METHOD AND APPARATUS FOR OPERATION OF A CRYOGENIC DEVICE IN A GASEOUS ENVIRONMENT

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Apparatus for providing a cryogenic gaseous environment (300). A chamber (320) for containing the cryogenic gaseous environment is immersed in liquid coolant (306) to effectively cool the interior chamber, during which time gas boiled off the coolant is allowed to escape. Gas is then either injected into or allowed to accumulate in the chamber, such that liquid coolant is forced out of the chamber under hydrostatic pressure, whether through an open under port (322) of the chamber of through a standpipe (324). The interior of the chamber then provides a gaseous environment at cryogenic temperatures.
BEGIN 502

OPEN VALVES 464, 462, 424
CLOSE VALVE 466 504

INJECT LIQUID COOLANT VIA VALVE 424, TO FILL CHAMBER AND DEWAR TO LEVEL 450 506

CLOSE VALVE 462 508

INJECT GAS VIA VALVE 424 UNTIL CHAMBER LIQUID LEVEL FALLS TO 452 510

CLOSE VALVES 464, 424 OPEN VALVE 466 512

END 514

FIGURE 5
METHOD AND APPARATUS FOR OPERATION OF A CRYOGENIC DEVICE IN A GASEOUS ENVIRONMENT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority from Provisional Patent Application No 2004903688 filed on 5 Jul. 2004, the content of which is incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates to the operation of a cryogenic device in a gaseous environment, and more particularly relates to a method and device for providing a gaseous environment at a temperature equal or close to liquid coolant temperature.

DESCRIPTION OF THE PRIOR ART

[0003] In the past, cryogenic cooling of cryogenic devices has been provided by immersing the cryogenic device in a liquid coolant such as liquid nitrogen or liquid helium, thus maintaining the temperature of the cryogenic device at or below the boiling temperature of the liquid coolant. The use of liquid nitrogen provides for cryogenic operation at or below 77.3 K, while the use of liquid helium provides for cryogenic operation at or below 4.2 K.

[0004] Recently, cryogenic devices have been designed which rely on movement of the device for operation. Such a device is set out in International Patent Publication No. WO 2004/015435 by CSIRO and Tilbrook, the content of which is incorporated herein by reference, which teaches rotation of one or more SQUIDs or superconducting field sensors in order to obtain information about a magnetic field. SQUIDs and superconducting field sensors must be maintained below the critical temperature $T_c$ of the superconducting material in order to achieve proper superconducting operation. However, should such a moving cryogenic device be immersed in liquid coolant, significant turbulence will be generated within the fluid, leading to acoustic, magnetic and electrical noise. Further, mechanical stress will be placed on the often delicate device by viscous drag and/or mechanical vibrations.

[0005] Throughout this specification the word “comprise”, or variations such as “comprises” or “comprising”, will be understood to imply the inclusion of a stated element, integer or step, or group of elements, integers or steps, but not the exclusion of any other element, integer or step, or group of elements, integers or steps.

[0006] Any discussion of documents, acts, materials, devices, articles or the like which has been included in the present specification is solely for the purpose of providing a context for the present invention. It is not to be taken as an admission that any or all of these matters form part of the prior art base or were common general knowledge in the field relevant to the present invention as it existed before the priority date of each claim of this application.

SUMMARY OF THE INVENTION

[0007] According to a first aspect the present invention is an apparatus for providing a cryogenic gaseous environment, the apparatus comprising:

[0008] a chamber for containing the cryogenic gaseous environment and for excluding external liquid coolant,

[0009] a liquid inlet for selectively flooding the chamber with liquid coolant; and

[0010] a chamber gas port for selectively permitting egress of gas from the chamber during liquid flooding of the chamber, and for selectively containing gas within the chamber.

[0011] According to a second aspect, the present invention is a method of providing a cryogenic gaseous environment, the method comprising:

[0012] flooding a chamber with liquid coolant; and

[0013] causing cryogenic gas to occupy the chamber and displace liquid coolant from the chamber.

[0014] The chamber gas port may comprise a gas injection port for purging the chamber with gas to evacuate liquid from the chamber. The gas injection port may itself permit egress of gas during liquid flooding of the chamber. Additionally or alternatively, the chamber may comprise a gas outflow port for permitting egress of gas from the chamber during liquid flooding of the chamber.

[0015] The chamber gas port may comprise a gas vent having open and closed positions, such that the gas vent when open allows egress of gas from the chamber during liquid flooding of the chamber, and such that the gas vent when closed contains gas within the chamber.

[0016] Accordingly, in a third aspect, the present invention is an apparatus for providing a gaseous environment for operation of a cryogenic device, the apparatus comprising:

[0017] a chamber for housing the cryogenic device;

[0018] a port in the chamber allowing the chamber to be flooded by liquid coolant; and

[0019] a gas vent for allowing escape of gas from the chamber;

[0020] wherein the chamber is configured such that, when the gas vent is closed, gas boiled off liquid coolant within the chamber will accumulate in the chamber and force liquid coolant out of the port.

[0021] According to a fourth aspect the present invention provides a method for providing a gaseous environment for operation of a cryogenic device; comprising:

[0022] flooding a chamber with liquid coolant; and

[0023] causing gas boiled off the liquid coolant to accumulate in the chamber, such that liquid coolant is forced out of the chamber.

[0024] The present invention provides for the chamber to be flooded with liquid coolant, followed by evacuation of the liquid coolant while maintaining the interior of the chamber at cryogenic temperatures. Flooding of the chamber is of value in order to provide for rapid and thorough cooling of the interior and contents of the chamber.

[0025] During such a cooling phase, gas boiled off the liquid coolant is allowed to exit the chamber and thus the chamber remains flooded.
In embodiments of the third and fourth aspects of the present invention, evacuation of the liquid coolant from the chamber can be initiated by closing the gas vent of the chamber. When the gas vent is closed, gas boiled off the liquid coolant will accumulate within the chamber, and displace the liquid coolant from the chamber via the port. That is, the pressure of the gas within the chamber will equal or exceed hydrostatic pressure of the liquid coolant in the chamber and thus displace the liquid coolant. Once the gas extends to the port, gas will escape out the under port at a rate equal to gas accumulating in the chamber, thus providing a quiescent state in which devices within the chamber are provided with a gaseous environment at substantially liquid coolant temperatures.

In use, the chamber is preferably positioned within a dewar, and is partially immersed or more preferably substantially immersed within liquid coolant held in the dewar, while maintaining a gaseous environment within the chamber. Immersing the chamber within a liquid coolant substantially eliminates transmission of heat to the chamber, such that the temperature of the gaseous environment within the chamber will remain substantially at the boiling temperature of the liquid coolant used. Heat may of course be generated within the chamber by operation of the cryogenic device(s), and/or by friction of any moving parts required for moving operation of the cryogenic device(s). The liquid coolant surrounding the chamber will act as a heat sink for such heat, as it will be carried away from the device and/or moving parts via conduction and/or convection in the gaseous environment and through the chamber walls and/or port to the liquid coolant. Accordingly the chamber walls are preferably formed of a heat conductive material.

The port of the chamber is, in use, preferably positioned at or proximal to a lower extremity of the chamber, such that the chamber can be substantially wholly evacuated when the gas vent is closed. However positioning of the port away from a lower extremity of the chamber, in use, providing for partial evacuation of the chamber, may suffice in some embodiments. The presence of liquid coolant in a lower portion of the chamber may assist in maintaining suitably low temperatures within the gaseous environment in the upper part of the chamber. The port may be a hole through a wall of the chamber. The port may comprise a valve to enable selective closing or sealing of the port.

In preferred embodiments of the invention, the chamber can be sealed in order to allow control of pressure within the chamber, for instance by use of a pressure valve.

Such embodiments are advantageous where a device to be operated within the chamber has pressure dependent characteristics. Such embodiments may further comprise a standpipe having an inlet within the chamber, and an outlet external to the chamber and above an external liquid level, for permitting liquid coolant to flow from the chamber when under hydrostatic pressure generated by gas within the chamber. The inlet of the standpipe is preferably proximal to a lower extremity of the chamber. In such embodiments, while the standpipe may allow for pressure equalisation between the interior and exterior of the chamber, a dewar containing the external liquid coolant and the chamber is preferably sealed to nevertheless provide for pressure control of the gaseous environment within the chamber.

Examples of the invention will now be described with reference to the accompanying drawings in which:

FIGS. 1A to 1D illustrate a dewar and chamber in accordance with an embodiment of the present invention;

FIG. 2 illustrates a chamber, gas vent and drive shaft in accordance with a second embodiment of the present invention;

FIG. 3 illustrates an apparatus for providing a cryogenic gaseous environment in accordance with a third embodiment of the present invention;

FIG. 4 illustrates an apparatus for providing a cryogenic gaseous environment in accordance with a fourth embodiment of the present invention; and

FIG. 5 is a flowchart illustrating the process of cooling and evacuation of the chamber of the apparatus of FIG. 4.

In accordance with the present embodiment of the invention, a cool-down mode of operation is shown in FIG. 1B. In the cool-down mode, liquid coolant 102 is introduced to dewar 100, and gas vent 124 serving as a chamber gas port is held open by valve 126, thus allowing coolant 102 to enter the chamber 120 through the under port 122 so as to flood chamber 120. Introduction of coolant 102 to flood chamber 120 allows the interior and contents of chamber 120 to be rapidly and thoroughly cooled. Boiled coolant from chamber 20 exits as gas through gas vent 124.

Once the interior and contents of chamber 120 are sufficiently cooled, a chamber evacuation step commences as illustrated in FIG. 1C. The temperature of chamber 120 may be assessed by monitoring the gas flow through vent 124, and determining that the interior and contents of chamber 120 are sufficiently cool once the gas flow reduces below a threshold rate. To cause evacuation of coolant 102 from chamber 120, gas vent 124 is closed by use of valve 126. When the gas vent 124 is closed, gas 104 boiled off coolant 102 accumulates in chamber 120, and continued boiling generates sufficient pressure to counteract the hydrostatic pressure of the coolant 102 within chamber 120 so as to force coolant 102 out of chamber 120 through under port 122.

FIG. 1D illustrates the quiescent state for operation of one or more cryogenic devices within a gaseous environment 104 provided within chamber 120. Valve 126 holds gas vent 124 closed. Liquid coolant 102 is maintained within dewar 100. Gas pressure within chamber 120 is equal to the head of liquid outside the chamber 120 and thus holds liquid coolant out of chamber 120. As chamber 120 is entirely immersed in liquid coolant, very little heat is able to enter chamber 120 and thus the interior and contents of chamber 120 remain substantially at the boiling temperature of the liquid coolant.
[0041] It is to be recognised that heat generated within chamber 120 may cause the temperature within the chamber 120 to rise. Accordingly, it is desirable to match the dimensions of chamber 120 closely to the dimensions of a device to be operated within chamber 120, such that the conduction of heat from the heat source out of the chamber to the heat sink provided by coolant within dewar 100 is made efficient in order to maintain suitable cryogenic temperatures within chamber 120. Also for this reason, chamber 120 is preferably made of heat conductive material.

[0042] FIG. 2 illustrates a dewar insert 200 comprising a chamber 220, gas vent 224 serving as a chamber gas port, and drive chain 240, 242 in accordance with a second embodiment of the present invention. Such an embodiment provides for operation of a moving cryogenic device in a gaseous environment. A superconducting gradiometer mounted on a flexible substrate, for example the type set out in International Patent Publication No. WO 2004/015435 or International Patent Publication No. WO 2004/015788 by CSIRO, Tilbrook and Leslie, the content of which is incorporated herein by reference, may be mounted on the lower curved portion of rotor device mount 230, which is driven by lower drive shaft 240. Lower drive shaft 240 is in turn driven by upper drive shaft 242. When dewar insert 200 is placed within a dewar holding liquid coolant, upper drive shaft 242 and gas vent 224 are immersed in liquid coolant and thus conduct little heat to the chamber 220. A stator device mount 232 is provided with an under port 222 to enable liquid from a dewar to flood, cool and evacuate chamber 220 in the manner described above with reference to FIGS. 1A to 1D.

[0043] As can be seen, a cavity 226 is provided outside under port 222 in order to create a further gaseous region within cavity 226. Altering the dimensions of cavity 226 will enable the dewar insert and dewar to be placed on an angle such that drive shaft 242 is off-vertical. Such a configuration may be desirable where the dewar insert is for use as one of a plurality of rotating gradiometers having orthogonally positioned axes, such a configuration is set out in FIG. 2 of WO 2004/015435, and in conjunction with which the present embodiment may be applied.

[0046] FIG. 4 illustrates an apparatus 400 for providing a cryogenic gaseous environment in accordance with a fourth embodiment of the present invention. Apparatus 400 comprises a dewar 402 being a glass vacuum flask refill, a chamber 420, valve 424 and a drive shaft 440. Apparatus 400 may be housed in a PVC tube (not shown), which may be coated on both inside and outside surfaces with silver paint in order to effect RF interference shielding, for example where a magnetic field detection device is to be operated within chamber 420. A superconducting device may be mounted on rotor device mount 430, which is driven by drive shaft 440. Drive shaft 440 may for example be driven by hand or by motor. Dewar 402 holds liquid coolant 406 immersing chamber 420. Apparatus 400 further comprises a standpipe 428 having an inlet within chamber 420 and proximal to a lower extremity of chamber 420 allowing liquid coolant within chamber 420 to be drawn down to level 452. The outlet of standpipe 428 is external to chamber 420 and above a level 450 to which liquid 406 initially fills dewar 402.

[0047] A valve 462 can be opened and closed, to selectively allow liquid flow into or out of chamber 420. Valve 464 can be opened to allow gas or liquid to be bled out of dewar 402. Valve 466 and pressure regulator 468 allow gas pressure within chamber 420 to be held at or below a level defined by pressure regulator 468. Burst disc 470 provides a failure mechanism should pressure within dewar 402 exceed the bursting pressure of the burst disc 470.

[0048] Stator device mount 432 is provided, for example to support a stationary SQUID to be flux coupled to a rotating gradiometer mounted on rotor 430. To maximise flux coupling, it may be desirable to minimise a gap between the rotor 430 and stator 432. In this event rotor 430 and stator 432 are preferably constructed of material(s) having low thermal expansion coefficient(s), such that temperature variations do not undesirably affect the physical gap between the rotor 430 and stator 432, for example by avoiding contact between rotor 430 and stator 432.

[0049] FIG. 5 is a flowchart illustrating the process 500 of cooling and evacuation of the chamber 420 of the apparatus 400 of FIG. 4. At step 502, the process begins. At step 504 valves 464, 462 and 424 are opened, and valve 466 is closed. At step 506 liquid coolant, in this instance liquid nitrogen, is injected through valve 424. During this step, the liquid coolant freely travels between chamber 420 and dewar 402, due to valve 462 being open. Entry of the liquid nitrogen through valve 424 displaces the atmosphere within the chamber 420 and dewar 402, which is allowed to exit through valve 464. Liquid nitrogen injection continues until the liquid level is substantially at level 450. A sensor (not shown) may be provided within dewar 402 to determine the liquid level.

[0050] Such flooding of both the chamber 420 and dewar 402 with liquid nitrogen provides for thorough and effective
cooling of all components within the dewar 402 and chamber 420. As temperatures within the dewar 402 and chamber 420 approach that of the liquid nitrogen, the liquid nitrogen will boil and produce nitrogen gas, which is also allowed to exit through valve 464. Liquid nitrogen is preferably introduced throughout this stage to maintain the liquid level substantially at level 450. The flow rate of gas out of valve 464 during this stage substantially corresponds to a boiling rate of liquid nitrogen within the chamber, which in turn is indicative of the temperature of the contents of the chamber. Thus monitoring the gas flow rate out of valve 464 can give an indication of the temperatures of the components within the chamber 420 and dewar 402.

[0051] Once it is considered that temperatures within the chamber 420 are at an appropriate level, valve 462 may be closed, at step 508. At step 510, nitrogen gas is then pumped into chamber 420 through valve 424. The nitrogen gas is preferably at a temperature close to the boiling temperature of nitrogen to avoid the introduction of excessive heat into chamber 420. Due to the gas entering through valve 424, and the likely production of nitrogen gas from the boiling of liquid nitrogen within the chamber 420, and due to valve 462 being closed, liquid nitrogen within chamber 420 is forced out of chamber 420 through standpipe 428 under hydrostatic pressure, such that a liquid level in dewar 402 may rise above level 450, for example to the level shown in FIG. 4. Gas is injected into and accumulated within chamber 420 until a liquid level in chamber 420 falls to substantially level 452. Level 452 may be monitored by positioning a liquid level sensor within chamber 420. Alternatively level 452 may be configured to be level with a lower extremity of standpipe 428, such that continued accumulation of gas within chamber 420 would cause gas to pass up standpipe 428 rather than liquid.

[0052] Once the liquid within chamber 420 has fallen substantially to level 452, valves 464 and 424 are closed at step 512 to provide a pressure seal of dewar 402 and chamber 420. Valve 466 is opened, such that a gas pressure within chamber 420 is regulated by a pressure regulator 468. Maintaining constant gas pressure will improve the sensitivity of devices with pressure dependent characteristics which may be operated within the gaseous environment of chamber 420. Having achieved the desired cryogenic gaseous operating environment within chamber 420, the process ends at step 514. It has proven possible to maintain suitable cryogenic conditions within such a gaseous environment for around 3 hours.

[0053] The device to be operated within the gaseous environment of any one of chambers 120, 220, 320 or 420 may be a magnetic sensor. In such embodiments, all materials of the apparatus 100, 200, 300, 400 are preferably non-magnetic. Further, moving parts of the embodiments of FIGS. 1 to 4 should be self-lubricating at cryogenic temperatures, and should generally have matching and/or low coefficients of thermal expansion. For example, the dewar insert 200 may comprise a number of sections each formed from epoxy impregnated woven fiberglass, each section having lapped faces to mate with the adjacent section. Such a modular construction is advantageous in permitting interchanging of sections, for example interchanging of chamber section 220 should a different device be used. Nylon screws hold the sections together and application of a small amount of silicone grease on the faces effectively, seals the sections together for the purpose of gas containment

[0054] Each rotor 230, 330, 430 may be formed of machinable ceramic, while the drive shaft 240, 340, 440 may be a ground Pyrex glass spindle. Referring to FIG. 3, the Pyrex spindle drive shaft 340 runs in a graphite bearing 344 pressed into the housing of chamber 320, with a fibreglass driving dog 346 pressed onto the spindle 340 on the outer side of the bearing 344. The running faces of the dog 346 and the bearing 344 govern the vertical clearance of the rotor 330 from the stator 332 and pre-load can be applied by a plastic spring between the rotor 330 and the bearing 344. A thin-walled cupro-nickel tube 304, carrying a graphite bearing 348 at its upper end and pressed into the upper portion of chamber 320 at its lower end, transmits rotation via a long thin ground Pyrex glass rod 342 to a sliding coupling 350 which engages the driving dog 346. In this way, variations in the length of the drive spindle 342 due to thermal effects, do not affect the separation of the rotor 330 and stator 332, and thus do not alter the tape-to-SQUID separation where such devices are mounted upon the rotor 330 and stator 332. In the room-temperature environment at the upper end of spindle 342, a paddle-wheel type air motor is used to drive the spindle 342 via a single-stage epicyclic plastic gearbox. Rotation angle is monitored by an optical shaft encoder mounted on the spindle.

[0055] A patterned superconducting thin-film magnetic shield may be mounted on the module immediately below the stator device, for example a SQUID, to attenuate the vertical field component seen by the SQUID. The modular mounting allows fine tilt and positioning of the shield by means of three differential screws, adjustable by thin rods taken out to the room-temperature environment.

[0056] It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive.

1. An apparatus for providing a cryogenic gaseous environment, the apparatus comprising:

   a chamber for containing the cryogenic gaseous environment and for excluding external liquid coolant;

   a liquid inlet for selectively flooding the chamber with liquid coolant; and

   a chamber gas port for selectively permitting egress of gas from the chamber during liquid flooding of the chamber, and for selectively containing gas within the chamber.

2. The apparatus of claim 1 wherein the chamber gas port comprises a gas injection port for purging the chamber with gas to evacuate liquid from the chamber.

3. The apparatus of claim 2 wherein the gas injection port permits egress of gas during liquid flooding of the chamber.

4. The apparatus of claim 1 further comprising a gas outflow port for permitting egress of gas from the chamber during liquid flooding of the chamber.

5. The apparatus of claim 1 wherein the chamber gas port comprises a gas vent having open and closed positions, such that the gas vent when open allows egress of gas from the
chamber during liquid flooding of the chamber, and such that the gas vent when closed contains gas within the chamber.

6. (canceled)

7. The apparatus of claim 1, wherein the chamber can be pressure sealed.

8. The apparatus of claim 7 further comprising a pressure regulator to regulate pressure within the chamber.

9. The apparatus of claim 1, further comprising a dewar containing the chamber, the dewar for containing liquid coolant to immerse the chamber.

10. The apparatus of claim 9, wherein the chamber comprises a second port allowing liquid exchange between the dewar and the chamber.

11. The apparatus of claim 10, wherein in use the second port is positioned proximal to a lower extremity of the chamber.

12. The apparatus of claim 9 wherein the second port can be selectively sealed.

13. The apparatus of claim 1, further comprising a standpipe having an inlet within the chamber, and having an outlet external to the chamber and in use above an external liquid level, for permitting liquid coolant to flow from the chamber when under hydrostatic pressure generated by gas within the chamber.

14. The apparatus of claim 13 wherein in use the inlet of the standpipe is proximal to a lower extremity of the chamber.

15. A method of providing a cryogenic gaseous environment, the method comprising:

flooding a chamber with liquid coolant; and

causing cryogenic gas to occupy the chamber and displace liquid coolant from the chamber.

16. The method of claim 15 wherein causing cryogenic gas to occupy the chamber comprises injecting gas into the chamber to evacuate liquid from the chamber.

17. The method of claim 15 wherein causing cryogenic gas to occupy the chamber comprises containing within the chamber gas boiled off the liquid coolant.

18. The method of claim 15 further comprising permitting egress of gas during the flooding of the chamber.

19. The method of claim 15 further comprising, after causing cryogenic gas to occupy the chamber, pressure sealing the chamber.

20. The method of claim 19 further comprising regulating pressure within the chamber.

21. The method of claim 15, further comprising immersing the chamber in liquid coolant.

22. The method of claim 15, further comprising allowing liquid exchange between the interior and exterior of the chamber during flooding.

23. The method of claim 15 further comprising preventing liquid from entering the chamber after flooding.

24. The method of claim 15, further comprising permitting liquid to exit the chamber under hydrostatic pressure after flooding.

25. An apparatus for providing a gaseous environment for operation of a cryogenic device, the apparatus comprising:

a chamber for housing the cryogenic device;
a port in the chamber allowing the chamber to be flooded by liquid coolant; and

a gas vent for allowing escape of gas from the chamber;

wherein the chamber is configured such that, when the gas vent is closed, gas boiled off liquid coolant within the chamber will accumulate in the chamber and force liquid coolant out of the port.

26. (canceled)