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(71) Applicant: **Sumitomo Heavy Industries, Ltd.**
Tokyo 141-6025 (JP)

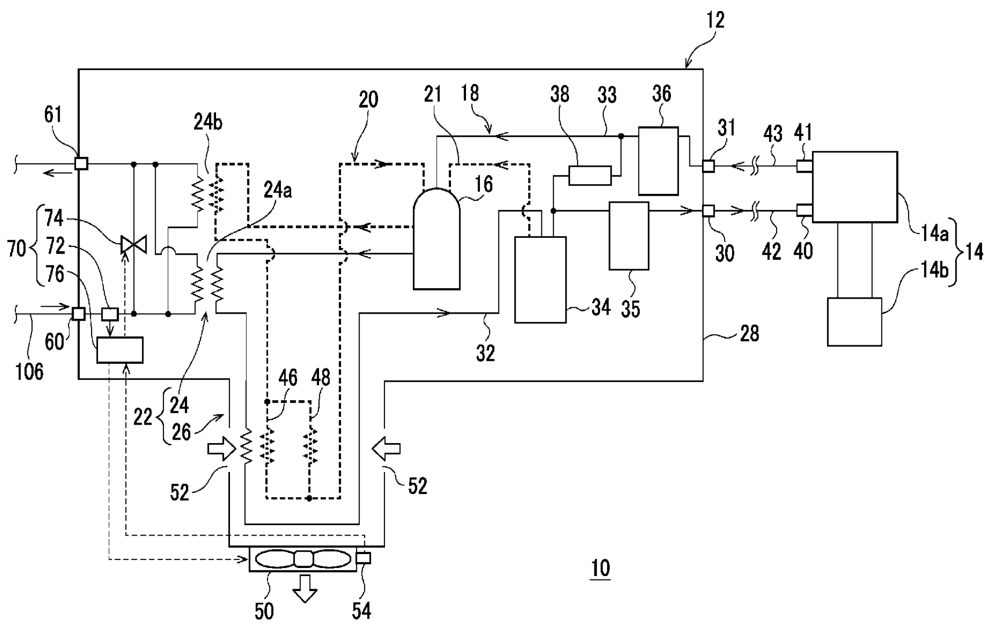
(72) Inventor: **SUZUKI, Sho**
Tokyo 188-8585 (JP)

(74) Representative: **Louis Pöhlau Lohrentz**
Patentanwälte
Postfach 30 55
90014 Nürnberg (DE)

(54) **OIL-LUBRICATED CRYOCOOLER COMPRESSOR AND OPERATION METHOD THEREOF**

(57) A cryocooler compressor (12) that makes load reduction of a cooler possible is provided. The oil-lubricated cryocooler compressor (12) that compresses a refrigerant gas of a cryocooler (10) is provided. The compressor (12) includes a liquid-cooled heat exchanger (24) that cools the refrigerant gas and/or an oil through heat exchange with a coolant and a cooling controller (70) that is configured to acquire a supply temperature of the coolant supplied to the liquid-cooled heat exchanger (24) and to control a flow rate of the coolant of the liquid-cooled heat exchanger (24) and/or an exhaust heat amount of the compressor (12) based on the acquired supply temperature of the coolant.

FIG. 2



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Description

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention relates to an oil-lubricated cryocooler compressor and an operation method thereof.

Description of Related Art

[0002] An oil-lubricated helium compressor with a dual aftercooler is proposed (for example, see Japanese Unexamined Patent Publication No. 2019-505751). Two aftercoolers that cool helium and an oil, that is, a water-cooled aftercooler and an air-cooled aftercooler are incorporated in the compressor. The air-cooled aftercooler is disposed in series or in parallel with the water-cooled aftercooler. By operating a fan of the air-cooled aftercooler, redundancy in a case where a cooling water circuit of the water-cooled aftercooler is blocked is provided.

SUMMARY OF THE INVENTION

[0003] A cryocooler is often used in cryogenic cooling for a cryogenic device that operates at a cryogenic temperature, such as a superconducting magnet. The cryogenic device can include various devices that generate heat, like a compressor of the cryocooler. Such heat generating devices are frequently cooled by a common cooler attached to the cryogenic device. The cooler can typically take a form of supplying a coolant to each heat generating device, such as an air-cooled chiller.

[0004] The cooling capacity of the cooler can be affected by an external factor such as an environment temperature. For example, in a case where the environment temperature is high such as in summer, the cooling capacity can be significantly decreased compared with a case where the temperature is low such as in winter (for example, in the case of the air-cooled chiller, the decrease reaches several tens of % in some cases). There is a concern about a risk of the cooling capacity of the cooler becoming tight or insufficient due to such an external factor or a variety of factors such as an increase in heat generation attributable to an operation situation of the cryogenic device. In a case where the temperature of the heat generating device rises excessively due to cooling capacity insufficiency, there is a concern that a deterioration in the performance of the device or an abnormal operation occurs. This can undesirably prevent the cryogenic device from operating.

[0005] An exemplary object of one embodiment of the present invention is to provide a cryocooler compressor that makes load reduction of a cooler possible.

[0006] According to an aspect of the present invention, there is provided an oil-lubricated cryocooler compressor that compresses a refrigerant gas of a cryocooler. The cryocooler compressor includes a liquid-cooled heat exchanger that cools the refrigerant gas and/or an oil through heat exchange with a coolant and a cooling controller that is configured to acquire a supply temperature of the coolant supplied to the liquid-cooled heat exchanger and to control a flow rate of the coolant of the liquid-cooled heat exchanger and/or an exhaust heat amount of the cryocooler compressor based on the acquired supply temperature of the coolant.

[0007] According to another aspect of the present invention, there is provided an operation method of an oil-lubricated cryocooler compressor that compresses a refrigerant gas of a cryocooler. The cryocooler compressor includes a liquid-cooled heat exchanger that cools the refrigerant gas and/or an oil through heat exchange with a coolant. The method includes acquiring a supply temperature of the coolant supplied to the liquid-cooled heat exchanger and controlling a flow rate of the coolant of the liquid-cooled heat exchanger and/or an exhaust heat amount of the cryocooler compressor based on the acquired supply temperature of the coolant.

[0008] Any combination of the components described above and a combination obtained by switching the components and expressions of the present invention between methods, devices, and systems are also effective as an embodiment of the present invention.

[0009] With the present invention, the cryocooler compressor that makes load reduction of the cooler possible can be provided.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010]

Fig. 1 is a diagram schematically showing a cryogenic device according to an embodiment.

Fig. 2 is a diagram schematically showing a cryocooler according to the embodiment.

Fig. 3 is a diagram schematically showing another example of a cooling controller according to the embodiment.

Fig. 4 is a diagram schematically showing still another example of the cooling controller according to the embodiment.

Fig. 5 is a diagram schematically showing still another example of the cooling controller according to the embodiment.

DETAILED DESCRIPTION OF THE INVENTION

[0011] Hereinafter, an embodiment for carrying out the present invention will be described in detail with reference to the drawings. In the description and drawings, the same or equivalent components, members, and processing will be assigned with the same reference symbols, and redundant description thereof will be omitted as appropriate. The scales and shapes of shown parts are set for convenience in order to make the description easy to understand and are not to be understood as limiting unless stated otherwise. The embodiment is merely an example and does not limit the scope of the present invention. All characteristics and combinations to be described in the embodiment are not necessarily essential to the invention.

[0012] Fig. 1 is a diagram schematically showing a cryogenic device 100 according to the embodiment. The cryogenic device 100 may be, for example, a superconducting magnet device. The superconducting magnet device is mounted on, for example, a high magnetic field using device as a magnetic field source of an accelerator such as a single crystal pulling device, a nuclear magnetic resonance (NMR) system, a magnetic resonance imaging (MRI) system, and a cyclotron, a high energy physical system such as a nuclear fusion system, or other high magnetic field using devices (not shown) and can generate a high magnetic field required for the devices.

[0013] The cryogenic device 100 includes a cryocooler 10 for cryogenic cooling of the superconducting magnet. The cryocooler 10 includes an oil-lubricated cryocooler compressor (hereinafter, also simply referred to as a compressor) 12 and a cold head 14.

[0014] The compressor 12 generates compression heat when a refrigerant gas is compressed. In addition, the cryogenic device 100 can include at least one of devices 102_1 to 102_n that can generate heat, in addition to the compressor 12. For example, in a case where the cryogenic device 100 is an MRI system (or a part thereof), the device 102 can include a gradient magnetic field coil, a gradient magnetic field amplifier, and an RF amplifier.

[0015] In order to cool the device 102 that can generate heat, the cryogenic device 100 is provided with a cooler 110 configured to control the temperature of a coolant and to circulate the coolant, including the compressor 12. The cooler 110 is shared by the compressor 12 and the device 102. The cooler 110 is, for example, a chiller and may be, for example, an air-cooled or other cooling type chiller. As an exemplary configuration, the cooler 110 is configured to supply a coolant (for example, cooling water) to a heat exchanger 104 provided at the cryogenic device 100. In addition, the cooler 110 is configured to collect the coolant used in cooling from the heat exchanger 104 and to cool again.

[0016] A coolant line 106 of each of the compressor 12 and the device 102 is connected to the heat exchanger 104. Heat exchange between a coolant supplied and cooled from the cooler 110 and a coolant of the coolant line 106 is performed by the heat exchanger 104, and thereby the coolant of the coolant line 106 is cooled. The coolant is supplied to the compressor 12 and the device 102 and cools the compressor 12 and the device 102. The coolant used in cooling is collected to the heat exchanger 104 through the coolant line 106 and is again cooled.

[0017] Fig. 2 is a diagram schematically showing the cryocooler 10 according to the embodiment.

[0018] The compressor 12 is configured to collect a refrigerant gas of the cryocooler 10 from the cold head 14, to pressurize the collected refrigerant gas, and to supply the refrigerant gas to the cold head 14 again. The compressor 12 is also referred to as a compressor unit. The cold head 14 is also referred to as an expander and includes a room temperature section 14a and a low-temperature section 14b which is also referred to as a cooling stage. The refrigerant gas is also referred to as a working gas, and other suitable gases may be used although a helium gas is typically used. The compressor 12 and the cold head 14 configure a refrigeration cycle of the cryocooler 10, and thereby the low-temperature section 14b is cooled to a desired cryogenic temperature. The low-temperature section 14b can cool an object to be cooled such as a superconducting magnet.

[0019] Although the cryocooler 10 is, for example, a single-stage or two-stage Gifford-McMahon (GM) cryocooler, the cryocooler 10 may be a pulse tube cryocooler, a Stirling cryocooler, or other types of cryocoolers. Although the cold head 14 has a different configuration depending on the type of the cryocooler 10, the compressor 12 can use the configuration described below regardless of the type of the cryocooler 10.

[0020] In general, both a pressure of a refrigerant gas supplied from the compressor 12 to the cold head 14 and a pressure of a refrigerant gas collected from the cold head 14 to the compressor 12 are considerably higher than the atmospheric pressure, and can be called a first high pressure and a second high pressure, respectively. For convenience of description, the first high pressure and the second high pressure are also simply called a high pressure and a low pressure, respectively. Typically, the high pressure is, for example, 2 to 3 MPa. The low pressure is, for example, 0.5 to 1.5 MPa and is, for example, approximately 0.8 MPa.

[0021] The compressor 12 includes a compressor main body 16, a refrigerant gas line 18, an oil circulation line 20, and a compressor cooling system 22. In Fig. 2, in order to facilitate understanding, the refrigerant gas line 18 is shown by a solid line, and the oil circulation line 20 is shown by a broken line. Although details will be described later, the compressor cooling system 22 is configured to include a liquid-cooled heat exchanger 24 and an air-cooled heat exchanger 26 and to cool the refrigerant gas line 18 and the oil circulation line 20. In addition, the compressor 12 includes a compressor casing 28 that accommodates each of components of the compressor 12, such as the compressor main body 16, the refrigerant gas line 18, the oil circulation line 20, and the compressor cooling system 22.

[0022] The compressor main body 16 is configured to internally compress a refrigerant gas sucked from a suction port thereof and to discharge the refrigerant gas from a discharge port. An oil is used in the compressor main body 16 for the sake of cooling and lubrication, and the sucked refrigerant gas is directly exposed to the oil in the compressor main body 16. Accordingly, the refrigerant gas is delivered from the discharge port in a state where the oil is slightly mixed.

[0023] The compressor main body 16 may be, for example, a scroll type pump, a rotary type pump, or other pumps that pressurize a refrigerant gas. The compressor main body 16 may be configured to discharge the refrigerant gas at a fixed and constant flow rate. Alternatively, the compressor main body 16 may be configured to have a variable flow rate of the refrigerant gas to be discharged. The compressor main body 16 is called a compression capsule in some cases.

[0024] The refrigerant gas line 18 includes a discharge port 30, a suction port 31, a discharge flow path 32, and a suction flow path 33. The discharge port 30 is an outlet of a refrigerant gas that is provided in the compressor casing 28 in order to deliver the refrigerant gas, which is pressurized to a high pressure by the compressor main body 16, from the compressor 12, and the suction port 31 is an inlet of the refrigerant gas that is provided in the compressor casing 28 in order for the compressor 12 to receive the low-pressure refrigerant gas. The compressor casing 28 accommodates the discharge flow path 32 and the suction flow path 33. The discharge port of the compressor main body 16 is connected to the discharge port 30 by the discharge flow path 32, and the suction port 31 is connected to the suction port of the compressor main body 16 by the suction flow path 33.

[0025] The liquid-cooled heat exchanger 24 and the air-cooled heat exchanger 26 that configure the compressor cooling system 22 are provided at the discharge flow path 32. In addition, an oil separator 34 and an adsorber 35 are provided downstream of the compressor cooling system 22 at the discharge flow path 32.

[0026] The oil separator 34 is provided in order to separate an oil, which is mixed in a refrigerant gas as passing through the compressor main body 16, out from the refrigerant gas. The adsorber 35 is provided in order to remove, for example, a vaporized oil and other contaminants remaining in the refrigerant gas from the refrigerant gas through adsorption. The oil separator 34 and the adsorber 35 are connected in series. In the discharge flow path 32, the oil separator 34 is disposed on a compressor main body 16 side, and the adsorber 35 is disposed on a discharge port 30 side.

[0027] An oil return line 21 that connects the oil separator 34 to the compressor main body 16 is provided. An oil collected by the oil separator 34 can return to the compressor main body 16 through the oil return line 21. In the middle of the oil return line 21, a filter that removes dust included in the oil separated out by the oil separator 34 and an orifice that controls the amount of the oil returning to the compressor main body 16 may be provided.

[0028] On the other hand, a storage tank 36 is provided at the suction flow path 33. The storage tank 36 is provided as a volume for removing pulsation included in a low-pressure refrigerant gas returning from the cold head 14 to the compressor 12.

[0029] In addition, a refrigerant gas bypass valve 38 that connects the discharge flow path 32 to the suction flow path 33 to bypass the compressor main body 16 is provided at the refrigerant gas line 18. For example, the refrigerant gas bypass valve 38 branches off from the discharge flow path 32 between the oil separator 34 and the adsorber 35 and is connected to the suction flow path 33 between the compressor main body 16 and the storage tank 36. The refrigerant gas bypass valve 38 is provided in order to control a flow rate of a refrigerant gas and/or in order to equalize the discharge flow path 32 and the suction flow path 33 when the compressor 12 is stopped.

[0030] The refrigerant gas line 18 of the compressor 12 is connected to the cold head 14. A high-pressure port 40 and a low-pressure port 41 are provided in the room temperature section 14a of the cold head 14. The high-pressure port 40 is connected to the discharge port 30 by a high-pressure pipe 42, and the low-pressure port 41 is connected to the suction port 31 by a low-pressure pipe 43.

[0031] The oil circulation line 20 connects an oil outlet to an oil inlet of the compressor main body 16 via the compressor cooling system 22 (that is, the liquid-cooled heat exchanger 24 and the air-cooled heat exchanger 26). Accordingly, an oil flowing out from the compressor main body 16 can be cooled by the compressor cooling system 22 and flow into the compressor main body 16 again.

[0032] In the embodiment, the oil circulation line 20 branches into a plurality of (two in the example) oil flow paths at the compressor cooling system 22 as will be described later. The branched oil flow paths merge between the compressor cooling system 22 and the oil inlet of the compressor main body 16 again.

[0033] An orifice that controls a flow rate of an oil flowing inside may be provided at the oil circulation line 20. In addition, a filter that removes dust included in the oil may be provided at the oil circulation line 20. Such an orifice and such a filter may be provided, for example, on a downstream side of the oil circulation line 20, that is, between the compressor cooling system 22 and the oil inlet of the compressor main body 16.

[0034] As described above, the compressor cooling system 22 includes the liquid-cooled heat exchanger 24 and the air-cooled heat exchanger 26. The liquid-cooled heat exchanger 24 and the air-cooled heat exchanger 26 are connected in series, and the liquid-cooled heat exchanger 24 is provided upstream of the air-cooled heat exchanger 26. Accordingly, an oil heated by compression heat generated with compression of a refrigerant gas in the compressor main body 16 and a high-pressure refrigerant gas initially flow from the compressor main body 16 into the liquid-cooled heat exchanger 24 to be cooled and then flow into the air-cooled heat exchanger 26.

[0035] In the embodiment, the liquid-cooled heat exchanger 24 is mounted on the compressor 12 as a main cooling device of the compressor 12, and the air-cooled heat exchanger 26 is mounted on the compressor 12 as a backup cooling device of the compressor 12. Accordingly, the liquid-cooled heat exchanger 24 operates at all times during an operation of the compressor 12, and the air-cooled heat exchanger 26 does not operate when the liquid-cooled heat exchanger 24 operates normally, but may operate when the liquid-cooled heat exchanger 24 does not operate due to a failure or when a cooling capacity thereof has decreased. Thus, the air-cooled heat exchanger 26 may be configured to switch on or off based on an output of a sensor provided at the compressor 12, such as a temperature sensor for an oil or a refrigerant gas.

[0036] The liquid-cooled heat exchanger 24 includes a first portion 24a that cools a refrigerant gas through heat exchange between the refrigerant gas and a coolant and a second portion 24b that cools an oil through heat exchange between the oil and the coolant. The first portion 24a is disposed between the compressor main body 16 and the oil separator 34 at the discharge flow path 32, more specifically, between the discharge port of the compressor main body 16 and the air-cooled heat exchanger 26 and cools the refrigerant gas flowing in the discharge flow path 32. The second portion 24b is disposed between the oil outlet of the compressor main body 16 and the air-cooled heat exchanger 26 at the oil circulation line 20 and cools the oil flowing in the oil circulation line 20.

[0037] Although water (for example, tap water and industrial water) is typically used as a coolant, other suitable coolants may be used. A supply side of the coolant line 106 is connected to a coolant inlet port 60 of the compressor 12, and a collection side of the coolant line 106 is connected to a coolant outlet port 61 of the compressor 12. Accordingly, the coolant is supplied from the supply side of the coolant line 106 to the compressor 12 through the coolant inlet port 60. The coolant from the coolant inlet port 60 is supplied to the first portion 24a and the second portion 24b of the liquid-cooled heat exchanger 24 in order to cool a refrigerant gas and an oil. The coolant used in cooling at the liquid-cooled heat exchanger 24 is discharged from the compressor 12 to the collection side of the coolant line 106 through the coolant outlet port 61. In this manner, compression heat generated by the compressor main body 16 is removed to the outside of the compressor 12 together with the coolant. The coolant may be cooled by a coolant circulation device (for example, the cooler 110 shown in Fig. 1), such as a known water chiller, and be supplied to the compressor 12 through the coolant line 106 again.

[0038] In addition, the air-cooled heat exchanger 26 includes a cooling fan 50, a first oil line 46 that is disposed to be forcibly cooled by the cooling fan 50, and a second oil line 48 that bypasses the first oil line 46 and that is disposed to be forcibly cooled by the cooling fan 50.

[0039] The first oil line 46 and the second oil line 48 are a portion of the oil circulation line 20 disposed in the air-cooled heat exchanger 26. The second oil line 48 branches off from the oil circulation line 20 upstream of the air-cooled heat exchanger 26, that is, between the liquid-cooled heat exchanger 24 and the air-cooled heat exchanger 26 and merges with the first oil line 46 again downstream of the air-cooled heat exchanger 26, that is, between the air-cooled heat exchanger 26 and the oil inlet of the compressor main body 16.

[0040] As an exemplary configuration, the cooling fan 50 is provided in the compressor casing 28 to exhaust air from the air-cooled heat exchanger 26 to the outside as the cooling fan 50 operates. Two air intakes 52 are provided at a portion of the compressor casing 28 surrounding the air-cooled heat exchanger 26, and air is taken into the air-cooled heat exchanger 26 through the air intakes 52 from the outside as the cooling fan 50 operates. An airflow that blows from one air intake 52 into the air-cooled heat exchanger 26 is used in forced cooling of the refrigerant gas line 18 and the first oil line 46, and another airflow that blows from the other air intake 52 into the air-cooled heat exchanger 26 is used in forced cooling of the second oil line 48. In Fig. 2, for the sake of understanding, the airflows are schematically shown by thick arrows.

[0041] The cooling fan 50 of the air-cooled heat exchanger 26 may be configured such that the cooling fan may generate an airflow in a direction opposite to the example described above and blow air from the outside into the air-cooled heat exchanger 26. The cooling fan 50 may be configured to blow air to the refrigerant gas line 18, the first oil line 46, and the second oil line 48.

[0042] During an operation of the cryocooler 10, a refrigerant gas collected from the cold head 14 to the compressor 12 flows from the low-pressure port 41 into the suction port 31 of the compressor 12 through the low-pressure pipe 43. The refrigerant gas is collected to the suction port of the compressor main body 16 via the storage tank 36 on the suction flow path 33. The refrigerant gas is compressed and pressurized by the compressor main body 16. The refrigerant gas delivered from the discharge port of the compressor main body 16 is cooled by the liquid-cooled heat exchanger 24 and the air-cooled heat exchanger 26 and exits the compressor 12 from the discharge port 30 via the oil separator 34 and the adsorber 35. The refrigerant gas is supplied into the cold head 14 via the high-pressure pipe 42 and the high-pressure port 40.

[0043] An oil flowing out from the oil outlet of the compressor main body 16 flows into the liquid-cooled heat exchanger 24 through the oil circulation line 20 and is cooled through heat exchange between the oil and a coolant at the liquid-cooled heat exchanger 24. The cooled oil flows from the liquid-cooled heat exchanger 24 into the air-cooled heat exchanger 26. The oil branches off and flows to the first oil line 46 and the second oil line 48 in the air-cooled heat exchanger 26. In a case where the cooling fan 50 operates, the oil is cooled with air when flowing in the first oil line 46 and the second oil line 48. The oil flowing out from the air-cooled heat exchanger 26 returns to the oil inlet of the compressor main body 16 through the oil circulation line 20.

[0044] In the embodiment, the compressor 12 includes a cooling controller 70 that is configured to acquire a supply temperature of a coolant supplied to the liquid-cooled heat exchanger 24 and to control a flow rate of the coolant of the liquid-cooled heat exchanger 24 based on the acquired supply temperature of the coolant. The cooling controller 70 is configured to compare the acquired supply temperature of the coolant with a temperature threshold value and to control the flow rate of the coolant of the liquid-cooled heat exchanger 24 in a case where the supply temperature exceeds the temperature threshold value.

[0045] The cooling controller 70 includes a temperature sensor 72 that measures a supply temperature of a coolant supplied to the liquid-cooled heat exchanger 24. The temperature sensor 72 is provided on the supply side of the coolant line 106 and in this example, between the coolant inlet port 60 and the liquid-cooled heat exchanger 24 in the compressor 12. The temperature sensor 72 may be provided at the coolant inlet port 60. The temperature sensor may be, for example, a thermistor.

[0046] In addition, the cooling controller 70 includes a coolant bypass valve 74 that is connected in parallel with the liquid-cooled heat exchanger 24 and a valve controller 76 that is configured to open the coolant bypass valve 74 or to increase an opening degree thereof in a case where a supply temperature of a coolant exceeds the temperature threshold value.

[0047] The cooling controller 70 and/or the valve controller 76 is realized by an element or a circuit including a CPU and a memory of a computer as a hardware configuration and is realized by a computer program as a software configuration, but is shown in the drawings as appropriate as a functional block realized in cooperation therewith. It is clear for those skilled in the art that the functional blocks can be realized in various manners in combination with hardware and software.

[0048] The valve controller 76 may be a valve drive circuit (valve driver) or may be incorporated in the coolant bypass valve 74 or other valves. Alternatively, the valve controller 76 may be provided outside the valve or may be connected to the valve.

[0049] The cooling controller 70 operates, for example, as follows. First, a supply temperature of a coolant supplied to the liquid-cooled heat exchanger 24 is acquired. The coolant temperature is measured by the temperature sensor 72. A signal indicating the measurement temperature is output from the temperature sensor 72 and is transmitted to the valve controller 76. The valve controller 76 receives the measurement temperature signal from the temperature sensor 72. In this manner, the valve controller 76 can acquire the supply temperature of the coolant supplied to the liquid-cooled heat exchanger 24.

[0050] The valve controller 76 controls a flow rate of a coolant of the liquid-cooled heat exchanger 24 based on an acquired supply temperature of the coolant. Specifically, for example, the valve controller 76 compares the acquired supply temperature of the coolant with the temperature threshold value. The coolant bypass valve 74 may be an on/off valve. In this case, the valve controller 76 opens and closes the coolant bypass valve 74 based on the comparison result. Alternatively, the coolant bypass valve 74 may be a flow rate control valve. In this case, the valve controller 76 may open and close the coolant bypass valve 74 based on the comparison result or adjust an opening degree thereof.

[0051] The temperature threshold value may be set based on an upper limit temperature (for example, approximately 30°C) on the specification of a coolant temperature at which the cooler 110 supplies a coolant and may be equal to, for example, the upper limit temperature. It is possible to set the temperature threshold value as appropriate based on empirical knowledge of a designer or experiments and simulations by the designer. The temperature threshold value may be set in advance and be stored in the valve controller 76.

[0052] When a supply temperature of a coolant falls below the temperature threshold value, the valve controller 76 closes the coolant bypass valve 74. In this case, the coolant supplied from the coolant line 106 flows into the liquid-cooled heat exchanger 24. Accordingly, the coolant is used in cooling of a refrigerant gas and an oil at the liquid-cooled heat exchanger 24.

[0053] On the other hand, when a supply temperature of a coolant exceeds the temperature threshold value, the valve controller 76 opens the coolant bypass valve 74. In this case, the coolant supplied from the coolant line 106 can flow to both the coolant bypass valve 74 and the liquid-cooled heat exchanger 24. However, since a flow path resistance of the liquid-cooled heat exchanger 24 is generally high, in reality, most or substantially all of the coolant flows to the coolant bypass valve 74 instead of the liquid-cooled heat exchanger 24.

[0054] In a case where the coolant bypass valve 74 is a type of which an opening degree can be controlled, the valve controller 76 may increase the opening degree of the coolant bypass valve 74 when a supply temperature of a coolant exceeds the temperature threshold value. When the supply temperature of the coolant falls below the temperature threshold value, the valve controller 76 may decrease the opening degree of the coolant bypass valve 74. Even in this manner, when a temperature of the coolant supplied to the liquid-cooled heat exchanger 24 is high, cooling of the liquid-cooled heat exchanger 24 can be limited. In addition, when the coolant temperature decreases, the limitation can be alleviated or lifted.

[0055] As described above, the cooling capacity of the cooler 110 is insufficient due to an external factor such as an environment temperature or other factors, and a situation in which a rise in a supply temperature of a coolant from the cooler 110 to the compressor 12 can be caused. According to the embodiment, the cooling controller 70 can limit a flow rate of the coolant of the liquid-cooled heat exchanger 24 using the coolant bypass valve 74. The coolant bypasses the liquid-cooled heat exchanger 24 through the coolant bypass valve 74. As a result, the coolant is mostly (or entirely) not supplied to the liquid-cooled heat exchanger 24, and cooling action of the liquid-cooled heat exchanger 24 is limited or practically eliminated. The compressor 12 can reduce the amount of heat radiation to the cooler 110 and that is, can reduce a load on the cooler 110.

[0056] The remaining capacity of the cooler 110 generated in this manner can be used in cooling of another device 102 in the cryogenic device 100 that requires heat radiation. In this manner, it is possible to respond to a cooling capacity insufficiency and a problem attributable thereto, which can occur in the cooler 110, and to continue operation of the cryogenic device 100.

[0057] Further, the cooling controller 70 may be configured to operate the air-cooled heat exchanger 26 in a case where a supply temperature of a coolant supplied to the liquid-cooled heat exchanger 24 exceeds the temperature threshold value. In this manner, in spite of supply limitation of the coolant to the liquid-cooled heat exchanger 24 described above, the compressor 12 can be maintained cool using the air-cooled heat exchanger 26 or a combination of the liquid-cooled heat exchanger 24 and the air-cooled heat exchanger 26.

[0058] In this case, for example, the valve controller 76 may be configured to control not only the coolant bypass valve 74 but also the cooling fan 50. The valve controller 76 may operate the cooling fan 50 in an interlocking manner with an operation of the coolant bypass valve 74 described above based on a supply temperature of a coolant.

[0059] That is, when a supply temperature of a coolant exceeds the temperature threshold value, the valve controller 76 opens the coolant bypass valve 74 and operates the air-cooled heat exchanger 26 (turns the cooling fan 50 on). On the other hand, when the supply temperature of the coolant falls below the temperature threshold value, the valve controller 76 closes the coolant bypass valve 74 and does not operate the air-cooled heat exchanger 26 (turns the cooling fan 50 off). The temperature threshold value may be the same value as the temperature threshold value that is used in order to open and close the coolant bypass valve 74 and that is described above.

[0060] By operating the air-cooled heat exchanger 26, heat generated by the compressor 12 is released to the periphery of the compressor 12 together with an airflow of the air-cooled heat exchanger 26. In some cases, this causes an excessive rise in an ambient temperature, and there is a concern that peripheral devices are adversely affected.

[0061] In order to respond to this, the cooling controller 70 may be configured to acquire an ambient temperature and to stop the air-cooled heat exchanger 26 based on the acquired ambient temperature. In addition thereto or instead thereof, the cooling controller 70 may be configured to acquire the ambient temperature and to release limitation of a flow rate of a coolant of the liquid-cooled heat exchanger 24 based on the acquired ambient temperature.

[0062] In order to acquire an ambient temperature, the cooling controller 70 may include an ambient temperature sensor 54 that measures the ambient temperature. The ambient temperature sensor 54 may be disposed, for example, at the compressor casing 28 in the vicinity of the air-cooled heat exchanger 26. The ambient temperature sensor 54 may be provided at the cooling fan 50.

[0063] For example, the cooling controller 70 (for example, the valve controller 76) acquires an ambient temperature measured by the ambient temperature sensor 54 and compares the ambient temperature with a predetermined ambient temperature threshold value. When the ambient temperature falls below the ambient temperature threshold value, the cooling controller 70 operates the air-cooled heat exchanger 26. In addition thereto or instead thereof, the cooling controller 70 limits a flow rate of a coolant of the liquid-cooled heat exchanger 24 as described above (for example, opens the coolant bypass valve 74). On the other hand, when the ambient temperature exceeds the ambient temperature threshold value, the cooling controller 70 does not operate the air-cooled heat exchanger 26. In addition thereto or instead thereof, the cooling controller 70 releases the limitation of the flow rate of the coolant of the liquid-cooled heat exchanger 24 (for example, closes the coolant bypass valve 74).

[0064] Fig. 3 is a diagram schematically showing another example of the cooling controller 70 according to the embodiment. In addition to the temperature sensor 72 and the valve controller 76 that are described above, the cooling controller 70 may include a control valve 75 that is connected to the liquid-cooled heat exchanger 24 in series. The control valve 75 may be an on/off valve. Alternatively, the control valve 75 may be a flow rate control valve. The cooling controller 70 may be configured to open and close the control valve 75 or to adjust an opening degree thereof based on a supply temperature of a coolant acquired from the temperature sensor 72 and thereby to control a flow rate of the coolant of the liquid-cooled heat exchanger 24.

[0065] For example, the valve controller 76 compares a supply temperature of a coolant acquired from the temperature sensor 72 with the temperature threshold value. When the supply temperature of the coolant falls below the temperature threshold value, the valve controller 76 opens the control valve 75. In this case, the coolant supplied from the coolant line 106 flows into the liquid-cooled heat exchanger 24. Accordingly, the coolant is used in cooling of a refrigerant gas and an oil at the liquid-cooled heat exchanger 24. On the other hand, when the supply temperature of the coolant exceeds the temperature threshold value, the valve controller 76 closes the control valve 75. In this case, the coolant supplied from the coolant line 106 is shut off. Accordingly, the coolant is not used in cooling at the liquid-cooled heat exchanger 24.

[0066] Even in this manner, the compressor 12 can reduce the amount of heat radiation to the cooler 110 as a countermeasure to a temperature rise of a coolant and reduce a load on the cooler 110.

[0067] In a case where the control valve 75 is a type of which an opening degree can be controlled, the valve controller 76 may decrease the opening degree of the control valve 75 when a supply temperature of a coolant exceeds the temperature threshold value. When the supply temperature of the coolant falls below the temperature threshold value, the valve controller 76 may increase the opening degree of the control valve 75. Even in this manner, when a temperature of the coolant supplied to the liquid-cooled heat exchanger 24 is high, cooling of the liquid-cooled heat exchanger 24 can be limited. In addition, when the coolant temperature decreases, the limitation can be alleviated or lifted.

[0068] In addition, as shown by a broken line in Fig. 3, the coolant bypass valve 74 described above may be used in combination with the control valve 75. The cooling controller 70 may be configured to interlock the coolant bypass valve 74 and the control valve 75 based on a supply temperature of a coolant. For example, the valve controller 76 may control both the coolant bypass valve 74 and the control valve 75. The valve controller 76 may control the control valve 75 in an interlocking manner with an operation of the coolant bypass valve 74 described above based on the supply temperature of the coolant. That is, when the supply temperature of the coolant exceeds the temperature threshold value, the valve controller 76 may open the coolant bypass valve 74 or close the control valve 75. On the other hand, when the supply temperature of the coolant falls below the temperature threshold value, the valve controller 76 may close the coolant bypass valve 74 or open the control valve 75.

[0069] Fig. 4 is a diagram schematically showing still another example of the cooling controller 70 according to the embodiment. The cooling controller 70 includes a second temperature sensor 73 and a flow rate sensor 78 on a collection side, in addition to the first temperature sensor 72 on a supply side. The second temperature sensor 73 measures a discharge temperature of a coolant discharged from the liquid-cooled heat exchanger 24. The second temperature sensor 73 may be provided between the coolant outlet port 61 and the liquid-cooled heat exchanger 24 or at the coolant outlet port 61. The flow rate sensor 78 measures a flow rate of the coolant of the liquid-cooled heat exchanger 24. The flow rate sensor 78 is provided on the supply side of the coolant line 106 and in this example, between the first temperature sensor 72 and the control valve 75.

[0070] As will be described below, the cooling controller 70 may be configured to acquire a supply temperature of a coolant supplied to the liquid-cooled heat exchanger 24, a discharge temperature of the coolant discharged from the liquid-cooled heat exchanger 24, and a flow rate of the coolant of the liquid-cooled heat exchanger 24, to calculate the amount of heat radiation to the liquid-cooled heat exchanger 24 based on the acquired supply temperature, the acquired discharge temperature, and the acquired flow rate of the coolant, and to limit the flow rate of the coolant of the liquid-cooled heat exchanger 24 such that the calculated amount of heat radiation is equal to or smaller than an allowable amount of heat radiation.

[0071] For example, the valve controller 76 first acquires a supply temperature of a coolant supplied to the liquid-cooled heat exchanger 24 from the first temperature sensor 72, acquires a discharge temperature of the coolant discharged from the liquid-cooled heat exchanger 24 from the second temperature sensor 73, and acquires a flow rate of the coolant of the liquid-cooled heat exchanger 24 from the flow rate sensor 78.

[0072] Next, the valve controller 76 calculates the amount of heat radiation to the liquid-cooled heat exchanger 24 based on the acquired supply temperature, the acquired discharge temperature, and the acquired coolant flow rate. The amount of heat radiation from the compressor 12 to the liquid-cooled heat exchanger 24 can be calculated, through a known method, from a temperature difference between the outlet and the inlet of the liquid-cooled heat exchanger 24 and the flow rate of the coolant flowing in the liquid-cooled heat exchanger 24.

[0073] Then, the valve controller 76 limits the flow rate of the coolant of the liquid-cooled heat exchanger 24 such that the calculated amount of heat radiation is equal to or smaller than the allowable amount of heat radiation. The allowable amount of heat radiation is an amount of heat radiation that is allowed to be radiated from the compressor 12 to the cooler 110 by the liquid-cooled heat exchanger 24, and for example, may be a value correlated with the supply temperature of the coolant or may be a constant value. It is possible to set the allowable amount of heat radiation as appropriate based on empirical knowledge of the designer or experiments and simulations by the designer.

[0074] The valve controller 76 compares the calculated amount of heat radiation with the allowable amount of heat radiation. When the calculated amount of heat radiation falls below the allowable amount of heat radiation, the valve controller 76 opens the control valve 75. In this case, the coolant supplied from the coolant line 106 flows into the liquid-cooled heat exchanger 24. Accordingly, the coolant is used in cooling of a refrigerant gas and an oil at the liquid-cooled heat exchanger 24. On the other hand, when the calculated amount of heat radiation exceeds the allowable amount of heat radiation, the valve controller 76 closes the control valve 75. In this case, the coolant supplied from the coolant line 106 is shut off. Accordingly, the coolant is not used in cooling at the liquid-cooled heat exchanger 24.

[0075] Even in this manner, the compressor 12 can reduce the amount of heat radiation to the cooler 110 and reduce a load on the cooler 110.

[0076] In a case where the control valve 75 is a type of which an opening degree can be controlled, the valve controller 76 may decrease the opening degree of the control valve 75 when the calculated amount of heat radiation exceeds the allowable amount of heat radiation. When the calculated amount of heat radiation falls below the allowable amount of heat radiation, the valve controller 76 may increase the opening degree of the control valve 75. Even in this manner, when the amount of heat radiation from the compressor 12 to the liquid-cooled heat exchanger 24 is large, cooling by the liquid-cooled heat exchanger 24 can be limited. In addition, when the amount of heat radiation decreases, the limitation can be alleviated or lifted.

[0077] In addition, also in the embodiment of Fig. 4, the coolant bypass valve 74 described above may be used in combination with the control valve 75 as in the embodiment of Fig. 3. The cooling controller 70 may be configured to interlock the coolant bypass valve 74 and the control valve 75 based on the calculated amount of heat radiation. For example, the valve controller 76 may control both the coolant bypass valve 74 and the control valve 75. The valve controller 76 may control the coolant bypass valve 74 in an interlocking manner with an operation of the control valve 75 described above based on the calculated amount of heat radiation. That is, when the calculated amount of heat radiation exceeds the allowable amount of heat radiation, the valve controller 76 may open the coolant bypass valve 74 or close the control valve 75. On the other hand, when the calculated amount of heat radiation falls below the allowable amount of heat radiation, the valve controller 76 may close the coolant bypass valve 74 or open the control valve 75.

[0078] Fig. 5 is a diagram schematically showing still another example of the cooling controller 70 according to the embodiment. The compressor 12 includes a compressor motor 80 that has a variable operation frequency (that is, a rotation speed), and the compressor main body 16 is driven by the compressor motor 80. The compressor motor 80 may be, for example, an electric motor or any other suitable type of motor. A discharge flow rate of the compressor main body 16 is increased by increasing the operation frequency of the compressor motor 80. In this case, an exhaust heat amount of the compressor 12 also increases. Conversely, the discharge flow rate of the compressor main body 16 is decreased by decreasing the operation frequency of the compressor motor 80. In this case, the exhaust heat amount of the compressor 12 also decreases.

[0079] The cooling controller 70 includes an inverter 82 that controls an operation frequency of the compressor motor 80. The compressor motor 80 and the inverter 82 are supplied with power from an external power source such as a commercial power source (three-phase alternating current power source). The inverter 82 is configured to adjust a frequency of power input from the external power source and to output any frequency to the compressor motor 80 under control by the cooling controller 70 as will be described later. The operation frequency of the compressor motor 80 corresponds to an output frequency of the inverter 82 and can be adjusted within, for example, a range of 30 Hz to 100 Hz or a range of 40 Hz to 70 Hz.

[0080] The cooling controller 70 is configured to acquire a supply temperature of a coolant supplied to the liquid-cooled heat exchanger 24 and to control an exhaust heat amount of the compressor 12 based on the acquired supply temperature of the coolant. The cooling controller 70 is configured to compare the acquired supply temperature of the coolant with the temperature threshold value and to control an operation frequency of the compressor motor 80 in a case where the supply temperature exceeds the temperature threshold value.

[0081] For example, the cooling controller 70 compares a supply temperature of a coolant acquired from the temperature sensor 72 with the temperature threshold value. When the supply temperature of the coolant falls below the temperature threshold value, the cooling controller 70 maintains an operation frequency of the compressor motor 80. Alternatively, the cooling controller 70 allows an increase in the operation frequency of the compressor motor 80. That is, an exhaust heat amount of the compressor 12 is allowed to increase.

[0082] On the other hand, when a supply temperature of a coolant exceeds the temperature threshold value, the cooling controller 70 decreases an operation frequency of the compressor motor 80. A decreased amount of the operation frequency may be a constant value or may be determined depending on a difference between the supply temperature of the coolant and the temperature threshold value. In this case, an exhaust heat amount of the compressor 12 can be decreased.

[0083] Even in this manner, the compressor 12 can decrease the amount of heat generated by the compressor 12 and can reduce a load on the cooler 110.

[0084] The embodiment described above, in which an operation frequency of the compressor motor is limited, may be used in combination with the embodiment which is described with reference to Figs. 1 to 4 and in which a flow rate of a coolant of the liquid-cooled heat exchanger 24 is limited.

[0085] The present invention has been described hereinbefore based on the examples. It is clear for those skilled in the art that the present invention is not limited to the embodiment, various design changes are possible, various modification examples are possible, and such modification examples are also within the scope of the present invention. Various characteristics described in relation to one embodiment are also applicable to other embodiments. A new embodiment generated through combination also has the effects of each of the combined embodiments.

[0086] In the embodiment described above, the liquid-cooled heat exchanger 24 and the air-cooled heat exchanger 26 are connected in series in the compressor cooling system 22, and the liquid-cooled heat exchanger 24 is provided upstream of the air-cooled heat exchanger 26. However, the compressor cooling system 22 can have other configurations. For example, the liquid-cooled heat exchanger 24 and the air-cooled heat exchanger 26 may be connected in series, and the air-cooled heat exchanger 26 may be provided upstream of the liquid-cooled heat exchanger 24. Alternatively, the liquid-cooled heat exchanger 24 and the air-cooled heat exchanger 26 may be connected in parallel.

[0087] In addition, the liquid-cooled heat exchanger 24 may be configured to cool only one of a refrigerant gas and an oil. Alternatively, the liquid-cooled heat exchanger 24 may include a first liquid-cooled heat exchanger that cools the refrigerant gas and a second liquid-cooled heat exchanger that cools the oil. Similarly, the air-cooled heat exchanger 26 may be configured to cool only one of the refrigerant gas and the oil. Alternatively, the air-cooled heat exchanger 26 may include a first air-cooled heat exchanger that cools the refrigerant gas and a second air-cooled heat exchanger that cools the oil.

[0088] In the embodiment described above, the cooling controller 70 is provided in the compressor 12, that is, in the compressor casing 28 of the compressor 12. Instead thereof, the cooling controller 70 may be provided outside the compressor 12. For example, the cooling controller 70 may be accommodated in a casing different from the compressor casing 28 or may be disposed adjacent to or close to the compressor casing 28 or away from the compressor 12.

[0089] The temperature sensor 72 for measuring a supply temperature of a coolant may be disposed at a location different from that of the compressor 12. For example, the temperature sensor 72 may be provided at the cooler 110. Alternatively, the temperature sensor 72 may be provided at a coolant line to the other device 102. The cooling controller 70 may acquire the supply temperature of the coolant from the temperature sensor 72 provided at the cooler 110 and/or the other device 102.

[0090] In order to alleviate or prevent a sudden change in a flow rate of a coolant of the liquid-cooled heat exchanger 24 in response to an operation of the coolant bypass valve 74 and/or the control valve 75, the cooling controller 70 may include an orifice or a constant flow rate valve that is provided in series with the coolant bypass valve 74 and/or in series with the control valve 75.

[0091] Although the present invention has been described using specific phrases based on the embodiment, the embodiment merely shows one aspect of the principles and applications of the present invention, and many modification examples and changes in disposition are allowed without departing from the concept of the present invention specified in the claims.

Brief Description of the Reference Symbols

[0092]

10 cryocooler
12 compressor
16 compressor main body
24 liquid-cooled heat exchanger
26 air-cooled heat exchanger
70 cooling controller
75 control valve
76 valve controller
80 compressor motor

Claims

1. An oil-lubricated cryocooler compressor (12) that compresses a refrigerant gas of a cryocooler (10), the cryocooler compressor (12) comprising:

a liquid-cooled heat exchanger (24) that cools the refrigerant gas and/or an oil through heat exchange with a coolant; and
a cooling controller (70) that is configured to acquire a supply temperature of the coolant supplied to the liquid-cooled heat exchanger (24) and to control a flow rate of the coolant of the liquid-cooled heat exchanger (24) and/or an exhaust heat amount of the cryocooler compressor (12) based on the acquired supply temperature of the coolant.

2. The cryocooler compressor (12) according to claim 1,
wherein the cooling controller (70) is configured to compare the acquired supply temperature of the coolant with a temperature threshold value and to limit the flow rate of the coolant of the liquid-cooled heat exchanger (24) in a case where the supply temperature exceeds the temperature threshold value.

3. The cryocooler compressor (12) according to claim 2,
wherein the cooling controller (70) includes

a control valve (75) that is connected in series with the liquid-cooled heat exchanger (24), and
a valve controller (76) that is configured to close the control valve (75) or to decrease an opening degree of the control valve (75) in a case where the supply temperature of the coolant exceeds the temperature threshold value.

4. The cryocooler compressor (12) according to claim 2,
wherein the cooling controller (70) includes

a bypass valve (74) that is connected in parallel with the liquid-cooled heat exchanger (24), and
a valve controller (76) that is configured to open the bypass valve (74) or to increase an opening degree of the bypass valve (74) in a case where the supply temperature of the coolant exceeds the temperature threshold value.

5. The cryocooler compressor (12) according to any one of claims 2 to 4, further comprising:

an air-cooled heat exchanger (26) that cools the refrigerant gas and/or the oil,
wherein the cooling controller (70) is configured to operate the air-cooled heat exchanger (26) in a case where the supply temperature exceeds the temperature threshold value.

6. The cryocooler compressor (12) according to claim 5,
wherein the cooling controller (70) is configured to acquire an ambient temperature and to stop the air-cooled heat exchanger (26) and/or to release limitation of the flow rate of the coolant based on the acquired ambient temperature.

7. The cryocooler compressor (12) according to claim 1,
wherein the cooling controller (70) is configured to

acquire a discharge temperature of the coolant discharged from the liquid-cooled heat exchanger (24) and the flow rate of the coolant of the liquid-cooled heat exchanger (24),
calculate an amount of heat radiation to the liquid-cooled heat exchanger (24) based on the acquired supply temperature, the acquired discharge temperature, and the acquired flow rate of the coolant, and
limit the flow rate of the coolant of the liquid-cooled heat exchanger (24) such that the calculated amount of heat radiation is equal to or smaller than an allowable amount of heat radiation.

8. The cryocooler compressor (12) according to claim 1, further comprising:

a compressor main body (16) that compresses the refrigerant gas; and
a compressor motor (80) that drives the compressor main body (16) and that has a variable operation frequency,
wherein the cooling controller (70) is configured to compare the acquired supply temperature of the coolant with a temperature threshold value and to limit the operation frequency of the compressor motor (80) in a case where the supply temperature exceeds the temperature threshold value.

9. An operation method of an oil-lubricated cryocooler compressor (12) that compresses a refrigerant gas of a cryocooler (10), the cryocooler compressor (12) including a liquid-cooled heat exchanger (24) that cools the refrigerant gas and/or an oil through heat exchange with a coolant, the method comprising:

acquiring a supply temperature of the coolant supplied to the liquid-cooled heat exchanger (24); and
controlling a flow rate of the coolant of the liquid-cooled heat exchanger (24) and/or an exhaust heat amount of the cryocooler compressor (12) based on the acquired supply temperature of the coolant.

FIG. 1

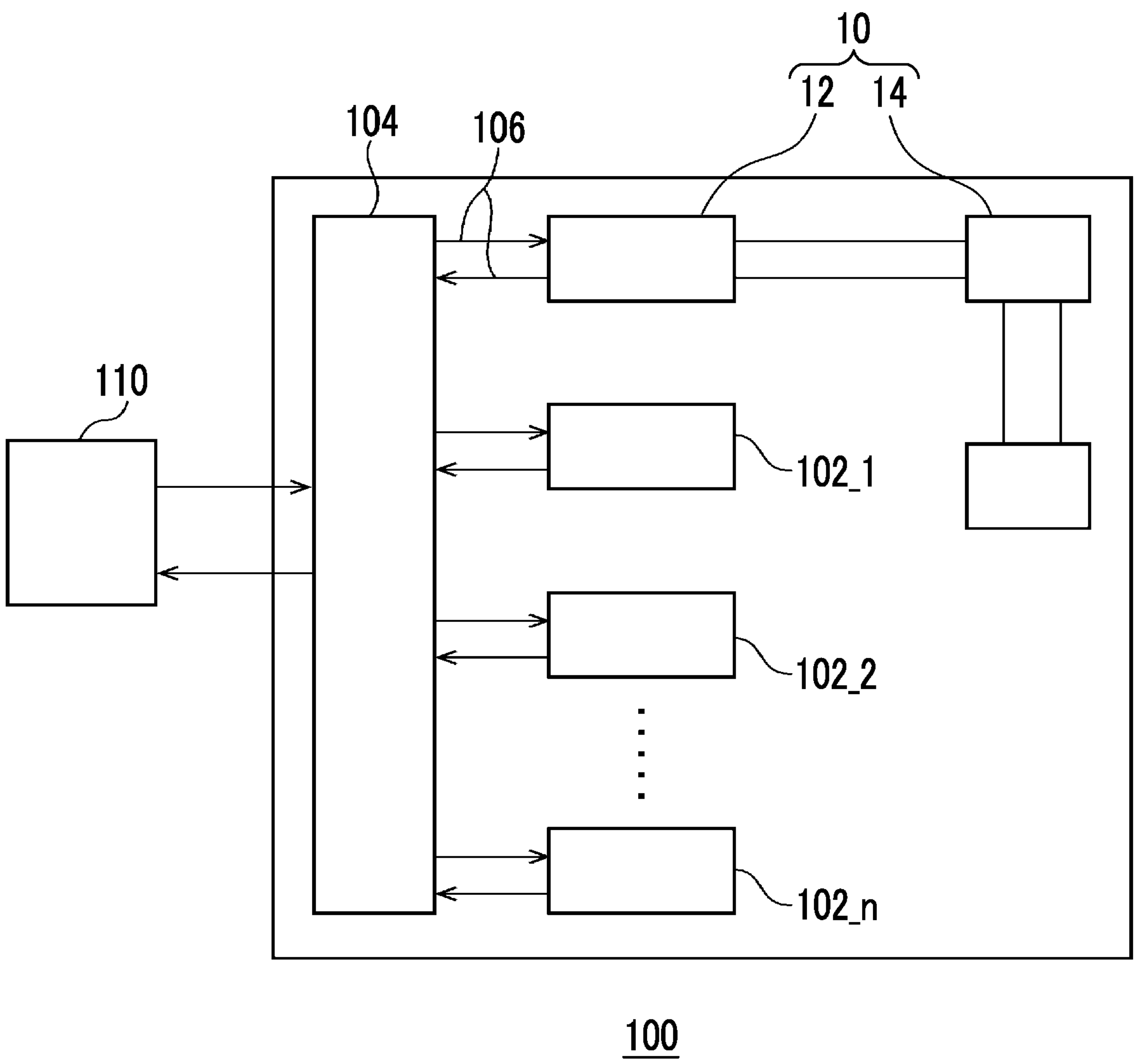

FIG. 2

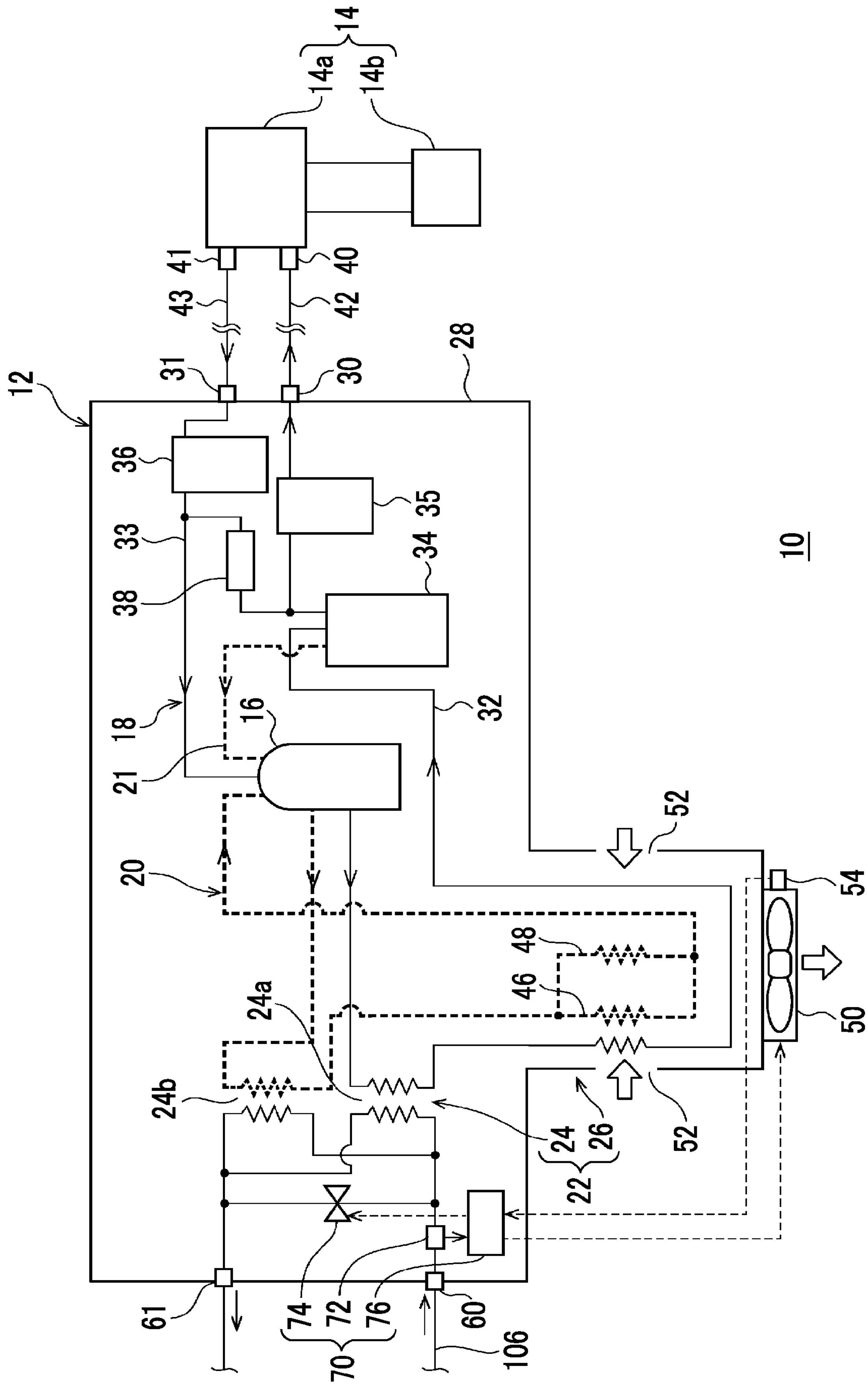
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FIG. 3

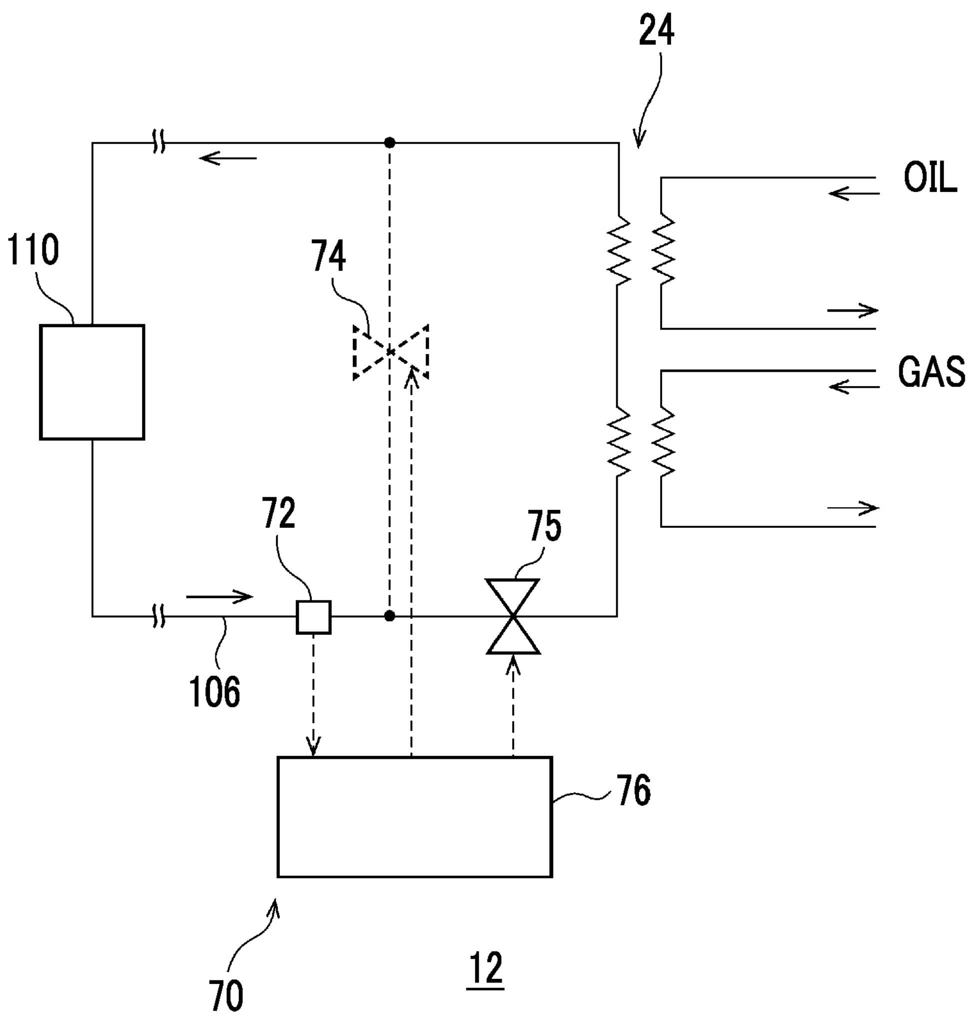


FIG. 4

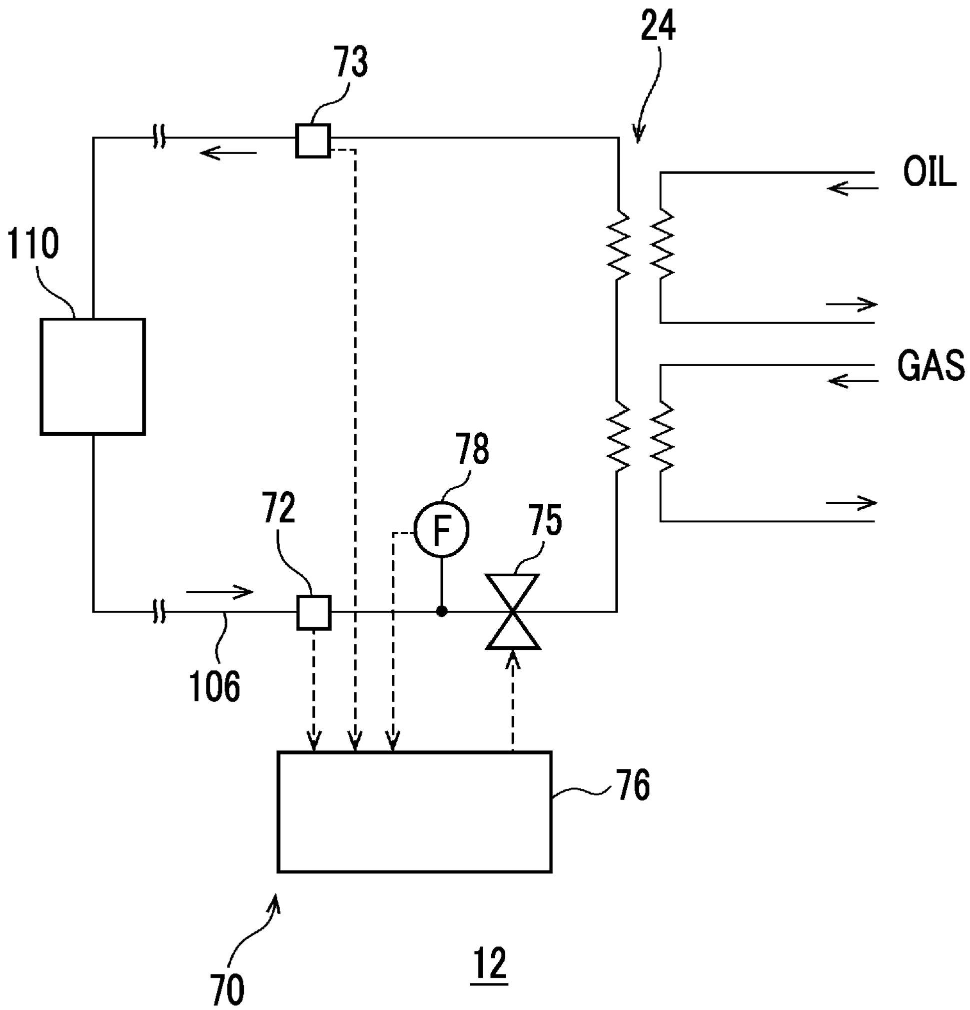
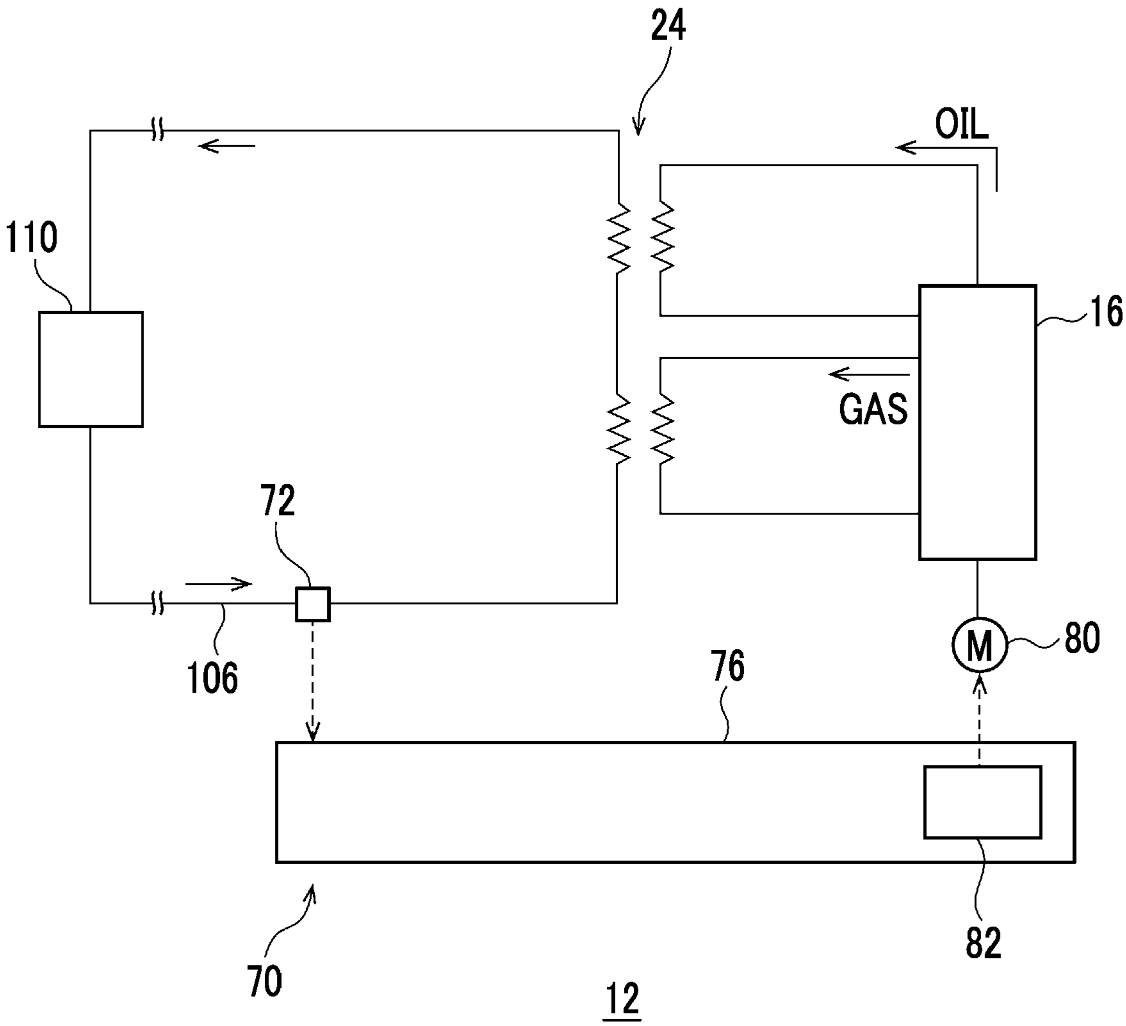


FIG. 5



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EUROPEAN SEARCH REPORT

Application Number
EP 23 20 2360

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	26 February 2024	Lucic, Anita

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