(54) Title: APPARATUS AND METHOD FOR COOLING A SUPER CONDUCTING MACHINE

(54) Bezeichnung : VORRICHTUNG UND VERFAHREN ZUR KÜHLUNG EINER SUPRALEITENDEN MASCHINE

FIG 2
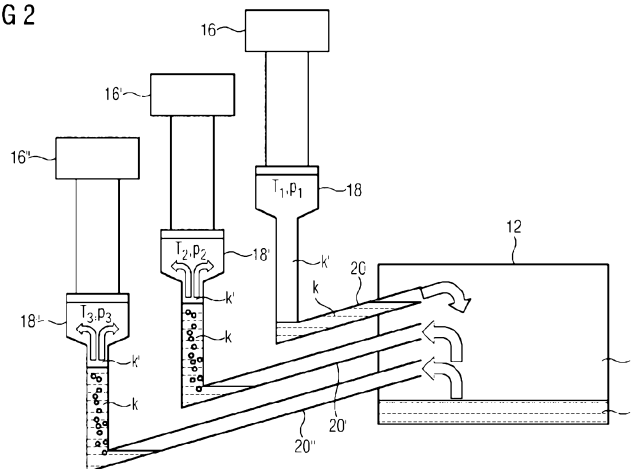
(57) Abstract: The present invention relates to an apparatus and a method for cooling a super conducting machine (2), in which apparatus and method at least two condenser areas (18, 18',18") each make thermal contact with a cold head (16, 16', 16"), and in which the at least two condenser areas (18, 18', 18") each have a connecting line (20, 20', 20"), via which the at least two condenser areas (18, 18', 18") are connected fluidically to an evaporator area (12). A liquid cooling fluid k can be moved or pumped from at least one condenser area (18, 18', 18") into the evaporator area (12) by means of a temperature difference, and a pressure difference associated therewith, in the at least two condenser areas (18, 18', 18").

(57) Zusammenfassung:

[Fortsetzung auf der nächsten Seite]

Die vorliegende Erfindung bezieht sich auf eine Vorrichtung und ein Verfahren zur Kühlung einer supraleitenden Maschine (2), bei welchen wenigstens zwei Kondensorräume (18, 18',18' ') jeweils mit einem Kaltkopf (16, 16', 16' ') in thermischen Kontakt stehen und bei welchen die wenigstens zwei Kondensorräume (18, 18', 18' ') jeweils eine Verbindungsleitung (20, 20', 20' ') aufweisen, über welche die wenigstens zwei Kondensorräume (18, 18', 18' ') fluidisch mit einem Verdampferraum (12) in Verbindung stehen. Über einen Temperatur- und damit verbundenen Druckunterschied in den wenigstens zwei Kondensorräumen (18, 18', 18' ') ist ein flüssiges Kühlfluid k von wenigstens einem Kondensorraum (18, 18', 18' ') in den Verdampferraum (12) beweg- bzw. pumpbar.

Description

Apparatus and method for cooling a superconducting machine

The present invention relates to an apparatus and a method for cooling a superconducting machine, in which at least two condenser chambers each make thermal contact with a cold head and in which the at least two condenser chambers each have a connecting line, via which the at least two condenser chambers are connected fluidically to an evaporator chamber.

Superconducting machines usually comprise superconducting coils which must be reliably cooled, at least during the operation of the machine. Metal oxide superconductive materials with critical temperatures T_c of over 77 K have been known since 1987. These materials are also known as High T_c Superconductive (or HTS) materials and, in principle, facilitate a cooling technique using liquid nitrogen (LN_2). Machines which include coils with HTS may thus be cooled and/or operated, for example, with liquid nitrogen (LN_2) or with liquid neon (LN_e).

Refrigeration units in the form of so-called cryocoolers with closed compressed helium gas circuits are preferred for the cooling of windings with HTS material. Such cryocoolers are in particular of the Gifford-McMahon or Stirling type, or are designed as so-called pulse tube refrigerators. They have the advantage that their refrigerating capacity is available almost at the touch of a button and the use of cryogenic fluids is avoided. When such refrigeration devices are used, the superconducting winding is indirectly cooled e.g. by heat conduction to a cold head of a refrigerator (cf. e.g. "Proc. 16th Int. Cryog. Engng. Conf. (ICEC 16)", Kitakyushu, JP, 20.-

24.05.1996, Verlag Elsevier Science, 1997, pages 1109 to 1129).

A refrigeration technique, such as the one described e.g. in DE 103 21 463 A1, can be used for cooling the rotors of electrical machines. The rotor contains a rotating winding comprising HTS conductors, which are located in a thermally conductive winding mount. This winding mount is equipped with a central, axially extending cylindrical cavity, to which are connected pipe sections that lead laterally out of the winding mount. These pipe sections lead to a condenser chamber of a refrigeration unit, which condenser chamber is located in a geodetically higher position, and, together with this condenser chamber and the central rotor cavity, form a closed one-pipe system. This pipe system contains a refrigerant or cooling fluid, which circulates using a so-called thermosiphon effect. Cooling fluid condensate in the condenser chamber is thus transported via the pipe sections into the central cavity, where it absorbs heat and evaporates due to the thermal coupling to the winding mount and thus to the HTS winding. The evaporated cooling fluid then flows, via the same pipes, back into the condenser chamber, where it is re-condensed. The refrigerating capacity required for this purpose is provided by a refrigerating machine, the cold head of which is thermally coupled to the condenser chamber.

This return flow of the refrigerant is driven by a slight overpressure into the central cavity, which acts as an evaporator part, to the parts of the refrigerating machine which act as a condenser unit. This differential pressure, which is produced by the creation of gas in the evaporator and by the liquefaction in the condenser chamber, therefore leads to the desired refrigerant return flow. Corresponding

refrigerant flows are known in principle from so-called heat pipes.

Therefore, among the known machines with thermosiphon cooling by means of a suitable refrigeration unit, the liquid refrigerant is transported using only the force of gravity, so that no further pumping systems are required. This requires a refrigeration unit or a condenser chamber, which must essentially be located in a geodetically higher position than the machine and/or the winding mount. The disadvantages associated with this are particularly prevalent where there are spatial limitations around the machine and the refrigeration unit structure. Thus, e.g. in a machine with vertically arranged machine axis, an object driven by the machine, e.g. a motor, may be disposed above the machine. The machine is installed in its surrounding area such that there is no free space available in the plane of the machine. The geodetically higher position is occupied by the object being driven, and a arrangement of the refrigeration unit geodetically higher is not possible in this situation. Even in complex applications, such as e.g. for railcars on railroads, the construction height of the railcar may be restricted e.g. due to regulations relating to the height of overhead lines and/or tunnels. If the machine dimensions are within the range allowed by the height regulations, it may still not be possible for the refrigeration unit to be arranged in a geodetically higher position than the machine, even if the machine axle is positioned horizontally.

A further case in which problems may occur with a purely gravity-driven refrigerant flow is on ships or offshore installations. If a machine installation as described above is used on ships or offshore installations, then static

imbalances, known as "trim", of e.g. up to ± 5º and/or dynamic
imbalances of e.g. up to ± 7.5º longitudinally, are frequently
to be expected. In order to obtain approval for use on vessels
from a classification body, the cooling system of such a
machine installation must consequently guarantee reliable
refrigeration on board a seagoing vessel even under these
conditions. If the said imbalances of the machine are to be
tolerated, then there is a risk that an area of the pipe
sections between the central rotor cavity and the
refrigeration unit will come to be geodetically lower than the
central rotor cavity. As a result, the refrigerant will not be
able to reach the rotor cavity to be cooled using the force of
gravity. The cooling of the machine and therefore its
operation would therefore no longer be guaranteed.

In order to guarantee reliable cooling even in the event of
machinery imbalances, it is possible for the machine to be
arranged at an angle to the horizontal, so that, even assuming
maximum trim positions or oscillation amplitudes in the
thermosiphon pipe system, an inclination toward the rotor
cavity is always present. However, it is precisely in
shipbuilding that such an inclined arrangement is undesirable,
especially with greater machine lengths, because of the large
space requirement that would be necessitated. Alternately,
instead of a one-pipe system for circulating refrigerant
between a condenser chamber and the evaporator chamber, in
which the liquid and the gaseous refrigerant flow to and from
the condenser chamber through the same pipe sections, a two-
pipe system may be used. This system uses the thermosiphon
effect as described e.g. in WO 00/13296 A. However, an
additional pipe for the gaseous refrigerant must be provided
in the area of the hollow rotor shaft. The condenser chamber
must be geodetically positioned in relation to the evaporator

chamber at a height that is sufficient to guarantee a reliable flow of cooling fluid by force of gravity from the condenser chamber into the evaporator chamber. This requires installation space, the availability of which may be limited, e.g. on ships.

A further alternative is offered by the use of a mechanical pump and/or mechanical valves. The refrigerant may be forced through by a pumping system. However, this would necessitate a considerable amount of equipment, particularly if the refrigerant has a temperature of 25 to 30 K, for example. Circulating pumps of this kind cause considerable losses and are scarcely able to fulfill the service life requirements of shipbuilding, which involve long maintenance intervals.

It is an object of the invention to improve upon the prior art at least to an extent or to provide an alternative thereto. A preferred embodiment aims to provide a method for cooling a superconducting machine, which facilitates reliable cooling even when the machine is affected by imbalances. It is therefore necessary to dispense with mechanically moving parts, such as e.g. mechanical pumps and valves, since at cryogenic temperatures these are complex, costly and prone to problems. A further aim of a preferred embodiment is to provide a method in which a cooling fluid can also be moved against the direction or effect of the force of gravity without mechanically moving parts, such as e.g. mechanical pumps and valves.

Advantageous embodiments of the apparatus and of the method for cooling a superconducting machine are described herein. The features of these subordinate claims may be combined with one another and with features of the subclaims, and features of the subclaims may be combined with one another.

The apparatus for cooling a superconducting machine according to the disclosure has at least two condenser chambers, which each make thermal contact with a cold head, the at least two condenser chambers each having a connecting line via which the at least two condenser chambers are connected fluidically to an evaporator chamber. The at least two condenser chambers are designed in such a way that a liquid

cooling fluid can move even against the force of gravity, from at least one condenser chamber into the evaporator chamber as a result of a pressure difference between a first pressure in the first condenser chamber and a second pressure in the second condenser chamber. The pressures are determined in each case by the temperature in the condenser chambers (boiling point curve of the coolant).

By using two condenser chambers, each with a connecting line to the evaporator chamber, the temperatures in the condenser chambers can be differently set via the cold heads that are in each case thermally coupled to the condenser chambers. This enables a pressure difference to be created between the condenser chambers or their interior areas, which are filled with liquid and/or gaseous cooling fluid. In a condenser chamber in which the temperature is increased, fluid evaporates and/or the gaseous cooling fluid expands and the pressure increases. In a condenser chamber in which the temperature is lowered or reduced, the pressure is reduced since gaseous coolant is condensed. By different variation of

the temperature in the condenser chambers or via the cold
heads, a pressure difference is formed between the condenser
chambers.

The pressure difference causes a movement of liquid cooling
fluid out of at least one connecting line into the evaporator
chamber. Thus, as a result of greater pressure in a condenser
chamber compared to the evaporator chamber, which may result
from greater pressure in one condenser chamber compared to
another condenser chamber, cooling fluid in the connecting
pipe of the one condenser chamber is also moved into the
evaporator chamber against the force of gravity, if the
pressure difference is sufficiently large. No moving parts
whatsoever, such as valves or mechanical pumps, are necessary
for this purpose.

At least three condenser chambers, each with a cold head, may
also be used, wherein, particularly in the at least three
condenser chambers, temperature can be set in a regulated or
controlled way via the respectively assigned cold
heads independently of one another. The temperature is then
advantageously lowered in two condenser chambers and increased
in one condenser chamber simultaneously. It is possible in
this case for the condenser chambers in which the temperature
is increased and lowered to be switched in succession, yet
with the temperature always being raised in one and lowered in
the others. As a result of this, liquid cooling fluid always
flows out of one connecting pipe and reliable cooling is
guaranteed. In the two condenser chambers in which the
temperature is lowered, while liquid cooling fluid flows out
of the connecting line of the third condenser chamber into the
evaporator chamber, gaseous cooling fluid can be liquefied,

which fluid can flow from the evaporator chamber into the two previous condenser chambers.

A closed, in particular a sealed, cooling circuit can be formed via the condenser chambers, the connecting pipes and the evaporator chamber. No cooling fluid is lost and the cooling circuit does not require any maintenance and does not need to be refilled with cooling fluid, particularly if a suitably dimensioned compensating reservoir is provided.

The apparatus can be filled with a cooling fluid, which comprises or consists of a homogeneous fluid, in particular liquid nitrogen or liquid neon, or which comprises a mixture of liquid coolants with different condensation temperatures. The evaporation temperature of the cooling fluid determines the temperature to which the superconducting winding or machine can be cooled, i.e. which superconducting materials can be used. The condensation temperature of the cooling fluid determines the temperature to which the cold heads must cool the condenser chamber, in order to reliquefy the evaporated gaseous cooling fluid. By means of mixtures or additions to the cooling fluids, temperatures at which the cooling fluid evaporates or is liquefied, which are between temperatures at which pure substances, e.g. pure nitrogen or pure helium, evaporate or are liquefied, can also be set.

The superconducting machine may be a motor or a generator, particularly with a rotor having at least one superconducting winding, wherein the rotor is rotatably arranged around an axis. The superconducting winding may consist of or comprise HTS material. This enables nitrogen to be used as the cooling fluid. The machine may be used e.g. in ships.

The condenser chambers and the cold heads respectively assigned to them may be arranged in a stationary position outside the rotor and the evaporator chamber may be rotatably arranged inside the rotor, in particular as a cylindrical cavity along the rotation axis of the rotor. The connecting pipes can extend into the evaporator chamber according to the thermosiphon principle and can also be stationary. Favorable features of the machine are thereby achieved.

There is disclosed herein a method for cooling a superconducting machine using the thermosiphon effect, comprising the steps:

A) that a temperature is increased in a first condenser chamber which is thermally connected to a first cold head, wherein the pressure in the condenser chamber is increased, and liquid cooling fluid is moved in a first connecting pipe between the first condenser chamber and an evaporator chamber by the temperature increase and/or gas expansion in the evaporator chamber;

B) that a temperature is constantly maintained or lowered simultaneously in at least one second condenser chamber, which is thermally connected to a second cold head, the temperature in particular being lower than in the first condenser chamber, as a result of which gaseous cooling fluid is moved from the evaporator chamber into the second condenser chamber, in particular via a second connecting pipe between the evaporator chamber and the second condenser chamber, as a result of the temperature increase in the first condenser chamber and/or the lowering of the temperature in the second condenser chamber;

C) that a constant temperature is maintained in a first condenser chamber, which is thermally connected to a cold head and which is fluidically connected to an evaporator chamber via a first connecting pipe;

D) that a temperature is lowered simultaneously in at least one second condenser chamber which is thermally connected to a second cold head, as a result of which gaseous cooling fluid is moved from the evaporator chamber into the second condenser chamber via a second

connecting pipe between the evaporator chamber and the second condenser chamber, as a result of the temperature reduction in the second condenser chamber;

and

E) as a result of which liquid cooling fluid is moved into the evaporator chamber in the first connecting pipe between the first condenser chamber and the evaporator chamber as a result of the temperature reduction in the at least second condenser chamber.

The pressure difference is created or increased as a result of the temperature reduction in the at least second condenser chamber, as a result of which the resulting overpressure in the first condenser chamber, even compared to the pressure in the evaporator chamber, causes the liquid cooling fluid to be forced into the evaporator chamber. If the temperature is lowered, gaseous cooling fluid in the at least second condenser chamber can be liquefied simultaneously, which liquid may be moved into the evaporator chamber at a later time.

A temperature can be constantly maintained or lowered simultaneously at least in one third condenser chamber, which is thermally connected to a third cold head. Thus e.g. in steps C) to E) a greater negative pressure can be generated in the first condenser chamber and, in a short time, more liquid cooling fluid can be moved into the evaporator chamber. In steps A) and B) the effect of a pressure difference being created between first and second condenser chamber may be supported by a third condenser chamber and, likewise in a short time, more liquid cooling fluid can be moved into the evaporator chamber.

Directly or indirectly subsequent to steps A) and B) or C) to E), in the at least one condenser chamber, in which the temperature at the time of steps A) and B) or C) to E) was increased or maintained at a constant level, the temperature can be lowered or maintained at a constant level. In the at least one second, in particular the second and third, condenser chamber, in which the temperature at the time of steps A) and B) or C) to E) was maintained at a constant level or

lowered, the temperature can be increased or maintained at a constant level.

A further alternate method for cooling a superconducting machine, in particular using the thermosiphon effect, comprises the steps that, in a first condenser chamber, which is thermally connected to a first cold head, and that, in at least one second condenser chamber which is thermally connected to a second cold head, a temperature is simultaneously increased, wherein the temperature and/or temperature increase in the first condenser chamber is greater than in the second condenser chamber, as a result of which in the first condenser chamber more cooling fluid is evaporated than in the second condenser chamber and/or gas is more expanded and/or a pressure difference is created or increased between the pressure in the first and second condenser chamber, as a result of which liquid cooling fluid k is moved in a first connecting pipe between the first condenser chamber and an evaporator chamber, and gaseous cooling fluid k' is moved from the evaporator chamber into the second condenser chamber, in particular via a second connecting pipe.

Alternately, a method for cooling a superconducting machine, in particular using the thermosiphon effect, may comprise the steps that, in a first condenser chamber which is thermally connected to a first cold head, and that, in at least one second condenser chamber which is thermally connected to a second cold head, a temperature is simultaneously reduced, wherein the temperature in the first condenser chamber is lower than in the second condenser chamber, and/or the temperature reduction in the first condenser chamber is greater than in the second condenser chamber, as a result of which more cooling fluid is condensed in the first condenser chamber than in the second condenser chamber and/or gas is more compressed and/or a pressure difference between the

pressure in the first and second condenser chamber is created or increased, as a result of which liquid cooling fluid k is moved in a second connecting pipe between the second condenser chamber and an evaporator chamber, and gaseous cooling fluid k' is moved from the evaporator chamber into the first condenser chamber, in particular via a first connecting pipe.

In the two last mentioned methods, a temperature may be increased, maintained or reduced simultaneously, at least in one third condenser chamber which is thermally connected to a third cold head.

Directly or indirectly subsequent thereto, the temperature can be reduced in condenser chambers in which the temperature was increased, and/or directly or indirectly subsequent thereto, the temperature can be increased in condenser chambers in which the temperature was reduced. The advantages described above for methods with at least three condenser chambers, in which their roles are chronologically interchanged, likewise apply in this case.

The method can therefore be carried out as a continuous or pulsed process of pumping liquid cooling fluid into the evaporator chamber.

A temperature reduction may be effected by cooling with the help of at least one cold head. A temperature increase may be effected with the help of at least one cold head and/or by heating with the help of a heating device.

A movement of cooling fluid can be regulated or controlled only via differences in pressure and/or temperature in the condenser chambers and the evaporator chamber, particularly in

the case of pressure equalization by cooling fluid movement and/or in particular against the force of gravity. Valves or mechanical pumps no longer need to be used in order to move liquid cooling fluid in a connecting line into the evaporator chamber, even against the force of gravity. Problems with mechanical parts at cryotemperatures are thus avoided and maintenance time and costs are reduced.

In the evaporator chamber, the cooling fluid can pass from a liquid into a gaseous state and can cool a rotating superconducting device, in particular a superconducting winding of a rotor of a motor or generator, wherein the superconducting winding comprises in particular HTS material. The evaporator chamber may be rotatably arranged inside the rotor, in particular as a cylindrical cavity along the rotation axis of the rotor.

The at least two cold heads and the at least two condenser chambers and, in particular, the at least two connecting pipes, which - in particular - are contained by an encasing composite pipe, may be arranged in a stationary position. The encasing of the connecting pipes by a composite pipe enables the number of seals and bearings at the transition between fixed and rotating parts to be reduced.

The advantages associated with the apparatus for cooling a superconducting machine, and with the method for cooling a superconducting machine, may be applied to one another by analogy.

Preferred embodiments of the invention with advantageous developments according to the features of the dependent claims

are described in greater detail below on the basis of the figures, without being limited thereto.

In the figures,

Fig. 1 is a schematic sectional view showing a superconducting machine 2 with an apparatus for cooling according to the prior art, and

Fig. 2 is a simplified schematic illustration of an apparatus for cooling according to the invention.

In the figures, corresponding parts are labeled with the same reference characters.

Machines according to the figures each comprise a stator and rotor and an assigned refrigeration unit. The embodiment of the machine described below may be in particular a synchronous motor or a generator. The machine comprises a rotating, superconducting winding, which principally uses metallic LTS material (low T_c superconductor material) or oxidic HTS material (high T_c superconductor material). It is assumed that the latter material is used for the following exemplary embodiment. The winding may comprise one coil or a system of coils arranged with two poles, four poles, or any other number of poles. The basic structure of a corresponding synchronous machine is shown in Figure 1, as known from the prior art.

The machine labeled 2 comprises a stationary outer housing 3, which is at room temperature, with a stator winding 4. Within this outer housing and surrounded by the stator winding 4, a rotor 5 is mounted in bearings 6, such that it can rotate around a rotation axis A. These bearings may be conventional

mechanical bearings or even magnetic bearings. The rotor
further has a vacuum vessel 7, in which a winding mount 9 with
an HTS winding 10 is held on e.g. hollow, cylindrical, torque-
transmitting suspension elements 8. An axially extending
central cavity 12, which may for example be cylindrical in
shape, is provided concentrically with respect to the rotation
axis A in this winding mount. The winding mount is designed to
be vacuum-tight with respect to this cavity. It seals this
cavity on one side of the rotor, which is supported on this
side by means of a solid axial rotor shaft part 5a. On the
opposite side, the central cavity 12 is connected to a lateral
cavity 13 with a comparatively smaller diameter. This lateral
cavity leads to the exterior out of the area of the outer
housing 3 from the area of the winding mount. A tubular rotor
shaft part which surrounds this lateral cavity 13 and is
mounted in one of the bearings, is labeled 5b.

For indirect cooling of the HTS winding 10 via thermally
conductive parts, a refrigeration unit, of which only one cold
head 16 is illustrated, is provided. This refrigeration unit
may be a cryocooler of the Gifford-McMahon type, or, in
particular, a regenerative cryocooler such as e.g. a pulse
tube refrigerator or a split Stirling cooler. In this case,
the cold head 16 and thus all the main, further parts of the
refrigeration unit, are located outside the rotor 5 and/or its
outer housing 3.

The cold part of the cold head 16, which is arranged, by way
of example, at a distance of several meters from the side of
the rotor 5, makes good thermal contact, in a vacuum vessel 23
via a heat-conducting body 17, with a refrigerant condenser
unit which has a condenser chamber 18. This condenser chamber
is connected to a vacuum-insulated, fixed-position heat pipe

20, which projects into the lateral, rotating cavity 13 or the central cavity 12, laterally in an axial area. A sealing device 21, which is not shown in greater detail in the figure but has at least one sealing element, which may be designed as a ferro fluid seal and/or a labyrinth seal and/or a gap seal, is used to seal the heat pipe 20 from the lateral cavity 13. The central cavity 12 is connected via the heat pipe 20 and the lateral cavity 13 to the heat exchanging area of the condenser chamber 18 such that it is sealed in a gas-tight manner from the exterior. The tubular parts running between the central cavity 12 and the condenser chamber 18, which are used for holding a refrigerant, are generally labeled as pipe sections 22. These pipe sections, together with the condenser chamber 18 and the central cavity 12, are regarded as a pipe system.

These cavities of this pipe system are filled with a refrigerant, which is selected according to the desired operating temperature of the HTS winding 10. Thus, for example, helium (condensation temperature 4.2 K at normal pressure), hydrogen (condensation temperature 20.4 K at normal pressure), neon (condensation temperature 27.1 K at normal pressure), nitrogen (condensation temperature 77.4 K at normal pressure) or argon (condensation temperature 87.3 K at normal pressure) may be considered. Mixtures of these gases may also be used. The refrigerant is circulated using a so-called thermosiphon effect. To achieve this, the refrigerant is condensed on a cold surface of the cold head 16 in the area of the condenser chamber 18. The refrigerant thus liquefied, labeled k, flows through the pipe sections 22 into the central cavity 12. The transport of the condensate takes place in this case under the influence of gravity. For this purpose the heat pipe 20 may advantageously be slightly inclined (by a few

degrees) with respect to the rotation axis A toward the
earth's center, in order thus to support the flowing of the
liquid refrigerant k out of the open end 20a of the pipe 20.
The liquid refrigerant is then evaporated in the interior of
the rotor. The evaporated refrigerant is labeled k'. This
refrigerant evaporated by the absorption of heat then flows
through the interior of the pipe sections 22 back into the
condenser chamber 18. In this case the return flow is driven
by a slight overpressure in the cavity 12, acting as the
evaporator, toward the condenser chamber 18, which
overpressure is caused by the creation of gas in the
evaporator and the liquefaction in the condenser chamber.
Since the circulation of the liquefied refrigerant from the
condenser chamber 18 into the central cavity 12 and the return
flow of the evaporated refrigerant k' from this cavity back to
the condenser chamber takes place in the pipe system formed
from the condenser chamber 18, the pipe sections 22 and the
cavity 12, this can be defined as a one-pipe system with
circulation of the refrigerant k, k' using a thermosiphon
effect.

As further shown in Figure 1, an imbalance may occur if the
machine 2 is used on ships or offshore installations, wherein
the rotation axis A is inclined with respect to the horizontal
H by an angle δ of a few degrees. A condensation of the
refrigerant still takes place in the condenser chamber 18, but
the refrigerant can no longer reach the central cavity 12, so
that the pipe sections 20 then gradually fill up with liquid
refrigerant k. If the filling quantity of the pipe system with
refrigerant is relatively low, the interior rotor space and/or
the cavity 12 may run dry and thus are no longer cooled. Even
if the pipe system has a greater filling quantity, the flow of
liquid refrigerant k in the pipe sections 20 toward the

evaporator chamber 12 is blocked after a certain time. A
reliable cooling of the rotor or of its superconducting
winding is likewise no longer guaranteed in this case.

According to the prior art, provision may therefore be made in
this state for the gas pressure to be briefly increased on the
condenser side to such an extent that the liquid refrigerant
is thereby forced from the pipe sections 20, against the force
of gravity (if there is an inclination at the angle δ), into
the central cavity 12. Such a pressure increase is effected
according to the prior art with the help of a warm buffer
volume PV_W and a mechanical pump 28. With the help of these
resources the gas pressure in the condenser chamber 18 can be
temporarily increased, so that liquid refrigerant k located
there and in the pipe sections 20 is forced into the central
cavity 12. A control valve 29 is therefore disposed in a
connecting line 24 between the overpressured buffer volume PV_W
and the condenser chamber 18, and opens the connection to the
pump 28, which then transports the gas k' out of the buffer
volume into the condenser chamber. A valve 30 allows surplus
gas to flow back out of the condenser chamber 18.

A pressure oscillation to be thus generated may take place
continuously, i.e. at short, recurrent intervals (for a short
period of time in each case), or may be controlled by a
position sensor 26 of known design from a control unit 27.
This position sensor detects the imbalance with the angle of
inclination δ of the machine 2 and thus triggers the explained
initiation of a pressure volume (gas pulse) via the control
unit 27.

Further parts for the provision and removal of gas, such as,
for example, by a filling valve, from which the system is to

be filled with gaseous refrigerant via the connecting line 24,
are not shown in Figure 1, since these parts are generally
known. Only an overpressure valve 31, which responds to
unauthorized overpressures in the system, is indicated.

Of course, the parts or receptacles that enclose the
refrigerant k or k' must be protected against the introduction
of heat. A vacuum surround is therefore expediently provided
as thermal insulation, with, if necessary, the possibility of
additional insulation such as superinsulation or insulation
foam also being provided in the corresponding vacuum areas.
The vacuum which is enclosed by the vacuum vessel 7 is labeled
V in Figure 1. This also surrounds the pipe which encloses the
lateral cavity 13 and extends as far as the seal 21. The
vacuum which surrounds the heat pipe 20 as well as the
condenser chamber 18 and the heat-conducting body 17 is
labeled V'. If required, a negative pressure may also be
generated in the inner cavity 32 which surrounds the rotor and
is enclosed by the outer housing 2.

A disadvantage of a system of mechanical pumps 28 and valves
29, 30, 31 is that, in an arrangement of parts in a cryogenic
area, which arrangement is not illustrated here for the sake
of simplicity, these parts are highly susceptible to problems
at cryogenic temperatures and the design of moving parts for
use at these temperatures is complex and costly. Particularly
with regard to their use on ships, but also in other machine-
related uses, maintenance-free operation over long periods is
necessary. Mechanically moving parts must therefore be reduced
to a minimum, since these are usually liable to break down.

According to the invention, as shown in Fig. 2, a novel
cooling principle is used in a machine 2 described above. In

this case, parts such as pump 28 and valves 29, 30, 31 can be dispensed with, with all further parts of the machine being analogous to those of the machine described above in Fig. 1, except where otherwise mentioned hereinafter.

In contrast to the apparatus illustrated in Fig. 1, with a cold head 16 and a condenser chamber 18, the exemplary embodiment of the inventive apparatus for cooling a superconducting machine 2, illustrated in Fig. 2, has a first, second and third condenser chamber 18, 18', 18'', each with an assigned cold head 16, 16', 16''. Alternately, though not shown in the diagram for the sake of simplicity, two or more than three condenser chambers 18 with assigned cold heads 16 may also be present. Each condenser chamber 18, 18', 18'' is fluidically connected via a heat pipe 20, 20', 20'', which is also referred to hereinafter as a connecting line 20, 20', 20'', to the evaporator chamber 12, which is provided in Fig. 1 by the central cavity 12. The connecting lines 20, 20', 20'' are designed and arranged with an inclination and a V-shaped or U-shaped bend, i.e. they are angled slightly with reference to the horizontal H as shown in Fig. 1, with a lowermost point at which a fluid can gather under the force of gravity. The connecting lines 20, 20', 20'' may however have different forms; what matters is that fluid can collect in their interior similarly to a U-tube manometer.

The condenser chambers 18, 18', 18'', with the corresponding connecting lines 20, 20', 20'' and the evaporator chamber 12, form a closed system, i.e. an inner cavity that is fluid-tight from the exterior. The inner cavity is filled with a refrigerant k, k', which is hereinafter also called cooling fluid. The cooling fluid may be in a liquid k and/or gaseous

k' aggregate state, i.e. may be present as a liquid cooling fluid k and/or as a gaseous cooling fluid k'.

During operation of the machine, in which the superconducting winding 10 of the rotor 5 as already described above in Fig. 1 is cooled to or below a cryogenic temperature T_k, the evaporator chamber 12 is partially filled with liquid cooling fluid k. The cooling fluid k evaporates and thereby conducts heat away from the rotor 5 and/or cools the superconducting winding 10 of the rotor 5. Fig. 2 shows the inventive apparatus for cooling a superconducting machine 2 at a first point in time. At this point in time the gaseous, evaporated cooling fluid k' is transported from the evaporator chamber 12 via the connecting lines 20' and 20'' into the condenser chambers 18' and 18''. A temperature T_2 and T_3 in the condenser chambers 18' and 18'' is below the condensation temperature of the cooling fluid k, in each case with the help of the assigned cold heads 16' and 16'', whereby heat is removed from the gaseous cooling fluid k' and condensed into liquid cooling fluid k. The liquid cooling fluid k gathers in the connecting lines 20' and 20''.

In the first condenser chamber 18, starting from a temperature below the condensation temperature of the cooling fluid k, the temperature T_1 is increased with the help of the assigned cold head 16 and/or a heating device (not shown for the sake of simplicity), to a temperature T_1^* above the condensation temperature of the cooling fluid k. Liquid cooling fluid thereby evaporates and/or the gaseous cooling fluid k' expands in the first condenser chamber 18, i.e. the pressure p_1 in the first condenser chamber 18 is increased to a level which is higher than the pressures p_v in the evaporator chamber 12 and in the two further condenser chambers 18', 18'', p_2 and p_3.

Thus liquid cooling fluid k, which is located in the connecting line 20, is forced against the effect of gravity into the evaporator chamber 12, with a compressive force that exceeds the force of gravity of the cooling fluid k. Cooling fluid k is forced from the condenser chamber 18 and the connecting line 20 into the evaporator chamber 12.

This effect is additionally enhanced by a negative pressure p_1 and p_2 in the condenser chambers 18' and 18'', which is produced by the reduction in volume of the gaseous cooling fluid k' during cooling and condensation in the condenser chambers 18' and 18''. This negative pressure draws gaseous cooling fluid k' out of the evaporator chamber 12 into the connecting lines 20' and 20'' and thus reduces the pressure p_v in the evaporator chamber 12. The pressure difference $\Delta p(p_1 - p_v)$ between the first condenser chamber 18 and the evaporator chamber 12 is thereby increased and, in addition to the pressure equalization, moves liquid cooling fluid k from the connecting line 20 into the evaporator chamber 12.

The process described above ends, inter alia, when the liquid cooling fluid k has been completely - or, at least, almost completely - moved from the connecting line 20 into the evaporator chamber 12. In order to guarantee continuous cooling or a continuous, quasicontinuous or pulsed flow of liquid cooling fluid k into the evaporator chamber 12, the temperatures T_1, T_2, T_3 in the condenser chambers 18, 18', 18'' may be exchanged in a timely manner via the cold heads 16, 16', 16''. In this case the condenser chamber 18 may be cooled to a temperature below the condensation temperature of the cooling fluid via the cold head 16, whereby, for example, the condenser chambers 18 and 18'' have the same temperature. The condenser chamber 18' can be heated via the cold head 16' or a

heating device (not illustrated for the sake of simplicity) to a temperature which is above the condensation temperature of the cooling fluid. This has the effect that, at a second point in time described in this paragraph, the condenser chamber 18' functions in the same way the condenser chamber 18 at the first point in time, and, at the second point in time, the condenser chambers 18 and 18'' function in the same way as the condenser chambers 18' and 18'' at the first point in time. In the condenser chamber 18' the increase in temperature creates an overpressure and moves liquid cooling fluid k from the connecting line 20' into the evaporator chamber 12. Since the situation is analogous to the situation illustrated in Fig. 2, only with the roles exchanged (temperatures, pressures and fluid flows) between the condenser chambers 18, 18' and 18'', the situation with regard to the process at the second point in time is not illustrated in the figure for the sake of simplicity.

At a third point in time, the action of the condenser chambers 18, 18', 18'' can be likewise exchanged, wherein the condenser chamber 18'' may be brought to a temperature above the evaporation temperature of the cooling fluid k with the help of the cold head 16''. In this case the condenser chambers 18 and 18' may, for example, have the same temperature, a temperature below the condensation temperature of the cooling fluid k'. The condenser chamber 18'' may be heated via the cold head 16'' or a heating device (not shown for the sake of simplicity) to a temperature, which is above the condensation temperature of the cooling fluid. This has the effect that, at the third point in time, the condenser chamber 18'' functions in the same way as the condenser chamber 18 at the first point in time, and, at the third point in time, the condenser chambers 18 and 18' function in the same way as the condenser

chambers 18' and 18'' at the first point in time. In the condenser chamber 18'', the increase in temperature creates an overpressure and moves liquid cooling fluid k from the connecting line 20'' into the evaporator chamber 12. Since the situation is analogous to the one illustrated in Fig. 2, only with the roles exchanged (temperatures, pressures and fluid flows) between the condenser chambers 18, 18' and 18'', the situation with regard to the process at the third point in time is likewise not shown in the figure for the sake of simplicity.

At a fourth point in time, the status of the first point in time may be reestablished. By regular exchanging of the actions of the condenser chambers 18, 18', 18'' after a fixed period of time or after different times, a continuous, quasicontinous or pulsed operation of the apparatus for cooling a superconducting machine 2 can be guaranteed.

Any other sequences for exchanging the action of the condenser chambers 18, 18', 18'' are possible, wherein the basic principle remains the same. A reliable cooling operation may thus be guaranteed, even if the machine 2 is tilted e.g. if used in a ship.

CLAIMS

1.   A method for cooling a superconducting machine using the thermosiphon effect, comprising the steps:

A) that a temperature is increased in a first condenser chamber, which is thermally connected to a first cold head, wherein cooling fluid is evaporated or gas in the condenser chamber expands or the pressure in the condenser chamber is increased, and liquid cooling fluid is moved in a first connecting pipe between the first condenser chamber and an evaporator chamber into the evaporator chamber by the temperature increase, evaporation or gas expansion;

B) that a temperature is constantly maintained or lowered simultaneously in at least one second condenser chamber, which is thermally connected to a second cold head, in particular a lower temperature than in the first condenser chamber, as a result of which gaseous cooling fluid is moved from the evaporator chamber into the second condenser chamber via a second connecting pipe, as a result of the temperature increase in the first condenser chamber or by the lowering of the temperature in the second condenser chamber;

C) that a constant temperature is maintained in a first condenser chamber, which is thermally connected to a first cold head and which is fluidically connected to an evaporator chamber via a first connecting pipe;

D) that a temperature is lowered simultaneously in at least one second condenser chamber, which is thermally connected to a second cold head, whereby gaseous cooling fluid is moved from the evaporator chamber into the second condenser chamber via a second connecting pipe, between the evaporator chamber and the second condenser chamber, as a result of the temperature reduction, a condensation of cooling fluid or a compression of gas in the second condenser chamber; and

E) whereby liquid cooling fluid is moved into the evaporator chamber in the first connecting pipe between the first condenser chamber and the evaporator chamber as a result of the temperature reduction, a

condensation of cooling fluid or a compression of gas in the at least second condenser chamber.

2.   The method as claimed in claim 1, wherein a temperature is constantly maintained or lowered simultaneously at least in one third condenser chamber, which is thermally connected to the third cold head.

3.   The method as claimed in claim 2, wherein, directly or indirectly subsequent to steps A) and B) or C) to E), in the at least one condenser chamber, in which the temperature at the time of steps A) and B) or C) to E) was increased or maintained at a constant level, the temperature is lowered or kept at a constant level and that, in the at least one second, in particular the second and third condenser chamber, in which the temperature at the time of steps A) and B) or C) to E) was maintained at a constant level or was lowered, the temperature is increased or maintained at a constant level.

4.   A method as claimed in any one of claims 1 to 3 for cooling a superconducting machine using the thermosiphon effect, comprising the steps that, in a first condenser chamber, which is thermally connected to a first cold head, and in at least one second condenser chamber, which is thermally connected to a second cold head, a temperature is simultaneously increased, wherein the temperature or temperature increase in the first condenser chamber is greater than in the second condenser chamber, as a result of which in the first condenser chamber more cooling fluid is evaporated than in the second condenser chamber or gas is more expanded or a pressure difference is created or increased between the pressure in the first and second condenser chamber, as a result of which liquid cooling fluid is moved in a first connecting pipe between the first condenser chamber and an evaporator chamber, and gaseous cooling fluid is moved from the evaporator chamber into the second condenser chamber via a second connecting pipe.

5.   A method as claimed in any one of claims 1 to 4 for cooling a superconducting machine using the thermosiphon effect, comprising the steps that, in a first condenser chamber which is thermally connected

to a first cold head, and in at least one second condenser chamber, which is thermally connected to a second cold head, a temperature is simultaneously lowered, wherein the temperature in the first condenser chamber is lower than in the second condenser chamber or the temperature reduction in the first condenser chamber is greater than in the second condenser chamber, as a result of which more cooling fluid is condensed in the first condenser chamber than in the second condenser chamber, or gas is more compressed or a pressure difference is created or increased between the pressure in the first and second condenser chamber, as a result of which liquid cooling fluid is moved in a second connecting pipe between the second condenser chamber and an evaporator chamber, and gaseous cooling fluid is moved from the evaporator chamber into the first condenser chamber via a first connecting pipe.

6.   The method as claimed in one of claims 4 or 5, wherein a temperature is increased, maintained or lowered simultaneously at least in one third condenser chamber, which is thermally connected to the third cold head.

7.   The method as claimed in claim 6, wherein directly or indirectly subsequent thereto, the temperature is reduced in condenser chambers in which the temperature was increased, or wherein, directly or indirectly subsequent thereto, the temperature is increased in condenser chambers in which the temperature was reduced.

8.   The method as claimed in any one of claims 1 to 7, wherein the method is carried out as a continuous or pulsed process of pumping liquid cooling fluid into the evaporator chamber.

9.   The method as claimed in any one of claims 1 to 8, wherein a temperature reduction is effected by cooling with the help of at least one cold head or a temperature increase is effected with the help of at least one cold head by heating with the help of a heating device.

10.   The method as claimed in any one of claims 1 to 9, wherein a movement of cooling fluid is regulated or controlled only via differences in pressure or temperature in the condenser chambers and

the evaporator chamber, particularly in the case of pressure equalization by cooling fluid movement or in particular against the force of gravity.

11.   The method as claimed in one of claims 1 to 10, wherein, in the evaporator chamber, the cooling fluid can pass from a liquid into a gaseous state, and cools a rotating superconducting device, in particular a superconducting winding of a rotor of a motor or generator, wherein the superconducting winding comprises in particular HTS material and wherein the evaporator chamber may be rotatably arranged inside the rotor, in particular as a cylindrical cavity along the rotation axis (A) of the rotor.

12.   The method as claimed in one of claims 1 to 11, wherein the at least two cold heads and the at least two condenser chambers and the at least two connecting pipes, which are contained by a composite pipe that encases the connecting pipes, are arranged in a stationary position.

13.   A method, substantially as hereinbefore described with reference to the accompanying Figure 2.

<div align="center">

Siemens Aktiengesellschaft

Patent Attorneys for the Applicant/Nominated Person
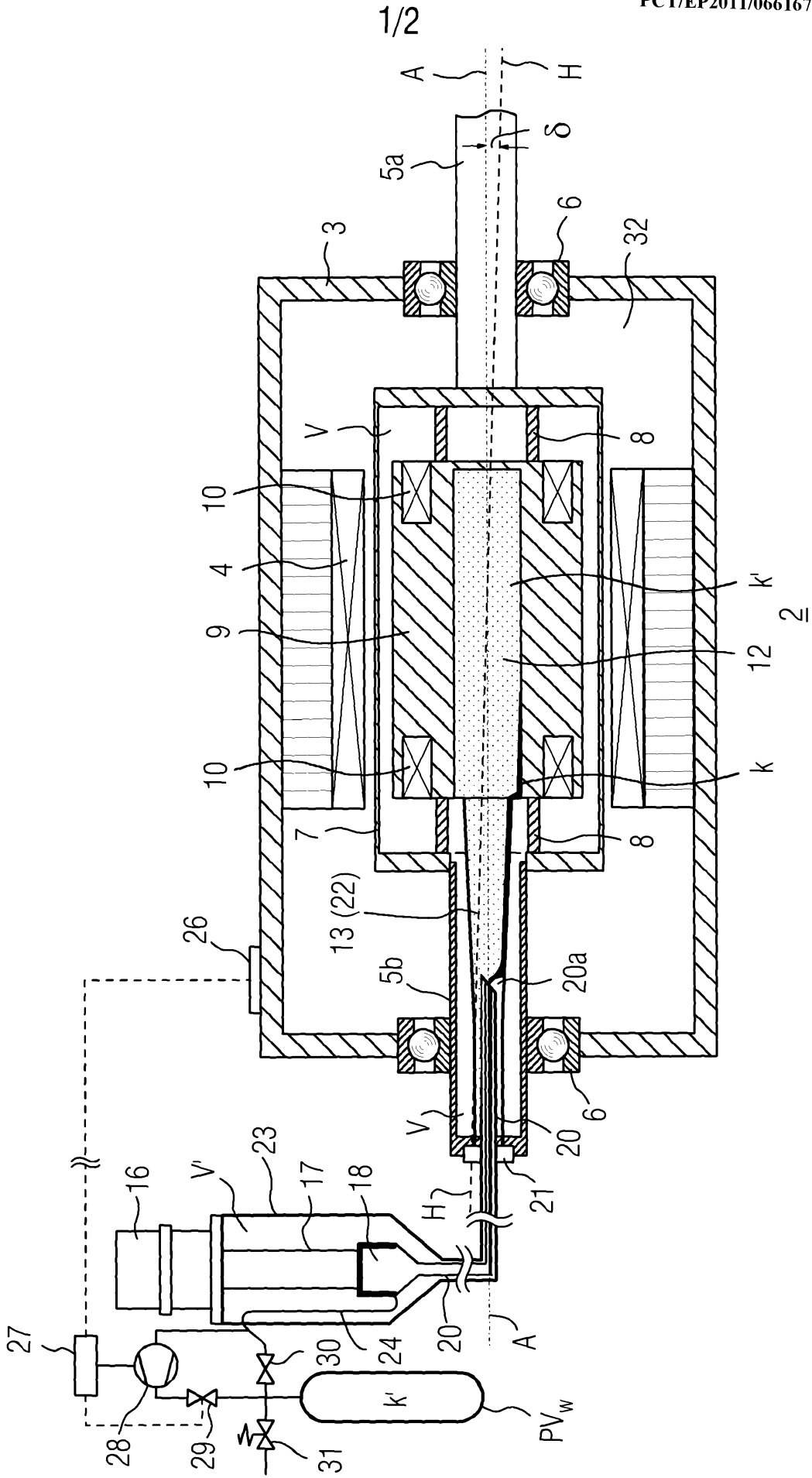
SPRUSON & FERGUSON

</div>

FIG 1

FIG 2