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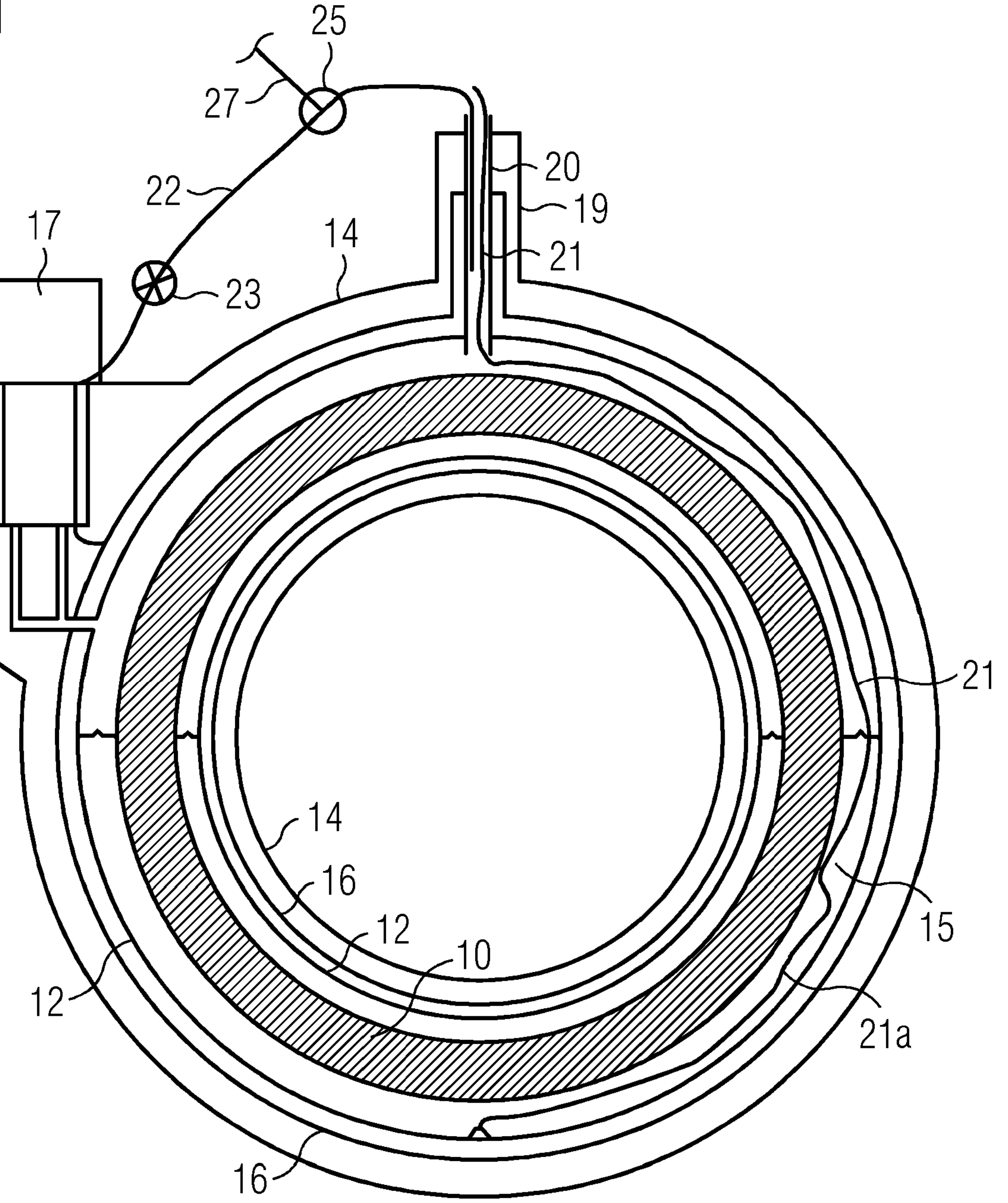
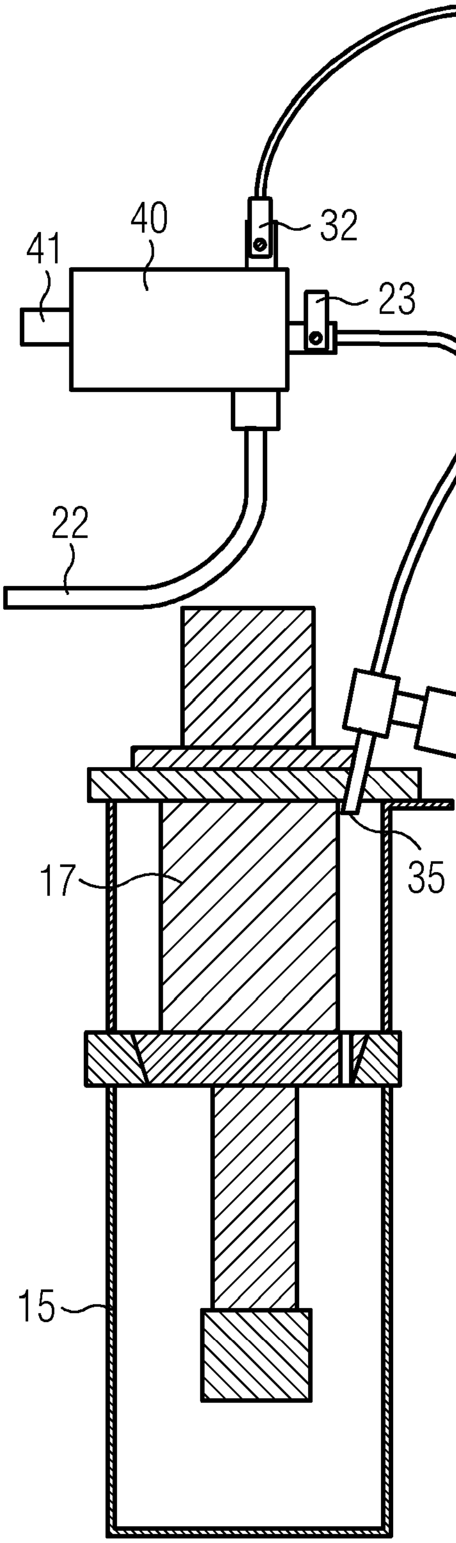
FIG 1



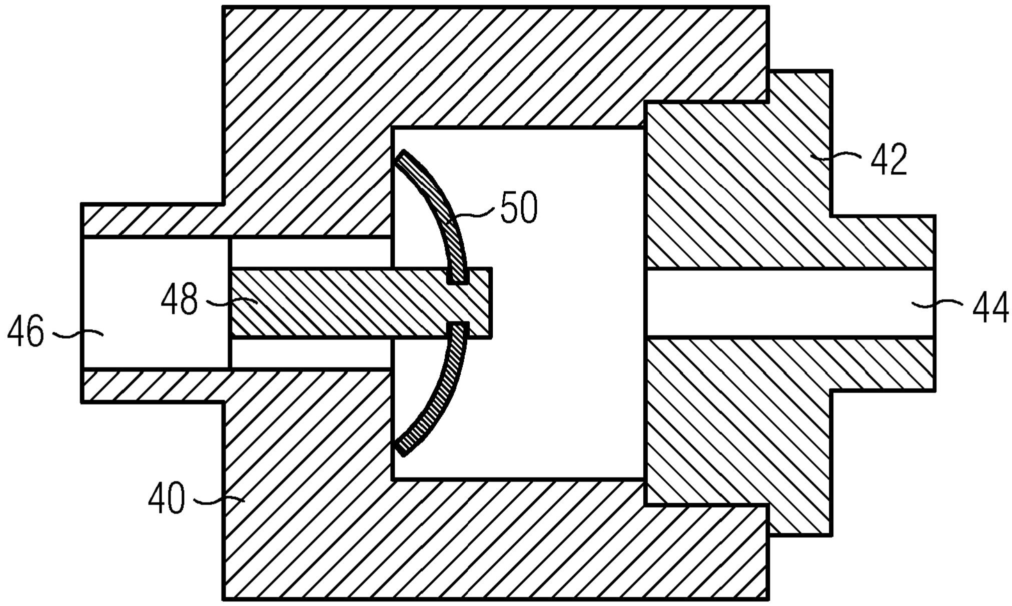
28 04 16

FIG 2



28 04 16

FIG 3A



28 04 16

FIG 3B

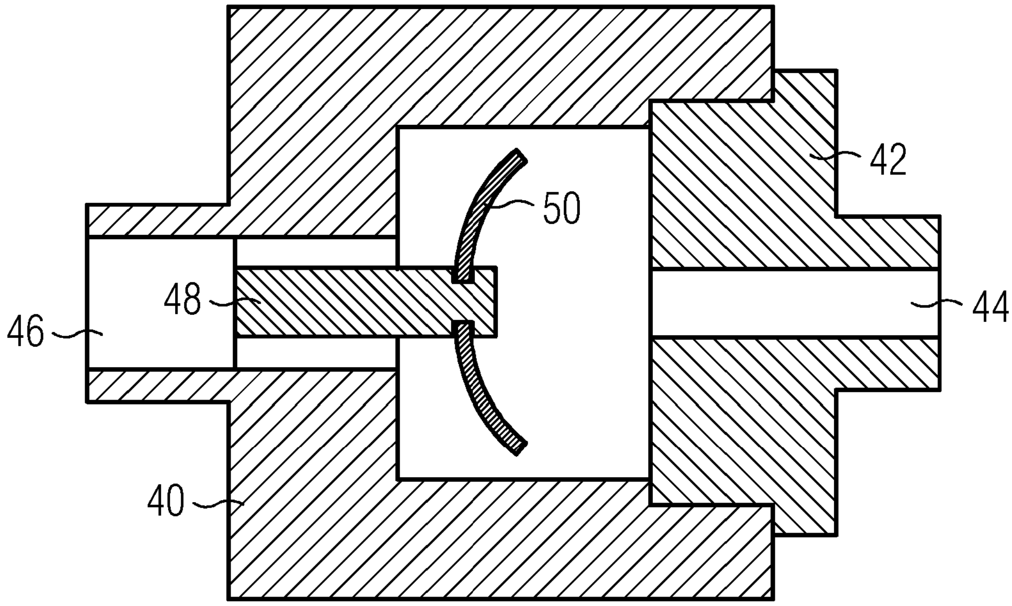


FIG 4A

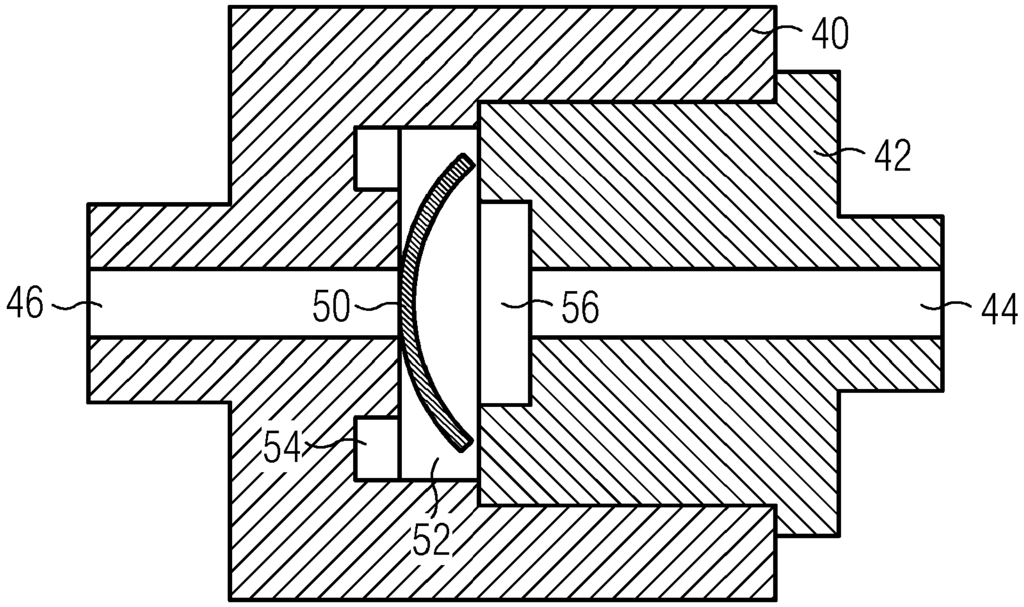
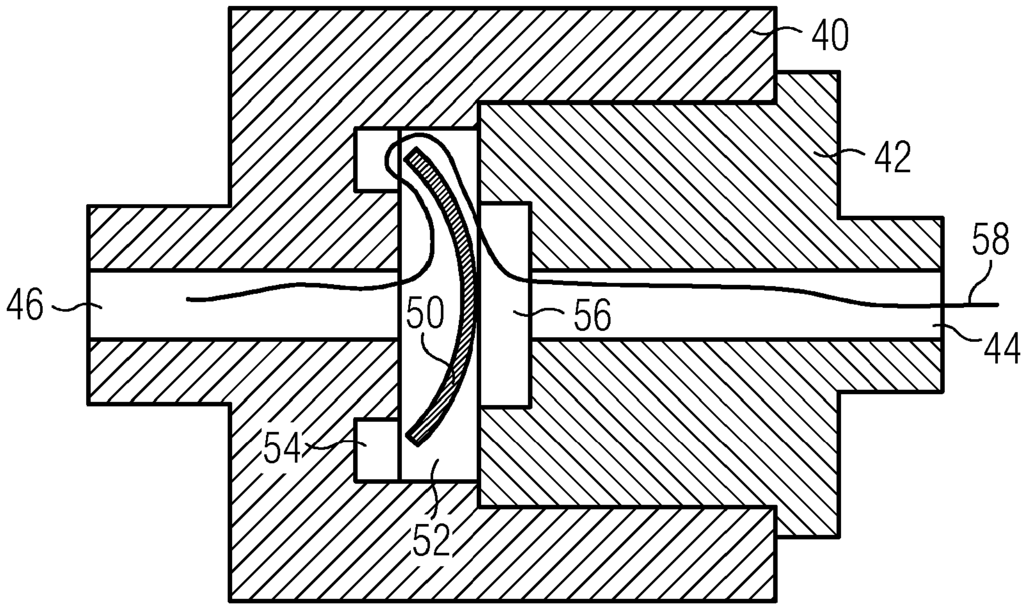


FIG 4B



28 04 16

A CRYOSTAT WITH CRYOGENIC REFRIGERATOR

The present invention relates to valve arrangements for control of flow of cryogen gas in a cryostat, particularly a cryostat containing a superconducting magnet, and yet more particularly a cryostat containing a superconducting magnet of an MRI system.

Fig. 1 shows a conventional arrangement of a cryostat including a cryogen vessel 12. A cooled superconducting magnet 10 is provided within cryogen vessel 12, itself retained within an outer vacuum chamber (OVC) 14. One or more thermal radiation shields 16 are provided in the vacuum space between the cryogen vessel 12 and the outer vacuum chamber 14. In some known arrangements, a refrigerator 17 is mounted in a refrigerator sock 15 located in a turret 18 provided for the purpose, towards the side of the cryostat. Alternatively, a refrigerator 17 may be located within access turret 19, which retains access neck (vent pipe) 20 mounted at the top of the cryostat. The refrigerator 17 provides active refrigeration to cool cryogen gas within the cryogen vessel 12, in some arrangements by recondensing it into a liquid. The refrigerator 17 may also serve to cool the radiation shield 16. As illustrated in Fig. 1, the refrigerator 17 may be a two-stage refrigerator. A first cooling stage is thermally linked to the radiation shield 16, and provides cooling to a first temperature, typically in the region of 80-100K. A second cooling stage provides cooling of the cryogen gas to a much lower temperature, typically in the region of 4-10K.

A negative electrical connection 21a is usually provided to the magnet 10 through the body of the cryostat. A positive electrical connection 21 is usually provided by a conductor passing through the vent pipe 20.

For some time it has been recognized that allowing a circulation of gas between the magnet turret through vent pipe 20 and refrigerator sock 15 increases the efficiency of the refrigerator 17. Pipe 22 in Fig. 1 is an example of an arrangement allowing such circulation. Valve 23 may be controlled to enable or restrict such circulation as required.

The efficiency of the refrigerator 17 may be measured by the amount of power a heater requires to maintain a constant gas pressure in the cryogen vessel. In order to gain an efficiency increase the valve 23 which connects the refrigerator sock 15 with an absolute pressure relief valve 25, which allows cryogen to vent through a quench line 27 in case of excessive pressure within the cryogen vessel. Valve 23 is is left open whilst the magnet is in operation as a part of an MRI system, keeping a cryogen gas flow path open between refrigerator sock 15 and turret 20. Absolute pressure relief valve 25 will open to allow cryogen to leave the cryogen vessel through quench path 27 in case of quench, or in case the cryogen pressure in the cryogen vessel reaches a high level for any other reason.

The function of the valve 23 is to allow cold gas to pass through the refrigerator sock 15 during shipping, to cool the refrigerator 17 and so to limit heat input through the refrigerator to the radiation shield.

It is desirable to leave the valve 23 open after shipping to enable the refrigerator 17 to be cooled in the event of a refrigerator, compressor or power failure. However if the valve 23 is left open there is a possibility of too much cooling of the refrigerator 17 during filling of the cryogen vessel, quenching of the magnet or during energisation of the magnet.

Over-cooling of the refrigerator can cause failure modes, for example due to rubber o-rings installed in the refrigerator becoming hard and leaking. A rubber o-ring sealing the refrigerator 17 to the refrigerator sock could leak.

Conventionally, this problem has been avoided by closing the valve 23 during normal operation, and the benefits of increased efficiency of the refrigerator 17 due to circulation of gas between the magnet turret through vent pipe 20 and refrigerator sock 15 are not available.

The present invention provides an arrangement for selectively enabling and blocking flow of cryogen gas through the refrigerator sock 15.

The present invention accordingly provides apparatus as defined in the appended claims.

The above, and further, objects, characteristics and advantages of the present invention will become more apparent from the following description of certain embodiments thereof, in conjunction with the appended drawings, wherein:

Fig. 1 shows a conventional arrangement of a cryostat including a cryogen vessel;

Fig. 2 shows an example refrigerator and venting arrangement, according to an embodiment of the present invention;

Figs. 3A-3B represent a valve using a bi-metallic ‘snap disc’ commonly used in thermostats; and

Fig. 4 illustrates components of a prototype valve.

According to the present invention, a temperature-sensitive valve is introduced, whereby flow of cryogen gas through the refrigerator sock 15 may be controlled.

Fig. 2 shows a refrigerator and venting arrangement, according to an embodiment of the present invention. An additional, temperature sensitive, valve 30 is provided, in series with an enabling valve 32. This arrangement is effectively connected in parallel to the conventional valve 23 described above.

During transit, the conventional valve 23 is opened, allowing a flow of cooling gas through the flow path in pipe 22 and past the refrigerator 17 to reduce heat influx by conduction. According to the illustrated embodiment, a further pipe 34 is added, providing a parallel path, bypassing valve 23, the pipe 34 allowing a flow of cryogen gas past the refrigerator 17 as controlled by the series combination of temperature-sensitive valve 30 and enabling valve 32, even while valve 23 is closed.

Both cryogen gas flow paths 33, 34 meet at absolute valve 40, which enables circulation of the cryogen gas back into the cryostat turret through pipe 22, while providing an egress path 41, similar to quench path 27 of Fig. 1, for cryogen gas in case of pressure build-up within the cryogen vessel such as during shipment or power failure.

The temperature sensitive valve 30 is preferably not relied upon to enable cryogen gas egress during transit, as the ambient temperature could fall sufficiently that the temperature sensitive valve closes. Rather, the conventional valve 23 is opened to ensure that an egress path is available for cryogen gas to exit the cryogen vessel and to cool the refrigerator as it passes.

After arrival on site, the conventional valve 23 is closed and the enabling valve 32 is opened, allowing bypass cryogen gas path 34 to be controlled by the temperature sensitive valve 30. A two way valve could be used instead, combining the functions of the conventional valve 23 and the enabling valve 32, so that only one or other of these valves may be open at any one time.

In an example embodiment, the temperature-sensitive valve 30 closes when its temperature decreases to 0°C, and opens when its temperature rises to 15°C.

The temperature sensitive valve 30 would operate to stop gas flow through the refrigerator sock 15 in the event of significant mass of cryogen being vented from the cryogen vessel, such as may occur during a cryogen fill procedure, or during a quench, as it would be cooled below the temperature required for its transition to a "closed" state. By closing, the temperature sensitive valve 30 protects the refrigerator 17 from being overcooled.

In the example embodiment illustrated, the temperature sensitive valve 30 is shown connected to a conventional gas outlet 35 at a mounting flange 37 of the refrigerator 17. In systems studied by the inventor, during cryogen filling, quenching and current ramping, absolute valve 40 may open, allowing venting 41 of cryogen gas. The area of the mounting flange 37 at the gas outlet 35 becomes coated in a frost of water ice on external surfaces if cryogen gas is allowed to egress due to the elevated cryogen pressure within the cryogen vessel. In such circumstances, the present invention requires that the temperature sensitive valve 30 should close and shut off cryogen gas flow past the refrigerator 17.

In the event of refrigerator 17 failure, the pressure within the cryogen vessel will rise, and open the absolute valve 40 to vent cryogen gas from the system. This indicates a lower flow rate and reduced cooling effect of cryogen egress through the refrigerator sock 15 as compared to the above examples of cryogen egress during cryogen filling, quenching and current ramping. In systems studied by the inventor, the area around the mounting flange shows condensed liquid water but not frozen water on the external surfaces. Therefore, in certain embodiments of the invention, the valve is arranged to close at or around 0°C to achieve the desired result of closing in case of cryogen filling, quenching and current ramping but remaining open in case of refrigerator failure. In alternative embodiments, the temperature sensitive valve 30 may be moved further from the refrigerator along pipe 34, reducing the cooling effect on the valve of escaping cryogen gas, as the escaping cryogen gas will have warmed to some extent by the time it reaches the valve and the temperature at which the valve closes could be raised.

The present invention accordingly provides a temperature sensitive valve 30 that is activated by the temperature of cryogen gas passing through the refrigerator sock, operating to stop gas flow through the refrigerator sock thereby preventing overcooling of the refrigerator and consequent damage or failure of the refrigerator.

The temperature sensitive valve 30 may itself be embodied in any of a number of types of valve, each conventional in its own right. For example, the temperature sensitive valve may include a bi-metallic element; or a substance that expands with temperature, such as a wax; or a gas that boils or expands housed in a bellows or diaphragm.

Figs. 3A-3B represent a valve using a bi-metallic ‘snap disc’ commonly used in thermostats. It consists of a dished bi-metallic disc 50 that reverses its direction of dish at a predetermined temperature.

The valve of Figs. 3A-3B comprises a housing 40 with a closure 42, having an inlet 44 and an outlet 46. A mounting post 48 retains dished bi-metallic disc 50 in position, adjacent to the outlet 46. Fig. 3A shows the valve in its “closed” status, at it would be at temperatures below 0°C in the described example. Outlet 46 is substantially blocked by the dished bi-metallic disc. By suitable positioning within the valve housing, such dished bi-metallic disc may operate to seal the inlet 44 or the outlet 46. If arranged with the flow direction as shown in Figs. 3A-3B, differential pressure across the valve, particularly significant in case of a quench, will help close the valve, and to maintain it in the closed position.

Fig. 3B shows the valve of Fig. 3A in its “open” status, as it would be at temperatures above 15°C in the described example. The direction of dishing of the dished bi-metallic disc 50 is reversed, allowing gas flow through the outlet 46.

Figs. 4A-4B illustrate operation of an alternative temperature-sensitive valve.

Parts corresponding to features shown in Figs. 3A-3B carry corresponding reference numerals. In this valve, dished bi-metallic disc 50 is not retained in position in the way it is in Figs. 3A-3B, but instead is enclosed within a cavity 52. Housing 40 provides recesses 54 opening into the cavity 52, as will be explained below. Closure 42 also provides a cavity 56 which opens into cavity 52.

In the status illustrated in Fig. 5A, the valve is in its “closed” position, as it would be in the described example when cooled to 0°C or below. The direction of dishing causes the dished bi-metallic disc 50 to block the outlet 46. The direction of cryogen flow, from inlet 44 to outlet 46, maintains the bi-metallic disc 50 in position, blocking the outlet 46.

Fig. 5B shows the valve in its other state, its "open" position such as the valve of the described embodiment would be at temperatures of 15°C and above. The direction of dish of the bi-metallic disc 50 is reversed. The bi-metallic disc 50 is retained within cavity 52, but recesses 54 and 56 provide a flow path for cryogen, around the periphery of the bi-metallic disc 50. The direction of cryogen flow, from inlet 44 to outlet 46, tends to maintain the bi-metallic disc 50 in position, keeping the flow path 58 open.

In the described example, the dished bi-metallic disc changes status on cooling to 0°C and on warming to 15°C. This prototype valve was attached to a conventional superconducting magnet for an MRI system in an arrangement corresponding to Fig. 2. The temperature-sensitive valve was arranged to vent to atmosphere rather than via an absolute valve for an initial test.

In operation, it was found that once the bi-metallic disc 50 had reversed dishing on cooling, virtually all cryogen gas flow was stopped. The temperature at which the disc reverses dishing is affected by its distance from the refrigerator and the direction of flow of the cryogen gas. The refrigerator was found not to cool significantly even in case of quench of the magnet in the cryogen vessel.

While the present invention has been explained with reference to certain particular types of valve, and certain particular temperature ranges, the present invention may be embodied with other valve types and at other temperature ranges, as suitable for the application and the type of cryogen used.

Also other pipe interconnection arrangements could be possible. While the described embodiments include a conventional valve 23 enabling a conventional path for circulation of a cryogen gas, some embodiments of the present invention may not include the conventional valve and the associated cryogen path, but may include only the path 34 controlled by the temperature sensitive valve 30. In such embodiments, enabling valve 32 may be unnecessary.

Claims:

1. A cryostat with cryogenic refrigerator (17) arranged to cool the interior of a cryogen vessel (12) within the cryostat, said cryogenic refrigerator arranged inside a refrigerator sock (15), and further comprising a fluid within a pipe controlled by a temperature-sensitive valve (30) to selectively provide a first path (34) for cryogen gas flow through the refrigerator sock, according to a temperature of the temperature-sensitive valve.

2. A cryostat according to claim 1 wherein the first path extends from the refrigerator sock to the cryogen vessel.

3. A cryostat according to claim 1 or claim 2 wherein the cryostat further comprises a further pipe (33) controlled by a valve (23) to selectively provide a second path for cryogen gas flow through the refrigerator sock, in parallel with the first path.

4. A cryostat according to claim 3 wherein the second path extends from the refrigerator sock to the cryogen vessel.

5. A cryostat according to any preceding claim, further comprising an absolute valve (40) arranged to vent cryogen from the cryogen vessel in case of excess cryogen gas pressure within the cryogen vessel.

6. A cryostat according to any preceding claim, wherein the temperature-sensitive valve comprises a bi-metallic element.

7. A cryostat according to claim 6 wherein the bi-metallic element is a dished bi-metallic disc (50).

8. A cryostat according to any of claims 1-5, wherein the temperature-sensitive valve comprises a wax that expands with temperature.

9. A cryostat according to any of claims 1-5, wherein the temperature-sensitive valve comprises a fluid that boils or expands housed in a bellows or diaphragm.

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