

# Research on optimization strategies for heat switches based on helium adsorption models

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**Abstract.** Heat switches play a crucial role in cryogenic systems, regulating thermodynamic cycles or accelerating cooling processes. Among them, active gas-gap heat switches (AGGHS) are extensively employed, typically utilizing activated carbon and helium as the adsorbent-gas pair. Thermal conductance in AGGHS is controlled by driving gas adsorption or desorption through heating or cooling of the adsorbent. Due to significant variations among different activated carbons and other adsorbents, and the substantial variations in design requirements for AGGHS, systematic research on the performance optimization of AGGHS remains very challenging and is currently lacking. To address this, this study investigates optimization strategies for heat switches based on the cryogenic adsorption characteristics of helium. Specifically, by defining parameters to evaluate the filling ratio, an optimization methodology for determining the suitable operational range of AGGHS is proposed. Further, targeted optimization directions for the filling ratio are provided to address diverse application needs, such as adjusting the switching temperature range of the adsorption pump or speeding up the response time of AGGHS.

## 1. Introduction

Heat switches, which control the conduction or interruption of heat flow, are critical components in cryogenic technologies. They play essential roles in regulating thermodynamic cycles, accelerating precooling processes, and are widely used in systems such as adiabatic demagnetization refrigerators (ADR), dilution refrigerators (DR), and adsorption refrigerators (AR). In the ON state, a heat switch transfers heat from the high-temperature end to the low-temperature end, functioning as a thermal conductor. In the OFF state, it blocks heat transfer between the two ends, providing thermal insulation.



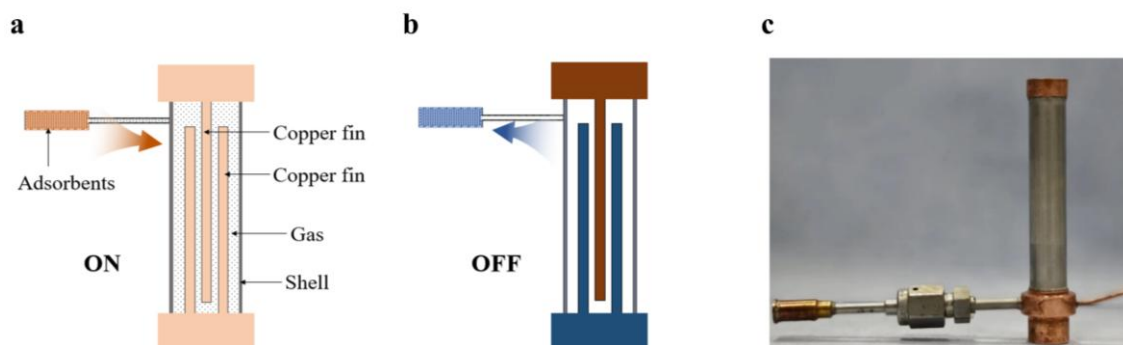


Figure 1. Typical active gas-gap heat switch at (a) ON and (b) OFF states. and (c) a photograph of the actual heat switch.

Heat switches can be classified into several types based on different physical mechanisms, including mechanical, superconducting, magneto-resistive, and gas-gap types<sup>[1]</sup>. Among these, active gas-gap heat switches (AGGHS) are the most widely used due to their compact size, absence of moving parts, high reliability, and stability. A typical AGGHS, as shown in Figure 1, consists of an adsorption pump, thermal fins at the hot and cold ends, an outer shell, and a working gas. The thermal conductance is controlled by adjusting the gas pressure in the gap via adsorption and desorption in the pump.

In other words, adsorption/desorption processes are central to switching the thermal conductance state of a AGGHS. A thorough understanding of the interactions between the adsorbent and the working gas, as well as proper control of the gas fill ratio, is crucial for optimizing the performance of the heat switch.

The working gases used in heat switches primarily include nitrogen, neon,  $^4\text{He}$ , and  $^3\text{He}$ , each suitable for different operating temperature ranges. It is essential to select an appropriate gas based on the target temperature region. Currently, the adsorbents used in heat switches are typically porous materials such as activated carbon or molecular sieves. However, it remains an open question whether there are adsorbent materials more suitable for heat switch applications. Furthermore, the type and amount of adsorbent filled can significantly affect the performance of the heat switch. These aspects merit further investigation and discussion.

In our previous work<sup>[2]</sup>, to better understand the adsorption and desorption behaviour within low-temperature gas-gap heat switches, we investigated the low-temperature adsorption characteristics of  $^4\text{He}$  on various carbon-based adsorbents. A modified Dubinin–Radushkevich (D-R) model was proposed to describe the monolayer adsorption behaviour, as will be introduced in the next section. By integrating this monolayer adsorption model with the rarefied gas thermal conduction model, we successfully applied it to different heat switches, achieving good agreement between the predicted thermal switching behaviour and experimental results.

In this study, we further utilize the above adsorption model to systematically explore the design and optimization of gas-gap heat switches. Specifically, we analysed the influence of adsorbent type, filling amount, and working gas charge on the switching performance. Based on these analyses, we aim to establish practical design guidelines and parameter optimization standards, which will help reduce the complexity of gas-gap heat switch design and provide a useful reference for future development and performance improvement.

## 2. Model of AGGHS

Based on the low-temperature adsorption measurements of  $^4\text{He}$  on activated carbon and carbon nanotubes, a monolayer adsorption model suitable for heat switch applications was developed, as shown in Equation 1<sup>[2]</sup>. It is hypothesized that different carbon-based adsorbent materials have the same  $^4\text{He}$  physical adsorption law in the range of monolayer adsorption: (1) even if the specific surface area and pore morphology of different materials are different, the difference reflected in the DR equation may not be large. (2)  $E_0$  increases linearly with the temperature. (3)  $n_{max}$  decreases linearly with temperature and is closely related to the specific surface area of the material.

Although the above assumptions are relatively simplified, Equation 1 provides a good prediction of the switching behaviours of the heat switch in our study. This provides practical guidance for the design of cryogenic helium adsorption components. While the model can also offer reference at higher temperatures, the accuracy may be somewhat compromised.

$$\begin{aligned} n/n_{max} &= \exp \left[ -\frac{1}{(E_0)^2} (RT_{sor} \ln \frac{P_0}{P})^2 \right] \\ E_0 &= (731.319 + 18.187 T); \\ n_{max} &= \frac{S_{N_2BET}(1.331 - 0.0145 T)}{\sigma N_A}; \end{aligned} \quad (1)$$

where  $n$  represents the specific adsorption amount (mol/g),  $n_{max}$  is the maximum monolayer adsorption amount,  $T_{sor}$  is the temperature of adsorbents,  $E_0$  is the characteristic free energy,  $P$  is the pressure at adsorption equilibrium, and  $P_0$  is the saturation pressure of the  $^4\text{He}$  corresponding to  $T_{sor}$ . When the temperature of the adsorbent is greater than the saturation temperature of  $^4\text{He}$ , a virtual saturation pressure  $P_0$  can be taken<sup>[3]</sup>:

$$P_0 = P_c (T/T_c)^2 = 8456.3 * T^2 \quad (2)$$

The thermal conductance switching behaviours of heat switch primarily rely on the variation of thermal conductivity caused by changes in gas pressure within the gap. Depending on the gas pressure, different flow regimes can be distinguished, which are typically characterized using the Knudsen number ( $Kn$ )<sup>[4]</sup>:

Viscous regime  $Kn < 0.01$

Transition regime  $0.01 \leq Kn \leq 10$

Molecular regime  $Kn > 10$

In different flow regimes, the thermal conductivity of gas exhibits distinct behaviors. In the viscous flow regime, the thermal conductivity remains almost independent of pressure. In the molecular flow regime, it is approximately proportional to the gas pressure. The transition regime lies between the two. Therefore, to achieve effective thermal switching, the gas-gap heat switch may be designed such that the gas operates in the viscous flow regime when in the ON state, and in the molecular flow regime when in the OFF state. The thermal conductance in the three regimes can be calculated using the following equations<sup>[5, 6]</sup>:

$$K_{trans} = \frac{1}{\frac{1}{K_m} + \frac{1}{K_v}} \quad (3)$$

$$K_m = A \frac{\gamma + 1}{\gamma - 1} \sqrt{\frac{R}{8\pi MT}} P \quad (4)$$

$$K_v = k(T) \frac{A}{d} \quad (5)$$

Where  $K_{trans}$ ,  $K_m$ , and  $K_v$  is the thermal conductance of transition state, molecular state, and viscous state respectively,  $A$  is the heat transfer area of the gas gap,  $M$  is the molar mass,  $\gamma$  is the ratio of specific heat capacities,  $d$  is the width of the gas gap, and  $k(T)$  is the thermal conductivity of helium in viscous state, which is mainly affected by the temperature.

Martins<sup>[5]</sup> pointed out that the thermal conductance of gases in different flow states can be predicted using the transition-state thermal conductance formula. In addition, the copper fins and the outer shell also contribute to the overall thermal conduction in the heat switch. Therefore, the total thermal conductance of the heat switch can be expressed as Equation 6. Where  $K_{HS}$  is the effective thermal conductance of the heat switch,  $K_{ss}$  denotes the conductance of the stainless-steel shell,  $K_c$  refers to the conductance of the copper fins,

$$K_{HS} = \frac{1}{\frac{1}{K_m} + \frac{1}{K_v} + \frac{1}{K_c}} + K_{ss} \quad (6)$$

Inside the heat switch, the gas is divided into the gas phase  $N_g$  and the adsorbed phase  $N_a$ , and the sum of the two is  $N_{all}$ . Based on the conservation of the mass of  $^4\text{He}$  molecules inside the heat switch, that is,  $N_{all}$  remains constant, the adsorption model Equation.1 can be coupled with the heat transfer model Eq.6, which can be used to predict the thermal conductance of the heat switch in different states.

$$N_{all} = N_g + N_a \quad (7)$$

### 3. Optimization Strategy of AGGHS

This section presents a methodology to determine the appropriate adsorbent–adsorbate ratio in AGGHSs, using a  $^4\text{He}$  heat switch working at 4 K as the case study. The type and filling ratio of the adsorbent and adsorbate pair in the heat switch play a critical role in determining its performance. Key factors affecting this include the gas pressure, internal volume, mass of the adsorbent, and the specific surface area of the adsorbent. To simplify the analysis, two parameters are defined: the volume-to-area ratio  $\beta$  and the gas coverage ratio:

$$\beta = \frac{V_{all}}{S_{all}} \quad (8)$$

$$\theta = \frac{n_a}{n_{max}} = \frac{n_a \sigma N_A}{S_{all}} \quad (9)$$

$$S_{all} = s_{sor} m_{sor} \quad (10)$$

Where  $\beta$  is defined as the ratio of the internal sealed volume to the total surface area of the adsorbent.  $\theta$  represents the ratio of the surface area occupied by the injected gas to the total surface area of the adsorbent.  $V_{all}$  indicates the internal volume of the heat switch,  $S_{all}$  represents the total surface area of all the adsorbents filled,  $s_{sor}$  is the specific surface area of the adsorbent,  $m_{sor}$  is the mass of the adsorbent,  $\sigma$  represents the cross-sectional area of the  $^4\text{He}$  gas molecule, and  $N_A$  is Avogadro's number.

In general, the parameter  $\beta$  reflects whether the amount of adsorbent loaded into the heat switch is sufficient, whereas  $\theta$  indicates the appropriateness of the gas filling quantity within the switch. A larger  $\beta$  indicates either insufficient filling of the adsorbent or an excessively large internal volume of the switch. A larger  $\theta$  signifies a greater volume of gas filled within the switch.

The custom-fabricated heat switch, shown in Figure 1(c), features a gas gap width of 0.1 mm, a heat transfer area of 13.3 cm<sup>2</sup>, and an internal volume of 0.88 cm<sup>3</sup>.  $\beta$  can be modified by changing the specific surface area and mass of the filling adsorbent, while  $\theta$  can be adjusted by

altering the room temperature gas pressure, given a constant internal volume. Since  $\theta$  may vary between the "ON" and "OFF" states, for the sake of convenience in this analysis,  $\theta$  is calculated based on the amount of adsorption at 5 K in the adsorption pump.

The temperatures of adsorption pump corresponding to the critical points for the "ON" and "OFF" states are selected for study, with  $\Delta T$  representing the temperature difference between the two states, as shown in Eq.9.

$$\Delta T = T_{sor@ON} - T_{sor@OFF} \quad (9)$$

Figure 2(a) and (b) illustrate the effects of  $\beta$  and  $\theta$  on the switching temperature of HS1 respectively. As shown in Figure 2 (a), when  $\theta$  is held constant,  $\beta$  has a minimal impact on  $T_{sor@OFF}$  due to the extremely low gas pressure in the "OFF" state, which results in a negligible quantity of  $N_g$ . However,  $\beta$  does slightly influence  $T_{sor@ON}$  and  $\Delta T$ ; a larger  $\beta$  may marginally increase the difficulty of achieving conduction.

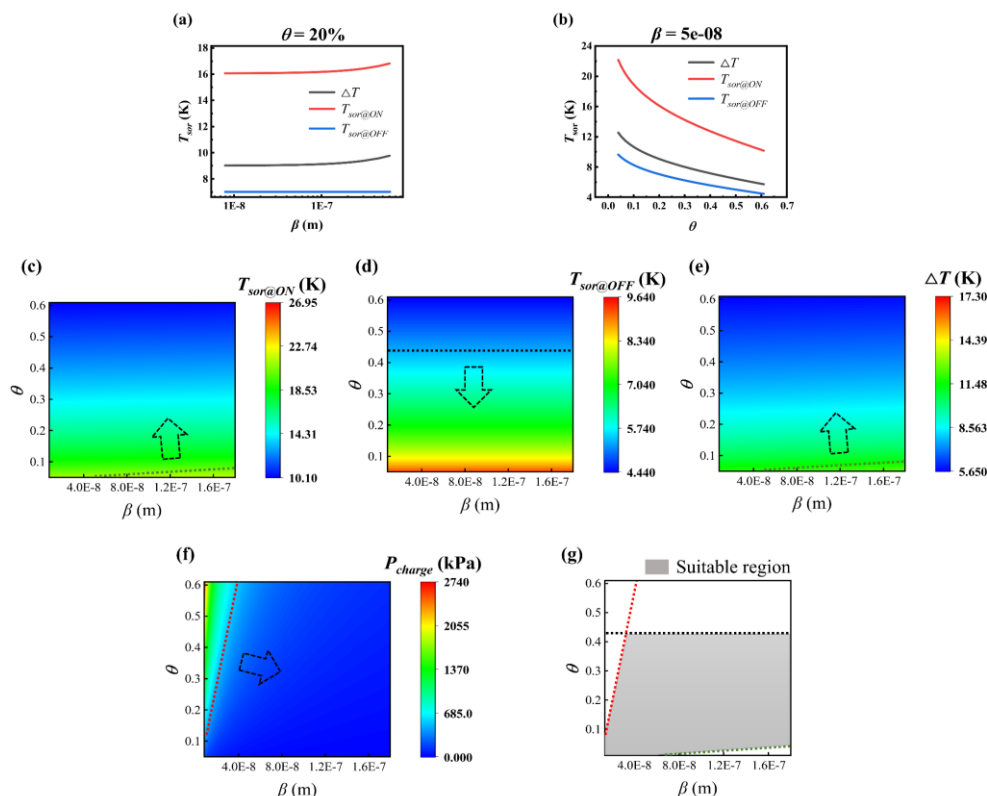
In contrast, the impact of  $\theta$  on the switching temperature is significantly greater. As shown in Figure 2 (b), as  $\theta$  increases, both the switching temperature and the temperature difference decrease, with the trend flattening out. If  $\theta$  falls below 0.1, it leads to substantial challenges in achieving conduction, necessitating a  $T_{sor@ON}$  exceeding 20 K.

Figure 2 c-f examine in detail the relationship between switching temperature and the filling amount of  $^4\text{He}$ , while Figure 2 (g) further refines the optimal range for  $\beta$  and  $\theta$ .

As shown in Figure 2 (c),  $T_{sor@ON}$  is influenced by both  $\beta$  and  $\theta$ . In practical applications, it is crucial to prevent  $T_{sor@ON}$  from becoming excessively high, as this could introduce significant thermal load and prolong the heating time required for switching. Figure 2 (d) illustrates that  $T_{sor@OFF}$  is primarily affected by  $\theta$ . Since the adsorbent is typically cooled to around 4 K by a cryocooler or liquid helium, ensuring the switch can effectively turn "OFF" requires avoiding excessively low  $T_{sor@OFF}$ . In Figure 2 (e), a smaller  $\Delta T$  corresponds to quicker and more efficient switching behavior.

Figure 2 (f) shows the room temperature filling pressure  $P_{charge}$ . Since the internal volume of HS1 is fixed, a higher  $P_{charge}$  signifies a larger amount of  $^4\text{He}$  being injected. As indicated in Figure 2 (f), reducing  $\beta$  and increasing  $\theta$  require higher filling pressures, potentially exceeding 10 MPa, which risks wasting  $^4\text{He}$  resources and introduces safety concerns.

Considering all these factors, Figure 2 (g) provides a suitable design parameter range for the heat switch, shown in the shaded region. It can be observed that the range for the heat switch is relatively flexible as long as it meets the usability requirements. However, if a more detailed customization is required, further optimization is necessary in conjunction with Figure 2 c-f. For instance, when the temperature of the heat sink is relatively high, making it difficult for the heat switch's adsorption pump temperature to be lowered below 5 K, careful consideration should be given to Figure 2(d). Conversely, when a smaller parasitic heat is required for the heat switch, along with a shorter actuation process, Figure 2(c) and (e) should be the primary focus during optimization.



**Figure 2.** The Influence Mechanism and Optimization Strategy of Coverage and Volume Ratio on Switching Performance and  $^4\text{He}$  Charge Quantity. (a) The effect of  $\beta$  on the switching temperature when  $\theta$  is constant. (b) The effect of  $\theta$  on the switching temperature when  $\beta$  is constant. (c) The influence of  $\theta$  and  $\beta$  on  $T_{sor@ON}$ , (d)  $T_{sor@OFF}$ , (e)  $\Delta T$ , and (f)  $P_{charge}$ , with lines and arrows indicating the optimal region. (g) The combined optimal region for  $\theta$  and  $\beta$ .

The optimization criteria outlined above can be used to identify a general operational region suitable for the heat switch, while also allowing for targeted optimization based on different purposes and requirements. In the following, we present a typical example to illustrate this.

If fast switching is desired, the coverage ratio needs to be increased to lower the adsorption bed temperature required for the ON state and reduce the temperature difference needed for switching. As shown in Figure 2(b), increasing the coverage ratio achieves this goal, especially when it is below 20%. However, coverage ratios above 30% offer diminishing benefits and may even compromise OFF performance. According to Eq. 9, the coverage ratio can be adjusted by decreasing the specific surface area or the mass of the adsorbent, or by increasing the amount of working gas.

Across all designs, if too much adsorbent is used, a correspondingly larger amount of working gas is required. This not only leads to waste but also may result in extremely high charging pressures, as shown in Figure 2(f), making the process difficult. On the other hand, if the adsorbent has a low specific surface area, a large quantity is required to provide sufficient adsorption capacity. Otherwise,  $\beta$  becomes large and the required gas pressure may become too low, which also presents challenges. Therefore, selecting an adsorbent with appropriate specific surface area and mass is an important consideration in heat switch design.

#### 4. Conclusion

This work employs a cryogenic monolayer helium adsorption model, derived from previous studies, coupled with a heat transfer model, as the basis for analysing the AGGHSs. Two new parameters  $\beta$  and  $\theta$  have been established to determine whether the filling ratio of adsorbent to adsorbate within the switch is appropriate. By analysing the effects of the parameters  $\beta$  and  $\theta$  on the switching conditions and charging pressure of the AGGHSs, the suitable operating range for AGGHSs can be identified. This provides guidance for the design and optimization of AGGHSs, making it easier to determine the required type and quantity of adsorbents, as well as the appropriate gas filling amount.

Although the analysis focuses on a specific prototype heat switch and its numerical results are influenced by its dimensions, the methodology is universal and applicable to other adsorbent–gas systems. This study focuses on  $^4\text{He}$  as the adsorbate. For other commonly used working gas in AGGHS, such as  $^3\text{He}$  and Ne, the optimization approach shares similarities. However, since this work is based on a monolayer adsorption model for carbon-based materials, its applicability to non-carbon-based adsorbents, such as zeolites or sintered metals, may be limited.

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