METHOD FOR COOLING A LIQUEFIED GAS

Technical field

The invention pertains to the field of cooling of gases stored in a liquefied form, in particular it concerns the cooling of a fuel gas such as liquefied natural gas (LNG).

Technological background

Liquefied natural gas is stored in sealed and thermally insulated vessels at cryogenic temperatures. Such vessels may be part of a land-based storage installation or be installed in a floating structure, such as an LNG carrier, for example.

The thermally insulating barriers of the storage vessels of liquefied natural gas are inevitably the site of a thermal flux tending to reheat the contents of the vessel. This reheating translates into an increase in the enthalpy of the contents of the vessel and, consequently, the distancing of some or all of the cargo from its equilibrium conditions at near-atmospheric pressure. This increase in enthalpy is thus liable to result in an evaporation of the liquefied natural gas and a loss of natural gas stored in liquid form.

In order to limit the increase in enthalpy of the liquefied natural gas, the thermal insulation of the vessels is routinely improved. However, even though the thermal insulation capabilities of the vessels show an improving trend, the rate of reheating of the liquefied natural gas remains significant.

It is of course known in the prior art how to utilize the gas resulting from the natural evaporation to power equipment using natural gas as a fuel. Thus, aboard an LNG carrier for example, the evaporated gas is used to power the propulsion engine group, making it possible to propel the ship, or electrical generator assemblies furnishing the electricity necessary for the functioning of the equipment on board. However, while such a method is able to valorize the gas evaporated in the vessel, it does not enable a control of the rate of evaporation of the liquefied gas or a preservation of the gas in a thermodynamic state allowing it to be stored in a durable manner. Furthermore, while it is known how to use a system of liquefaction to reliquefy the excess evaporated gas, the efficiency of such a liquefaction system is low.

Summary

One idea on which the invention is based is to propose a method for cooling of a liquefied gas and an installation for storage and cooling of a liquefied gas enabling a better control of the natural evaporation of the liquefied gas while preserving a major fraction of liquefied gas in a thermodynamic state allowing it to be stored in a durable manner.

According to one embodiment, the invention provides a method for cooling of a liquefied gas stored in the inner space of a sealed and thermally insulated vessel; said liquefied gas being stored

in the inner space of the vessel in a state of two-phase liquid-vapor equilibrium and having a lower liquid phase and an upper vapor phase separated by an interface, said method involving the steps of:

- drawing a stream of gas in vapor phase into a zone of the vapor phase in contact with a zone of the interface; said step of drawing a stream of gas in vapor phase generating in said zone of the vapor phase a pressure P1 of less than the atmospheric pressure such that vaporization of the liquid phase is promoted in the area of the zone of the interface and the liquefied gas in contact with the zone of the interface is placed in a state of two-phase liquid-vapor equilibrium in which the liquefied gas has a temperature less than the liquid-vapor equilibrium temperature of said liquefied gas at atmospheric pressure; and
- guiding the drawn stream of gas in vapor phase toward a circuit for use of gas in vapor phase.

Thus, such a method allows taking full advantage of the vaporization of the gas intended to power equipment consuming gas in the vapor phase to cool the liquefied gas stored in the vessel by removing the latent heat of vaporization from it.

Moreover, by placing the inner space of the vessel at an absolute pressure lower than the atmospheric pressure, the liquefied gas stored in the vessel can be cooled to a temperature below its equilibrium vaporization temperature at atmospheric pressure. Hence, the liquefied gas can be maintained in an undercooled thermodynamic state, enabling its storage or its transfer to a vessel at atmospheric pressure while maintaining a low rate of evaporation of the liquefied gas, or even a zero rate. Thus, such a method allows a better control of the vaporization of the liquefied natural gas. One thus generates a reduction in the loss of cargo, and therefore an increase in the financial valorization of the cargo.

Moreover, thanks to such a method, the vaporization of the liquefied gas intended to power the equipment consuming gas in the vapor phase can be realized without the aid of an outside heat source, unlike the forced vaporization installations using a heat exchange with sea water, an intermediate liquid, or combustion gases coming from the engine system or specific burners. However, in certain embodiments, such an outside heat source may likewise be provided in supplemental fashion.

According to other advantageous embodiments, such a method for cooling may have one or more of the following characteristics:

- the pressure P1 is greater than 120 mbars absolute. It is in fact essential for the pressure inside the vessel to be greater than the pressure corresponding to the triple point of the methane phase diagram in order to prevent a solidification of the natural gas inside the vessel.
- the pressure P1 may in particular be between 750 mbars and 980 mbars absolute.
- the drawing of the stream of gas in vapor phase is achieved by means of a vacuum pump.

- according to one embodiment, the vacuum pump is controlled as a function of a flow rate setpoint generated by the circuit for use of gas in vapor phase.

- according to another embodiment, the pressure is measured in the zone of the vapor phase and the vacuum pump is controlled as a function of a pressure setpoint and the measured pressure.

- according to one embodiment, the vessel comprises a multilayered structure mounted on a carrier structure, the multilayered structure comprising a sealing membrane in contact with the liquefied gas contained in the vessel and a thermally insulating barrier disposed between the sealing membrane and the carrier structure, said thermally insulating barrier comprising insulating blocks and a gas phase, the method involving the step of maintaining the gas phase of the thermally insulating barrier at a pressure P2 less than or equal to the pressure P1.

- according to one embodiment, the multilayered structure comprises, from the outside to the inside of the vessel, a secondary thermally insulating barrier comprising insulating blocks resting against a carrier structure and a gas phase, a secondary sealing membrane resting against the insulating blocks of the secondary thermally insulating barrier, a primary thermally insulating barrier comprising insulating elements resting against the secondary sealing membrane and a gas phase and a primary sealing membrane designed to be in contact with the liquefied gas contained in the vessel, the method involving the step of maintaining the gas phase of the primary thermally insulating barrier and the gas phase of the secondary thermally insulating barrier respectively at a pressure P2 and at a pressure P3, said pressures P2 and P3 being less than or equal to the pressure P1. The pressure P1 being less than the atmospheric pressure, the pressures P2 and P3 are thus also less than the atmospheric pressure.

- advantageously, for the aforementioned embodiment, the pressure P3 is greater than or equal to the pressure P2. Thus, in the event of gas leaks and gas invasion of the primary thermally insulating barrier, one avoids drawing gas from within the secondary thermally insulating barrier. Thus, a slight overpressure of the secondary thermally insulating barrier with respect to the primary thermally insulating barrier may even be beneficial. In this case, the pressure differential between the pressures P2 and P3 is less than 100 mbars and preferably between 10 and 50 mbars.

- the vessel is filled with a liquefied fuel gas chosen from among liquefied natural gas, ethane and liquefied petroleum gas.

- the circuit for use of gas in the vapor phase comprises energy production equipment.

- according to one embodiment, the vessel is equipped with a vacuum bell jar lodged in the inner space of the vessel and comprising an upper portion disposed in the vapor phase and a lower portion immersed in the liquid phase and in which the zone of the vapor phase into which the stream of gas is drawn in the vapor phase is defined by the upper portion of the vacuum bell jar.

- according to another embodiment, the pressure P1 is generated in an upper portion of the vessel containing the entire vapor phase.

According to one embodiment, the invention provides an installation for storage and cooling of a liquefied gas, comprising:

- a sealed and thermally insulated vessel having an inner space designed to be filled with a liquefied gas stored in a state of two-phase liquid-vapor equilibrium such that the liquefied gas has a lower liquid phase and an upper vapor phase separated by an interface ; and
- a circuit for removal of gas in the vapor phase comprising:
  - an intake emerging into the inner space of the vessel above a maximum fill height of the vessel so that when the vessel is full it empties into a zone of the vapor phase in contact with a zone of the interface; and
  - a vacuum pump able to draw a stream of gas in vapor phase present in the zone of the vapor phase through the intake, to pump this to a circuit for use of gas in the vapor phase, and to maintain in the zone of the vapor phase a pressure P1 less than the atmospheric pressure, such that vaporization of the liquid phase is promoted in the area of the interface zone and the liquefied gas in contact with the zone of the interface is placed in a state of two-phase liquid-vapor equilibrium in which the liquefied gas has a temperature less than the liquid-vapor equilibrium temperature of said liquefied gas at atmospheric pressure.

According to other advantageous embodiments, such an installation may have one or more of the following characteristics:

- the installation comprises a sensor to measure the flow rate, able to provide a signal representative of the flow rate of vapor drawn in through the intake and pumped to the circuit for use and a control device able to control the vacuum pump as a function of the signal representative of the flow rate of vapor and a flow rate setpoint generated by the circuit for use of gas in the vapor phase.
- the installation comprises a pressure sensor able to provide a signal representative of the pressure prevailing in the inner space of the vessel above the maximum fill height and a control device able to control the vacuum pump as a function of the signal representative of the pressure and a pressure setpoint.
- the installation furthermore comprises a circuit for use of gas in the vapor phase comprising energy production equipment.
- the vessel comprises a multilayered structure mounted on a carrier structure, the multilayered structure comprising a sealing membrane in contact with the liquefied gas contained in the vessel and a thermally insulating barrier disposed between the sealing membrane and the carrier structure, and comprising insulating blocks and a gas phase, the installation furthermore

comprising a vacuum pump designed to maintain the gas phase of the thermally insulating barrier at a pressure P2 less than or equal to the pressure P1.

- the multilayered structure comprises, from the outside to the inside of the vessel, a secondary thermally insulating barrier comprising insulating blocks resting against a carrier structure and a gas phase, a secondary sealing membrane resting against the insulating blocks of the secondary thermally insulating barrier, a primary thermally insulating barrier comprising insulating elements resting against the secondary sealing membrane and a gas phase and a primary sealing membrane designed to be in contact with the liquefied gas contained in the vessel, the installation furthermore comprising a first vacuum pump designed to maintain the gas phase of the primary thermally insulating barrier at a pressure P2 less than or equal to the pressure P1 and a second vacuum pump designed to maintain the gas phase of the secondary thermally insulating barrier at a pressure P3 less than or equal to the pressure P1.

- the vessel is equipped with a vacuum bell jar lodged in the inner space of the vessel and comprising an upper portion designed to be placed in contact with the vapor phase of the liquefied gas stored in the inner space of the vessel and a lower portion designed to be immersed in the liquid phase of the liquefied gas stored in the inner space of the vessel and in which the intake of the circuit for removal of gas in vapor phase empties into the interior of the upper portion of the vacuum bell jar.

- the vacuum bell jar is made of metal.

- the vacuum bell jar comprises a horizontal section between 1/5 and 1/100 of the horizontal section of the vessel, for example of the order of 1/10.

- according to one embodiment, the vacuum bell jar comprises hollow tubes passing through it transversely from one side to the other.

- the installation comprises a pressure sensor able to provide a signal representative of the pressure prevailing in the upper portion of the vacuum bell jar.

According to one embodiment, the invention concerns a ship or off-shore liquefaction equipment, such as a liquefaction barge, comprising an aforementioned installation for the storage and cooling of a liquefied gas.

According to one embodiment, the ship comprises a shell and the sealed and thermally insulated vessel of the installation is disposed in said shell.

According to one embodiment, the circuit for use of the gas in the vapor phase is energy production equipment, such as equipment for the propulsion of the ship.

According to one embodiment, the invention also provides a method for loading or unloading of such a ship, in which a fluid is routed through insulated conduits from or to a floating or land-based storage installation to or from the vessel of the ship.

Brief description of the figures

The invention will be better understood, and its further purposes, details, characteristics and advantages will appear more clearly in the course of the following description of several particular embodiments of the invention, given solely for purposes of illustration and not limitation, making reference to the enclosed drawings.

- **Figure 1** illustrates schematically an installation for storage and cooling of a liquefied gas.

- **Figure 2** is an equilibrium liquid-vapor diagram for methane.

- **Figure 3** is a schematic representation of the installation for storage and cooling of a liquefied gas.

- **Figure 4** is a schematic cutaway representation of an LNG carrier equipped with a vessel and a terminal for loading/unloading of this vessel.

- **Figure 5** illustrates schematically an installation for storage and cooling of a liquefied gas according to a second embodiment.

Detailed description of embodiments

In the description and the claims, the term "gas" is generic in nature and pertains indiscriminately to a gas comprised of a single pure substance or a gas mixture composed of a plurality of components. A liquefied gas thus denotes a chemical substance or a mixture of chemical substances which has been placed in a liquid phase at low temperature and which would be present in a vapor phase under normal conditions of temperature and pressure.

In figure 1, an installation 1 for storage and cooling of a liquefied gas according to a first embodiment is represented. Such an installation 1 may be installed on land or on a floating structure such as a liquefaction or regasification barge. In the case of a structure on land, the installation may be designed for a storage unit associated with one or more consumers of gas in the vapor state, such as electricity generators, steam generators, burners or any other element consuming gas in the vapor state, whether attached to the storage unit or in a distribution network for gas in the vapor phase supplied by the storage unit.

In the case of a floating structure, the installation may be designed for a transport ship of liquefied natural gas, such as an LNG carrier, but it may also be designed for any ship whose engine propulsion assembly, electricity generators, steam generators or any other consumers are supplied

with gas. As an example, it may be a freight transport ship, a passenger transport ship, a fishing boat, a floating electricity production unit or other kinds.

The installation 1 comprises a sealed and thermally insulated vessel 2.

In the embodiment represented in figure 1, the vessel 2 is a membrane type vessel. Such a membrane vessel may comprise in particular a multilayered structure comprising, from the outside to the inside of the vessel 2, a secondary thermally insulating barrier 3 comprising insulating elements resting against a carrier structure 4, a secondary sealing membrane 5 resting against the secondary thermally insulating barrier 3, a primary thermally insulating barrier 6 comprising insulating elements resting against the secondary sealing membrane 5 and a primary sealing membrane 7 designed to be in contact with the liquefied gas 8 contained in the vessel. As an example, such membrane vessels 2 are described in the patent applications WO14057221, FR2691520 and FR2877638.

According to other alternative embodiments, the vessel 1 may also be a vessel of type A, B or C. Such a vessel is self-supporting and may in particular have a parallelepiped, prismatic, spherical, cylindrical or multilobed shape. The vessels of type C have the peculiarity of allowing a storage of the liquefied natural gas at pressures significantly higher than the atmospheric pressure.

The liquefied gas 8 is a fuel gas. In particular, the liquefied gas 8 may be a liquefied natural gas (LNG), that is, a gaseous mixture comprising mainly methane, as well as one or more other hydrocarbons such as ethane, propane, n-butane, i-butane, n-pentane, i-pentane, neopentane, and nitrogen in slight proportion.

The fuel gas may likewise be ethane or a liquefied petroleum gas (LPG), that is, a mixture of hydrocarbons resulting from the refining of petroleum and comprising substantially propane and butane.

The liquefied gas 8 is stored in the inner space of the vessel in a state of two-phase liquid-vapor equilibrium. Thus, the gas is present in the vapor phase in the upper portion of the vessel and in the liquid phase in the lower portion of the vessel. The temperature of equilibrium of the liquefied natural gas corresponding to its state of two-phase liquid-vapor equilibrium is around -162° C when it is stored at atmospheric pressure.

The installation 1 comprises a circuit for removal of gas in the vapor phase 9. The circuit for removal of gas in the vapor phase 9 comprises a conduit 10 passing through a wall of the vessel 2 in order to define a passage for evacuation of the vapor phase, from the interior to the exterior of the vessel 2. The conduit 10 comprises an intake 11 emerging into the interior of the inner space of the vessel 2. The intake 11 emerges into an upper portion of the inner space of the vessel 2. The intake 11 may in particular emerge above the maximum fill limit of the vessel so as to emerge in the gas phase.

The removal circuit 9 also comprises a vacuum pump 12 which is connected, upstream, to the conduit 10, and downstream to a circuit for use of gas in the vapor phase 13. The vacuum pump 12

is thus able to draw in, through the conduit 10, a stream of gas in the vapor phase which is present in the inner space of the vessel 2 and to pump it toward the circuit for use of gas in the vapor phase 13. In the embodiment represented, the removal circuit 9 comprises a check valve 19 or gate, situated upstream or downstream from the vacuum pump 12 and thus avoiding a return of the stream of gas in the vapor phase to the inner space of the vessel 2.

The vacuum pump 12 is able to generate, in the vapor phase disposed in the upper portion of the inner space of the vessel 2, a pressure P1 less than the atmospheric pressure. Thus, when the vacuum pump 12 is placed in operation and draws in a stream of gas in the vapor phase from the interior of the inner space of the vessel 2 and pumps it toward the circuit for use of gas in the vapor phase 13, the vacuum pump 12 also generates a pressure P1 less than the atmospheric pressure in the vapor phase of the inner space of the vessel.

Hence, the vapor phase having been placed at a pressure P1 less than the atmospheric pressure, the vaporization of the liquefied gas 8 present in the vessel 2 is promoted at the liquid/vapor interface, while the liquefied gas 8 stored in the vessel 2 is placed in a state of two-phase liquid-vapor equilibrium in which the liquefied gas has a temperature less than the liquid-vapor equilibrium temperature of said liquefied gas at atmospheric pressure.

These phenomena are explained below in connection with figure 3, which represents a liquid-vapor equilibrium diagram for methane. This diagram represents a region, denoted L, in which the methane is present in the liquid phase, and a region, denoted V, in which the methane is present in the vapor phase, as a function of the temperature represented along the ordinate axis and the pressure along the abscissa axis.

The point P_{t1} represents a state of two-phase equilibrium corresponding to the state of the methane stored in a vessel at the atmospheric pressure and at a temperature of around -162° C. When the storage pressure of the methane in the vessel has fallen below the atmospheric pressure, for example, to an absolute pressure of around 500 mbars, the equilibrium of the methane is shifted to the left, up to the point P_{t2}. Once at equilibrium, the methane so expanded thus undergoes a decrease in temperature of around 7° C, while a portion of the methane in liquid phase evaporates, subtracting from the liquid methane stored in the vessel the heat needed for its vaporization. Hence, by placing a liquefied gas at an absolute pressure less than the atmospheric pressure, the liquefied gas is maintained in a thermodynamically undercooled state, such that a return to a storage in the vessel at atmospheric pressure or its further transfer to a vessel at atmospheric pressure may be done by maintaining a low rate of evaporation of the liquefied gas, even a zero rate, thus preventing or reducing phenomena of flash vaporization at the start of the transfer.

The vacuum pump 12 is a cryogenic pump, that is, a pump able to sustain cryogenic temperatures less than -150° C. It should further comply with the standard ATEX, that is, be designed to prevent any risk of explosion.

Figure 3 shows schematically the installation 1 to illustrate the fact that the removal circuit 9 and the vacuum pump 12 make it possible to provide both a refrigeration capacity P to the liquefied gas contained in the vessel 2 and a flow rate of gas in vapor phase Q to the circuit for use 13.

In certain applications, the demand for gas in vapor phase required in the circuit for use 13 might be the primary criterion for the dimensioning and control of the vacuum pump 12. In this case, the vacuum pump 12 is controlled as a function of a flow rate setpoint generated by the circuit for use of the gas in the vapor phase 12. To accomplish this, the installation 1 is equipped with a flow rate measuring sensor able to provide a signal representative of the flow rate of vapor pumped by the vacuum pump 12 and a control device 18 able to control the vacuum pump 12 such that the measured value of flow rate is dependent on the flow rate setpoint. In this embodiment, the pressure prevailing inside the vessel thus evolves as a function of time and of the flow rate setpoint generated by the circuit for use 13.

Furthermore, for these embodiments, the vacuum pump 12 is dimensioned so as to generate a sufficient flow rate to supply the circuit for use 13. As an illustration, the mean power of the main motor in ocean-going ships is typically of the order of several MW to several dozen MW. If the flow rate of gas in the vapor phase Q pumped by the vacuum pump 12 is unable to produce a refrigeration capacity corresponding to the entire need in the storage vessel, it is possible to provide an auxiliary cooling device, not represented, to provide an auxiliary refrigeration capacity P_{aux} for the liquefied gas contained in the vessel 2.

In other applications, the refrigeration capacity needed to maintain the gas contained in the vessel at a target temperature below its temperature of vaporization at atmospheric pressure might be the criterion for dimensioning and control of the vacuum pump 12, especially if the need for gas in the vapor phase of the circuit for use 8 is high and if one does not wish to cool in an excessive manner the gas in the liquid phase contained in the receptacle. In this case, the vacuum pump is controlled as a function of a setpoint of the pressure prevailing in the inner space of the vessel. To accomplish this, the installation 1 is equipped with a pressure sensor designed to measure the pressure in the inner space of the vessel and a control device 18 able to control the vacuum pump 12 so that the value of the pressure measured is dependent on the pressure setpoint. In this embodiment, after a transitory period of pressure drop during which the temperature and the pressure of the liquefied natural gas decrease, a steady state is achieved corresponding to a target pair of pressure and temperature. The absolute setpoint pressure is greater than 120 mbars and for example lies between 750 mbars and 980 mbars.

For these embodiments, the vacuum pump 12 is dimensioned so as to generate a vacuum in the inner space of the vessel corresponding to the target pressure. Furthermore, if the steady state is unable to produce the flow rate of gas in the vapor phase corresponding to the entire need in the circuit for use 13, it is possible to provide an auxiliary vaporization device, not represented, to provide an auxiliary flow rate of vapor Q_{aux} to the circuit for use 13.

Thus, from the foregoing it will be understood that the vacuum pump needs to have a flow rate/pressure characteristic adapted to the need of the circuit for use of gas in the vapor phase 13 and to the necessary refrigeration capacity.

In the case of an installation 1 aboard a ship, the circuit for use 13 may comprise in particular energy production equipment of the engine propulsion assembly, not represented, enabling the propulsion of the ship. Such energy production equipment is chosen in particular among thermal engines, fuel cells, and gas turbines. When the energy production equipment is a thermal engine, the engine may have mixed diesel/natural gas feed. Such engines can operate either in diesel mode in which the engine is fed diesel entirely or in natural gas mode in which the fuel of the engine consists primarily of natural gas, while a small amount of pilot diesel is injected to initiate the combustion.

Moreover, according to one embodiment, the circuit for use 13 further comprises a heat exchanger, not illustrated, allowing for further heating of the stream of gas in the vapor phase up to temperatures compatible with the operation of the gas consuming equipment. The supplemental heat exchanger may in particular ensure a thermal contact between the stream of gas in the vapor phase and the sea water, between the stream of gas in the vapor phase and the combustion gases generated by energy production equipment or by the engine directly, or between the stream of gas in the vapor phase and air used as oxidizer by the engine in order to boost its efficiency. According to one embodiment, the circuit for use 13 may likewise comprise a compressor enabling the heating of the stream of gas in the vapor phase and its compressing to pressures compatible with the specifications of the energy production equipment being fed with fuel gas, for example, of the order of 5 to 6 bars absolute.

It is noted that when the liquefied gas is a gas mixture composed of a plurality of components, the vapor phase resulting from evaporation inside the vessel has a composition which is richer in the most volatile components, such as nitrogen, than does the liquid phase. Thus, the stream of gas removed by the circuit for removal of gas in the vapor phase 9 may have significant contents of the most volatile components and consequently be incompatible with the feeding of energy production equipment. Hence, according to one embodiment not illustrated, the installation 1 likewise comprises a forced vaporization device which removes a stream of liquefied gas in the liquid phase from the inner space of the vessel 2 and vaporizes it with the aid of a heat exchanger. Such a stream of gas has a composition substantially identical to that of the liquefied gas contained in the inner space of the vessel. Hence, the stream of gas in the vapor phase obtained in this way may be mixed in with the stream of gas removed via the removal circuit 9 in order to achieve contents of the most volatile components compatible with the feeding of the energy production equipment.

Returning to figure 1, one notices that the installation 1 comprises, in the embodiment represented, a vacuum pump 16 which is connected to a pipeline 17 emerging into the internal space of the primary thermally insulating barrier 6 so as to enable a maintaining of the gas phase of the

primary thermally insulating barrier 6 below a pressure P2 which is less than the atmospheric pressure.

Likewise, the installation comprises a vacuum pump 14 which is connected to a pipeline 15 emerging into the internal space of the secondary thermally insulating barrier 3 and is thus able to maintain the gas phase of the secondary thermally insulating barrier 3 below an absolute pressure P3 which is less than the atmospheric pressure.

The maintaining of the thermally insulating barriers below pressures P2 and P3 which are less than the atmospheric pressure is particularly advantageous. In fact, this allows, on the one hand, a boosting of the insulating capacity of those thermally insulating barriers. On the other hand, this also ensures that the pressure prevailing in the thermally insulating barriers 3, 6 is not much greater than the pressure prevailing in the inner space of the vessel 2, which would be liable to damage the sealing membranes 7, 5 and especially the primary sealing membrane 7, causing it to tear off.

Also advantageously the vacuum pumps 14, 16 are controlled such that the pressure P2 of the gas phase of the primary thermally insulating barrier 6 and the pressure P3 of the gas phase of the secondary thermally insulating barrier 3 are less than or equal to the pressure P1 prevailing in the internal space of the vessel.

According to one particular embodiment, it may be provided that the pressure P3 is greater than or equal to the pressure P2 which makes it possible to prevent liquefied gas from being drawn into the secondary thermally insulating barrier in the event of a failure in the tightness of the sealing membranes. Advantageously, the pressure differential between the pressures P2 and P3 is less than 100 mbars and is preferably between 10 and 50 mbars.

Moreover, in one embodiment not represented, the installation 1 comprises an agitation device able to create a current inside the internal space of the vessel 2. Such an agitation device is meant to limit the thermal stratification inside the vessel 2 and thus allow a homogenization of the temperature of the liquefied gas and thus optimize the efficiency of the method. The agitation device may comprise in particular a recirculation loop for the liquefied gas. To accomplish this, the agitation device comprises one or more pumps, such as a drain pump for the vessel, associated with a drainage line able to be placed in communication with a vessel charging line so as to create a circulation loop of the liquefied gas.

In the embodiment represented in figure 4, the installation 1 comprises in addition a vacuum bell jar 20 lodged in the inner space of the vessel 2. The vacuum bell jar 20 is a hollow body disposed in the upper portion of the inner space of the vessel 2 such that its upper portion is in contact with and filled by the gas phase of the gas stored in the vessel 2 and its lower portion is immersed in the liquid phase of the gas stored in the vessel 2. The vacuum bell jar 20 here is cylindrical in shape with a circular cross section. However, the vacuum bell jar 20 may have other shapes, such as parallelepiped with square or rectangular cross section.

The intake 11 of the circuit for removal of gas in the vapor phase 9 emerges into the upper portion of the vacuum bell jar 20. Thus, the vacuum pump 12 is able to generate in the upper portion of the vacuum bell jar a pressure P1 less than the atmospheric pressure, enabling a promoting of the vaporization of the liquefied gas inside the vacuum bell jar 20.

It will be noted that, in such an embodiment, when the vacuum pump 12 is controlled so that a measured pressure value is dependent on a pressure setpoint, the pressure sensor is advantageously disposed inside the upper portion of the vacuum bell jar 20.

The use of such a vacuum bell jar 20 has in particular the advantages of reducing the dimensioning constraints for the vacuum pump 12 and of limiting the vacuum prevailing in the rest of the inner space of the vessel 2 so as to limit the stresses exerted on the primary sealing membrane 7 in the case of a membrane vessel of type A, B or C. In other words, the vacuum bell jar 20 makes it possible to confine the vacuumization to an element of smaller dimensions than those of the vessel and whose design and dimensioning may be optimized to have the target vacuum without thereby subjecting the entire vessel to this dimensioning constraint. The dimensioning of the vessel may thus be optimized as a function of an internal operating pressure when the vacuum bell jar is dimensioned as a function of the target vacuum.

For the dimensioning of the vacuum bell jar, the following considerations may be taken into account:

- the strength at the target vacuum of the vacuum bell jar should be ensured by using thicknesses of material and optionally reasonable reinforcements in terms of the fabrication costs;
- the ratio between the free surface inside the vacuum bell jar 20, that is, the surface of the interface zone between the liquid phase and the gas phase in the vacuum bell jar, and that of the free surface in the rest of the vessel, is chosen such that the application of the target vacuum inside the vacuum bell jar 20 translates into an admissible vacuum in the vessel 2.

The vacuum generated inside the vessel may be estimated with the aid of the following relation: $\Delta P_{Vessel} \approx \frac{S_{Bell\ jar}}{S_{Vessel}} * \Delta P_{Bell\ jar}$

where:

$S_{Bell\ jar}$ and S_{Vessel} are the free surface of the liquefied gas in the bell jar and in the rest of the vessel; and

ΔP_{Vessel} and $\Delta P_{Bell\ jar}$ are the relative negative pressure of the vapor phase in the vessel and in the bell jar.

Thus, if one wishes to limit the vacuum in the vessel to 1/10 of the vacuum in the vacuum bell jar 20, the free surface inside the bell jar should be of the order of 1/10 of the free surface inside the vessel.

It will be noted furthermore that, as regards vessels of type C which are designed to store liquefied gas at a pressure significantly larger than the atmospheric pressure, typically of the order of 3 to 9 bars, these are dimensioned as a function of the maximum internal operating pressure which they are able to withstand. For the storage of liquefied natural gas, the maximum internal operating pressure is generally equal to or less than 10 bars. Moreover, the following relation can be established between the critical buckling pressure of such a vessel when it is subjected to an internal vacuum and the maximum internal operating pressure:

$$P_{Cr} = \frac{K^3 \times E}{4 \times \sigma^3 \times \sqrt{1-\nu^2}} \times {P_{max}}^3$$

where:

P_{Cr} : is the critical buckling pressure;

P_{max} : is the maximum operating pressure;

K : is the safety coefficient > 1;

E : is Young's modulus for the material of the sealing membrane of the vessel;

ν : is the Poisson coefficient of said material; and

σ : is the elastic limit of said material.

The critical buckling pressure of the vessel is thus substantially proportional to the cube of its maximum operating pressure multiplied by a constant which depends on the material used and the safety coefficient chosen by the designer. For the majority of candidate materials, this constant is less than 1 and often less than 0.1. Thus, the critical buckling pressure when the vessel is subjected to a vacuum is often more than 10 times less than the maximum operating pressure.

As an example, for a cylindrical vessel of type C dimensioned to resist a maximum operating pressure of 10 bars and a target vacuum inside the vacuum bell jar 20 of the order of 100 mbars, one may choose a ratio between the free surface inside the vacuum bell jar 20, and that of the free surface in the rest of the vessel, of the order of 10, so that the vacuum prevailing in the rest of the vessel is limited to 10 mbars. In this case, the vacuum bell jar 20 is thus able reduce the vacuum liable to prevail in the rest of the gas phase of the vessel from 100 mbars to 10 mbars, which allows in particular a limiting of the thickness of the membrane of the vessel. As an example, for a cylindrical vessel of type C with 10 meters diameter and whose membrane is made of stainless steel, the vacuum bell jar 20 in the mentioned instance is able to limit the thickness of the membrane to 25 mm, whereas it would have had to be 29 mm in the absence of a vacuum bell jar 20.

For the majority of applications, the cross section of the vacuum bell jar is advantageously between 1/5 and 1/100 of the cross section of the vessel.

For a cylindrical vessel whose generatrices are horizontal, the free surface of the liquefied gas inside the vessel is made to evolve as a function of the degree of filling of the vessel. In fact, the free surface is at maximum when the vessel is filled to mid-height and diminishes as one approaches the maximum degree of filling of the vessel. Thus, the dimensioning of the vacuum bell jar 20 may be different according to whether one considers the dimensioning criterion to be the maximum free surface of the liquefied gas – that is, the one corresponding to a vessel which is filled to mid-height – or a free surface of the liquefied gas when the vessel is near its maximum degree of filling.

As an example, taking a pressure ratio of 10 between the vacuum of the vapor phase in the vessel and in the bell jar, for a cylindrical vessel of 20 meters length and 4 meters radius, the radius of a cylindrical vacuum bell jar would be around 2.25 meters, using the maximum free surface of the liquefied gas. However, the vessels of a liquefied natural gas transport ship being designed to be filled near their maximum degree of filling, a lesser bell jar radius of the order of 2 is sufficient and makes it possible to reduce the footprint of the vacuum bell jar 20. Under these same conditions, a vacuum bell jar of square cross section might have a side dimension of 4 meters.

According to one embodiment, the vacuum bell jar 20 has a more complex shape and its cross section evolves as a function of the height of the vessel, such that the ratio between the free surface inside the vacuum bell jar 20 and that of the free surface in the rest of the vessel remains substantially constant over the entire height of the vacuum bell jar 20.

The vacuum bell jar 20 is made of metal for example, in order to promote heat exchange between the gas present on the inside and on the outside of the vacuum bell jar 20.

The vacuum bell jar 20 may be outfitted with elements reinforcing the structure and allowing it to withstand the target vacuum. The reinforcing elements may be of any type and in particular they may be hollow or solid reinforcing elements, passing transversely through the bell jar or arranged on the periphery inside or outside the vacuum bell jar 20.

According to one embodiment, the vacuum bell jar 20 may be crossed by hollow tubes extending substantially horizontally and passing through said vacuum bell jar from one side to the other. Such hollow tubes allow the movement of fluid and are able to promote heat exchange between the gas present on the inside and on the outside of the vacuum bell jar 20. Moreover, such hollow tubes are also able to contribute to the reinforcing of the vacuum bell jar 20.

When the vessel 2 is outfitted with a loading and unloading tower, not represented, the vacuum bell jar 20 may in particular be supported by said loading and unloading tower in order to support the forces due to its weight and to the movements of the liquefied gas. Such a loading and unloading tower extends substantially over the entire height of the vessel and is suspended from the

ceiling wall. The tower may consist of a structure of tripod type, that is, comprising three vertical masts. The loading and unloading tower supports one or more unloading lines and one or more loading lines, each of the unloading lines being associated with an unloading pump which is itself supported by the loading and unloading tower. The vacuum bell jar 20, however, may be supported by any other appropriate means.

The vacuum bell jar 20 is immersed quite deeply inside the liquid phase so that its lower portion remains immersed in the liquid phase when the liquefied gas is subjected to the "sloshing" effect. To accomplish this, the vacuum bell jar 20 may in particular extend more than 1 meter below the height of the vessel corresponding to the maximum fill height.

Referring to figure 4, one notices a cutaway view of an LNG carrier 70 equipped with such an installation for storage and cooling of liquefied natural gas. Figure 4 shows a sealed and insulated vessel 71 of general prismatic shape, mounted in the double hull 72 of the ship. The wall of the vessel 71 comprises a primary sealing membrane designed to be in contact with the liquefied natural gas contained in the vessel, a secondary sealing membrane arranged between the primary sealing barrier and the double hull 72 of the ship, and two thermally insulating barriers arranged respectively between the primary sealing membrane and the secondary sealing membrane and between the secondary sealing membrane and the double hull 72.

In a known manner per se, loading and unloading pipelines 73 arranged on the upper bridge of the ship can be connected by means of suitable connectors to a maritime or harbor terminal to transfer a cargo of liquefied natural gas from or to the vessel 71.

Figure 4 also represents an example of a maritime terminal comprising a loading and unloading station 75, an underwater conduit 76 and a land installation 77. The loading and unloading station 75 is a fixed off-shore installation comprising a movable arm 74 and a tower 78 which supports the movable arm 74. The movable arm 74 carries a bundle of flexible insulated pipes 79 able to be connected to the loading and unloading pipelines 73. The orientable movable arm 74 is adapted to all sizes of LNG carriers. A connection conduit, not represented, extends inside the tower 78. The loading and unloading station 75 enables the loading and the unloading of the LNG carrier 70 from or to the land installation 77. The latter comprises vessels for storage of liquefied gas 80 and connection conduits 81 joined by the underwater conduit 76 to the loading or unloading station 75. The underwater conduit 76 enables the transfer of liquefied gas between the loading or unloading station 75 and the land installation 77 over a great distance, for example, 5 km, which allows holding the LNG carrier 70 at great distance from the coast during the loading and unloading operations.

In order to create the pressure needed for the transfer of the liquefied gas, one turns on pumps aboard the ship 70 and/or pumps outfitting the land installation 77 and/or pumps outfitting the loading and unloading station 75.

Although the invention has been described in connection with several particular embodiments, it is quite evident that it is in no way limited to them and that it encompasses all the technical equivalents of the means described, as well as their combinations, if these fall within the scope of the invention.

The use of the verb "contain", "comprise" or "include" and its conjugated forms does not rule out the presence of other elements or other steps beyond those mentioned in a claim. The use of the indefinite article "a" or "an" for an element or a step does not rule out the presence of a plurality of such elements or steps, unless otherwise specified.

In the claims, any reference sign inside parentheses shall not be interpreted as being a limitation of the claim.

CLAIMS

1. A method for cooling of a liquefied gas (8) stored in the inner space of a sealed and thermally insulated vessel (2), said liquefied gas (8) being stored in the inner space of the vessel (2) in a state of two-phase liquid-vapor equilibrium and having a lower liquid phase and an upper vapor phase separated by an interface, said method involving the steps of:

- drawing a stream of gas in vapor phase into a zone of the vapor phase in contact with a zone of the interface, said step of drawing a stream of gas in vapor phase generating in said zone of the vapor phase a pressure P1 of less than the atmospheric pressure such that vaporization of the liquid phase is promoted in the area of the zone of the interface and the liquefied gas in contact with the zone of the interface is placed in a state of two-phase liquid-vapor equilibrium in which the liquefied gas has a temperature less than the liquid-vapor equilibrium temperature of said liquefied gas at atmospheric pressure; and
- guiding the drawn stream of gas in vapor phase toward a circuit for use of gas in vapor phase (13).

2. The method for cooling as claimed in claim 1, wherein the pressure P1 is greater than 120 mbars absolute.

3. The method for cooling as claimed in claim 1 or 2, wherein the drawing of the stream of gas in vapor phase is achieved by means of a vacuum pump (12) and wherein said vacuum pump (12) is controlled as a function of a flow rate setpoint generated by the circuit for use of gas in vapor phase (13).

4. The method for cooling as claimed in claim 1 or 2, wherein the drawing of the stream of gas in vapor phase is achieved by means of a vacuum pump (12) and wherein the pressure is measured in the zone of the vapor phase and said vacuum pump (12) is controlled as a function of a pressure setpoint and the measured pressure.

5. The method for cooling as claimed in any one of claims 1 to 4, wherein the pressure P1 is between 750 mbars and 980 mbars absolute.

6. The method as claimed in any one of claims 1 to 5, wherein the vessel (2) comprises a multilayered structure mounted on a carrier structure (4), the multilayered structure comprising a sealing membrane in contact (7) with the liquefied gas contained in the vessel and a thermally insulating barrier (6) disposed between the sealing membrane (7) and the carrier structure (4), said thermally insulating barrier (6) comprising insulating blocks and a gas phase, the method involving the step of maintaining the gas phase of the thermally insulating barrier (6) at a pressure P2 less than or equal to the pressure P1.

7. The method as claimed in claim 6, wherein the multilayered structure comprises, from the outside to the inside of the vessel (2), a secondary thermally insulating barrier (3) comprising insulating blocks resting against a carrier structure (4) and a gas phase, a secondary sealing membrane (5) resting against the insulating blocks of the secondary thermally insulating barrier (3), a primary thermally insulating barrier (6) comprising insulating elements resting against the secondary sealing membrane (5) and a gas phase and a primary sealing membrane (7) designed to be in contact with the liquefied gas contained in the vessel, the method involving the step of maintaining the gas phase of the primary thermally insulating barrier (7) and the gas phase of the secondary thermally insulating barrier (3) respectively at a pressure P2 and at a pressure P3, said pressures P2 and P3 being less than or equal to the pressure P1.

8. The method as claimed in claim 7, wherein the pressure P3 is greater than or equal to the pressure P2.

9. The method as claimed in any one of claims 1 to 8, wherein the vessel (2) is filled with a liquefied fuel gas (8) chosen from among liquefied natural gas, ethane and liquefied petroleum gas.

10. The method as claimed in any one of claims 1 to 9, wherein the vessel (2) is equipped with a vacuum bell jar (20) lodged in the inner space of the vessel (2) and comprising an upper portion disposed in the vapor phase and a lower portion immersed in the liquid phase and in which the zone of the vapor phase into which the stream of gas is drawn in the vapor phase is defined by the upper portion of the vacuum bell jar (20).

11. The method as claimed in any one of claims 1 to 9, wherein the pressure P1 is generated in an upper portion of the vessel containing the entire vapor phase.

12. An installation for storage and cooling of a liquefied gas, comprising:

- a sealed and thermally insulated vessel (2) having an inner space designed to be filled with a liquefied gas (8) stored in a state of two-phase liquid-vapor equilibrium such that the liquefied gas has a lower liquid phase and an upper vapor phase separated by an interface; and
- a circuit for removal of gas in the vapor phase (9) comprising:
    - an intake (11) emerging into the inner space of the vessel (2) above a maximum fill height of the vessel so that when the vessel is full it empties into a zone of the vapor phase in contact with a zone of the interface; and
    - a vacuum pump (12) able to draw a stream of gas in vapor phase present in the zone of the vapor phase through the intake (11), to pump this to a circuit for use of gas in the vapor phase (13), and to maintain in the zone of the vapor phase a pressure P1 less than the atmospheric pressure, such that vaporization of the liquid phase is promoted in the area of the interface zone and the liquefied gas in contact with the zone of the interface is placed in state of a two-phase liquid-vapor equilibrium in which the liquefied gas has a temperature

less than the liquid-vapor equilibrium temperature of said liquefied gas at atmospheric pressure.

13. The installation as claimed in claim 12, comprising a sensor to measure the flow rate, able to provide a signal representative of the flow rate of vapor drawn in through the intake and pumped to the circuit for use and a control device (18) able to control the vacuum pump (12) as a function of the signal representative of the flow rate of vapor and a flow rate setpoint generated by the circuit for use of gas in the vapor phase (13).

14. The installation as claimed in claim 12, comprising a pressure sensor able to provide a signal representative of the pressure prevailing in the inner space of the vessel above the maximum fill height and a control device (18) able to control the vacuum pump (12) as a function of the signal representative of the pressure and a pressure setpoint.

15. The installation as claimed in any one of claims 12 to 14, further comprising a circuit for use of gas in the vapor phase (13) comprising energy production equipment.

16. The installation as claimed in any one of claims 12 to 15, wherein the vessel (2) comprises a multilayered structure mounted on a carrier structure (4), the multilayered structure comprising a sealing membrane (7) in contact with the liquefied gas (8) contained in the vessel (2) and a thermally insulating barrier (6) disposed between the sealing membrane (7) and the carrier structure (4), and comprising insulating blocks and a gas phase, the installation furthermore comprising a vacuum pump (16) designed to maintain the gas phase of the thermally insulating barrier (6) at a pressure P2 less than or equal to the pressure P1.

17. The installation as claimed in any one of claims 12 to 15, wherein the multilayered structure comprises, from the outside to the inside of the vessel (2), a secondary thermally insulating barrier (3) comprising insulating blocks resting against a carrier structure (4) and a gas phase, a secondary sealing membrane (5) resting against the insulating blocks of the secondary thermally insulating barrier (3), a primary thermally insulating barrier (6) comprising insulating elements resting against the secondary sealing membrane (5) and a gas phase and a primary sealing membrane (7) designed to be in contact with the liquefied gas (8) contained in the vessel (2), the installation furthermore comprising a first vacuum pump (16) designed to maintain the gas phase of the primary thermally insulating barrier (6) at a pressure P2 less than or equal to the pressure P1 and a second vacuum pump (14) designed to maintain the gas phase of the secondary thermally insulating barrier (3) at a pressure P3 less than or equal to the pressure P1.

18. The installation as claimed in any one of claims 12 to 17, wherein the vessel is equipped with a vacuum bell jar (20) lodged in the inner space of the vessel (2) and comprising an upper portion designed to be placed in contact with the vapor phase of the liquefied gas stored in the inner space of the vessel and a lower portion designed to be immersed in the liquid phase of the liquefied gas stored in the inner space of the vessel and in which the intake (11) of the circuit for

removal of gas in vapor phase empties into the interior of the upper portion of the vacuum bell jar (20).

19. The installation as claimed in claim 18, comprising a pressure sensor able to provide a signal representative of the pressure prevailing in the upper portion of the vacuum bell jar (20).

20. A ship (70) or off-shore liquefaction equipment, comprising an installation (1) as claimed in any one of claims 12 to 19.

21. A method for loading or unloading of a ship (70) as claimed in claim 20, wherein a fluid is routed through insulated conduits (73, 79, 76, 81) from or to a floating or land-based storage installation (77) to or from a vessel (71) of the ship (70).

22. A system of transfer for a fluid, the system comprising a ship (70) as claimed in claim 20, insulated conduits (73, 79, 76, 81) disposed to connect the vessel (71) installed in the hull of the ship to a floating or land-based storage installation (77), and a pump to drive a fluid through the insulated conduits from or to the floating or land-based storage installation to or from the vessel of the ship.