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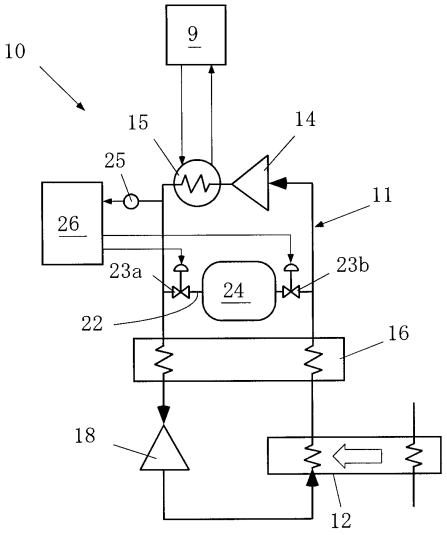
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(54) CRYOGENIC REFRIGERATOR AND CONTROL METHOD THEREFOR

(57) A cryogenic refrigerator (10) which generates a cryogenic temperature by compressing and expanding a working gas in a closed loop (11). The cryogenic refrigerator comprises a bypass line (22) allowing a high-pressure portion and a low-pressure portion to communicate with each other, a gas storage tank (24) located midway in the bypass line and having pressure regulation valves (23a, 23b) on the high-pressure side and the low-pressure side, respectively, and a pressure control unit (26) controlling the pressure regulation valves. The pressure control unit (26) controls the pressure regulation valves (23a, 23b) so that the pressure in the gas storage tank (24) is equal to the pressure in the closed loop at room temperature and in a stopped state and so that the pressure in the gas storage tank (24) is between the pressures in the high-pressure portion and in the low-pressure portion and is close to the pressure in the low-pressure portion in an operating state.

Fig.4



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Description

BACKGROUND OF THE INVENTION

Technical Field of the Invention

[0001] The present invention relates to a cryogenic refrigerator having a cooling capacity of cooling a cooled object up to cryogenic temperatures and a control method therefor.

Description of the Related Art

[0002] A cryogenic refrigerator (for example, a Brayton cycle refrigerator or an Ericsson cycle refrigerator) is used to cool down high temperature superconducting (HTS) equipment (for example, a superconducting transmission cable, a superconducting transformer, a superconducting motor, a superconducting coil for storing superconducting power, a large accelerator, a nuclear fusion test facility, MHD power generation, a superconducting coil, or the like). For example, in the case of using the cryogenic refrigerator for cooling the high temperature superconducting equipment, the lowest temperature is 65K, 40K, 30K, 20K, or the like, though it depends on the type and application of a superconducting wire. Moreover, cooling output is 1 to 10kW or so at each temperature, and helium (the boiling point is approx. 4K), neon (the boiling point is approx. 27K), or a mixture gas of helium and neon is used as a refrigerant gas.
This type of cryogenic refrigerator is disclosed in, for example, Patent Documents 1 and 2 and Non-patent Document 1.

[0003] As shown in Fig. 1, the cascade-turbo helium refrigerating liquefier in Patent Document 1 includes a neon refrigeration cycle, which has a turbo type compressor 51, heat exchangers 52a to 52e, and a turbo type expander 53, and a helium refrigeration cycle, which has a turbo type compressor 54, heat exchangers 55a to 55c, an expansion turbine 56, and a Joule-Thomson valve 57. It is **characterized that** the neon refrigeration cycle previously cools helium.

[0004] The refrigerator disclosed in Patent Document 2 is intended to prevent a cooling medium from being solidified, to extend the maintenance period, to enable a large output, and to eliminate vibration. As shown in Fig. 2, the refrigerator 61 includes a centrifugal compressor 62 and a turbine 63 with a one-stage wing 64 of the compressor 62 and converts a gas 65, which is compressed by the compressor 62 and introduced to the turbine 63, to, for example, a gas mixture of helium and argon or of helium and nitrogen or the like.

[0005] Non-patent Document 1 discloses a cryogenic refrigerator for cooling liquid nitrogen (the boiling point is approx. 77K) up to 65K in order to cool a high temperature superconducting cable as shown in Fig. 3.

[0006]

[Patent Document 1]
Japanese Patent Application Laid-Open No. S59-122868
[Patent Document 2]
Japanese Patent Application Laid-Open No. H11-159898.

[0007]

[Non-patent Document 1]
N. Saji, et. al, "DESIGN OF OIL-FREE SIMPLE TURBO TYPE 65K/6KW HELIUM AND NEON MIXTURE GAS REFRIGERATOR FOR HIGH TEMPERATURE SUPERCONDUCTING POWER CABLE COOLING," CP613, Advances in Cryogenic Engineering: Proceedings of the Cryogenic Engineering Conference, Vol. 47, 2002

[0008] While the working gases (helium, neon, and the like) for use in the foregoing cryogenic refrigerator have extremely low liquefaction temperatures and therefore are excellent in preventing liquefaction in the inside of an expander, there is a problem that the working gases are very expensive.
The cryogenic refrigerator using the expensive working gases is required to minimize a gas charging weight and to stabilize the internal pressure from the start of the refrigerator to the steady operation.

[0009] If, however, a low-pressure low-temperature portion of the running cryogenic refrigerator is cooled from, for example, a room temperature (for example, 300 K) to a cryogenic temperature (for example, 60 K) along with a decrease in temperature of the inside of the refrigerator, the gas volume of the low-pressure low-temperature portion is reduced to one fifth (1/5). Therefore, in order to maintain a predetermined pressure (for example, one half (1/2) of the pressure on start-up), the low-pressure low-temperature portion is required to be supplied with a working gas so that the working gas is five halves (5/2) of the working gas on start-up.

[0010] Contrarily, the pressure rises after the stop of the operation and therefore it is necessary to discharge the working gas to the outside or to bleed the working gas to a pressure vessel, which is provided separately. In this case, discharging the working gas to the outside causes a great loss of the expensive working gas, and bleeding the working gas to the pressure vessel causes excess pressure resistance of the pressure vessel.

[0011] Moreover, if the entire refrigerator is stopped directly without using the pressure vessel, it is necessary to increase the pressure resistance of the entire refrigerator in advance. In this case, there is a problem that an excess load is applied to the compressor on start-up. Furthermore, if the refrigerator is suddenly stopped in an emergency stop or the like, the working gas on the high-pressure side flows backward passing through the compressor and the compressor turns in reverse, which adversely affects a drive system or the like in some cases.

SUMMARY OF THE INVENTION

[0012] The present invention has been devised in order to solve the above problems. Specifically, it is an object of the present invention to provide a cryogenic refrigerator and a control method therefor, the cryogenic refrigerator having a cooling capacity of cooling a cooled object up to a predetermined cryogenic temperature, capable of maintaining the pressure in a high-pressure portion at a substantially constant level from a room temperature in a stopped state to a cryogenic temperature in an operating state without using a pressure vessel whose pressure resistance exceeds a predetermined pressure (for example, 1 MPa) and without discharging or supplying a working gas, and capable of preventing a reverse rotation of a compressor even in the case of an emergency stop.

[0013] According to the present invention, there is provided a cryogenic refrigerator which generates a cryogenic temperature by compressing a working gas in a closed loop and expanding the compressed working gas, the cryogenic refrigerator comprising: a bypass line which allows a high-pressure portion and a low-pressure portion in the closed loop to communicate with each other; a gas storage tank which is located midway in the bypass line and has pressure regulation valves on the high-pressure side and the low-pressure side, respectively; and a pressure control unit which controls the pressure regulation valves, wherein the pressure control unit controls the pressure regulation valves so that the pressure in the gas storage tank is equal to the pressure in the closed loop at room temperature and in a stopped state and controls the pressure regulation valves so that the pressure in the high-pressure portion is equal to a predetermined pressure in an operating state in which the cryogenic temperature is generated.

[0014] According to a preferred embodiment of the present invention, the capacity of the gas storage tank is set so as to enable the pressure in the gas storage tank to be maintained at a predetermined reference pressure or lower at room temperature and in the stopped state and so as to enable the pressure in the high-pressure portion to be maintained at a predetermined operating pressure in the operating state in which the cryogenic temperature is generated.

[0015] Preferably, the pressure control unit maintains the pressure regulation valves to be fully opened in the stopped state of the cryogenic refrigerator and opens the pressure regulation valve connected to the high-pressure side in the case where the pressure in the high-pressure portion exceeds a predetermined maximum pressure and opens the pressure regulation valve connected to the low-pressure side in the case where the pressure in the high-pressure portion is equal to or lower than a predetermined minimum pressure.

[0016] Further, according to a preferred embodiment of the present invention, the cryogenic refrigerator further comprises: a room-temperature compressor which is installed in a room temperature portion in the closed loop to compress the working gas from a predetermined low pressure to a predetermined high-pressure; a first intermediate heat exchanger which is located between a cryogenic temperature portion in the closed loop and the room temperature portion to perform a heat exchange between the working gases; and an expander which is installed on the cryogenic temperature portion side from the first intermediate heat exchanger to isentropically expand the working gas.

[0017] Moreover, the room-temperature compressor includes a plurality of turbo compressors which compress the working gas in multiple stages from the predetermined low pressure to the high pressure; the expander includes a plurality of expansion turbines which expand the working gas in multiple stages from the high pressure to the low pressure; and a plurality of intermediate heat exchangers which perform a heat exchange between working gases are disposed in the middle of the plurality of expansion turbines.

[0018] Moreover, according to the present invention, there is provided a control method for a cryogenic refrigerator which generates a cryogenic temperature by compressing a working gas in a closed loop and expanding the compressed working gas, the control method comprising: providing the cryogenic refrigerator with a bypass line which allows a high-pressure portion and a low-pressure portion in the closed loop to communicate with each other and a gas storage tank which is located midway in the bypass line and has pressure regulation valves on the high-pressure side and the low-pressure side, respectively; and controlling the pressure regulation valves so that the pressure in the gas storage tank is equal to the pressure in the closed loop at room temperature and in a stopped state and controlling the pressure regulation valves so that the pressure in the high-pressure portion is equal to a predetermined pressure in an operating state in which a cryogenic temperature is generated.

[0019] Furthermore, according to a preferred embodiment of the present invention, the capacity of the gas storage tank is set so as to enable the pressure in the gas storage tank to be maintained at a predetermined reference pressure or lower at room temperature in the stopped state and so as to enable the pressure in the high-pressure portion to be maintained at a predetermined operating pressure in the operating state in which the cryogenic temperature is generated.

[0020] According to the cryogenic refrigerator and the method of the present invention, the cryogenic refrigerator comprises a bypass line which allows a high-pressure portion and a low-pressure portion in the closed loop, which constitutes the cryogenic refrigerator, to communicate with each other and a gas storage tank which is located midway in the bypass line and has pressure regulation valves on the high-pressure side and the low-pressure side, respectively, and therefore it is possible to set the pressure of the entire system, which includes the closed loop, the bypass line, and the gas storage

tank, to a predetermined reference pressure or lower by controlling the pressure regulation valves (for example, maintaining the pressure regulation valves to be fully opened in the stopped state) so that the pressure in the gas storage tank is equal to the pressure in the closed loop at room temperature and in a stopped state. Moreover, this enables the pressures on the inlet side and outlet side of the compressor to be equalized in the stopped state of the refrigerator, and therefore it is possible to prevent a reverse rotation of the compressor caused by a pressure difference between the inlet side and the outlet side of the compressor after the stop.

[0021] Moreover, even if the low-pressure low-temperature portion of the cryogenic refrigerator in the operating state requires, for example, five halves of the working gas on start-up due to a decrease in temperature and in pressure, it is possible to supply the required working gas from the gas storage tank by controlling the pressure regulation valves so that the pressure in the high-pressure portion is equal to a predetermined pressure in the operating state where the cryogenic temperature is generated.

[0022] Therefore, the capacity of the gas storage tank is set so that the pressure in the gas storage tank is able to be maintained at a predetermined reference pressure or lower level at room temperature in the stopped state and so that the pressure in the high-pressure portion is able to be maintained at a predetermined operating pressure level in the operating state in which the cryogenic temperature is generated, thereby enabling the cryogenic refrigerator to have a cooling capacity of cooling an cooled object up to a predetermined cryogenic temperature and to maintain the pressure in the high-pressure portion at a substantially constant level from the room temperature in the stopped state to the cryogenic temperature in the operating state without using a pressure vessel whose pressure resistance exceeds a predetermined pressure (for example, 1 MPa) and without discharging or supplying the working gas.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023]

Fig. 1 is a schematic diagram of an apparatus in Patent Document 1.

Fig. 2 is a block diagram of a refrigerator in Patent Document 2.

Fig. 3 is a schematic diagram of an apparatus in Nonpatent Document 1.

Fig. 4 is a diagram illustrating a first embodiment of a cryogenic refrigerator according to the present invention.

Fig. 5 is a diagram illustrating a second embodiment of the cryogenic refrigerator according to the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

[0024] Preferred embodiments of the present invention will be described hereinafter with reference to the accompanying drawings. In the drawings, the same reference numerals are used for the same parts and the overlapped description thereof is omitted.

[0025] Referring to Fig. 4, there is shown a diagram illustrating a first embodiment of a cryogenic refrigerator according to the present invention.

The cryogenic refrigerator 10 according to the present invention is a cryogenic refrigerator which generates a cryogenic temperature by compressing a working gas in a closed loop 11 and expanding the compressed working gas. The expansion by an expansion turbine is preferably an isentropic expansion.

[0026] In this figure, the cryogenic refrigerator 10 according to the present invention has the closed loop 11 in which a working gas circulates, and the closed loop 11 is provided with a cryogenic heat exchanger 12, a room-temperature compressor 14, a first intermediate heat exchanger 16, and an expander 18. The working gas used to circulate in the closed loop 11 is helium (the boiling point is approx. 4K), neon (the boiling point is approx. 27K), or a mixture gas of helium and neon.

[0027] The cryogenic heat exchanger 12 is installed in a cryogenic temperature portion of the closed loop 11 and indirectly cools down a cooled object with the working gas. The cooled object is high temperature superconducting (HTS) equipment (for example, a superconducting transmission cable, a superconducting transformer, a superconducting motor, a superconducting coil for storing superconducting power, a large accelerator, a nuclear fusion test facility, MHD power generation, a superconducting coil, or the like), and the outlet temperature of the cryogenic heat exchanger 12 in the cryogenic temperature portion is, for example, 65K.

[0028] The room-temperature compressor 14 is, for example, a turbo compressor, which is installed in a room temperature portion (for example, in a room at a temperature around 300 K) of the closed loop 11 to compress the working gas from a predetermined low pressure to a predetermined high pressure. Preferably the predetermined low pressure is, for example, 0.5 to 0.6 MPa, the predetermined high pressure is, for example, 1.0 to 1.2 MPa, and the compression ratio of the compressor is around 2.

A water-cooled gas cooler 15 is installed on the downstream side (high-pressure side) of the room-temperature compressor 14 to cool the working gas, which has increased in temperature as a result of the compression, preferably up to around 300 K by using cooling water supplied from an external cooling water circulation unit 9.

[0029] The first intermediate heat exchanger 16 is located between the cryogenic temperature portion and the room temperature portion to perform a heat exchange between the working gas in the high-pressure side and the working gas in the low pressure side. The heat ex-

change cools the working gas on the high-pressure side preferably up to 65 to 70 K.

The expander 18 is, for example, an expansion turbine and is installed on the cryogenic temperature portion side from the first intermediate heat exchanger 16 to isentropically expand the working gas, which has been cooled by the first intermediate heat exchanger 16. The expansion by the expansion turbine causes the working gas to generate a predetermined cryogenic temperature (for example, 56 K). The expansion turbine is coaxial with the turbo compressor, and preferably the same electric motor drives the expansion turbine and the turbo compressor. The working gas at the cryogenic temperature is supplied to the cryogenic heat exchanger 12 to cool the cooled object indirectly with the working gas, and cools the working gas on the high-pressure side indirectly in the first intermediate heat exchanger 16. Subsequently, the working gas is supplied to the room-temperature compressor 14 and is compressed again.

[0030] The foregoing structure allows the cooled object up to the predetermined cryogenic temperature by compressing the working gas in the closed loop 11 and expanding the compressed working gas using the expander 18 to generate a cryogenic temperature.

[0031] In Fig. 4, the cryogenic refrigerator 10 according to the present invention further includes a bypass line 22, a gas storage tank 24, and a pressure control unit 26.

[0032] The bypass line 22 allows a high-pressure portion and a low-pressure portion of the closed loop 11 to communicate with each other directly. The above high-pressure portion is on the downstream side from the compressor 14 in this example, and more specifically, has the volume of the high-pressure side of the gas cooler 15 and the first intermediate heat exchanger 16, and a connecting pipe located from the outlet of the compressor 14 to the inlet of the expander 18. The above low-pressure portion is on the upstream side from the room-temperature compressor 14 in this example, and more specifically, has the volume of the low-pressure side of the cryogenic heat exchanger 12 and the first intermediate heat exchanger 16, and a connecting pipe from the outlet of the expander 18 to the inlet of the room-temperature compressor 14.

[0033] The gas storage tank 24 is located midway in the bypass line 22, having pressure regulation valves 23a and 23b on the high-pressure side and the low-pressure side, respectively.

The capacity of the gas storage tank is set so that the pressure in the gas storage tank 24 is able to be maintained at a predetermined reference pressure (for example, 1 MPa) or lower level at room temperature in a stopped state and so that the pressure in the high-pressure portion is able to be maintained at a predetermined operating pressure level (for example, 1.0 to 1.2 MPa) in an operating state in which a cryogenic temperature is generated.

[0034] The capacity of the gas storage tank 24 requires a volume of the gas storage tank, which satisfies the condition that a difference between the total mass of a gas exclusive of the gas storage tank 24 in the closed loop 11 calculated from the temperature and pressure in the operating state and the mass of a gas loaded at the pressure (for example, 1 MPa) in the high-pressure portion (on the downstream side from the gas cooler 15 in Fig. 4) in the operating state for the volume of the closed loop 11 exclusive of the gas storage tank 24 in the stopped state and at room temperature is equal to a difference between the mass of a gas obtained in the case where the gas storage tank 24 is filled with the pressure in the high-pressure portion in the operating state and the mass of a gas obtained in the case where the gas storage tank 24 is filled with the pressure in the low-pressure portion (the upstream side from the room-temperature compressor 14 in Fig. 4) in the operating state.

The temperature of the gas storage tank is always constant. The pressure in the gas storage tank is maximum when it is equal to the pressure on the high-pressure side in the operating state and is minimum when it is equal to the pressure on the low-pressure side in the operating state. The mass of the gas which the gas storage tank is able to absorb is obtained from the pressure difference at the constant temperature and the volume.

Therefore, the capacity of the gas storage tank 24 is preferably set so as to be 3 or more times, preferably 4 or 5 times, the volume of the low-temperature low-pressure portion at cryogenic temperature and low pressure.

[0035] Moreover, a pressure sensor 25 is installed in the high-pressure portion in the closed loop 11, and detected pressure data is input to the pressure control unit 26. The pressure control unit 26 controls the pressure regulation valves 23a and 23b so that the pressure in the gas storage tank 24 is equal to the pressure in the closed loop 11 at room temperature and in a stopped state on the basis of the detected pressure data and controls the pressure regulation valves 23a and 23b so that the pressure in the gas storage tank 24 is between the pressures in the high-pressure portion and in the low-pressure portion and close to the pressure in the low-pressure portion (a pressure slightly higher than the pressure in the low-pressure portion) in the operating state in which the cryogenic temperature is generated.

[0036] In the control method for the cryogenic refrigerator according to the present invention, the pressure control unit 26 performs the following controls by using the cryogenic refrigerator 10 having the above configuration:

(A) The pressure regulation valves 23a and 23b are maintained to be fully opened in the stopped state of the cryogenic refrigerator 10. This operation enables the pressure on the inlet side of the compressor 14 to be equalized with the pressure on the outlet side of the compressor 14 in the stopped state of the refrigerator, and therefore it is possible to prevent a reverse rotation of the compressor caused by pressure after the stop of the refrigerator.

(B) The pressure regulation valves 23a and 23b are fully closed before the start-up of the cryogenic refrigerator 10. This operation enables the gas storage tank 24 to be isolated from pressure fluctuations on the high-pressure side and on the low-pressure side caused immediately after the start-up, by which the cryogenic refrigerator 10 is able to be started only in the closed loop 11.

(C) During the start-up of the cryogenic refrigerator 10, the pressure regulation valve 23a on the high-pressure side is opened if the pressure in the high-pressure portion exceeds a predetermined maximum pressure (for example, 1.1 MPa). This operation prevents the pressure in the high-pressure portion from exceeding the predetermined maximum pressure and enables excess working gas to be collected into the gas storage tank 24.

(D) During the start-up of the cryogenic refrigerator 10, the pressure regulation valve 23b on the low-pressure side is opened if the pressure in the high-pressure portion is equal to or lower than a predetermined minimum pressure (for example, 0.9 MPa). This operation enables the low-pressure portion in the closed loop 11 to be supplied with working gas from the gas storage tank 24, thereby inhibiting the pressure in the high-pressure portion from decreasing.

Through the operations of (B) to (D), it is possible to complete the start-up of the cryogenic refrigerator 10 and to perform the steady operation which generates the cryogenic temperature.

[0037] Moreover, the same controls are performed to stop the cryogenic refrigerator 10 from the steady operation which generates the cryogenic temperature. More specifically, the pressure on the high-pressure side rises up along with an increase in the temperature and pressure of the low-temperature low-pressure portion at cryogenic temperature and low pressure in the operating state, and therefore it is possible to collect excess working gas into the gas storage tank 24 by the above operation (C).

Further, in the stopped state of the cryogenic refrigerator 10, the operation (A) for maintaining the pressure regulation valves 23a and 23b to be fully opened enables the pressure on the inlet side of the compressor 14 to be equalized with the pressure on the outlet side of the compressor 14 in the stopped state of the refrigerator, and therefore it is possible to prevent a reverse rotation of the compressor caused by a pressure difference between the inlet side and outlet side of the compressor 14 after the stop of the refrigerator.

[0038] According to the above refrigerator and method of the present invention, the cryogenic refrigerator 10 includes the gas storage tank 24, which is located midway in the bypass line 22 allowing the high-pressure portion and the low-pressure portion in the closed loop 11 to communicate with each other, and which has the pressure regulation valves 23a and 23b on the high-pressure side and the low-pressure side, respectively. Therefore, it is possible to set the pressure in the entire system, which includes the closed loop 11, the bypass line 22, and the gas storage tank 24, to a predetermined reference pressure (for example, 1 MPa) or lower by controlling the pressure regulation valves so that the pressure in the gas storage tank 24 is equal to the pressure in the closed loop 11 at room temperature and in the stopped state (for example, by maintaining the pressure regulation valves 23a and 23b to be fully opened in the stopped state).

Moreover, this enables the pressure on the inlet side of the compressor 14 to be equalized with the pressure on the outlet side of the compressor 14 in the stopped state of the refrigerator, and therefore it is possible to prevent a reverse rotation of the compressor caused by pressure after the stop of the refrigerator.

[0039] Furthermore, the pressure regulation valves 23a and 23b are controlled so that the pressure in the gas storage tank 24 is between the pressures in the high-pressure portion and in the low-pressure portion and close to the pressure in the low-pressure portion in the operating state in which the cryogenic temperature is generated, and therefore it is possible to supply the corresponding working gas from the gas storage tank even if the pressure of the working gas in the closed loop drops along with a decrease in the temperature of the low-temperature portion in the refrigerator after the start of the operation.

[0040] For example, if the capacity of the gas storage tank 24 is set so as to be 3 or more times the volume V of the low-temperature low-pressure portion at cryogenic temperature and low pressure in the operating state, it is necessary to supply the low-temperature low-pressure portion with working gas so that the gas volume of the portion is five halves (2.5) of the gas volume on start-up in order to maintain the pressure (for example, one half of the pressure on start-up) in the low-temperature low-pressure portion due to a decrease in temperature (for example, 300 K to 60 K) and a decrease in pressure (for example, to one half).

Therefore, even if the working gas corresponding to the shortfall of 1.5 V is supplied from the gas storage tank 24 to the low-temperature low-pressure portion, it is possible to maintain the pressure in the gas storage tank 24 at one half or more of the pressure in the stopped state.

[0041] More specifically, the capacity of the gas storage tank 24 is set so that the pressure in the gas storage tank 24 is able to be maintained at the predetermined reference pressure (for example, 1 MPa) or lower level at room temperature in the stopped state and so that the pressure in the high-pressure portion is able to be maintained at the predetermined operating pressure level in an operating state in which the cryogenic temperature is generated, thereby enabling the cryogenic refrigerator to have a cooling capacity of cooling the cooled object up to the predetermined cryogenic temperature and to main-

tain the pressure in the high-pressure portion at a substantially constant level from the room temperature in the stopped state to the cryogenic temperature in the operating state without using a gas storage tank whose pressure resistance exceeds the predetermined pressure (for example, 1 MPa) and without discharging or supplying the working gas.

[Embodiment]

[0042] Referring to Fig. 5, there is shown a diagram illustrating a second embodiment of the cryogenic refrigerator according to the present invention. The outlet temperature of the cryogenic temperature portion is 65 K and the cooling capacity thereof is 3 kW in this example, where P, T and G in this figure represent the pressure (bar), the temperature (K), and the mass flow rate (g/s), respectively.

[0043] In this example, the room-temperature compressor 14 includes a first stage compressor 14A, which compresses a working gas from a predetermined low pressure (5.57 bar) to a first intermediate pressure (8.03 bar) between the low pressure and the high pressure, and a second stage compressor 14B, which compresses the working gas from the first intermediate pressure to a high pressure (11.0 bar). Water-cooled gas coolers 15 are installed on the downstream side (the high-pressure side) of the first stage compressor 14A and the second stage compressor 14B, respectively.

Moreover, the expander 18 includes a first expander 18A, which expands the working gas from the high pressure (11.0 bar) to a second intermediate pressure (10.29 bar) between the low pressure and the high pressure, and a second expander 18B, which expands the working gas from the second intermediate pressure to the low pressure (5.57 bar).

[0044] Furthermore, there is provided a second intermediate heat exchanger 17, which exchanges heat between the low-pressure working gas and the high-pressure working gas, between the first expander 18A and the second expander 18B. The first stage compressor 14A and the second stage compressor 14B are turbo compressors, and the first expander 18A and the second expander 18B are expansion turbines. The first stage compressor 14A is coaxial with the second expander 18B, and the second stage compressor 14B is coaxial with the first expander 18A. Preferably the same electric motor drives the turbo compressors and the expansion turbines.

Other parts of the configuration are the same as in Fig. 4.

[0045] It is confirmed that this configuration enables the generation of a cryogenic temperature of 56 K by compressing the working gas in the closed loop 11 and expanding the compressed working gas by using the first expander 18A and the second expander 18B, thereby enabling an absorption of 3 kW heat from the cooled object.

[0046] As described above, in the present invention, a room temperature portion is provided with the gas storage tank 24 and is connected via a pipe (the bypass line 22) having the pressure regulation valves 23a and 23b on the high-pressure side (the outlet side of the compressor) and the low-pressure side (the return side) of the refrigerator, respectively.

While both of the reference pressures in the control of the pressure regulation valves 23a and 23b are high-pressure side pressures, the pressure regulation valve 23a with the pipe connected to the high-pressure side is "opened" when the pressure exceeds a specified pressure and the pressure regulation valve 23b with the pipe connected to the return side is "opened" when the high-pressure side pressure drops to a lower value than the specified pressure to increase the pressure in the system.

Moreover, the volume of the gas storage tank 24 is set to a value as small as possible within a scope that the pressure is maintained at a slightly higher level than the return-side pressure in the operating state and the pressure does not exceed a design pressure even at room temperature in the system in the stopped state.

[0047] Furthermore, the expansion turbines (the first expander 18A and the second expander 18B) are adapted to be coaxial with the turbo compressors (the first stage compressor 14A and the second stage compressor 14B) and the same electric motor drives the expansion turbines and the turbo compressors, thereby enabling the collection of the power of the expansion turbines so as to reduce the electric motor power and enabling the rotational speed of the expansion turbines to be limited to that of the electric motor so as to essentially prevent the overspeed of the expansion turbines. Therefore, there is no need to use bypass valves for the expansion turbines or throttle valves in the inlet and the compressors are able to operate at a rated speed from the start-up.

[0048] Moreover, both of the pressure regulation valves 23a and 23b are opened in the stopped state of the refrigerator to equalize the pressures on the inlet side and outlet side of the compressor, thereby preventing the reverse rotation of the compressors (the first stage compressor 14A and the second stage compressor 14B) caused by a pressure difference between the inlet side and the outlet side of the compressors after the stop of the refrigerator.

[0049] According to the above configuration, the room-temperature compressor 14 increases the pressure of the working gas, the gas cooler 15 decreases the increased temperature of the gas up to close to a room temperature, and then the working gas passes through the first intermediate heat exchanger 16 and the expander 18, thereby decreasing the temperature and decreasing the pressure. A return gas, which has removed heat from the cooled object which is a refrigeration load, increases in temperature up to close to a room temperature while cooling the working gas on the high-pressure side in the first intermediate heat exchanger 16 and then returns to the room-temperature compressor 14. A pres-

sure ratio between the high-pressure side and the low-pressure side is around 2. The gas storage tank 24 is connected via the pipe (the bypass line 22) having the pressure regulation valves 23a and 23b on the high-pressure side of the refrigerator (the outlet side from the compressor) and the return side of the refrigerator (the inlet side from the compressor), respectively.

[0050] While both of the reference pressures in the control of the pressure regulation valves 23a and 23b are high-pressure side pressures, the pressure regulation valve 23a with the pipe connected to the high-pressure side is "opened" when the pressure exceeds a specified pressure and the pressure regulation valve 23b with the pipe connected to the return side is "opened" when the high-pressure side pressure drops to a lower value than the specified pressure to increase the pressure in the system. Due to the functions of the two pressure regulation valves 23a and 23b, the pressure on the high-pressure side is maintained at a constant level in the operating state, on start-up, and in the stopped state.

[0051] Naturally, the present invention is not limited to the embodiments described above, but may be changed in various ways so as not to deviate from the scope of the present invention.

Claims

1. A cryogenic refrigerator which generates a cryogenic temperature by compressing a working gas in a closed loop and expanding the compressed working gas, the cryogenic refrigerator comprising:

   a bypass line which allows a high-pressure portion and a low-pressure portion in the closed loop to communicate with each other;
   a gas storage tank which is located midway in the bypass line and has pressure regulation valves on the high-pressure side and the low-pressure side, respectively; and
   a pressure control unit which controls the pressure regulation valves,
   wherein the pressure control unit controls the pressure regulation valves so that the pressure in the gas storage tank is equal to the pressure in the closed loop at room temperature and in a stopped state and controls the pressure regulation valves so that the pressure in the high-pressure portion is equal to a predetermined pressure in an operating state in which a cryogenic temperature is generated.

2. The cryogenic refrigerator according to claim 1, wherein the capacity of the gas storage tank is set so as to enable the pressure in the gas storage tank to be maintained at a predetermined reference pressure or lower at room temperature and in the stopped state and so as to enable the pressure in the high-pressure portion to be maintained at a predetermined operating pressure in the operating state in which the cryogenic temperature is generated.

3. The cryogenic refrigerator according to claim 1, wherein the pressure control unit:

   maintains the pressure regulation valves to be fully opened in the stopped state of the cryogenic refrigerator; and
   opens the pressure regulation valve connected to the high-pressure side in the case where the pressure in the high-pressure portion exceeds a predetermined maximum pressure and opens the pressure regulation valve connected to the low-pressure side in the case where the pressure in the high-pressure portion is equal to or lower than a predetermined minimum pressure.

4. The cryogenic refrigerator according to claim 1, further comprising:

   a room-temperature compressor which is installed in a room temperature portion in the closed loop to compress the working gas from a predetermined low pressure to a predetermined high-pressure;
   a first intermediate heat exchanger which is located between a cryogenic temperature portion in the closed loop and the room temperature portion to perform a heat exchange between the working gases; and
   an expander which is installed on the cryogenic temperature portion side from the first intermediate heat exchanger to isentropically expand the working gas.

5. The cryogenic refrigerator according to claim 4, wherein:

   the room-temperature compressor includes a plurality of turbo compressors which compress the working gas in multiple stages from the predetermined low pressure to the high pressure;
   the expander includes a plurality of expansion turbines which expand the working gas in multiple stages from the high pressure to the low pressure; and
   a plurality of intermediate heat exchangers which perform a heat exchange between the working gases are disposed in the middle of the plurality of expansion turbines.

6. A control method for a cryogenic refrigerator which generates a cryogenic temperature by compressing a working gas in a closed loop and expanding the compressed working gas, the control method comprising:

providing the cryogenic refrigerator with a bypass line which allows a high-pressure portion and a low-pressure portion in the closed loop to communicate with each other and a gas storage tank which is located midway in the bypass line and has pressure regulation valves on the high-pressure side and the low-pressure side, respectively; and

controlling the pressure regulation valves so that the pressure in the gas storage tank is equal to the pressure in the closed loop at room temperature and in a stopped state and controlling the pressure regulation valves so that the pressure in the high-pressure portion is equal to a predetermined pressure in an operating state in which a cryogenic temperature is generated.

7. The control method for the cryogenic refrigerator according to claim 6, wherein the capacity of the gas storage tank is set so as to enable the pressure in the gas storage tank to be maintained at a predetermined reference pressure or lower at room temperature in the stopped state and so as to enable the pressure in the high-pressure portion to be maintained at a predetermined operating pressure in the operating state in which the cryogenic temperature is generated.

Fig.1

Prior Art

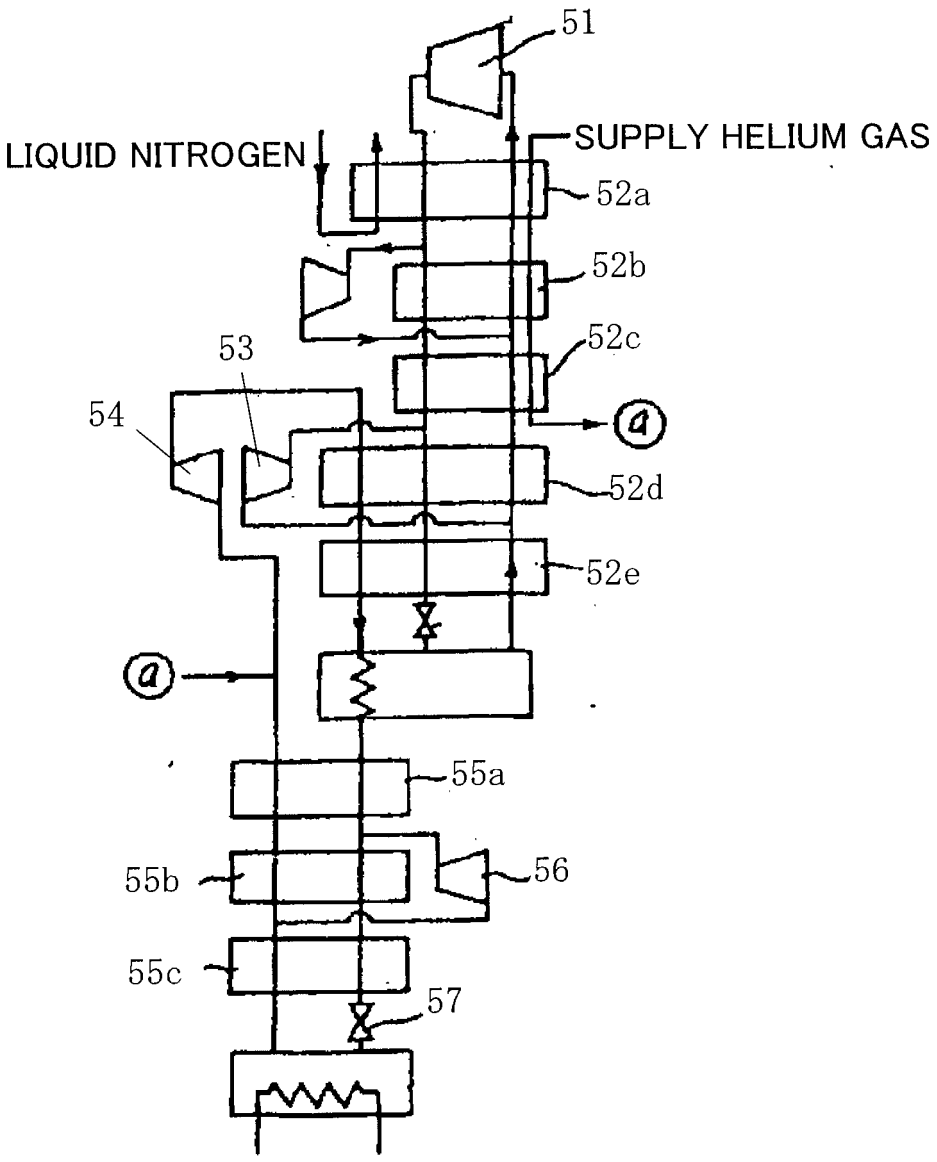


Fig.2

Prior Art

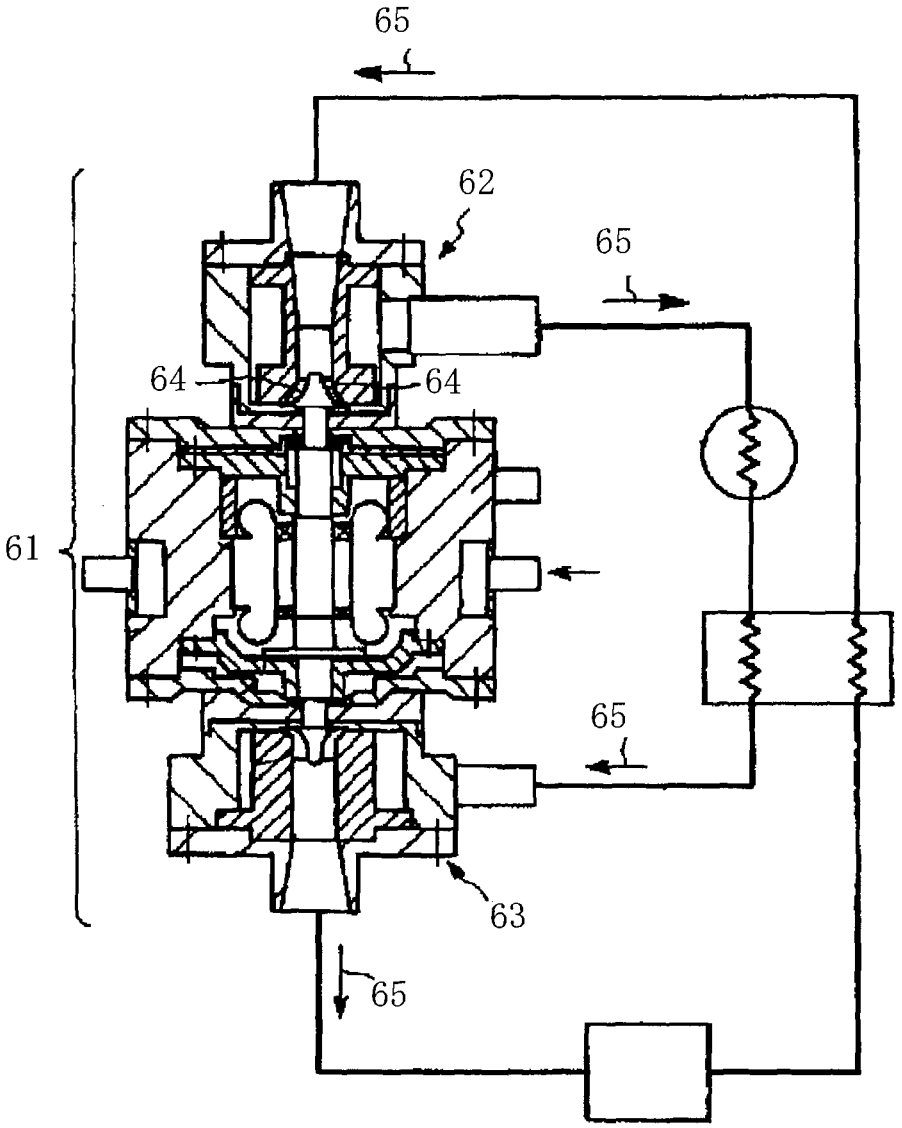


Fig.3

Prior Art

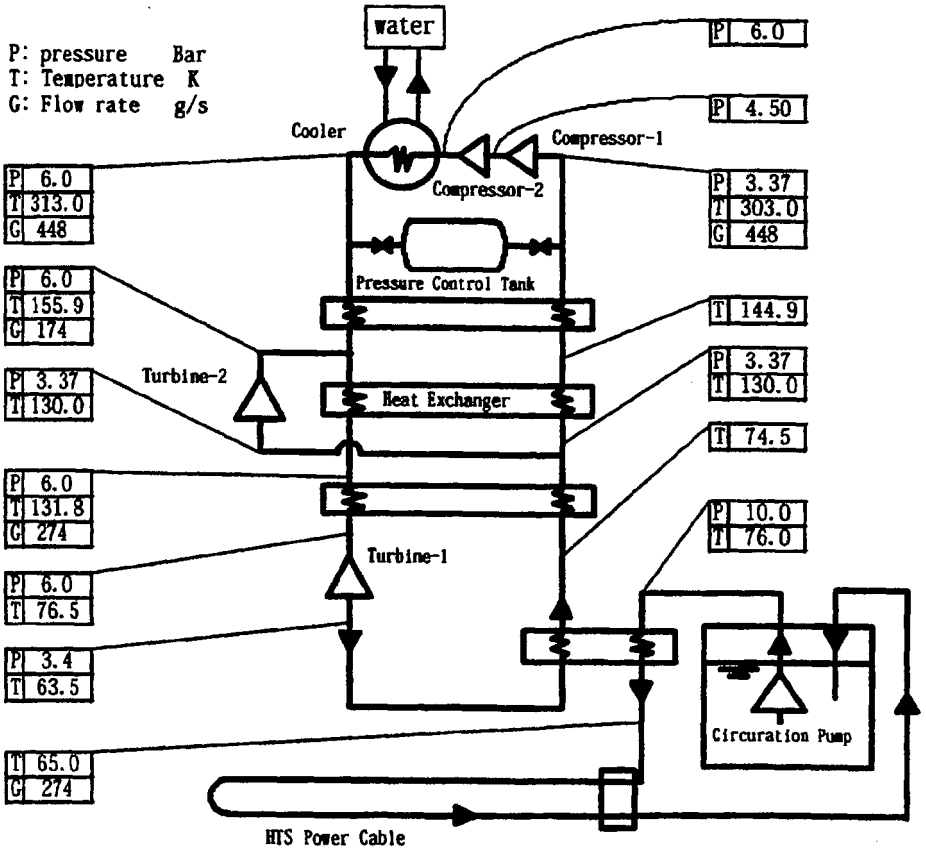


Fig.4

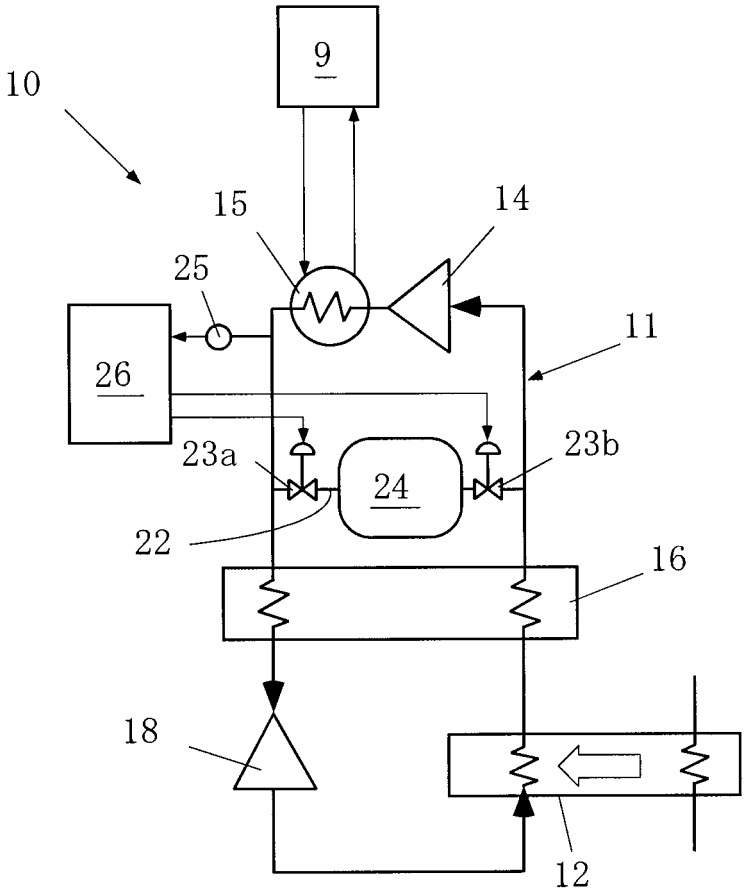
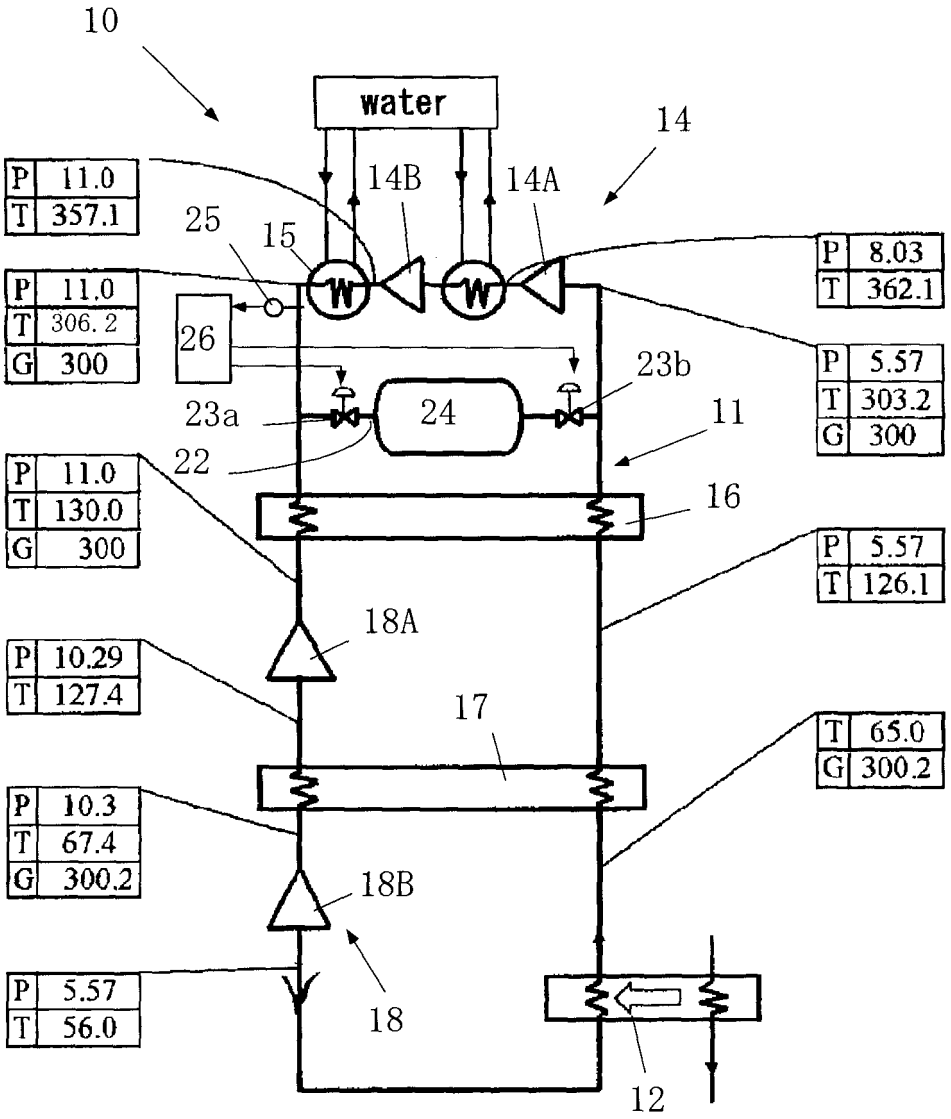


Fig.5


10
water
14
14B
14A
25
15
26
23a
23b
24
22
11
16
18A
17
18B
18
12
P 11.0
T 357.1
P 11.0
T 306.2
G 300
P 11.0
T 130.0
G 300
P 10.29
T 127.4
P 10.3
T 67.4
G 300.2
P 5.57
T 56.0
P 8.03
T 362.1
P 5.57
T 303.2
G 300
P 5.57
T 126.1
T 65.0
G 300.2

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2008/070108

A. CLASSIFICATION OF SUBJECT MATTER
F25B9/06(2006.01)i, *F25B9/00*(2006.01)i, *F25J1/00*(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F25B9/06, F25B9/00, F25J1/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Jitsuyo Shinan Koho 1922-1996 Jitsuyo Shinan Toroku Koho 1996-2008
Kokai Jitsuyo Shinan Koho 1971-2008 Toroku Jitsuyo Shinan Koho 1994-2008

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 5-79717 A (Hitachi, Ltd.), 30 March, 1993 (30.03.93), Par. No. [0017]; Fig. 1 (Family: none)	1-7
Y	JP 11-257768 A (Sanyo Electric Co., Ltd.), 24 September, 1999 (24.09.99), Par. Nos. [0005] to [0007], [0019]; Figs. 1 to 3 (Family: none)	1-7
Y	JP 63-210573 A (Daikin Industries, Ltd.), 01 September, 1988 (01.09.88), Page 3, lower left column, lines 7 to 12; Figs. 1 to 3 (Family: none)	1-7

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
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Date of the actual completion of the international search	Date of mailing of the international search report
28 November, 2008 (28.11.08)	16 December, 2008 (16.12.08)
Name and mailing address of the ISA/ Japanese Patent Office Facsimile No.	Authorized officer Telephone No.

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2008/070108

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 6-159927 A (Liquid Air Engneering Corp.), 07 June, 1994 (07.06.94), Par. No. [0027]; Figs. 3 to 9 & US 5271231 A & EP 583189 A1	5
A	JP 8-313085 A (Daikin Industries, Ltd.), 29 November, 1996 (29.11.96), Par. Nos. [0005], [0042]; Figs. 1 to 3 (Family: none)	1-7
P	JP 2008-138910 A (Taiyo Nippon Sanso Corp.), 19 June, 2008 (19.06.08), Full text; Figs. 1 to 3 (Family: none)	1-7
A	JP 11-159898 A (Ishikawajima-Harima Heavy Industries Co., Ltd.), 15 June, 1999 (15.06.99), Claim 1; Fig. 1 (Family: none)	5
A	JP 9-089399 A (Hitachi, Ltd.), 04 April, 1997 (04.04.97), Full text; Fig. 1 (Family: none)	1-7

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REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP S59122868 B **[0006]**
- JP H11159898 B **[0006]**

Non-patent literature cited in the description

- **N. Saji.** DESIGN OF OIL-FREE SIMPLE TURBO TYPE 65K/6KW HELIUM AND NEON MIXTURE GAS REFRIGERATOR FOR HIGH TEMPERATURE SUPERCONDUCTING POWER CABLE COOLING. *CP613, Advances in Cryogenic Engineering: Proceedings of the Cryogenic Engineering Conference,* 2002, vol. 47 **[0007]**