PASSIVE GAS-GAP HEAT SWITCH FOR ADIABATIC DEMAGNETIZATION REFRIGERATOR

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Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 24 days.

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Field of Search 62/3.1, 51.1; 165/275

References Cited
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ABSTRACT
A passive gas-gap heat switch for use with a multi-stage continuous adiabatic demagnetization refrigerator (ADR). The passive gas-gap heat switch turns on automatically when the temperature of either side of the switch rises above a threshold value and turns off when the temperature on either side of the switch falls below this threshold value. One of the heat switches in this multistage process must be conductive in the 0.25°K to 0.3°K range. All of the heat switches must be capable of switching off in a short period of time (1–2 minutes), and when off to have a very low thermal conductance. This arrangement allows cyclic cooling cycles to be used without the need for separate heat switch controls.

32 Claims, 4 Drawing Sheets
FIG. 6a

FIG. 6b

FIG. 6c

FIG. 6d

FIG. 6e
PASSIVE GAS-GAP HEAT SWITCH FOR ADIABATIC DEMAGNETIZATION REFRIGERATOR

CROSS-REFERENCE TO RELATED APPLICATION

ORIGIN OF THE INVENTION
The invention described herein was made by employees of the United States Government, and may be manufactured and used by or for the Government for government purposes without the payment of any royalty thereon or therefore.

TECHNICAL FIELD
This invention relates generally to refrigeration heat switches and more particularly to a heat switch used for adiabatic refrigeration devices.

BACKGROUND OF THE INVENTION
Heat switches are needed to control the heat flow between adjacent stages in an Adiabatic Demagnetization Refrigeration (ADR) process. Heat switches are typically one of two types: those that use a metallic switching element and those that use a gas or fluid switching element. The heat switches that use a metallic switching element are typically mechanical, super conducting or magnetoresistive switches. Heat switches that use a gas as the switching element are called gas-gap switches. The concept is to place two conductive metal plates close to each other and introduce a gas between them to turn the switch On, and remove the gas to turn the switch Off. One of the disadvantages of all of the aforementioned switches is the need for some sort of actuator. Not only does this require ancillary control electronics, software and sensors, these requirements may have a significant thermal impact on the system. Actuators require wiring or drive shafts which conduct heat and dissipate heat when used. This could be a concern when operating in a cryogenic environment.

An ADR stage produces cooling (or heating) by the interaction of a magnetic field with the magnetic spins in a paramagnetic salt. Magnetizing the salt produces heating, and demagnetizing the salt produces cooling. A conventional "single-shot" ADR consists of a "salt pill" containing the magnetic salt, a superconducting magnet, and a heat switch. The salt pill is located in the bore of the magnet, and the heat switch links it to a heat sink. Regardless of the initial conditions, the refrigeration cycle consists of the following steps: First, the salt pill is magnetized, causing it to warm up. Second, when its temperature exceeds that of the heat sink, the heat switch is powered into the on state. Third, the salt continues to be magnetized, generating heat which flows to the sink. This continues until full field is reached, which necessarily is strong enough to significantly align the spins and suppress the entropy of the salt. Fourth, at full magnetic field, the heat switch is deactivated to thermally isolate the salt from the heat sink. Fifth, the salt is demagnetized to cool it to the desired operating temperature. In general, the salt will then be receiving heat from components parts. The heat is absorbed and operating temperature maintained by slowly demagnetizing the salt at just the right rate. Heat can continue to be absorbed until the magnetic field is reduced to zero, at which point the ADR has run out of cooling capacity.

SUMMARY OF THE INVENTION
Accordingly, it is an object of the present invention to provide an improvement in a passive gas-gap heat switch for use in an ADR environment.

It is another object of the invention to provide a passive gas-gap heat switch that can cool a device below room temperature.

It is a further object of this invention to provide a passive gas-gap heat switch that is capable of conducting heat at sub-Kelvin temperatures (down to approximately 200 mK) and is capable of being turned off at those temperatures. Existing gas-gap switches that use a getter to remove the conductive gas from the switch body cannot meet the latter requirement. As the benefits of using ADRs become more widely known it is anticipated that a wider array of industries will take advantage of this efficient cooling process.

The present invention, in a more general application, provides an easy way to cool something below room temperature and then automatically thermally isolate it at a low temperature. This is made possible by providing a heat switch that is capable of conducting heat at temperatures ranging from 0.25 K to above room temperature. One of the heat switches in this multistage process must be conductive in the 0.25 K to 0.3 K range. All of the heat switches must be capable of switching Off in a short period of time (1-2 minutes), and when Off to have a very low thermal conductance. Currently, no heat switches are capable of meeting these requirements. Superconducting switches have too much conductance in the Off state. Mechanical heat switches have too little conductance in the On state. Finally, traditional getter-activated gas-gap heat switches have long turn-off times. Thus there is a need in the industry for a passive gas-gap heat switch that can facilitate the heating/cooling of a device in the 0.25 K to above 1 K range in a manner such that the heat switch does not require long turn-off times.

The trend in developing ADRs is toward using multiple cooling stages as this arrangement allows for greater efficiency, by reducing parasitic heat flows within the refrigerator, and greater operating temperature range. In this process each stage is thermally connected to the next via a heat switch. Thus, for low temperature ADR systems there exists a need for a heat switch that is capable of conducting heat at sub-Kelvin temperatures (down to approximately 200 mK) and is capable of being turned off at those temperatures. Existing gas-gap switches that use a getter to remove the conductive gas from the switch body cannot meet the latter requirement. As the benefits of using ADRs become more widely known it is anticipated that a wider array of industries will take advantage of this efficient cooling process.

It is yet another object of the present invention to provide a passive gas-gap heat switch that can automatically thermally isolate a device once it is cooled down to liquid helium temperature.

Advantages and disadvantages will take advantage of this efficient cooling process.
temperature of either side of the switch rises above a threshold value, and rapidly turns off if either side of the switch falls below the threshold value. This arrangement allows cyclic cooling cycles to be used without the need for separate heat switch controls.

BRIEF DESCRIPTION OF DRAWINGS

The following detailed description of the invention will be more readily understood when considered together with the accompanying drawings wherein:

FIG. 1 is an isometric view generally illustrative of the passive gas-gap heat switch of the present invention;

FIG. 2 is a cross-sectional view of FIG. 1;

FIG. 3 is illustrative of a conductor component of the passive gas-gap heat switch of the present invention;

FIG. 4 is illustrative of an axial view of FIG. 3;

FIG. 5 is an exploded view of FIG. 1, and

FIGS. 6a–6e are illustrative of the heating and cooling stages of a continuous adiabatic demagnetization refrigeration process.

DETAILED DESCRIPTION OF THE INVENTION

To those skilled in the art, many modifications and variations of the present invention are possible in light of the teachings contained herein. It is therefore to be understood that the present invention can be practiced otherwise than as specifically described by these teachings and still be within the spirit and scope of the claims.

Referring now to the drawings and more particularly to FIGS. 1 and 2 which show passive gas-gap heat switch 10. Heat switches that use a gas to complete a thermal circuit are called gas-gap switches. The concept is to place two conductive surfaces close to each other and introduce a gas (not shown) between them to turn the switch On, and remove the temperature drops. This happens regard-

fins specifically described by these teachings and still be within the spirit and scope of the claims. The concept is to place two conductive surfaces close to each other and introduce a gas (not shown) between them to turn the switch On, and remove the temperature drops. This happens regard-

Heat switches that use a gas to complete a thermal circuit are derived from two different mechanisms. For the low temperature switch, the attractive force between helium-3 atoms causes them to condense rapidly out of the gas phase as the temperature drops.

For the higher temperature switch, the switch being strongly temperature dependent. For the higher temperature switch, the attractive force between helium-3 atoms causes them to condense rapidly out of the gas phase as the temperature drops. This threshold depends on the amount of helium present. For the higher temperature switch, the attractive force between helium atoms and the internal components of the switch causes the helium to bind (i.e., adsorb) to those surfaces as the temperature drops. As long as the amount of helium present is less than the amount that would form a single atomic layer, there will be a threshold temperature in the 1–5°K range where the vapor pressure of the helium is strongly dependent on temperature. This threshold depends on the amount of helium present and the type of surface used. Thus this switch can be tailored to passively turn on and off over a range of temperatures.

Now referring to FIG. 5, fins 20 of conductor 40 are inserted into end 72 of containment tube 70 and fins 30 of conductor 50 are inserted into end 74, the opposite end of containment tube 70. Containment tube 70 is rigid and holds conductors 40 and 50 together such that fins 20 and 30 interleave but do not touch. Containment tube 70 must be capable of providing low thermal conductivity, high strength and it must be impermeable to the gas (not shown) that is used as the conducting agent. The low thermal conductivity is required because containment tube 70 still conducts heat between the two ends 72 and 74 which contact thermal/ mechanical interfaces 11 and 12 of conductors 40 and 50 respectively, when the switch is in the Off state. This heat flow is undesirable and should be as low as possible. The high strength is necessary because containment tube 70 physically supports conductors 40 and 50. It is important that fins 20 and 30 of conductors 40 and 50 not touch and that the gap 60 remain intact. Since some small mechanical
loads may result from how the heat switch 10 is attached to other components (not shown), containment tube 70 must have enough strength to absorb these loads without distorting fins 20 and 30. Impermeability is required because the gas (not shown) must not leak over time or the heat switch 10 will be inoperable. There are several options one can consider for meetings these requirements. In the present invention two different materials are used to meet these requirements. One material provides structural support and the other provides a surface that is impermeable by the gas (not shown). Both materials must have low thermal conductivity. Containment tube 70 is attached to conductors 40 and 50 so as to create a hermetic seal. The hermetic seal may be achieved via an epoxy or an indium seal. A small access tube 80 is soldered into end cap 90 to allow heat switch 10 to be evacuated and filled with the appropriate amount of gas (not shown). End cap is sealed onto thermal/mechanical interface 11 in such a way as to be removable and replaceable. Helium 3 gas is used in the present invention as this gas is most suitable at temperatures below 0.7 K and without regard to orientation (presence of gravity). The total volume of liquid helium required for the switch is small because the saturated vapor pressure in liquid helium is a few atomic layers binding energy of 0.4 Pa at about 57° K and a binding energy when the magnetic field of the first stage 101 reaches an upper threshold, the heat switch 120 is deactivated and the first stage 101 is demagnetized because the heat flow out has ceased and there is a net heat flow into the stage. The important feature here is that the temperature control system 130 automatically magnetizes or demagnetizes the first stage 101, so this process of recycling the first stage 102 "on the fly" does not involve a loss of temperature control.

In FIG. 6c after recycling the first stage 101, the second stage 102 is magnetized to a higher temperature and the third stage 103 is demagnetized to a slightly lower temperature. The temperatures are chosen based on a number of factors, including the thermal conductance of the heat switch 10 and parasitic heat flow to the lower stages. In the present invention, the passive gas-gap heat switch 10 is used to connect the second and third stages 102 and 103 respectively, so the temperatures are dictated almost entirely by the dependence of the thermal conductance on temperature. Passive operation turns out to be possible because the thermal conductance of the switch drops off extremely rapidly below 0.2 K. (This is due to the particular properties of helium-3 which is the gas used inside the switch). The recycling process consists of magnetizing the second stage 102 to about 0.275° K and the third stage to about 0.25° K. Heat will flow from the second stage 102 to the third stage 103, requiring the second stage 102 to be magnetized and the third stage 103 to be demagnetized to maintain these temperatures. Magnetization of the second stage 102 is stopped once the second stage 102 hits its upper field threshold. The second stage 102 is then cooled to 0.15° K, the passive gas-gap heat switch 10 is completely off, and then the third stage 103 is warmed and recycled.

In FIG. 6d the process is essentially the same: The third stage 103 is magnetized to a higher temperature and the fourth stage 104 is demagnetized to a slightly lower temperature and the heat switch between the two stages is activated. The third stage 103 will continue to be magnetized and the fourth stage 104 is demagnetized as heat flows from stage 103 to 104. Again, once the stage 103 hits its upper field threshold, the heat switch 10 is deactivated. Stage 103 can be cooled and stage 104 warmed up to dump its heat to the heat sink 140 via heat switch. This whole process is then repeated to keep transferring heat from the first stage 101. The time required is on the order of 1 hour. The faster it can be done, the more heat we can absorb at the first stage. In practice we can speed things up by having two recycling events occurring at the same time (i.e. stage 101 transfers heat to stage 102 while stage 103 transfers heat to stage 104). Helium-3 refrigerators typically cool down to about 0.3° K, while better designs can cool to 0.25° K or a little lower. This is precisely the temperature required for the third stage during the recycling operation. The steep drop in the vapor pressure of helium-3 below 0.2° K prevents helium-3 refrigerators from cooling much below 0.25° K, and it causes the thermal conductance of the passive gas-gap heat switch to drop off precipitously. Therefore an alternate use for the passive gas-gap heat switch is to connect two ADR stages to a helium-3 refrigerator. For laboratory systems, helium-3 refrigerators can be quite inexpensive, so a hybrid system could be very attractive for its low cost.

To those skilled in the art, many modifications and variations of the present invention are possible in light of the teachings contained herein. It is therefore to be understood that the present invention can be practiced otherwise than as specifically describe by these teachings and still be within the spirit and scope of the claims.

We claim:

1. A heat switch for a refrigeration process wherein said heat switch comprises:
   a first conductor element;
   a first set of fins connected with said first conductor element;
   a second conductor element;
a second set of fins connected with said second conductor element;
a containment tube for physically supporting said first and second conductor elements; and
adsorption means within the containment tube for continuously varying said heat switch on/off temperature over a range of temperatures.

2. The device according to claim 1 wherein said first and second sets of fins are interleaved.

3. The device according to claim 1 wherein a gap exists between said first and second sets of fins.

4. The device according to claim 3 wherein said first and second conductor elements each include a thermal interface.

5. The device according to claim 4 wherein said first and second conductor elements each include a mechanical interface.

6. The device according to claim 5 wherein said thermal interface and said mechanical interface are one in the same.

7. The device according to claim 1 wherein said containment tube is impermeable to helium gas.

8. The device according to claim 7 wherein said containment tube is hermetically sealed with said first and second conductor elements.

9. The device according to claim 1 wherein said refrigeration process is a continuous adiabatic refrigeration process.

10. The device according to claim 9 wherein said heat switch is a passive gas-gap heat switch.

11. The device according to claim 1 wherein said heat switch is capable of conducting heat from 0.25° K to above 1° K.

12. A passive gas-gap heat switch for a continuous adiabatic refrigeration process wherein said heat switch comprises:
a first conductor element;
a first set of fins integrally formed with said first conductor element;
a second conductor element;
a second set of fins integrally formed with said second conductor element wherein said first and second sets of fins are interleaved and do not touch;
a containment tube for physically supporting said first and second conductor elements wherein said containment tube hermetically seals said first and second sets of fins; and
adsorption means for continuously varying said heat switch on/off temperature over a range of temperatures.

13. The heat switch as claimed in claim 1, wherein the adsorption means is a helium adsorption means.

14. A heat switch comprising:
a thermally conductive gas, the gas having a mean free path;
a first conductor element;
a first set of fins connected to said first conductor element;
a second conductor element;
a second set of fins connected to said second conductor element; and
hermetically sealed containment tube for physically supporting said first and second conductor elements, wherein the heat switch operates in a molecular region where thermal conductance of the gas is pressure dependent and the gas pressure in the heat switch is temperature dependent resulting in the thermal conductance of the heat switch being strongly temperature dependent at varying on/off temperatures over a range of temperatures.

15. The heat switch as claimed in claim 14 further comprising a gap between said first and second sets of fins, said gap being larger than the mean free path of the gas.

16. The heat switch as claimed in claim 15, wherein the gap is larger than maximum bending of the first and second set of fins.

17. The heat switch as claimed in claim 14, wherein attractive forces between gas atoms cause the gas to bind to the surfaces of the first and second conductor elements within the containment tube such that varying the gas pressure changes the on/off temperature of the heat switch.

18. The heat switch as claimed in claim 14, wherein the heat switch on/off temperatures vary from about 25 degrees Kelvin to about 10 degrees Kelvin.

19. The heat switch as claimed in claim 16, wherein the gas is a helium gas.

20. The heat switch as claimed in claim 18 wherein the helium gas is helium-3.

21. The heat switch as claimed in claim 14, wherein surface area of the first and second set of fins is maximized due to the thermal conductance of the gas being proportional to the surface area of the first and second set of fins when the heat switch is on.

22. The heat switch as claimed in claim 14, wherein the heat switch is a passive switch and operates absent external sorption means.

23. The heat switch as claimed in claim 14, wherein response time is rapid at the on/off temperature.

24. A heat switch comprising:
a gas;
a first conductor element;
a first set of fins connected to said first conductor element;
a second conductor element;
a second set of fins connected to said second conductor element; and
a containment tube for physically supporting said first and second conductor elements, the heat switch operation relying on adsorption of the gas within the containment tube to continuously vary the heat switch on/off temperature over a range of temperatures.

25. The heat switch as claimed in claim 24, wherein the heat switch on/off temperature range over a range of temperatures.

26. The heat switch of claim 24 wherein the on/off temperature range over a range of temperatures.

27. The heat switch as claimed in claim 24 wherein the gas is helium-3.

28. The heat switch as claimed in claim 24, wherein the on/off temperature operates at a rapid response time.

29. A heat switch comprising:
a thermally conductive gas, the gas having a mean free path;
a first conductor element;
a first set of fins connected to said first conductor element;
a second conductor element;
a second set of fins connected to said second conductor element; and
a containment tube for physically supporting said first and second conductor elements, the heat switch for use in a continuous refrigeration process wherein said heat switch comprises:
a gas;
a first conductor element;
a first set of fins connected to said first conductor element;
a second conductor element;
a second set of fins connected said second conductor element;
a containment tube for physically supporting said first and second conductor elements wherein said containment tube hermetically seals said first and second sets of fins;
a first and a second refrigerator stage, the heat switch operating at a first on/off temperature for the first refrigerator stage and the heat switch operating at a second on/off temperature for the second refrigerator stage, wherein the first on/off temperature is lower than the second on/off temperature and the gas is the same gas at a different pressure.

31. The heat switch as claimed in claim 30, wherein the first on/off temperature is about .25 degrees Kelvin and the second on/off temperature is about 1 degree Kelvin.

32. The heat switch as claimed in claim 30, wherein the heat switch is a passive gas-gap heat switch.
UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO.: 6,959,554 B1
APPLICATION NO.: 10/192886
DATED: November 1, 2005
INVENTOR(S): Shirron et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title Page
Please insert (*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days. Please delete 24 days.

Signed and Sealed this
Twenty-ninth Day of May, 2007

JON W. DUDAS
Director of the United States Patent and Trademark Office