A Mechanical Thermal Switch for Conduction-cooled Cryogenic System

Monan Li¹,², Lifeng Li¹,², Dong Xu¹

¹Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China
²University of Chinese Academy of Sciences, Beijing, China

Xudong@mail.ipc.ac.cn

Abstract. A mechanical thermal switch is designed and fabricated to shorten the cool-down time of a conduction-cooled cryogenic system in which several copper heat loads are selected as experimental object. It is the first try of mechanical thermal switch for this application. Compared with the behavior of gas-gap thermal switch, the mechanical thermal switch is easy to manufacture, able to turn off at any temperature. The heat leak is little when it turns off. The drawback is that mechanical thermal switch need people to operate. The result shows that gas-gap thermal switch reduces the cooling time of our experimental system from 41.15 hours to 35.16 hours, while mechanical thermal switch reduces the time to 30.9 hours. In the situations for which frequent switches not needed, mechanical thermal switch is a competitive choice.

1. Introduction

The conduction-cooled cryogenic system, using a compact cryocooler instead of cryogenic liquid, is getting popular due to its compactness, easy and safe handling and low running cost. A typical conduction-cooled cryogenic system includes the object to be cooled, thermal radiation shield, GM cryocooler or Pulse-tube cryocooler, vacuum vessel, and other accessories. Thermal radiation shield is connected with the first stage of cryocooler and cooled by its cooling power, whereas the lowest temperatures of the closed-cycle refrigerator are reached at the second stage where experiments are attached. In commercial two-stage closed-cycle cryocoolers, the first stage is always considerably more powerful than the second stage over a wide temperature range. When an object with a large heat capacity has to be cooled by the second stage, the temperature of the first stage approaches its final temperature quickly, whereas it can take many hours for the second stage to cool the experimental object with its high
heat reservoir to its lowest temperature. In order to reduce the initial cool-down time of conduction-cooled cryogenic system, a thermal switch can be installed between the first and second stage of a cryocooler, or between the first stage and the object. At on-state, the thermal switch is a very efficient heat transfer device, therefore, the large cooling capacity of the first stage can be used to cool the object to temperature as low as possible for precooling. Once the combined stages reach the final temperature of the first stage, the thermal switch has to be interrupted and the second stage can continue to cool to its final temperature.

There have been a number of previous works to shorten the cool-down time of conduction-cooled cryogenic system:

1) Gas-gap thermal switch (GGTS). The presence/absence of the gas in the small gap enables/disables a thermal contact. It is divided into active and passive GGTS depending on if there are adsorbers or valves connected to gas reservoirs.

1.1) Passive GGTS. At cryogenic temperature, the thermal isolation (off-state) can be achieved without any external actuation, because the gas is frosted and the corresponding vapor pressure is significantly decreased.

Bywaters [1] firstly came up with a gas-gap thermal switch in 1973. A gas-gap thermal switch filled with helium was designed, fabricated and tested. The switch resistance ratio, \( R_{off}/R_{on}= 512 \) when the helium gas-gap was 0.254mm. In 2000, Ho-Myung Chang [2] fabricated a new configuration for the switch and tested the new one and the conventional structure switch in a G-M cooler cooled superconducting magnet system. The experiment showed that the newly developed gas-gap switch achieved a superior thermal performance. For both switches, the overall cool down time was shorten (shown in Fig.1). In 2012, Wang Q.L. [3] checked the performance of a gas-gap thermal switch filled with air using a superconducting magnet whose weight was 41.5kg as background device. The experiment showed that the cool-down time was shortened from 25 hours to 20 hours.

![Figure 1. Performance of two gas-gap thermal switches. [2]](image)

1.2) Active GGTS. The pressure of a gas in a small gap is controlled by use of adsorbers or valves connected to gas reservoirs. J Barreto[4] developed and built a prototype of a heat switch to be implemented at the Inter University Accelerator Centre according to thermal and
mechanical requirements of the magnet cryostat coupled with a 1.5 W @ 4.2 K Gifford-McMahon CCR.

2) Detachable thermal switch. In 2006, a group in Korea[5] uses a thermosiphon between the first and second stages of a cryocooler in a conduction-cooled superconducting magnet. It can be detached mechanically from the magnet. This year, D.Xu in our laboratory used a mechanical-thermal switch worked as a novel pre-cooling system for a conduction-cooled test bed.

3) Thermal shunt. Kurt Uhlig [6] tested an efficient and easy-to-build gas circuit acting as a thermal shunt between the two stages of a Gifford–McMahon cooler during the cool-down period of an experiment.

Mechanical thermal switch is a kind of detachable thermal switch. Here we designed a mechanical thermal switch and a gas-gap thermal switch to shorten the cool-down time of a conduction-cooled cryogenic system with copper blocks acting as heat load, and compared their performances.

![Figure 2](image_url)

**Figure 2.** Schematic diagram of experimental setup:

1. copper blocks of mechanical thermal switch;
2. switch rod;
3. gas-gap thermal switch.

2. Experimental apparatus

2.1. Cryocooler and heat loads

A two-stage GM cryocooler (RDK415D, Sumitomo Heavy Industries, Ltd., Japan) with cooling power around 1.5 W at 4.2 K is used. The copper block and thermal radiation shield connected with the first stage of the cryocooler compose the 1st stage heat load which weighs 56 kg in total. The copper block connected with the second stage of the cryocooler which weights 42 kg acts as the 2nd stage heat load. Between the 1st and 2nd stage heat loads and cold flanges, a thin indium foil and contact grease are applied to improve thermal contact. Both heat loads are
covered with 30 layers of aluminium-foil paper to reduce the radiation heat. Temperature measurements of 1st and 2nd stage heat loads (T1 and T2) are performed with two standard Rhodium–Iron resistance thermometers plugged in the holes of the two copper blocks, and the lead wires are thermally sunk to the thermal anchor. The conductivity of copper is better than actual experimental object, so a piece of teflon is placed between the 2nd stage heat load and cold flange to add a thermal resistance. The size of the teflon is the same as 2nd stage cold flange, and the thinkness is 0.5mm.

2.2. Mechanical thermal switch
The mechanical thermal switch is thermally connected to the 1st stage heat load through 12 copper braids. Every two copper braids are welded together at two ends with copper terminal in order to reduce the thermal resistance of braids by increasing the cross section area. Copper block ① is tightly connected with the 2nd stage heat load through indium foil and contact grease. On the top surface of copper block ①, indium foil and contact grease are also used to optimize thermal contact with copper block ② when the mechanical thermal switch is on. Copper block ② could be moved up and down to keep thermal contact or not with block by spinning the end of switch rod at room temperature. Thus, the mechanical thermal switch could be turned on during the pre-cooling process and off during the test process.

![Figure 3. Mechanical thermal switch.](image)

(a) mechanical thermal switch with copper braids; 
(b) mechanical thermal switch without copper braids in test-bed.

2.3. Gas-gap thermal switch
The structure of gas-gap thermal switch is shown in Fig. 4. It is actually a closed container, composed of two caps with several straight and parallel fins which are made of copper. The 1 mm thick fins are inserted each other and form gas-gap space. The outer shell is made of stainless steel and its thickness is 0.3 mm. The outer diameter of the switch is 37.6 mm and the total height is about 64 mm. The gap between adjacent walls is 1 mm, and filled with nitrogen.
3. Experimental procedure

3.1. No thermal switch
In this experiment, both thermal switches are installed in the system, while no copper braids connect them with 1st stage heat load. The thermal switches act as a part of 2nd stage heat load here. After the inside of vacuum vessel is pumped to vacuum ($\leq 10^{-4}$ Pa at room temperature), GM cryocooler is turned on to cool the 2nd stage heat load to 50K.

3.2. Mechanical thermal switch
After the temperature of the experiment system back to room temperature, the mechanical thermal switch is connected with the 1st stage heat load through aforementioned 12 copper braids. Contact grease is used to reduce thermal contact resistance between both ends of copper braids and 1st stage heat load or the upper copper block of mechanical thermal switch. Then the end of switch rod is spinned to guarantee tight junction of two copper blocks. Repeat the operation in the first experiment to cool the 2nd stage heat load to 50K.

3.3. No thermal switch
The system is warmed to room temperature, and move one end of the copper braids from mechanical thermal switch to gas-gap thermal switch. The thermal switch is purified with 99.999% nitrogen gas and charged to 150 kPa. Then the operation in the first experiment is repeated to cool the 2nd stage heat load.

In addition, the experimental setup comprises measurement devices and a data acquisition system. The control electronics for the measurement are driven by a data collection computer via the IEEE-488 General Purpose Interface Bus (GPIB). Based on Labview Software, a custom designed data acquisition program is developed that automates the data acquisition process.

4. Results and discussion
Figure 5 shows the cool-down curves of 2nd stage heat load: (1) no thermal switch; (2) connecting 1st stage heat load and mechanical thermal switch with same copper braids; (3) connecting 1st stage heat load and gas-gap thermal switch with 12 copper braids. In the case of no thermal switch, it takes 41.15 hours to cool down 2nd stage heat load to 50K. With gas-gap
thermal switch, it takes 35.16 hours to cool down to 50K. While the total cool down time is 30.9 hours using mechanical thermal switch.

**Figure 5.** Cool-down curves of 2nd stage heat load

**Table 1.** Cool-down time of three experiments

|               | Initial temperature | Target Temperature | Cool-down time |
|---------------|---------------------|--------------------|----------------|
| No thermal switch | 290 K               | 50                 | 41.15 h        |
| Gas-gap thermal switch | 298 K               | 50                 | 35.16 h        |
| Mechanical thermal switch | 300 K               | 50                 | 30.9 h         |

The mechanical thermal switch can significantly shorten the cool-down time from 41.15 h to 30.9 h by making use of the large cooling power of the first stage. Comparing two switches, mechanical thermal switch performs better. In order to make full use of the cooling power of the first stage, we hope the switch can turn off at the final temperature of the first stage. The switching temperature of a passive gas-gap thermal switch depends on the property of the filling gas, while the mechanical thermal switch can turn off at any temperature we want, so that the large cooling power of 1st stage can be used to cool the 2nd stage heat load to temperature as low as possible. In addition, mechanical thermal switch is much easier to fabricate. But mechanical thermal switch need people to turn it off and on, which limits its application. While in some applications, like conduction cooled superconducting magnet, where it does not need to switch frequently, mechanical thermal switch is more flexible. Meanwhile, the heat leak is little at off state. Later, we will test the performance of mechanical thermal switch in a real superconducting magnet.

5. Conclusions
In order to use mechanical thermal switch in some specific applications, such as superconducting magnet, we test its performance in a system whose heat loads consist of several red copper blocks and compare with the performance of a gas-gap thermal switch. Three
experiments are carried out: no thermal switch, with gas-gap thermal switch, with mechanical thermal switch. The cool-down time from room temperature to 50K is 41.15 h, 35.16 h and 30.9 h respectively. The result shows mechanical thermal switch can significantly shorten the cool-down time of the conduction-cooled cryogenic system. In some applications such as superconducting magnet, where the system do not need to be cooled down frequently, mechanical thermal switch is a good choice to reduce the cool-down time, because it can be turned on and off at any temperature and is easy to fabricate.

Acknowledgements
The authors appreciate the financial support from the National Natural Science Foundation of China (Grant No.: 51677186).

References
[1] R.P. Bywaters, R.A. Griffin 1973 Cryogenics 13 344-349
[2] H.-M. Chang, H.-J. Kim 2000 Cryogenics 40 769-777
[3] B. Zhao, Q. Wang, L. Li, H. Liu, S. Chen, Y. Dai, Y. Lei, H. Wang, Z. Ni 2012 IEEE Transactions on Appl. Supercon. 22 4700904-4700904
[4] J. Barreto, P.B. de Sousa, D. Martins, S. Kar, G. Bonfait, I. Catarino 2015 Mater. Sci. & Eng. 101 012144
[5] S. Jeong, Y. Kim, C. Noh, S. Kim, H. Jin 2006 Cryogenics 46 705-710
[6] K. Uhlig 2002 Cryogenics 42 67-69