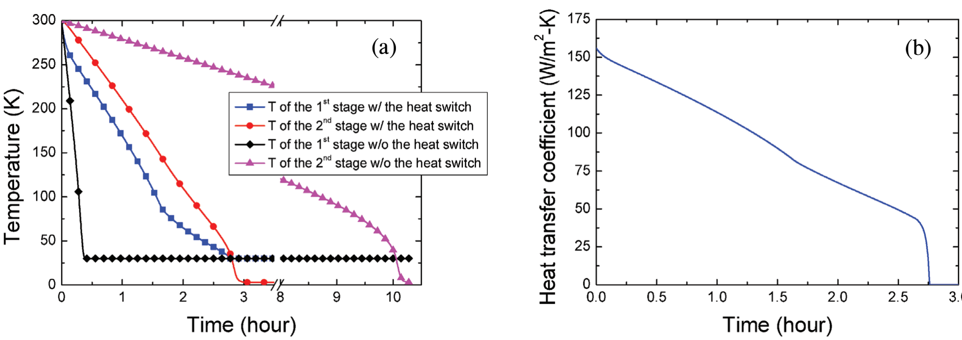

Figure 7. Calculated the cool down time with and without the heat switch (a), and the estimated heat transfer coefficient during cool down (b).

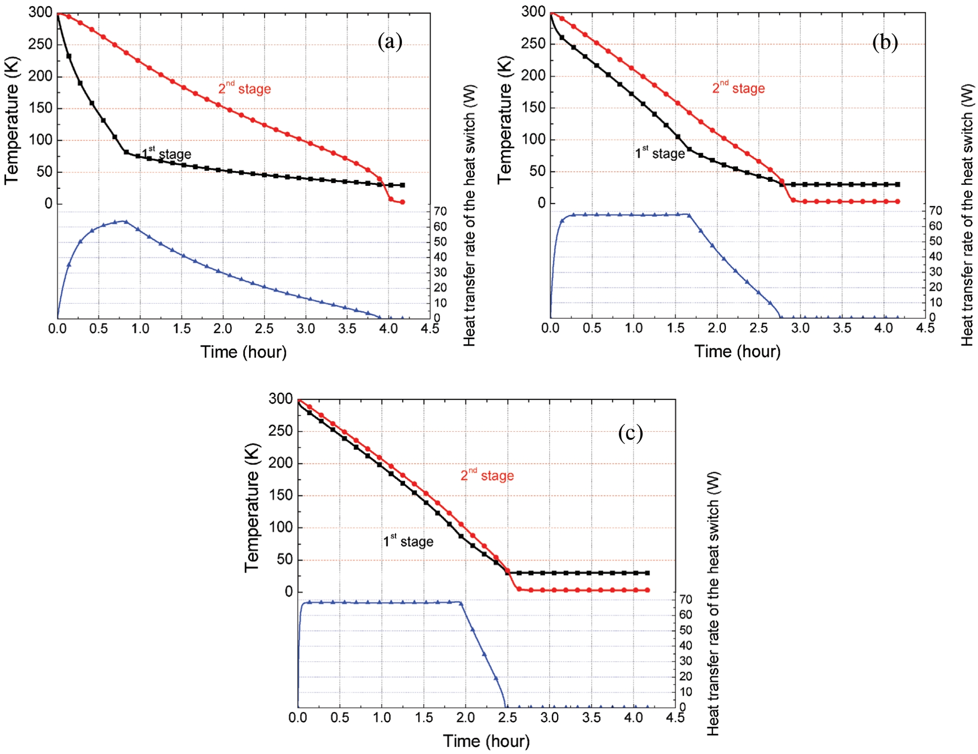

Figure 8. The cooling time and heat transfer rate of the heat switch with a heat transfer area of A_{HT} = 0.004 m^2 (a), 0.0145 m^2 (b), and 0.05 m^2 (c), respectively.

Figure 8 shows how the cooling time and the heat transfer rate vary with the heat transfer area of the fins. The results show that the cooling time decreases as the heat transfer area increases. However, there is a limit to reduce the cooling time. If the heat transfer area is infinite at the ON state, the maximum heat transfer rate of the heat switch can be calculated by the following equation:

$$q_{\max} = \left(q_{1st}(T_{1st}, T_{2nd}) + q_{2nd}(T_{1st}, T_{2nd})\right) \cdot \frac{m_1 \cdot c_{v,1st}}{m_1 \cdot c_{v,1st} + m_2 \cdot c_{v,2nd}} - q_{2nd}(T_{1st}, T_{2nd}) \tag{13}$$

Since the cooling capacities of the first and second stages (q_{1st}, q_{2nd}) are set to constant values of 80 W and 20 W, respectively, we can deduce from Eq. (13) that the maximum heat transfer rate is 70 W. For this reason, the heat transfer rates shown in Fig. 8 cannot exceed 70 W, although the heat transfer area is further increased.

CONCLUSION

In this paper, we have presented a new design of a helium heat switch using adsorption characteristic of activated charcoal. The designed heat switch can change its thermal resistance passively with the variation of temperature. The numerical analysis predicts that the switch resistance ratio can be on the order of 2000. The cooling time of a copper block is estimated using the simplified cooling capacity map of a two-stage cryocooler. In spite of the simplification, the calculation results clearly demonstrate the effectiveness of the heat switch on the cooling time. Although the performance of the designed heat switch is not yet verified, our study provides a framework for the development of an efficient helium gas heat switch.

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REFERENCES

1. Bywaters, R. P. and Griffin, R. A., "A gas-gap thermal switch for cryogenic applications," *Cryogenics*, vol. 13, no. (1973), pp. 344-349.

2. Shirron, P. J., Canavan, E. R., DiPirro, M. J., Jackson, M., Panek, J., and Tuttle, J. G. "Passive gas-gap heat switches for use in adiabatic demagnetization refrigerators," *AIP Conference Proceedings*, (2002), pp. 1175-1182.

3. Watanabe, K., Awaji, S., Sakuraba, J., Watazawa, K., Hasebe, T., Jikihara, K., Yamada, Y., and Ishihara, M., "11 T liquid helium-free superconducting magnet," *Cryogenics*, vol. 36, no. 12 (1996), pp. 1019-1025.

4. Kobayashi, T., Sato, Y., Sasaki, T., and Mine, S., "Manufacturing of Liquid Helium Free Superconducting Magnets for Industrial Use," *Advances in Cryogenic Engineering*, Vol. 43. (1998), pp. 157-163.

5. Hasebe, T., Sakuraba, J., Jikihara, K., Watazawa, K., Mitsubori, H., Sugizaki, Y., Okubo, H., Yamada, Y., Awaji, S., and Watanabe, K., "Cryocooler Cooled Superconducting Magnets and Their Applications." *Advances in Cryogenic Engineering*, Vol. 43. (1998), pp. 291-297.

6. Hase, T., Shibutani, K., Hayashi, S., Shimada, M., Ogawa, R., and Kawate, Y., "Generation of 1 T, 0.5 Hz alternating magnetic field in room temperature bore of cryocooler-cooled Bi-2212 superconducting magnet," *Cryogenics*, vol. 36, no. 12 (1996), pp. 971-977.

7. Choi, Y. S., Kim, D. L., and Shin, D. W., "Optimal cool-down time of a 4 K superconducting magnet cooled by a two-stage cryocooler," *Cryogenics*, vol. 52, no. 1 (2012), pp. 13-18.

8. Jeong, S., Kim, Y., Noh, C., Kim, S., and Jin, H., "Experimental investigation on the detachable thermosiphon for conduction-cooled superconducting magnets," *Cryogenics*, vol. 46, no. 10 (2006), pp. 705-710.

9. Prenger, F. C., Hill, D. D., Daney, D. E., Daugherty, M. A., Green, G. F., Chafe, J., Heiberger, M., and Langhorn, A., "Performance of Cryocooler Shunt Heat Pipes," *Advances in Cryogenic Engineering*, Vol. 43, (1998), pp. 1521-1528.

10. Prenger, F. C., Hill, D. D., Daney, D. E., Daugherty, M. A., Green, G. F., and Roth, E. W., "Nitrogen Heat Pipe for Cryocooler Thermal Shunt," *Advances in Cryogenic Engineering*, Vol. 41. (1996), pp. 147-154.

11. Chang, H.-M. and Kim, H.-J., "Development of a thermal switch for faster cool-down by two-stage cryocooler," *Cryogenics*, vol. 40, no. 12 (2000), pp. 769-777.

12. Nast, T., Bell, G., and Barnes, C., "Development of gas gap cryogenic thermal switch," *Advances in Cryogenic Engineering*, Vol. 27, (1981), pp. 1117-1124.

13. Martins, D., Ribeiro, L., Lopes, D., Catarino, I., Esteves, I. A. A. C., Mota, J. P. B., and Bonfait, G., "Sorption characterization and actuation of a gas-gap heat switch," *Sensors and Actuators A: Physical*, vol. 171, no. 2 (2011), pp. 324-331.

14. Martins, D., Catarino, I., Lopes, D., Esteves, I. A. A. C., Mota, J. P. B., and Bonfait, G., "Low temperature adsorption versus pore size in activated carbons," *Cryocoolers 16*, ICC Press, Boulder CO, pp. 567-573.

15. Duband, L., Ravex, A., and Chaussy, J., "Adsorption isotherms of helium on activated charcoal," *Cryogenics*, vol. 27, no. 7 (1987), pp. 397-400.

16. Barron, R. F., *Cryogenic systems* 2nd ed., Oxford (1985).

17. White, G. K., *Experimental techniques in low-temperature physics*. 3rd ed., Oxford (1979).

18. RDK-415D 4K Cryocooler Series, Available from: http://www.shicryogenics.com/products/4k-cryocoolers/rdk-415d-4k-cryocooler-series/.