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Latching Permanent Magnet Electro-Mechanical Heat Switch for Cryogenic Applications

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Latching Permanent Magnet Electro-Mechanical Heat Switch for Cryogenic Applications

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Background

In low-temperature research and applications it is often required to reversibly and controllably change the thermal conductance between two parts of an apparatus. Classic examples where this is required include adiabatic heat capacity measurements and the adiabatic demagnetization refrigerator. In those procedures it is necessary to first establish strong thermal contact between a source of refrigeration, either a mechanical refrigerator or a liquid cryogen, and an experimental stage. After the stage has equilibrated to the temperature of the refrigerator, the thermal contact must be reduced or eliminated in order to perform the measurement, which involves changing the temperature of the stage by other means.

The function of reversibly and controllably altering thermal conductance may be accomplished in a several ways. Among these techniques are:

1. The provision of helium or other “exchange gas”. When the gas is present the two components can transfer heat via the gas, and when the gas is evacuated from the system the two components cannot. The exchange gas may contained hermetically within a separate demountable housing, or it may be introduced to a hermetic container that surrounds the two components of interest.
2. The provision of a length of superconducting material that connects the two components. When the material is well below its superconducting transition temperature its thermal conductance is very low. If the superconductivity is destroyed by, for example, the application of a magnetic field in excess of the superconducting critical field of the superconductor, the thermal conductance can be raised by orders of magnitude.
3. The provision of a length of electrically conductive material that connects the two components, where the electrically conductive material displays a large change in its thermal conductivity upon the application of a magnetic field, “magneto-resistance”
4. The provision of a mechanical apparatus that provides a clamping force and some arrangement of intermediate components such that, when the clamping force is applied, the two components are strongly connected thermally, and when the clamping force is removed, the two components are disconnected thermally.

Each of these approaches involves different tradeoffs, and there is no unique “best” solution for all applications.

In recent years there has been strong growth in the use of adiabatic demagnetization refrigerators which require heat switches. Mechanical heat switches of type 4 in the list above are almost universally used in these devices.

The invention described in this disclosure is a significant improvement on the state of the art of the 4th type of heat switch, as described below.

Prior art is further described in US Patent No. 6,532,759, March 18, 2003.

Brief Description of the Invention

The present invention is a latching electromechanical heat switch which is most closely related to the device described in US Patent No. 6,532,759. "Latching" of a solenoid-driven heat switch is highly advantageous relative to a non-latching version because power (and thus heat) only needs to be dissipated in the cryostat when the state of the heat switch is changed. This reduces the heat load on the source of refrigeration as the heat switch state is typically only changed infrequently, often on a time scale of hours or days.

However, the device described in US Patent No. 6,532,759 achieved its latching function by use of a mechanical linkage providing an "over-center" clamping action, and thus requires the use of two actuation solenoids: one to close the jaws of the switch and one to open them. The requirement for two actuation solenoids, rather than one, creates several disadvantages:

- increased mass to be cooled, increasing cooldown times
- increased size of the heat switch, a problem for tight geometries
- increased wire count to control two solenoids

The present invention completely eliminates the need for the second solenoid by instead combining a single solenoid with a "pole piece" that contains one or more permanent magnets. The provision of a pole piece containing one or more permanent magnets confers two distinct advantages:

1. the single solenoid can now attract **or repel** the pole piece by simply reversing the direction of current through the solenoid.
2. the heat switch is now latched in the "closed" (conductive) position by the magnetized pole piece's attraction to the magnetic yoke of the solenoid.

Advantage 1 eliminates the requirement for the second solenoid, and advantage 2 creates two less-obvious further benefits

1. because the latching action in the closed position is provided by the passive attraction of the pole piece to the solenoid magnetic yoke, there is no requirement to go "over center" in the mechanical linkage as was done in US Patent No. 6,532,759. This means that the mechanical linkage can be tuned to be in the "on-center" position in the latched-closed position, providing maximum mechanical advantage and thus greater closing force, all other things being equal.

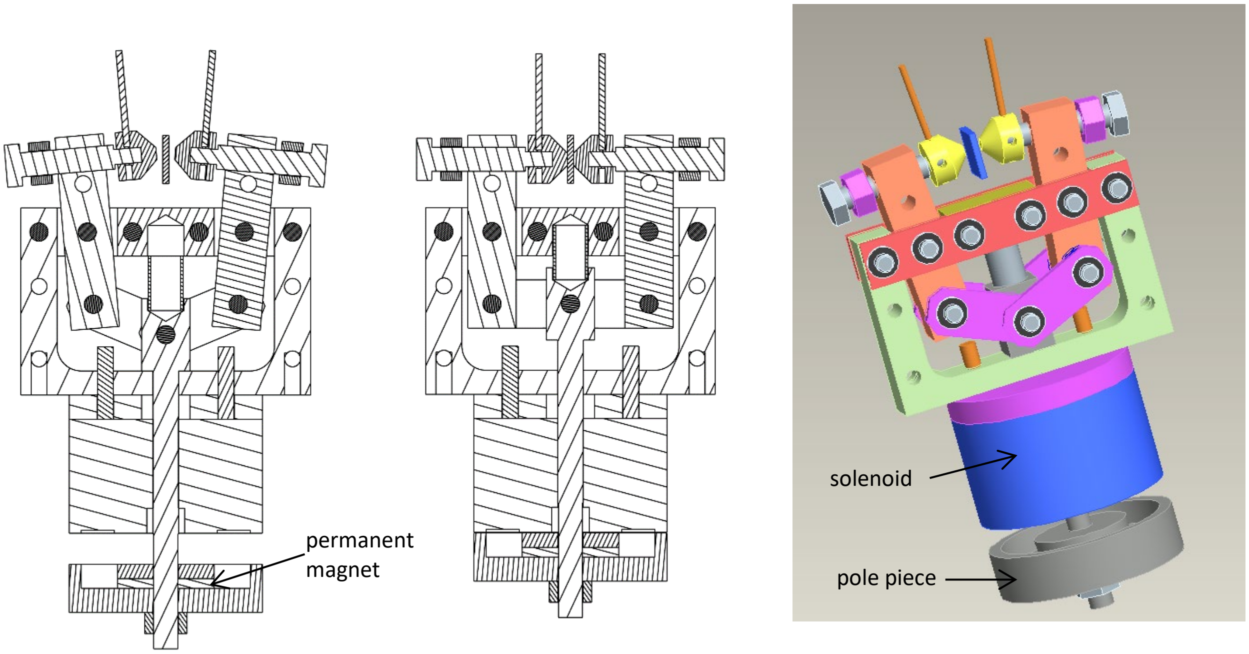
Greater closing force yields a higher thermal conductance in the closed position so this is highly desirable.

2. With proper choice of permanent magnet and magnetic design, the passive attraction of the pole piece to the solenoid's magnetic yoke can be engineered to rise very steeply, and become very strong, as the distance between the pole piece and the solenoid's magnetic yoke decreases.

The combined effect of advantages 1 and 2 is that the new approach provides both maximum mechanical advantage and a very strong latching force, which combine to maximize the clamping force in the latched-closed position.

The advantages of the new invention are thus

- elimination of requirement for second solenoid
- optimized tuning of mechanical linkage for maximum mechanical advantage in the latched-closed position
- very strong clamping force in the latched-closed position
- reduced wire count
- reduced part count

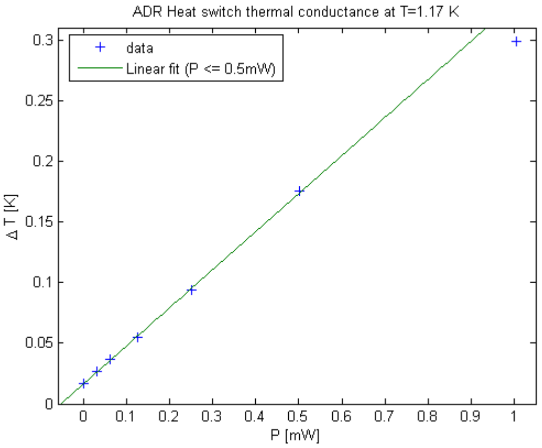


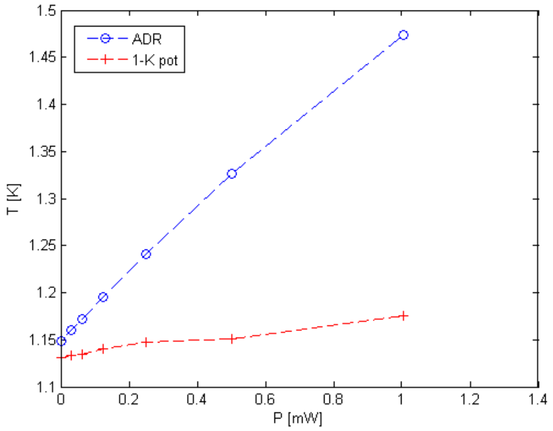
An embodiment of the present invention. Left: section view in open position. Middle: section view in closed position. Here the pole piece is clamped to the magnetic yoke of the solenoid by the influence of the permanent magnet. Also in this view is shown the optimal alignment of mechanical linkage for maximum mechanical advantage in the closed position. Right: perspective view in open position.

Performance Measurements

Thermal Conductance

Thermal conductance of one embodiment of the heat switch was measured with the heat switch in latched-closed position by applying a known amount of current via a known series resistance (1.006kOhm) which was thermally anchored to the ADR-side of the heat switch. The voltage across the resistor was also recorded in a 4-wire configuration using a digital multimeter to obtain the amount of power dissipated as P=I*V. Temperatures were recorded versus time and the equilibrium values of ADR and heat-sink (1K-pot) temperatures were used to plot the temperature standoff ΔT = T_ADR – T_HeatSink as a function of applied power. The thermal resistance of the heat switch can then be obtained as the slope of a straight line fitted to the datapoints.

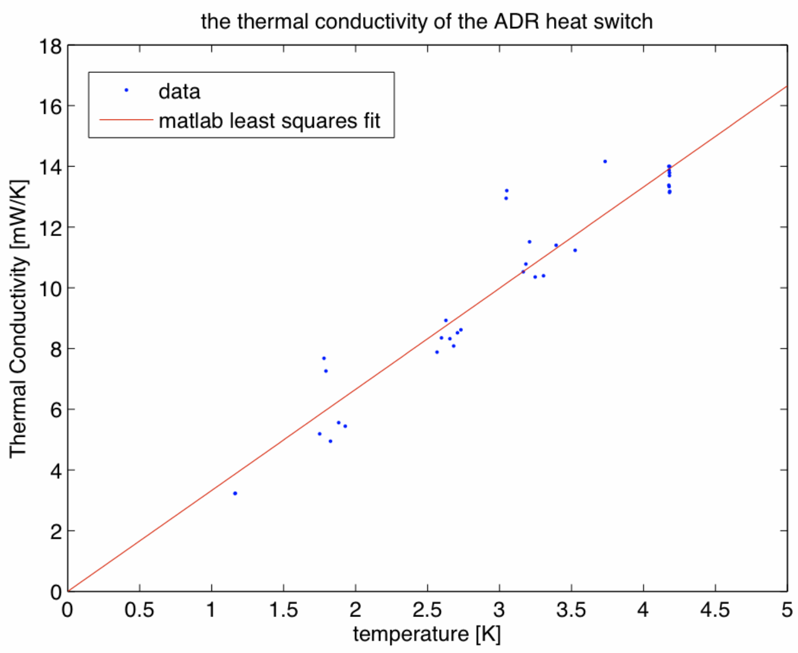




An example of the recorded equilibrium temperatures and thermal stand-off is shown in Figures 1 and 2. The thermal conductances thus determined were 3.19mW/K at 1.17K and 7.09mW/K at 2.24K.

Thermal and electrical conductance versus temperature

In an automated procedure the above experiment was conducted and analyzed over a range of temperatures and thus a plot of conductance versus temperature was obtained.



The thermal conductance is directly proportional to temperature, i.e. follows a Wiedemann-Franz law kappa = a * T, where a = 3.323 mW/K^2 in our case.

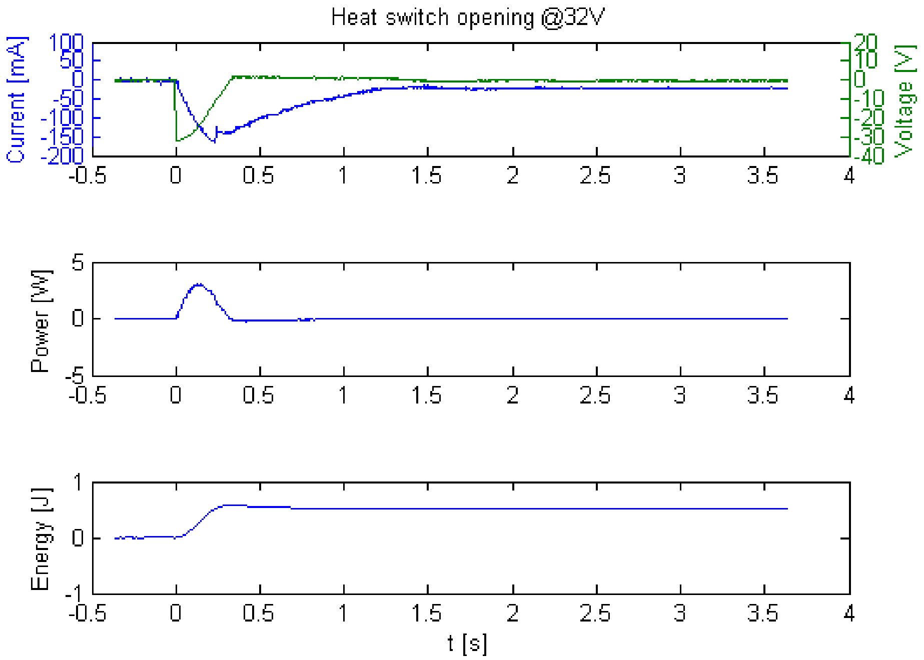
Additionally, the electrical resistance across the heat switch jaws was also measured in a four wire arrangement with excitation from a Keithley 220 current source and readout accomplished with a SQUID picovoltmeter. The electrical resistance was found to be about 4.7E-6 Ohm at 1.2K. From the Wiedemann-Franz law, one would expect 7.34E-6 Ohm, which is comparable.

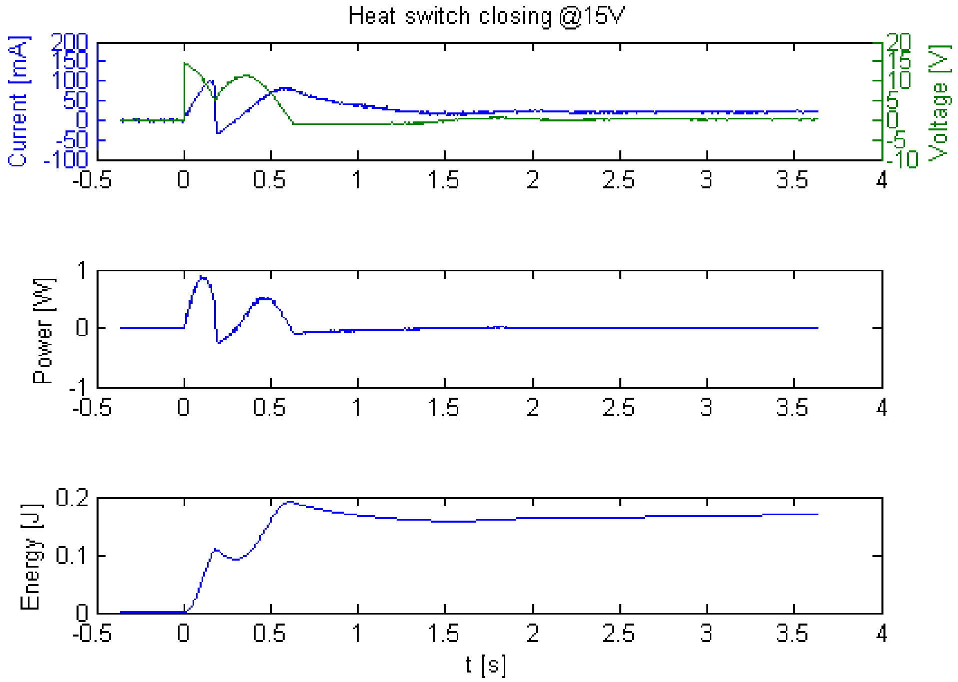
Electrical power dissipation

The electrical power required to open and close the heat switch was determined by recording current through the solenoid and voltage across the solenoid. The current was recorded using a digital storage oscilloscope as the voltage drop across a 1 Ohm sensing resistor. The voltage was recorded using a 10X probe in a separate oscilloscope trace.

A minimum voltage of 12.8V was required to close the heat switch. A minimum of 31V was required to overcome the magnetic latching and open the heat switch.

For reliable operation, the actual closing and opening voltages used in the experiments were 15V and 32V.





From the traces of current (I) and voltage (V), the instantaneous power can be calculated as P=I*V, with the total energy dissipation given by the integral P dt.

The electrical energy dissipation is about 0.16 Joule for closing of the heat switch, and 0.5 Joule for opening.

Mechanical heat release when opening the heat switch

It is desirable that during the opening of the heat switch jaws, the amount of heat released into the ADR is small. The following procedure was performed to quantify the amount of heat release into the ADR:

The ADR was brought into a constant magnetic field of about 40kGauss/44.45A * 25.0A = 22.5kGauss. With the heat switch closed. Then the heat switch was repeatedly cycled between the open and closed positions. After each state change, a sufficient amount of time was allowed for the temperatures on the 1K-pot heatsink and the ADR to equilibrate. Using the experimentally determined heat capacity of the ADR at the same conditions (1.377 J/K at 1.16K and 22.5kGauss), the change in temperature of the ADR due to the opening of the heat switch was converted to the heat released during the opening of the heat switch. At an average temperature of 1.16K, the mean temperature change was 2.92mK, corresponding to a heat release of 4.02 mJ.