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A ^3He gas heat switch for the 0.5–2 K temperature range

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Abstract

We have constructed a prototype heat switch for use in a cyclic demagnetization apparatus. The desired operating range of the switch is from 0.5 to 1.8 K. The measured conductivity of the switch is 50 $\mu\text{W/K}$ at 1.5 K when 'off' and 8 mW/K at 0.5 K when 'on'. The switching is carried out by ^3He gas which is admitted and extracted from the device by a miniature charcoal adsorption pump which is controlled by electrical heat and a weak thermal link to a pumped ^4He bath. In this paper we discuss details of construction and the performance as a function of temperature, and consider the switching time between on and off states. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Cryogenic techniques; Heat switch; Thermal link

We have a need for a heat switch which can conduct 1 mW at 0.5 K with a temperature difference of 50 mK in its on state, yet provide isolation between 0.5 and 1.8 K with no more than 50 μW in the off state, as a component in a cyclic magnetic refrigerator. Ideally, the switching time should be no more than a few minutes. Many gas heat switches have been constructed in the past [1,2], but none which quite meet these criteria.

A schematic diagram of the construction we have used is shown in Fig. 1. Two concentric cylinders of copper with a 0.1 mm gap between them at 7 mm diam. are spaced by another cylinder of 0.2 mm-walled copper-nickel tubing, providing a hermetic seal. ^3He gas may be introduced into the 25 mm long gap between the cylinders through a 30 mm length of copper-nickel tubing, 0.55 mm id and 0.8 mm od, leading to a volume of 0.02 cm^3 containing activated charcoal. This whole assembly was filled to a pressure of 2 bar (absolute) with ^3He gas through a small capillary which was pinched off after the filling. The pinched-off end was capped by an epoxy-filled sleeve afterwards to ensure mechanical stability. The charcoal-filled cavity had a small ruthenium oxide thick film resistor glued to the outside, which serves simultaneously as a heater and thermometer to regulate

the adsorption or desorption of the ^3He gas which provides the switching action. The mid-section of the 0.8 mm od capillary was thermally anchored to the 1.8 K reservoir, to limit the thermal load resulting from elevating the charcoal reservoir to about 12 K during the operation of the switch. There is considerable resemblance to the device of Torre and Chanin [1], but the use of ^3He rather than ^4He extends the working region much lower in temperature.

The thermal conductivity in the on and off states for this switch is shown in Fig. 2. In the off state, the conductivity is essentially limited by the outer copper-nickel tubing, and is less than 0.05 mW/K in the temperature range of interest. In the on state, at 0.5 K the conductivity is over 10 mW/K, and is probably limited by the Kapitza boundary resistance between the ^3He gas and the copper walls. (Computations indicate that the conductivity within the gas and the conductivity of the copper should both be greater.) Thus, we see that the ultimate values of on and off state conductivities are approximately adequate for our task. The switching time to turn the switch to the on state is also very fast – a matter of less than 10 s to desorb an adequate quantity of gas from the charcoal using 2 mW heater power. The first part of the switching to the off state is, while slower, still within expectations. We are in a Knudsen flow regime for the gas, whose mean free path is limited by the space between the cylinder walls, and with the dimensions of this device the

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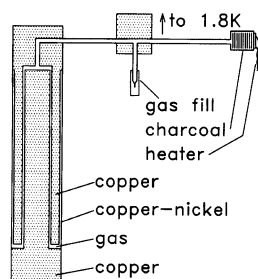


Fig. 1. Schematic construction.

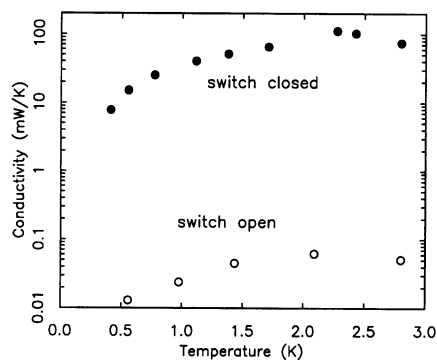


Fig. 2. Heat switch performance.

relaxation time for the pressure should be several seconds. We find, for example, that within 10 min of switching off the heat to the charcoal that the conductivity of the heat switch has dropped to about 0.05 mW/K at 0.5 K, which is probably adequate for the intended use.

However, this is still a factor of three higher than the ultimate thermal resistance which will be achieved if one waits several hours. An earlier version of the heat switch displayed a much slower switching time. This was because we had used a single cylinder of activated charcoal, and diffusion of the gas into the charcoal seemed to be the rate limiting process. The current version has 10 thin slices, to provide a more direct path.

The response time of the switch in turning off is slower than would be ideal. It is conceivable that further segmentation of the charcoal would aid in the gas extraction, but it may be that a monolayer or two of gas adsorbed on the metal surfaces of the switch limits the rate of pumping of the residual gas, by reducing the partial pressure of gas in the vapor phase. It is possible that redesigning the geometry of the switch might make improvements of a factor of 2–5 in the pumpout time at the lower pressures.

Acknowledgements

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