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[54] **METHOD OF AND APPARATUS FOR THE COOLING OF AN OBJECT**

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[58] **Field of Search** 62/45, 50–55, 62/467, 512, 514, 62, 64, 376, 218

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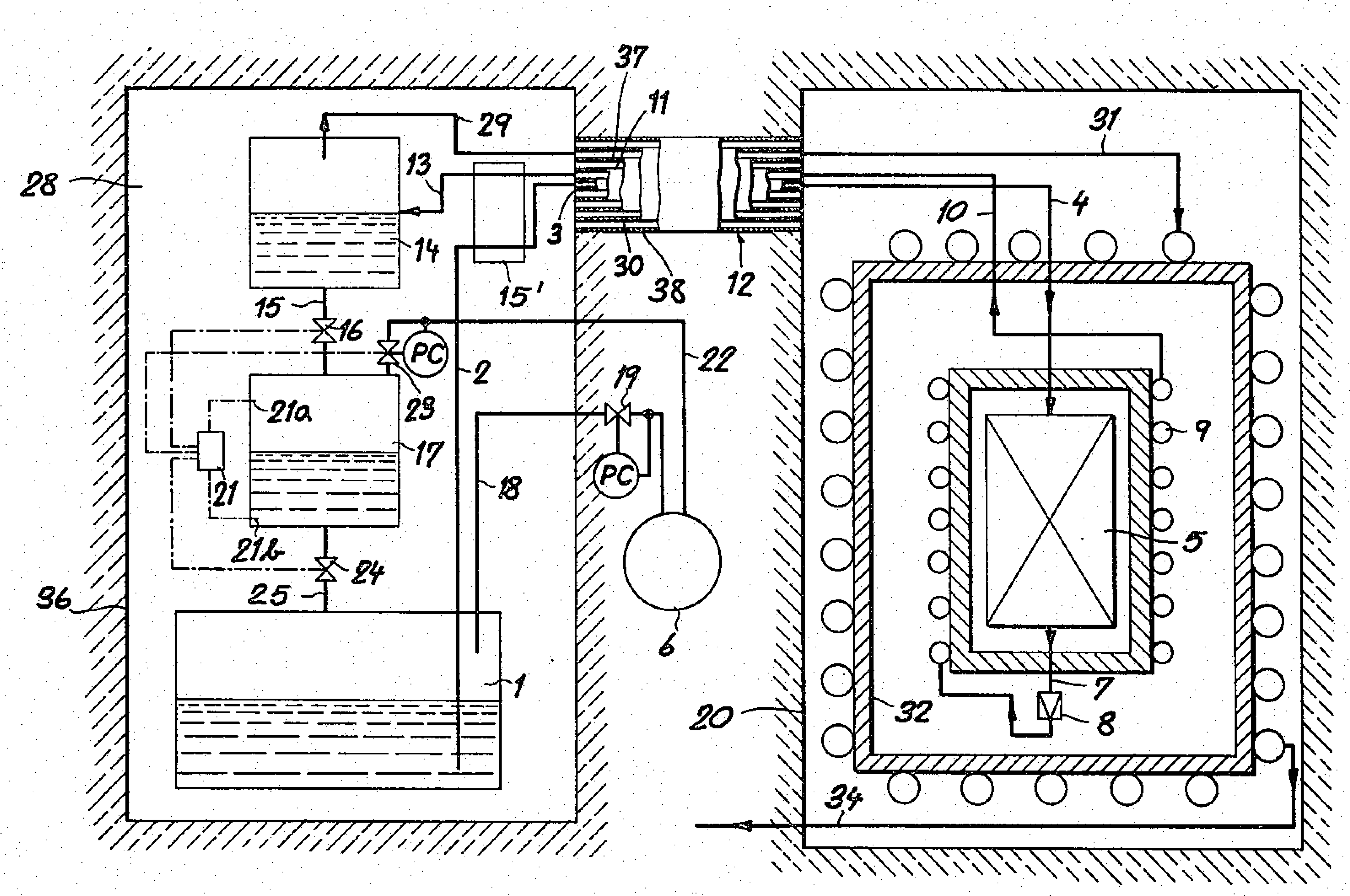
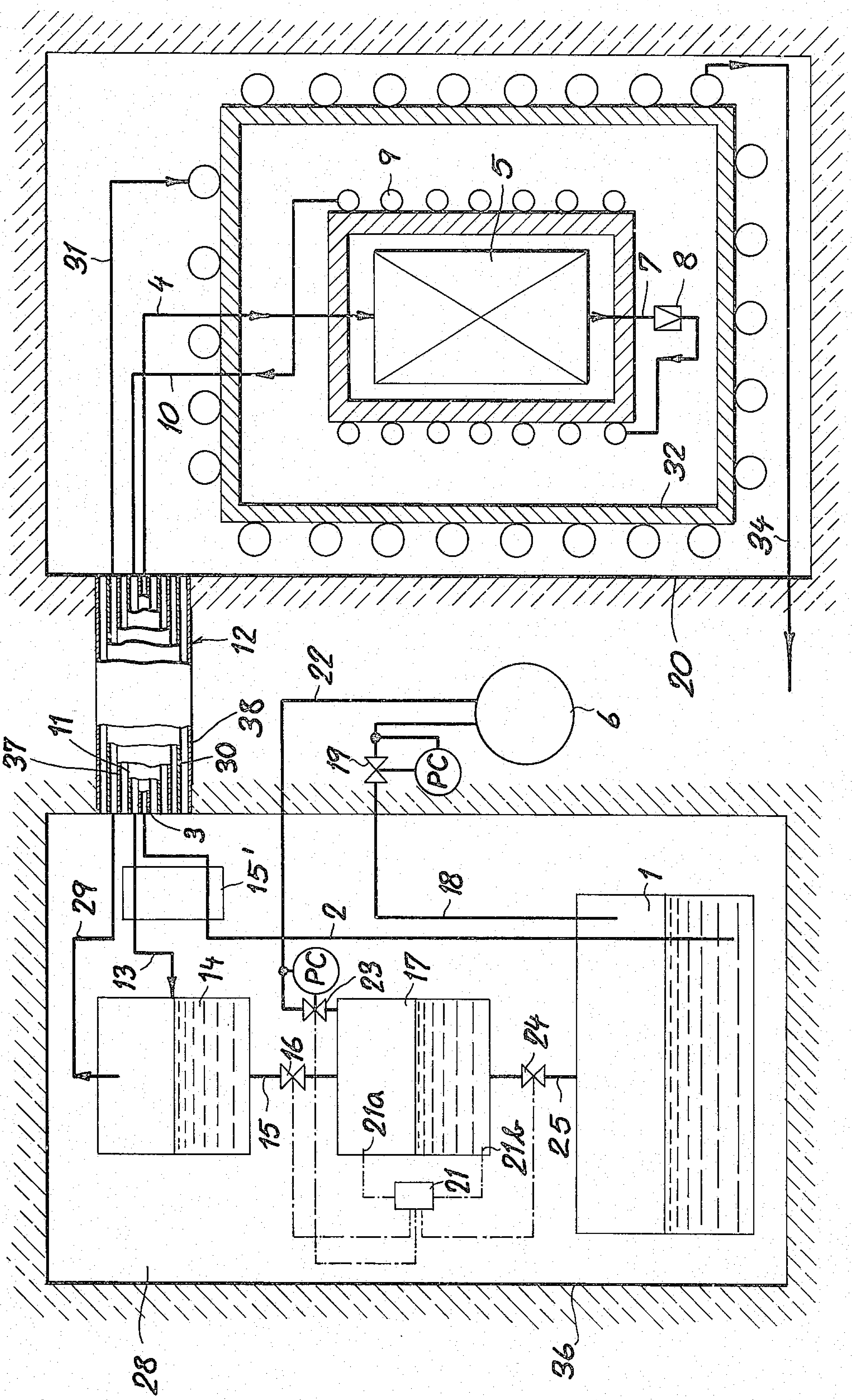
[57] **ABSTRACT**

An object, such as a superconductive magnet or a super-conductor cable in a housing or cryostat, is cooled with a cryogenic fluid passed continuously from one vessel into the housing or cryostat and then conducted after expansion into a second vessel where part of the cryogenic liquid is converted to vapor by expansion. A vapor/liquid separation is carried out in the second vessel and the liquid phase is delivered to a third vessel serving as a storage reservoir and intermittently connected to the first vessel to return liquid coolant thereto. During the accumulation of liquid in the third vessel, both the second and third vessels are maintained at a pressure lower than that in the first vessel, the pressure difference driving the liquid coolant through the housing or cryostat.

12 Claims, 1 Drawing Figure





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METHOD OF AND APPARATUS FOR THE COOLING OF AN OBJECT

FIELD OF THE INVENTION

Our present invention relates to a method of and an apparatus for the cooling of an object such as a superconductive magnet or a superconductive cable in a housing or cryostat with a liquid coolant, e.g. liquid helium.

BACKGROUND OF THE INVENTION

The deep cooling of objects has been found to be especially advantageous in recent years for the cooling of conductors in electrical systems, the conductivity of a conductor increasing as its temperature is reduced in the great majority of cases. The development of superconductive materials has caused increasing interest in cooling systems adapted to reach superconductive temperatures, i.e. temperatures of 14°k or below and in the handling of cryogenic liquids, i.e. liquefied gases capable of reaching these low temperatures.

Superconductors are used, for example, in magnets of particle accelerators and other systems in which high magnetic field strengths must be developed and an increasing cross-section of the conductor cannot be tolerated either because of high cost or other factors. Moreover, superconductors are used in cables for the transmission of large currents over both small and large distances.

A typical cryogenic-liquid-cooled cable may comprise a plurality of coaxial ducts in which the superconductor is received in the inner duct and an outer space is evacuated and/or provided with so-called superinsulation composed of alternating layers of fiberous material and reflective foil. The cryogenic liquid or cryogen is caused to flow through the innermost duct in direct contact or heat-exchanging relation with the superconductor.

Superconductor magnets are often enclosed in highly insulated housings or cryostats to which the superconductive liquid is admitted.

In a conventional process for the cooling of objects enclosed in a housing, e.g. a duct or cryostat, it has been the practice to supply liquid helium from a first storage vessel to the housing and to conduct the liquid after it has traversed the housing into a second storage vessel. A pressure differential, produced by some pressure buildup means, is maintained across the vessels to obtain the driving pressure necessary to displace the liquid from the first vessel to the housing and thence to the second vessel. When the first vessel is emptied, the pressure differential is reversed and the liquid now collected in the second vessel is displaced by the opposite pressure differential through the housing and into the first vessel in the opposite direction.

The disadvantage of this system is that the housing cannot be supplied for prolonged periods continuously with the cryogenic liquid from one vessel and hence there are periods in which the flow of the cryogen must be interrupted. This, of course, has the disadvantage that uniform flow and cooling cannot be guaranteed and that even brief interruptions in the continuity of coolant flow may cause detrimental results when the cooled object is a superconductive magnet or superconductive cable.

OBJECTS OF THE INVENTION

It is, therefore, the principal object of the present invention to provide a process for the cooling of an object in a housing, e.g. a superconductive magnet in the cryostat or a superconductive cable, whereby the aforementioned disadvantages are obviated.

Another object of the invention is to provide an apparatus or system for the cooling of objects with a liquid cryogen whereby the continuity of flow to the cooled object from a supply vessel can be maintained for much longer periods than heretofore.

Yet another object of the invention is to provide a method of an apparatus for the continuous supply of a cryogen to and effective cooling of an object to be cooled, especially a superconductive system, for long periods and with a single supply vessel serving as the source of the liquid cryogen to the housing of the object to be cooled.

SUMMARY OF THE INVENTION

These objects and others which will become apparent hereinafter are attained, in accordance with the present invention, in a method of cooling an object in a housing, especially a superconductive magnet or a superconductive cable, which comprises feeding a cryogenic liquid from a first or supply vessel to the housing, collecting cyrogenic liquid from said housing in a second vessel, expanding the liquid in said second vessel to cool the liquid and separating a vapor phase from the liquid phase of said second vessel, feeding the liquid phase to a third storage vessel and at least intermittently returning liquid from the storage vessel to the supply vessel.

In other words, the present invention provides for expansion of the liquid cryogen or coolant, after it has been used to cool the object, thereby lowering the temperature of the liquid phase and abstracting heat therefrom equivalent to the latent heat of vaporization of the cryogen. Thereafter a phase separation is carried out whereby the liquid component is collected in the third or storage vessel and is resupplied to the first.

The system of the present invention is thus able to achieve, in a simple manner, the aforestated object of permitting one-way, continuous and long duration cooling of an object, e.g. a superconductive system, with a liquid coolant or cryogen, e.g. liquid helium.

The liquid coolant is displaced through the system under appropriate driving pressures and thus, according to the present invention, the pressure differential between the first and second vessels is maintained at a level necessary to drive the liquid cryogen from the first vessel through the cryostat or housing of the object and into the second vessel.

During the accumulation of the liquid in the storage vessel, the latter is maintained at the same pressure as the second vessel, i.e. at a pressure lower than that in the first vessel. Even the expansion step within the second vessel takes place to a pressure below that in the first vessel.

As soon as the third or storage vessel is filled to a sufficient degree with the liquid cryogen recovered from the first separation in the second vessel, the connection between the second and third vessels is closed with a valve and a valve between the third vessel and the first or supply vessel is opened. The pressure is developed in the third or storage vessel which is somewhat higher than the pressure maintained in the first vessel to drive the liquid cryogen into the latter.

When the third vessel is completely or partly emptied or discharges into the first vessel, the valve between them is again closed and simultaneously the second valve is opened so that the pressure in the third vessel again assumes a level identical to that in the second vessel and the liquid coolant can flow from the second vessel to the third. Consequently, the second vessel serves for temporary storage of the liquid phase only during the period in which the third vessel is being discharged into the first.

The pressure differential required to drive the liquid from the first vessel to the second and from the third vessel to the first as described above can be generated by a pressure buildup means of any conventional design.

An important feature of the present invention resides in the fact that, during the two switch-over phases, i.e. the filling of the third or storage vessel and the discharge of the storage vessel into the supply vessel, the displacement of the liquid cryogen from the first or supply vessel to housing of the object to be cooled is neither influenced nor completely interrupted. The object to be cooled is thus subjected to a continuous flow of the liquid cryogen at a constant rate from a single supply vessel for long periods, i.e. until all of the liquid cryogen has been converted into vapor.

The method of the present invention has been found to be especially advantageous, for the cooling of superconductive systems such as conductive magnets, superconductive cables or the like.

According to another feature of the present invention the first valve between the third (storage) and first (supply) vessels and the second valve between the second (phase-separation and liquid-collection) and third vessels can be controlled by a liquid-level indicator, sensor or controller responsive to the liquid level in the third or storage vessel and having upper and lower threshold values.

As soon as the liquid level in the third or storage vessel reaches the upper threshold valve, the level indicator or sensor generates a first pulse to close the second valve and open the first valve while energizing or operating the pressure control device for the third vessel to bring the pressure entrainment to a level above that in the first vessel. The pressure differential between the third and first vessels can thus displace the accumulated liquid cryogene and coolant into the first vessel.

Conversely, when the liquid-level senses a liquid level in the third vessel which falls to the lower threshold value, a second pulse is generated which once again closes the first valve and the pressure-control device while opening the second valve. The liquid cryogen or coolant then flows from the second vessel to the third while the pressure in the latter vessel is reduced to that of the second vessel; especially when the object to be cooled is a super-conductive system it has been found to be advantageous to pass the liquid coolant supplied to the object to be cooled in indirect heat exchange with the oppositely flowing expanded coolant, thereby super-cooling the oncoming coolant and insuring that the liquid cryogen will maintain its liquid state as it traverses the system to be cooled.

Furthermore, the coolant withdrawn from the system to be cooled may advantageously be expanded and pass through separate cooling zones to shield the liquid of the first or supply vessel from the input of heat from the exterior. These separate cool zones may be provided around the duct whereby the liquid cryogen is delivered to the cryostat around the chambers of the cryostat traversed by the liquid coolant and around the body of liquid cryogen maintained in the supply vessel.

According to still another feature of the invention, radiation shields preventing the loss of cold within the duct system and the cryonate are cooled with cold coolant vapor from the second vessel.

An apparatus for carrying out the method of the present invention thus comprises three vessels whereby the third or storage vessel is connected with the first by a duct and a first valve and the second vessel is connected to the third by a duct and a second valve. Preferably the third or storage vessel underlies the second or phase-separation vessel (the latter is disposed above the third or storage vessel) and suitable conduits, ducts or the like are provided between the first or supply vessel and a cryostat containing one or more objects to be cooled and between the cryostat and the second vessel.

The duct means connecting the interior of the cryonate with the second vessel is provided with an expansion valve.

Still another feature of the invention resides in the provision of a level indicator in the third vessel having the upper and lower threshold valves as described above whereby the valves are automatically controlled in response to the level in the third or storage vessel.

In accordance with another feature of the apparatus aspect of this invention, all of the connecting ducts between the vessel and the cryogen or the object to be cooled are formed as coaxial conduits with a central passage and the coaxial annular passages surrounding same. The central passage serves for the feed of the liquid cryogen to the object to be cooled. The innermost or first annular passage serves to conduct expanded cryogen or coolant from the object to be cooled and the third annular passage forms a radiation shield and a path for the vapor of the liquid cryogen between the second storage vessel and a further radiation shield within the cryostat. The two other annular passages, i.e. the second and fourth, are evacuated.

Within the cryostat there is formed, a cooling zone immediately surrounding the object to be cooled which is cooled by the expanded coolant from this object for the supercooling of the incoming liquid, the outflowing coolant is passed through a heat exchange with one section traversed by the liquid cryogen from the supple vessel and another section traversing by expanded cryogen from the cooled object. Of course, while the system has been described for a single object to be cooled, it may also be used to cool a number of objects in parallel or in series with respect to the flow of the liquid cryogen.

BRIEF DESCRIPTION OF THE DRAWING

The above and other objects, features and advantages of the present invention will become more readily apparent from the following description, reference being made to the accompanying drawing in which the sole FIGURE is a flow diagram illustrating a system according to the present invention.

SPECIFIC DESCRIPTION

The system illustrated in the drawing comprises a supply vessel 1 (first vessel), connected by a duct 2 to one section of a heat exchanger **15** and then to the central passage **3** of a coaxial-conduit system having four annular passages **11, 37, 30** and **38** surrounding the central passage. The coaxial duct system may extend over long distances and is represented generally by the numeral **12.** From the central passage the liquid cryogen is introduced at **4** into the object **5** to be cooled in a cryostat represented generally at **20.** The object may be a superconductive magnet.

The supercooled liquid cryogen, somewhat heated to contact with the object **5,** is conducted away at **7** and enters an expansion valve **8** in which the liquid cryogen is expanded to form a vapor-liquid mixture which traverses a helical duct system **9** in heat exchanging relation with a radiation shield directly surrounding the object **5** and forming a cold zone therearound. The cooling avoided by the passage of the mixture through the ducts **9** has been found to stabilize the temperature of the space in which object **5** is disposed.

A duct **10** carries the two-phase mixture from the cold zone through the first annular space **11** of the coaxial-duct system **12,** through another section of the heat exchanger **15** and, via line **13,** to the second or separation vessel **14.**

The mixture of vapor and liquid phases is separated in vessel **14** and the liquid phase can be transferred via duct **15** and an automatically controlled valve **16** to the third or storage vessel **17.** The latter is connected by a duct **25** and a valve **24** to the first vessel **1.**

To create the displacement pressure driving the liquid from the vessel **1** through the object **5** to be cooled and into the vessel **14,** we provide a pressure-generating device which comprises a duct **18** connected to a controlled-pressure valve **19** and a pressurized gas source **6** which is also connected via line **22** and the pressure-controlled valve **23** to the gas space of vessel **17.**

A level sensor **21** responds to the liquid level in the storage vessel **17** and has upper and lower thresholds represented by the inlets **21***a* and **21***b* of the controller **21** whose outputs are applied to the valves **16** and **24** and to the pressure-regulating valve **23** respectively.

The gas derived from the liquid/vapor separator **14** is fed by line **29** to the third annular passage **30** of the coaxial duct system **12** and then passes through tubes of a heat shield **32** surrounding the heat shield **9** and enclosing the space in which the expansion valve **8** is provided. The latter heat shield **32** is endlosed in the insulated walls of the cryogen **20** and delivers its vapor via line **34** to a condensing station or the like not shown.

The operation of the system will be more readily apparent with reference to a specific example as given below.

Liquid helium at a pressure of about 1 – 8 atmospheres absolute and a temperature of 4.9°K passes from the first vessel **1** via the line **2** through the heat exchanger **15,** the central passage **3** of the coaxial duct system **12** and by line **4** is admitted to the object **5** to be cooled, especially a conductive magnet.

In the heat exchanger **15** the liquid helium is supercooled to a temperature of about 4.5°K and the supercooled liquid helium is expanded at valve **8** to a pressure of 1.2 atmospheres absolute before entering the cooling zone **9.**

Within the cooling zone, the helium vapor liquid mixture passes in counterflow to the liquid super-cooled helium at a temperature of 4.5°K and thereby stabilizes the temperature within the object **5.**

The object is thus cooled with super-critical helium at a pressure of about 1.8 atmospheres absolute and a temperature of about 4.5°K.

From this second vessel **14,** liquid helium is transferred to the open valve (second valve) **16** into the third or storage vessel **17** which is at the same pressure as that of the phase-separation vessel **14.** A gravity transfer of the liquid takes place during this period.

The latter pressures are about 1.2 atmospheres absolute and hence a pressure differential of 0.6 atmospheres absolute is applied between the first vessel **1** and the second vessel **14** to displace the liquid helium.

As soon as the liquid level in the third vessel **17** reaches its upper limits as defined by the inlet **21***a*, the level sensor **21** applies a signal which closes the second valve **16,** opens the first valve **24,** and overlies upon the pressure controller **23** to raise the pressure in the third vessel **17** above 1.8 atmospheres absolute, e.g. to 2.0 atmospheres absolute. The liquid is driven out of the storage vessel **17** into the supply vessel **1** and the flow of liquid helium through the object **5** is not interrupted. Of course, vessel **14** remains under its original pressure 1.2 atmospheres absolute or slowly increases in pressure, but well below 1.8 atmospheres absolute.

As soon as the liquid level in the third vessel **17** falls to its lower threshold value as sensed by the inlet **21***b*, the sensor **21** closes valve **24,** opens valve **16** and restores the pressure control **23** to its original level while venting excess pressure and permits the pressure to be repeated. The vapor of course is used to cool the radiation shield **32.** The passages **37** and **38** of the coaxial duct system **12** are evacuated and the compartment e.g. **28,** within the cryogen **20** and the housing **36** surrounding the vessels **14, 17** and **1** can also be evacuated.

We claim:

1. A method of cooling an object to be maintained at a cryogenic temperature comprising the steps of: continuously feeding a liquid cryogen from a supply vessel to said object; maintaining a pressure in said vessel sufficient to displace said liquid cryogen to said object; expanding liquid cryogen upon its passage to said object to form a vapor/liquid phase mixture of the liquid cryogen; separating said phase mixture into a liquid phase and a vapor phase in a second vessel; transferring the liquid phase from said second vessel directly to a third storage vessel; and at least intermittently feeding said liquid cryogen from said storage vessel to said supply vessel upon the liquid level in said storage vessel attaining a predetermined height and at substantially the pressure in said supply vessel.

2. The method defined in claim **1** wherein a first valve is provided between said storage vessel and said supply vessel and a second valve is provided between said second vessel and said storage vessel, said method further comprising the step of controlling said valves in response to the liquid level in said storage vessel.

3. The method defined in claim **1,** further comprising the step of super-cooling the liquid cryogen from said supply vessel prior to its use to cool said object in heat exchange with the expanded cryogen.

4. The method defined in claim **1,** further comprising the step of shielding the liquid cryogen in contact with said object with the expanded cryogen.

5. The method defined in claim **1**, further comprising the step of shielding the liquid cryogen between said supply vessel and said object with the expanded cryogen.

6. The method defined in claim **1** wherein a radiation shield is provided around said object, said method further comprising the step of cooling said radiation shield with the vapor phase separated from said liquid phase.

7. An apparatus for cooling an object, comprising a supply vessel for a liquid cryogen; conduit means connecting said supply vessel with said object; an expansion valve receiving liquid cryogen from said object; a second vessel communicating with said expansion valve and receiving a vapor-liquid phase mixture of said cryogen therefrom; a storage vessel connected to said supply vessel for delivering liquid cryogen thereto; and means connecting said second vessel to said storage vessel for delivering said liquid cryogen to said storage vessel upon its separation from the vapor phase of said mixture in response to the liquid level in said storage vessel.

8. The apparatus defined in claim **7** further comprising a heat exchanger having a first section traversed by the liquid cryogen between said supply vessel and said object and a second section traversed by a vapor-liquid phase mixture from said expansion valve for supercooling the liquid cryogen prior to the use thereof to cool said object.

9. The apparatus defined in claim **7**, further comprising a radiation shield surrounding said object and means for passing the vapor-liquid phase mixture formed upon expansion of said liquid cryogen in said expansion valve into heat exchanging relation with said radiation shield.

10. An apparatus for cooling an object, comprising a supply vessel for a liquid cryogen; conduit means connecting said supply vessel with said object; an expansion valve receiving liquid cryogen from said object; a second vessel communicating with said expansion valve and receiving a vapor-liquid phase mixture of said cryogen therefrom; a storage vessel connected to said supply vessel for delivering liquid cryogen thereto; and means connecting said second vessel to said storage vessel for delivering said liquid cryogen to said storage vessel upon its separation from the vapor phase of said mixture a valve being provided between said second vessel and said third vessel and another valve being provided between said second vessel and said storage vessel and another valve being provided between said storage vessel and said supply vessel, said apparatus further comprising a liquid level sensor in said storage vessel for controlling said valves.

11. The apparatus defined in claim **10** wherein a pressure control device is provided for regulating the relative pressures in said vessels above that in said supply vessel to displace liquid cryogen from said storage vessel to said supply vessel.

12. The apparatus defined in claim **10** wherein said conduit means comprises a central passage traversed by the liquid cryogen and a plurality of annular passages surrounding said central passage, at least one of said annular passages being connected to one of said vessels for passage of cryogenic fluid therethrough.

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