Design and testing of a tin superconducting heat switch for adiabatic demagnetization refrigerators

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Abstract. The superconducting heat switch (SCHS) is a critical component in an adiabatic demagnetization refrigerator (ADR) to achieve a temperature down to 50 mK, and its switching performance significantly affects the overall efficiency of the ADR. We have designed a superconducting heat switch utilizing high-purity tin (99.99%) as the superconducting material and conducted experimental testing on its performance. The results show that the superconducting heat switch achieves full conduction under an applied magnetic field of 0.067 T. The thermal conductivities of the designed SCHS in both the normal and superconducting states were measured. The switching ratios were calculated, and the discrepancies between experimental results and theoretical values were analyzed. This heat switch is expected to be primarily used in temperature regions below 500 mK to manage the thermal connection between the single-stage ADR and the ^{3}He sorption cooler.

Keywords: Superconducting heat switch; Thermal conductivity; Switching ratio

1. Introduction

ADR is a common technique for achieving ultra-low temperatures. Notably, its insensitivity to gravity makes it particularly advantageous for space applications. The heat switch is one of the

Table 1. Heat switch operating temperatures

Heat switch type	Applicable temperature range	Comments
Mechanical	Any temperature	Zero conductance in off-state
Gas-gap	≳0.2 K	Limited by the saturated vapour pressure of ^{3}He or ^{4}He
Magnetoresistive	≲20 K	High magnetic field required in off-state
Superconducting	≲0.5 K	The lower the temperature, the better the performance

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key components of ADR. It controls the heat exchange between the magnetocaloric material and the heat sink, and its performance is one of the crucial factors in determining the overall cooling efficiency of the ADR. Common types of heat switches include mechanical heat switches, gas-gap heat switches, magnetoresistive heat switches[1], and SCHSs. **Table 1** shows the operating temperatures of these heat switches.

Mechanical heat switches are highly attractive due to their zero thermal conductance in off-state. However, achieving significant thermal conductance in the milliKelvin temperature range requires applying several thousand Newtons of force. Gas-gap heat switches cannot operate below 0.2 K due to the properties of the working medium. SCHSs have a higher switching ratio than magneto-resistive heat switches, especially at ultra-low temperatures. HEER and DAUNT were the first to propose using superconductors as heat switches. They measured the thermal conductivity ratio of tin between its normal and superconducting states (k_n/k_s), which is approximately 40 at 0.65 K[2]. Shirron et al. proposed the concept of continuous ADR, in which SCHS is used in the continuous stage[3]. We plan to use a SCHS between the ^{3}He sorption cooler and the ADR. This paper briefly introduces the working principle of superconducting heat switches and presents the design and preliminary experimental results of a tin superconducting heat switch.

2. Working principle

SCHSs operate based on the properties of superconductors, utilizing the significant difference in thermal conductivity between their normal and superconducting states to control heat flow. The thermal conductivity of a material is determined by both electronic and phonon conduction, with the thermal conductivity being the sum of their contributions. Under normal conditions, electronic conduction is several orders of magnitude higher than phonon conduction in thermal conductivity. For superconductors, when the temperature is above the critical temperature (T_c), the material is in the normal state, and thermal conductivity is primarily dominated by electronic conduction. Below the critical temperature, the superconductor enters the superconducting state, where electrons form Cooper pairs and no longer contribute to heat conduction, leaving phonon conduction as the dominant mechanism. At temperatures below 0.1 T_c, the thermal conductivity in the superconducting state can be considered to be entirely governed by phonon transport. The phonon thermal conductivity is proportional to the temperature cube[4]. Applying a magnetic field to a superconductor in the superconducting state can drive it into the normal state. This magnetic field is known as the critical magnetic field (H_c). SCHSs are commonly fabricated using Type-I

Table 2. The properties of several Type-I superconductors.

Material	T_c (K)	H_c (mT)	T_{upper} (K)
Zn	0.85	5.3	<0.1
Al	1.2	10.5	0.1
In	3.4	29.3	0.5
Sn	3.7	30.9	0.52
Pb	7.2	80.3	0.5

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superconductors because their critical magnetic field is much smaller than Type-II superconductors. **Table 2**[5]lists the critical temperatures and critical magnetic fields of several Type-I superconductors and the upper temperature (T_{upper}) limit for their use when the switching ratio is at least 100.

The T_{upper} of Zn and Al are relatively low and typically used in nuclear adiabatic demagnetization refrigeration. In this study, we have designed a SCHS using tin material and carried out experimental test on its thermal performance. Future tests will also be conducted on indium and lead heat switches.

3. Design

A SCHS primarily consists of a coil that provides the magnetic field, a superconducting material, and copper joints at both ends. **Figure 1** is the schematic diagram of the SCHS. To prevent flux pinning, thin tin foils are used as the superconducting material, with some oriented perpendicular to the magnetic field direction. The tin foil has a width of 4 mm and a purity of 99.99%. A groove

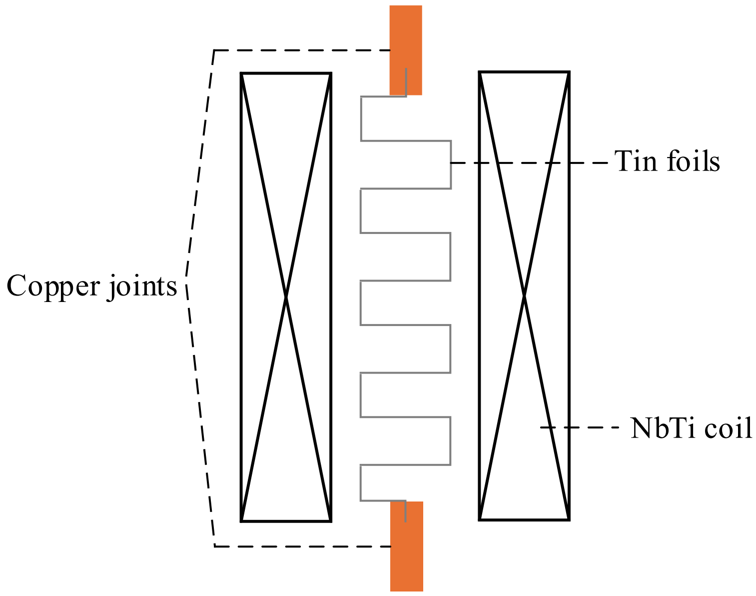

Figure 1. The schematic diagram of the SCHS.

is designed on one side of the copper joint to connect with the tin foil. Woods Metal is used as the solder to bond the tin foil to the copper joints through a low-temperature soldering process. A small superconducting solenoid coil was wound using niobium-titanium wire. When a current of 0.4 A is applied, it can generate a magnetic field of approximately 30 mT. In the tests, the coil was usually run with 0.6~0.8 A current to ensure proper switching of the SCHS.

In this test, one end of the SCHS was connected to the evaporator of the ^{3}He sorption cooler, while the other end was equipped with a 25 Ω heater. The thermal conductivity of the heat switch in both the normal and superconducting states was tested through heating experiments. The heater was controlled by Lakeshore 372. The experimental setup is shown in **Figure 2**.

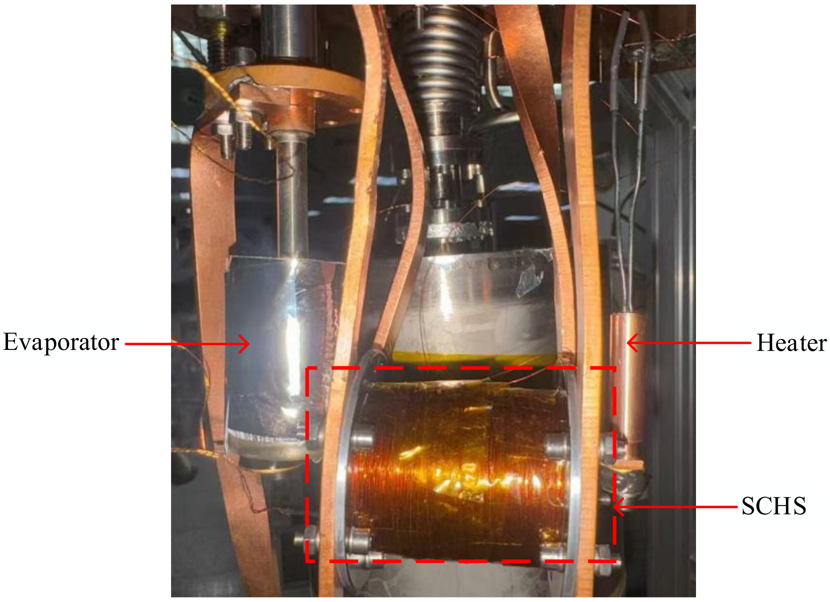

Figure 2. The experimental setup for SCHS.

4. Experimental results and analysis

Figure 3 and **Figure 4** show the conduction process of the SCHS. We test two tin SCHSs with different thicknesses: 0.05 mm and 0.4 mm. As the magnetic field increases to approximately 0.067 T, the temperature difference between the two ends of the SCHS ceases to change, indicating full conduction. This value is higher than the critical field of tin, which may be attributed to the non-uniform axial magnetic field generated by the NbTi coil.

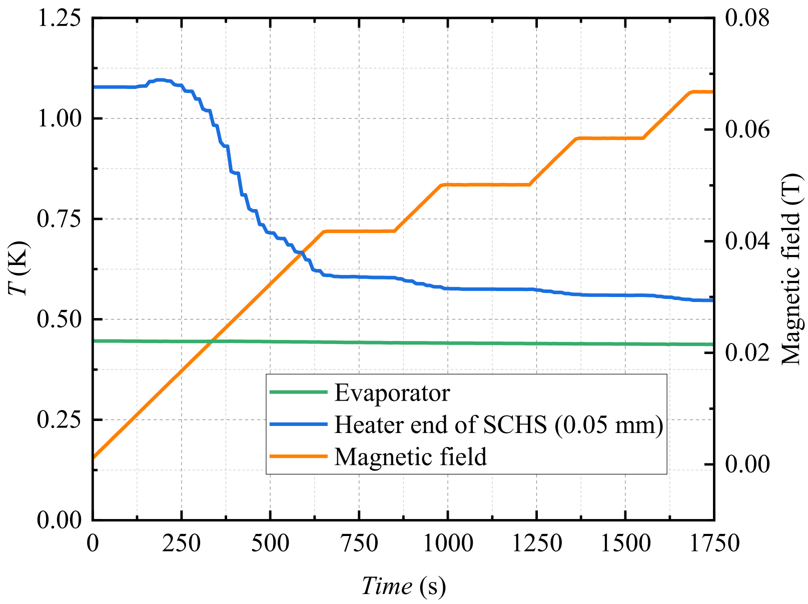

Figure 3. The magnetization process of the 0.05 mm thickness tin SCHS.

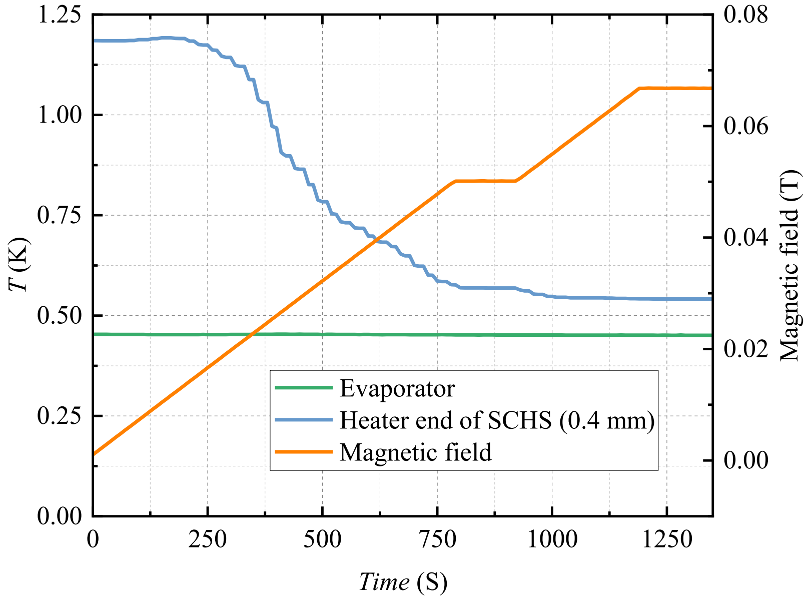

Figure 4. The magnetization process of the 0.4 mm thickness tin SCHS.

We also measured the thermal conductivity of these two tin foils in both the superconducting and normal states, as shown in **Figure 5**. Theoretically, for sufficiently pure superconductors (99.9999% purity), the thermal conductivity in the normal state is primarily governed by electron transport. In thin foil samples, it is also significantly influenced by boundary scattering[6]. In our experimental results, the thermal conductivity of the 0.05 mm thick foil in the normal state is higher than that of the 0.4 mm thick foil. It is indicated that our samples are not sufficiently pure, impurity scattering significantly affects electron transport. The thicker the sample, the more severe the impact of impurity scattering. Impurity scattering can significantly reduce the thermal conductivity in the normal state. Moreover, the temperature range of our measurements is above

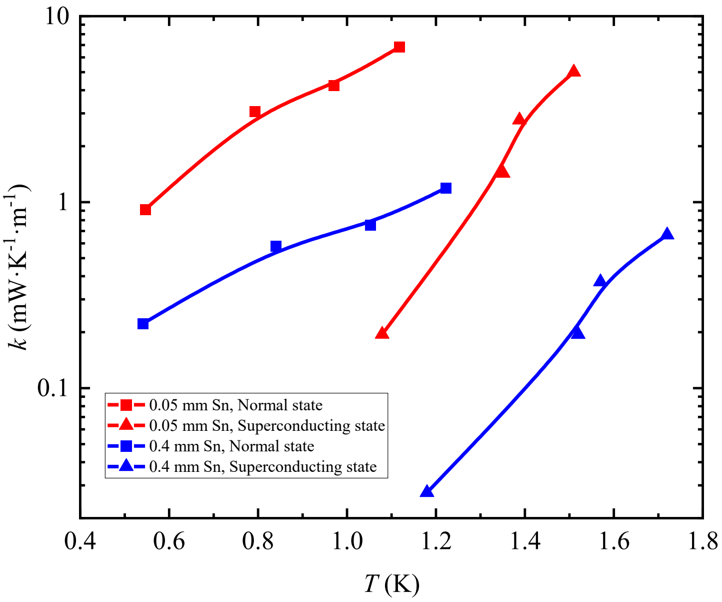

Figure 5. Thermal conductivity of tin in normal and superconducting states.

0.1 T_c, which means that the thermal conductivity in the superconducting state is not solely determined by phonon transport. It is also partially influenced by residual electronic conduction.

In addition to the thermal conductivities in the normal and superconducting states, the switching ratio is also of significant interest for a heat switch. The theoretical switching ratio of a superconducting thermal switch can be calculated using the following formula (1)[6]:

$$k_n/k_s = 0.053\Theta^2 T^{-2} \quad (1)$$

Where Θ is Debye temperature. The Debye temperature of pure tin is 200 K. Then the theoretical value of the switching ratio is equal to 2120 T^{-2}. Based on our experimental data, the switching ratio for the 0.05 mm thick tin foil is 33.62 T^{-2}, while for the 0.4 mm thick tin foil is 45.47 T^{-2}. The experimentally measured switching ratios show a noticeable deviation from the theoretical values. We believe there are two main reasons for this discrepancy. First, the superconducting tin used in our experiments is not sufficiently pure. Second, the measurements were conducted at temperatures above 0.1 T_c, where electronic conduction still partially influences thermal conductivity in the superconducting state.

For our application needs, we prioritize the heat switch's ability to effectively isolate heat in the off state to ensure the adiabatic condition of the salt pill of ADR. Although the conduction performance of our current heat switch is not yet ideal, its isolation capability is satisfactory, and overall, its performance basically meets our requirements.

5. Conclusion

We design a tin SCHS and test the thermal conductivities of tin foils with thicknesses of 0.05 mm and 0.4 mm in both the normal and superconducting states. Based on the experimental data, the switching ratios were calculated to be 33.62 T^{-2} and 45.47 T^{-2}, respectively. Due to factors such as material purity and the temperature range of the measurements, the experimental switching ratios show some deviation from the theoretical values. In future work, we plan to use this SCHS to connect a ^{3}He sorption cooler and a single-stage ADR to evaluate its performance further and test the tin SCHS for data below 0.5 K.

Acknowledgments

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