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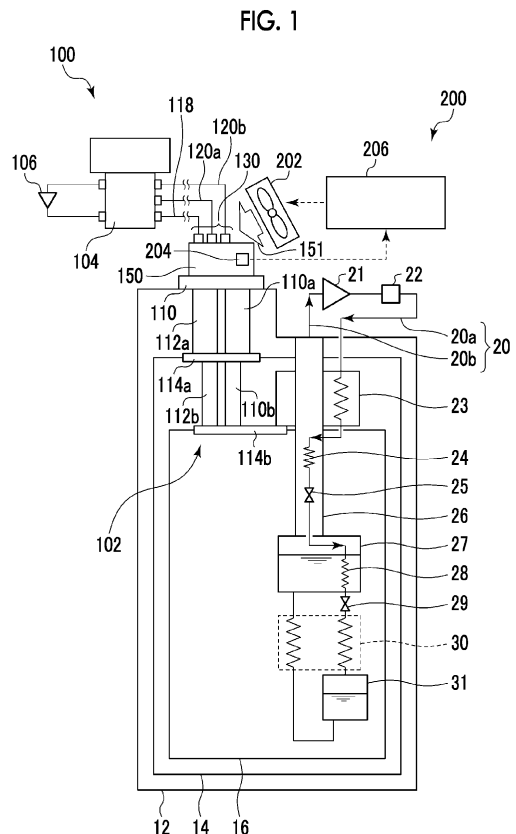
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PULSE TUBE CRYOCOOLER AND METHOD FOR COOLING DOWN PULSE TUBE CRYOCOOLER

(57) It is possible to promote heat radiation from a cold head of a pulse tube cryocooler (100). A pulse tube cryocooler (100) includes a cold head (102) including a first-stage pulse tube (110a) and a radiator (150) thermally coupled to a high-temperature end of the first-stage pulse tube (110a), and a forced cooling device (200) that forcibly cools the radiator (150) in cool-down of the pulse tube cryocooler (100) from an ambient temperature to a cryogenic temperature. The forced cooling device (200) may stop the forced cooling of the radiator (150) after the cool-down.



Description

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention relates to a pulse tube cryocooler and a method for cooling down a pulse tube cryocooler.

Description of Related Art

[0002] In the related art, there is known a cryogenic refrigerator using a phenomenon in which heat is absorbed in a case where helium-3 (^3He) of a liquid is dissolved and diluted in helium-4 (^4He) of the liquid, called a dilution refrigerator. The dilution refrigerator can provide cryogenic cooling equal to or lower than 0.1 K. An example of the dilution refrigerator is of a type in which a small-sized mechanical refrigerator, such as a Gifford-McMahon (GM) cryocooler, is mounted for precooling (for example, Japanese Unexamined Patent Publication No. 2005-90928).

SUMMARY OF THE INVENTION

[0003] For example, in advanced usage, such as cooling of a superconducting element of a quantum computer, there is a case where a dilution refrigerator that realizes cryogenic cooling of an order of millikelvin (mK) is used. In such cryogenic cooling, even vibration acceleration due to the operation of the GM cryocooler may turn into a heat source. Therefore, it has been proposed that, instead of the GM cryocooler, a pulse tube cryocooler that is operable with less vibration is employed as a precooling refrigerator of the dilution refrigerator.

[0004] In general, at the start of the dilution refrigerator, the precooling refrigerator is cooled from an ambient temperature (for example, a normal temperature of about 300K) to an intended cryogenic temperature (for example, a liquid helium temperature of about 4K). Such initial cooling is also called cool-down. Because the dilution refrigerator is a comparatively large-sized device, the heat capacity of a low-temperature section cooled by the precooling refrigerator tends to be increased, and a precooling refrigerator having a comparatively large cooling capacity (for example, a cooling capacity of more than 1 W at 4.2K) is desirably employed. For this reason, in cool-down, a comparatively large amount of heat corresponding to the cooling capacity of the precooling refrigerator is generated from an adiabatic compression process in a refrigeration cycle of the precooling refrigerator. The heat is radiated from a cold head high-temperature end of the precooling refrigerator to the outside. In a dilution refrigerator of existing design, a cold head high-temperature end of a GM cryocooler is exposed to outside air, and required heat radiation is obtained by natural convection cooling.

[0005] Note that the present inventors have recognized that, in a case where a pulse tube cryocooler is mounted as a precooling refrigerator in a dilution refrigerator, heat radiation in cool-down may be insufficient.

5 There is a concern that a cold head high-temperature end of the pulse tube cryocooler is heated to a considerably high temperature (for example, higher than an environmental temperature by tens of $^{\circ}\text{C}$) due to insufficient heat radiation, and due to the heating of the cold head high-temperature end of the pulse tube cryocooler, a time
10 required for cooling down the precooling refrigerator is extended. Because the cool-down of the precooling refrigerator is only part of preparation work for cooling a desired object to be cooled to a cryogenic temperature by the dilution refrigerator, it is desirable that the required time is as short as possible.

[0006] An exemplary object of a certain aspect of the present invention is to promote heat radiation from a cold head of a pulse tube cryocooler.

20 **[0007]** According to a certain aspect of the present invention, there is provided a pulse tube cryocooler including a cold head including a pulse tube and a radiator thermally coupled to a high-temperature end of the pulse tube, and a forced cooling device that forcedly cools the radiator in cool-down of the pulse tube cryocooler from
25 an ambient temperature to a cryogenic temperature.

[0008] According to a certain aspect of the present invention, there is provided a method for cooling down a pulse tube cryocooler. The pulse tube cryocooler includes a cold head including a pulse tube and a radiator thermally coupled to a high-temperature end of the pulse tube. The method includes performing cool-down of the pulse tube cryocooler from an ambient temperature to a cryogenic temperature, and forcedly cooling the radiator
30 in the cool-down of the pulse tube cryocooler.

[0009] According to the present invention, it is possible to promote heat radiation from the cold head of the pulse tube cryocooler.

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 pulse tube cryocooler according to the embodiment.

Fig. 3 is a diagram schematically showing another example of a high-temperature end of a cold head of the pulse tube cryocooler according to the embodiment.

Fig. 4 is a diagram schematically showing another example of a forced cooling device of the pulse tube cryocooler 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 the drawings, the same or equivalent components, members, and processes will be represented by the same reference numerals, and overlapping description will be omitted as appropriate. The scale and the shape of each of parts shown in the drawings are set for convenience to make the description easy to understand, and are not to be interpreted as limiting unless stated otherwise. The embodiment is merely an example and does not limit the scope of the present invention. All features described in the embodiment or combinations thereof are not necessarily essential to the present invention.

[0012] Fig. 1 is a diagram schematically showing a cryogenic device 10 according to an embodiment. The cryogenic device 10 is configured as a dilution refrigerator, and includes a pulse tube cryocooler 100 for precooling the dilution refrigerator. Though details will be described below, the pulse tube cryocooler 100 includes a cold head 102 and a forced cooling device 200. A radiator 150 is provided at a high-temperature end of the cold head 102, and the forced cooling device 200 is configured to forcibly cool the radiator 150 in cool-down of the pulse tube cryocooler 100 from an ambient temperature to a cryogenic temperature.

[0013] As shown in Fig. 1, the cryogenic device 10 includes a vacuum chamber 12, a first heat shield 14 and a second heat shield 16, and a helium circulation circuit 20 that operates as a dilution refrigerator.

[0014] The vacuum chamber 12 is an adiabatic vacuum chamber that provides a cryogenic temperature vacuum environment suitable for the dilution refrigerator, and is also called a cryostat. The vacuum chamber 12 is a casing of the dilution refrigerator. In general, the vacuum chamber 12 has a cylindrical shape, and includes a top plate and a bottom plate having a substantially flat circular shape, and a cylindrical sidewall that connects the top plate and the bottom plate. The pulse tube cryocooler 100 is provided on, for example, the top plate of the vacuum chamber 12. The vacuum chamber 12 is formed of, for example, a metallic material, such as stainless steel, or other suitable high strength materials to withstand ambient pressure (for example, atmospheric pressure).

[0015] To thermally protect a low-temperature section of the helium circulation circuit 20 from an external environment and radiant heat from the vacuum chamber 12, the first heat shield 14 and the second heat shield 16 are disposed to surround the low-temperature section of the helium circulation circuit 20 in the vacuum chamber 12. The heat shield is formed of, for example, a metallic material, such as copper, or other materials having high thermal conductivity. The first heat shield 14 is cooled to a first cooling temperature, for example, less than 100K (for example, about 30K to 60K), and the second heat shield 16 is disposed inside the first heat shield 14 and is cooled to a second cooling temperature lower than the first cooling temperature, for example, about 3K to 10K. For cooling, the first heat shield 14 is thermally coupled

to a first cooling stage 114a of the pulse tube cryocooler 100, and the second heat shield 16 is thermally coupled to a second cooling stage 114b of the pulse tube cryocooler 100.

[0016] The helium circulation circuit 20 includes a pump 21 that circulates ^3He gas. The pump 21 is, for example, a vacuum pump, and is disposed outside the vacuum chamber 12, that is, in the ambient environment. ^3He gas at an ambient temperature (for example, room temperature) delivered by the pump 21 is sent into an outward-side flow path 20a of the helium circulation circuit 20 through a trap 22.

[0017] The outward-side flow path 20a is provided with a precooling heat exchanger 23, a ^3He condenser 24, and main impedance 25. The precooling heat exchanger 23 is thermally coupled to the second cooling stage 114b of the pulse tube cryocooler 100, and cools ^3He gas to the above-described second cooling temperature. The outward-side flow path 20a enters a return pipe 26 that is a part of an inward-side flow path 20b extending from a fractional distillation chamber 27 to the pump 21, downstream of the precooling heat exchanger 23, and the ^3He condenser 24 and the main impedance 25 are disposed in the return pipe 26. ^3He gas cooled by the precooling heat exchanger 23 is condensed and liquefied by the ^3He condenser 24 and the main impedance 25.

[0018] The outward-side flow path 20a is further provided with a first heat exchanger 28, sub-impedance 29, and a second heat exchanger 30, and the outward-side flow path 20a is connected to a mixing chamber 31 in front. The first heat exchanger 28 is provided in the fractional distillation chamber 27, and the sub-impedance 29 and the second heat exchanger 30 are provided outside the fractional distillation chamber 27. The second heat exchanger 30 is provided between the fractional distillation chamber 27 and the mixing chamber 31, and is configured to exchange heat between a flow path entering the mixing chamber 31 and a flow path exiting the mixing chamber 31.

[0019] Liquid ^3He liquefied by the ^3He condenser 24 and the main impedance 25 is delivered to the first heat exchanger 28. The fractional distillation chamber 27 selectively extracts ^3He from a ^3He - ^4He mixed solution using a difference in saturated vapor pressure of ^3He and ^4He , and is maintained at a temperature of about 0.5 to 0.7K, for example. Liquid ^3He delivered to the first heat exchanger 28 is cooled to a cooling temperature of the fractional distillation chamber 27 by heat exchange with a liquid in the fractional distillation chamber 27. Liquid ^3He is further cooled (for example, about 100mK) by the second heat exchanger 30 by way of the sub-impedance 29 and is delivered to the mixing chamber 31.

[0020] Liquid helium of the mixing chamber 31 is separated into two phases of a dense phase of 100% ^3He and a dilute phase of ^4He -6.4% ^3He in which ^3He is blended in ^4He , and based on a difference in density, an upper phase is a dense phase (^3He liquid) and a lower phase is a dilute phase (^4He -6.4% ^3He liquid). Heat

absorption occurs in a case where ^3He in a dense phase is blended in a dilute phase, and tens of mK or a lower temperature is generated. A desired object to be cooled is disposed in the mixing chamber 31. In this manner, the dilution refrigerator can provide cryogenic cooling of an order of millikelvin (mK).

[0021] Fig. 2 is a diagram schematically showing the pulse tube cryocooler 100 according to the embodiment. Referring to Figs. 1 and 2, in the embodiment, the pulse tube cryocooler 100 is a GM type four-valve two-stage pulse tube cryocooler, and includes a two-stage cold head 102, a valve unit 104, and a compressor 106. The pulse tube cryocooler 100 is configured as a valve unit separation type in which the valve unit 104 is disposed to be separated from the cold head 102.

[0022] The cold head 102 includes a first-stage pulse tube 110a, a first-stage regenerator 112a, the first cooling stage 114a, a second-stage pulse tube 110b, a second-stage regenerator 112b, the second cooling stage 114b, a top flange 116, and the radiator 150.

[0023] As shown in Fig. 1, the cold head 102 is provided in the vacuum chamber 12 by attaching the top flange 116 to the vacuum chamber 12. In many cases, the cold head 102 is provided to be attachable to and detachable from the top plate or the top of the vacuum chamber 12 in such a manner that a tube axis direction of pulse tubes (110a, 110b) matches a vertical direction, and the pulse tubes, the regenerators (112a, 112b), and the cooling stages (114a, 114b) are disposed in the vacuum chamber 12. The cold head 102 may be provided in the vacuum chamber 12 in other postures and dispositions.

[0024] The first-stage pulse tube 110a and the first-stage regenerator 112a connect the top flange 116 to the first cooling stage 114a, and the second-stage pulse tube 110b and the second-stage regenerator 112b connect the top flange 116 to the second cooling stage 114b. The second-stage regenerator 112b is connected in series to the first-stage regenerator 112a. The two regenerators, the first-stage pulse tube 110a, and the second-stage pulse tube 110b are disposed in parallel with each other.

[0025] As shown in Fig. 2, a low-temperature end of the first-stage regenerator 112a communicates with a low-temperature end of the first-stage pulse tube 110a, and a low-temperature end of the second-stage regenerator 112b communicates with a low-temperature end of the second-stage pulse tube 110b. The first cooling stage 114a is provided at the low-temperature ends of the first-stage pulse tube 110a and the first-stage regenerator 112a, and the second cooling stage 114b is provided at the low-temperature ends of the second-stage pulse tube 110b and the second-stage regenerator 112b. The first cooling stage 114a and the second cooling stage 114b are formed of, for example, a metallic material, such as copper, and other materials having high thermal conductivity.

[0026] The radiator 150 is thermally coupled to high-temperature ends of the first-stage pulse tube 110a and the second-stage pulse tube 110b. The radiator 150 is

fixed to the top flange 116 on an opposite side of the cooling stages. The radiator 150 is formed of, for example, aluminum or an aluminum alloy. Alternatively, the radiator 150 may be formed of, for example, a metallic material, such as copper, or other materials having high thermal conductivity.

[0027] In the example shown in the drawing, end surfaces of the high-temperature ends of the first-stage pulse tube 110a and the second-stage pulse tube 110b are in contact with a bottom surface of the radiator 150 or only the high-temperature ends of the pulse tubes slightly penetrate the radiator 150. Note that greater portions of the pulse tubes may be disposed in the radiator 150.

[0028] For example, at most 1/4 of a total length of the first-stage pulse tube 110a in an axial direction may extend inside the radiator 150. With this, a 1/4 portion or less on a high-temperature side of the length in the axial direction of the first-stage pulse tube 110a is disposed in the radiator 150, and a remaining 3/4 portion or more is disposed in the vacuum chamber 12. A high-temperature section of the first-stage pulse tube 110a disposed in the radiator 150 can actively exchange heat with outside air through the radiator 150, and this may advantageously act on cooling of a cold head high-temperature end.

[0029] As required, along with the first-stage pulse tube 110a or in place of the first-stage pulse tube 110a, at most 1/4 of a total length of the second-stage pulse tube 110b in an axial direction may extend inside the radiator 150.

[0030] The radiator 150 is disposed outside the vacuum chamber 12 and is exposed to the ambient environment, and can come into contact with outside air. Accordingly, the radiator 150 can be cooled by natural convection. The radiator 150 can be cooled by the forced cooling device 200 described below. In the radiator 150, as described below, a radiating fin may be formed to increase a surface area (heat exchange area).

[0031] The valve unit 104 includes main pressure switching valves (V1, V2), first-stage sub-pressure switching valves (V3, V4), and second-stage sub-pressure switching valves (V5, V6). Typically, the valve unit 104 is configured in a form of a rotary valve in which the main pressure switching valves, the first-stage sub-pressure switching valves, and the second-stage sub-pressure switching valves are incorporated. Accordingly, the valve unit 104 includes the rotary valve and a valve motor that rotates the rotary valve.

[0032] The main pressure switching valves (V1, V2) are connected to the high-temperature end of the first-stage regenerator 112a by a regenerator communication passage 118, the first-stage sub-pressure switching valves (V3, V4) are connected to the high-temperature end of the first-stage pulse tube 110a by a first-stage pulse tube communication passage 120a, and the second-stage sub-pressure switching valves (V5, V6) are connected to the high-temperature end of the second-stage pulse tube 110b by a second-stage pulse tube com-

munication passage 120b. The main pressure switching valves (V1, V2) operate to alternately connect the first-stage regenerator 112a and the second-stage regenerator 112b to a discharge port and a suction port of the compressor 106, the first-stage sub-pressure switching valves (V3, V4) operate to alternately connect the first-stage pulse tube 110a to the discharge port and the suction port of the compressor 106, and the second-stage sub-pressure switching valves (V5, V6) operate to alternately connect the second-stage pulse tube 110b to the discharge port and the suction port of the compressor 106.

[0033] The first-stage pulse tube communication passage 120a may be provided with, for example, a first-stage flow adjustment element 122a, such as an orifice, and the second-stage pulse tube communication passage 120b may be provided with a second-stage flow adjustment element 122b.

[0034] The pulse tube cryocooler 100 may be provided with a first-stage buffer line 124a that connects a first-stage buffer volume 126a to the high-temperature end of the first-stage pulse tube 110a via a first-stage buffer orifice 128a, and a second-stage buffer line 124b that connects a second-stage buffer volume 126b to the high-temperature end of the second-stage pulse tube 110b via a second-stage buffer orifice 128b. The first-stage buffer line 124a may be connected to the first-stage pulse tube communication passage 120a between the first-stage pulse tube 110a and the first-stage flow adjustment element 122a, and the second-stage buffer line 124b may be connected to the second-stage pulse tube communication passage 120b between the second-stage pulse tube 110b and the second-stage flow adjustment element 122b. In Fig. 1, for convenience, the buffer lines are not shown.

[0035] Because the valve unit 104 is disposed to be separated from the cold head 102, the valve unit 104 is connected to the high-temperature ends of the first-stage regenerator 112a, the first-stage pulse tube 110a, and the second-stage pulse tube 110b by pipes. The pipes may be, for example, flexible pipes, such as flexible hoses, or may be rigid pipes.

[0036] The radiator 150 is provided with, for example, fluid couplings 130, such as self-sealing couplings, to which the pipes, that is, the regenerator communication passage 118, the first-stage pulse tube communication passage 120a, and the second-stage pulse tube communication passage 120b are connected. As shown in Figs. 1 and 3, the fluid couplings 130 may be provided on, for example, a top surface of the radiator 150. To prevent or reduce an influence of a temperature increase of the radiator 150 on the fluid coupling 130, a heat insulator may be interposed between the fluid couplings 130 and the radiator 150. The heat insulator may be, for example, a plate made of engineering plastic.

[0037] Because the GM type four-valve pulse tube cryocooler itself has been well known, further description of each component of the pulse tube cryocooler 100 will be

omitted.

[0038] With such a configuration, the pulse tube cryocooler 100 can generate PV work at the low-temperature end of the pulse tube by appropriately delaying a phase of displacement oscillation of a gas element (also called gas piston) in the pulse tube with respect to pressure oscillation of working gas, and can cool the cooling stage to an intended cooling temperature. The first cooling stage 114a may be cooled to the first cooling temperature, for example, less than 100K (for example, about 30K to 60K), and the second cooling stage 114b may be cooled to the second cooling temperature lower than the first cooling temperature, for example, about 3K to 10K.

[0039] However, at the start of the dilution refrigerator, the pulse tube cryocooler 100 is rapidly cooled from the ambient temperature (for example, a normal temperature of about 300K) to the intended cryogenic temperature (that is, the above-described first and second cooling temperatures). After such cool-down is completed, the pulse tube cryocooler 100 transits to a normal cooling operation to maintain the reached cooling temperature.

[0040] In the cool-down, a comparatively large amount of heat corresponding to the cooling capacity of the pulse tube cryocooler 100 is generated from an adiabatic compression process in a refrigeration cycle of the pulse tube cryocooler 100. In particular, because the dilution refrigerator is a comparatively large-sized device, the heat capacity of a low-temperature section, such as the first heat shield 14, the second heat shield 16, and the helium circulation circuit 20, tends to be increased, and an amount of heat that is generated in the cool-down to cool the low-temperature section is also increased. The heat is radiated from the cold head high-temperature end of the pulse tube cryocooler 100, that is, the radiator 150 to the outside.

[0041] As described at the beginning of the present specification, the present inventors have recognized that, in a case where the pulse tube cryocooler 100 is mounted as a precooling refrigerator in a dilution refrigerator, heat radiation from the cold head 102 in the cool-down is insufficient, and the radiator 150 may be heated to a considerably high temperature (for example, higher than 60°C to 90°C).

[0042] In a dilution refrigerator of existing design, a GM cryocooler is used as a precooling refrigerator. In the GM cryocooler, in general, a pressure switching mechanism, such as a rotary valve, is incorporated at a high-temperature end of a cold head. The pressure switching mechanism of the cold head is connected to a compressor by a pipe exclusively for supply and a pipe exclusively for collection of working gas. For this reason, working gas heated at the cold head high-temperature end flows from the cold head to the compressor in one direction through a collection pipe. Along with the working gas flow, a comparatively large amount of heat can be carried away from the cold head to the compressor. In the GM cryocooler, in addition to natural convection cooling of the cold head high-temperature end, such working gas collection flow

advantageously acts on heat radiation.

[0043] However, in the pulse tube cryocooler 100, the valve unit 104 is separated from the cold head 102. The separated valve unit 104 is connected to the cold head 102 by pipes as described above. All of the regenerator communication passage 118, the first-stage pulse tube communication passage 120a, and the second-stage pulse tube communication passage 120b that connect the valve unit 104 and the cold head 102 are bidirectional flow paths of working gas. That is, in these flow paths, working gas inflow from the compressor 106 to the cold head 102 and working gas outflow from the cold head 102 to the compressor 106 backward alternately occur, and working gas flows in a reciprocating manner. Because the working gas flow is not in one direction, the amount of heat that is carried away from the radiator 150 by working gas may be made comparatively small.

[0044] As a result, in a case where the amount of heat that is generated in the cool-down exceeds a heat radiation amount by natural convection cooling, a large temperature increase may occur in the cold head high-temperature end of the pulse tube cryocooler 100. Due to the temperature increase in the cold head high-temperature end of the pulse tube cryocooler 100, there is a concern that a cool-down time of the pulse tube cryocooler 100 is extended. Because the cool-down of the pulse tube cryocooler 100 is only part of preparation work for cooling a desired object to be cooled to a cryogenic temperature by the dilution refrigerator, it is desirable that the required time is as short as possible.

[0045] Accordingly, in the embodiment, the pulse tube cryocooler 100 includes the forced cooling device 200. The forced cooling device 200 is configured to forcibly cool the radiator 150 in the cool-down of the pulse tube cryocooler 100 from the ambient temperature to the cryogenic temperature.

[0046] As an example, the forced cooling device 200 includes an air-cooled cooler that is configured to provide an air flow 151 for cooling to the radiator 150, for example, a cooling fan 202. The cooling fan 202 is disposed close to or adjacent to the radiator 150 to blow air into the radiator 150 (or to suck air around the radiator 150).

[0047] Therefore, according to the embodiment, it is possible to promote heat radiation from the high-temperature end of the cold head 102 of the pulse tube cryocooler 100 by forced cooling of the radiator 150 using the cooling fan 202. With this, it is possible to suppress an excessive temperature increase of the high-temperature end of the cold head 102 and an increase in cool-down time due to the temperature increase.

[0048] The cooling fan 202 may be disposed to be separated from the cold head 102. That is, the cooling fan 202 may not be mounted on the cold head 102 and may be disposed away from the cold head 102. With such a configuration, vibration that may be caused by the cooling fan 202 in the operation of the cooling fan 202 is prevented from being transmitted to the low-temperature section of the dilution refrigerator through the cold head 102. In

this case, the cooling fan 202 may be supported by a support structure that supports the dilution refrigerator on a floor surface, such as a support frame. Alternatively, the cooling fan 202 may be supported by a dedicated support structure that is provided separately from the support structure of the dilution refrigerator to dispose the cooling fan 202 near the radiator 150.

[0049] Fig. 3 is a diagram schematically showing another example of the high-temperature end of the cold head 102 of the pulse tube cryocooler 100 according to the embodiment. As shown in Fig. 3, the cooling fan 202 may be mounted on the cold head 102. The cooling fan 202 is attached to a bracket 160 provided on the top flange 116 of the cold head 102 and is disposed adjacent to the radiator 150. With the operation of the cooling fan 202, it is possible to provide an air flow for cooling to the radiator 150.

[0050] The radiator 150 includes radiating fins 152 to increase a heat exchange area with the air flow. The radiating fins 152 extend in the axial direction of the pulse tube. Accordingly, as shown in the drawing, the radiating fins 152 protrude upward from a bottom plate of the radiator 150 in contact with the top flange 116. The cooling fan 202 is disposed obliquely upward of the radiating fins 152. Therefore, the cooling fan 202 blows an air flow toward slits between the radiating fins 152 (or sucks an air flow from the slits), and as a result, the cooling fan 202 can promote heat exchange of the air flow of the radiating fins 152, and can effectively cool the radiator 150. From the same viewpoint, the cooling fan 202 may be disposed upward of the radiating fin 152.

[0051] In the example shown in the drawing, one cooling fan 202 is provided on one side of the radiator 150. Instead of this, a plurality of cooling fans 202 may be provided around the radiator 150. For example, a set of cooling fans 202 may be disposed on both sides of the radiator 150. Alternatively, four cooling fans 202 may be disposed around the radiator 150 at intervals of 90 degrees.

[0052] The forced cooling device 200 may be configured to stop the forced cooling of the radiator 150 after the cool-down. With such a configuration, in a normal cooling operation (that is, in cooling of the desired object to be cooled by the dilution refrigerator) after the cool-down of the pulse tube cryocooler 100 is completed, the forced cooling device 200 is not operated, and vibration transmission from the forced cooling device 200 to the low-temperature section of the dilution refrigerator cannot occur. Therefore, it is possible to restrain a bad influence of vibration on the cooling performance of the dilution refrigerator.

[0053] Referring to Fig. 1 again, the forced cooling device 200 may include a sensor that detects the state of the pulse tube cryocooler 100, for example, a temperature sensor 204, and a controller 206 that is configured to determine whether or not the pulse tube cryocooler 100 is in the cool-down, based on an output of the sensor and operate the cooler (for example, the cooling fan 202)

in the cool-down.

[0054] The controller 206 is realized by elements or circuits including a CPU or a memory of a computer in terms of a hardware configuration and is realized by a computer program and the like in terms of a software configuration, but is shown in the drawing as appropriate as a functional block that is realized by cooperation of the hardware configuration and the software configuration. It will be understood by those skilled in the art that the functional block can be realized in a variety of manners by a combination of hardware and software.

[0055] The temperature sensor 204 is provided in the cold head 102, specifically, for example, the radiator 150. The controller 206 may be configured to compare a measured temperature (in this case, a measured temperature of the radiator 150) of the cold head 102 measured by the temperature sensor 204 with a temperature threshold, and operate the cooler in a case where the measured temperature of the cold head 102 exceeds the temperature threshold. The temperature threshold may be set based on the temperature of the radiator 150 assumed in the cool-down of the pulse tube cryocooler 100 or can be set as appropriate based on empirical knowledge of a designer, an experiment or a simulation by the designer, or the like.

[0056] In this case, the temperature sensor 204 is connected to the controller 206 in a communicable manner to transmit measured temperature data indicating the measured temperature to the controller 206. The controller 206 receives the measured temperature data from the temperature sensor 204 and compares the measured temperature with the temperature threshold. The controller 206 operates the cooling fan 202 in a case where the measured temperature exceeds the temperature threshold. That is, the controller 206 starts the cooling fan 202 by switching the cooling fan 202 from off to on. On the other hand, the controller 206 does not start the cooling fan 202 (remains the cooling fan 202 off) in a case where the measured temperature does not exceed the temperature threshold.

[0057] In this way, the controller 206 regards a state in which the radiator 150 is heated compared to the ambient temperature (specifically, a case where the measured temperature of the radiator 150 is higher than the temperature threshold), as the pulse tube cryocooler 100 being in the cool-down, and operates the forced cooling device 200 to forcibly cool the radiator 150. On the other hand, the controller 206 regards a state in which the radiator 150 is cooled to about the ambient temperature (specifically, a case where the measured temperature of the radiator 150 is lower than the temperature threshold), as the end of the cool-down of the pulse tube cryocooler 100 ends, and stops the operation of the forced cooling device 200. After the end of the cool-down, as described above, the pulse tube cryocooler 100 transits to the normal cooling operation. In such a manner, in the normal cooling operation of the pulse tube cryocooler 100, the forced cooling device 200 is stopped, and the occurrence

of vibration by the operation is prevented.

[0058] The temperature sensor 204 may be provided in the first cooling stage 114a or the second cooling stage 114b, instead of being provided in the radiator 150. The temperature sensor 204 may be provided in the first heat shield 14 or the second heat shield 16. Also in such a manner, the controller 206 can determine whether or not the pulse tube cryocooler 100 is in the cool-down, based on the output of the temperature sensor 204. The temperature sensor 204 may be provided a cooling stage (not shown) of the cryogenic device 10 (dilution refrigerator) or an object to be cooled.

[0059] The sensor that detects the state of the pulse tube cryocooler 100 may be a pressure sensor that measures working gas pressure of the cold head 102 or a sensor that measures power consumption of the compressor 106, in place of the temperature sensor 204. It is assumed that the working gas pressure or the power consumption increases in the cool-down compared to the normal cooling operation. Therefore, the controller 206 can determine whether or not the pulse tube cryocooler 100 is in the cool-down, based on the output of such a sensor.

[0060] Fig. 4 is a diagram schematically showing another example of the forced cooling device 200 of the pulse tube cryocooler 100 according to the embodiment. The forced cooling device 200 may include a liquid-cooled cooler, and an internal flow path 154 through which a coolant (for example, cooling water) flows may be formed in the radiator 150. Also in such a manner, similarly to the cooling fan 202, it is possible to forcibly cool the radiator 150.

[0061] For example, a coolant 156 is supplied from a coolant source (not shown) to the internal flow path 154 of the radiator 150. In the internal flow path 154, the coolant 156 cools the radiator 150 by heat exchange with the radiator 150. The coolant (schematically represented by an arrow 158) that is discharged from the internal flow path 154 may be returned to the coolant source, cooled again, and supplied to the radiator 150.

[0062] The present invention has been described above based on the examples. It will be understood by those skilled in the art that the present invention is not limited to the embodiment, various modification examples are possible, and such modification examples are also within the scope of the present invention. Various features described concerning a certain embodiment are also applicable to other embodiments. A new embodiment resulting from combinations also has the effects of each of the combined embodiments.

[0063] In the above-described embodiment, although a case where the pulse tube cryocooler 100 is the four-valve type has been described as an example, the pulse tube cryocooler 100 may have other forms, such as a double inlet type. The pulse tube cryocooler 100 is not limited to the GM type, and may be a Stirling type pulse tube cryocooler. The pulse tube cryocooler 100 is not limited to a two-stage type, and may be a single-stage

type, or a three-stage type or other multi-stage pulse tube cryocoolers.

[0064] In the above-described embodiment, although a case where the pulse tube cryocooler 100 is applied to the dilution refrigerator has been described as an example, the pulse tube cryocooler 100 may be applied in other applications in which the pulse tube cryocooler 100 is mounted as a precooling refrigerator in other forms of cryogenic refrigerators.

[0065] Although the present invention has been described using specific words and phrases based on the embodiment, the embodiment merely shows one aspect of the principle and application of the present invention, and various modifications and improvements can be made within the scope of the present invention described in claims.

Brief Description of the Reference Symbols

[0066]

100: pulse tube cryocooler
102: cold head
104: valve unit
110a: first-stage pulse tube
110b: second-stage pulse tube
150: radiator
152: radiating fin
200: forced cooling device
202: cooling fan
204: temperature sensor
206: controller

Claims

1. A pulse tube cryocooler (100) comprising:

a cold head (102) including a pulse tube (110a, 110b) and a radiator (150) thermally coupled to a high-temperature end of the pulse tube (110a, 110b); and
a forced cooling device (200) that forcedly cools the radiator (150) in cool-down of the pulse tube cryocooler (100) from an ambient temperature to a cryogenic temperature.

2. The pulse tube cryocooler (100) according to claim 1, wherein the forced cooling device (200) stops the forced cooling of the radiator (150) after the cool-down.

3. The pulse tube cryocooler (100) according to claim 1,

wherein the forced cooling device (200) includes a sensor that detects a state of the pulse tube cryocooler (100),
an air-cooled or liquid-cooled cooler that cools

the radiator (150), and

a controller (206) configured to determine whether or not the pulse tube cryocooler (100) is in the cool-down, based on an output of the sensor, and operate the cooler in the cool-down.

4. The pulse tube cryocooler (100) according to claim 3,

wherein the sensor includes a temperature sensor (204) provided in the cold head (102), and the controller (206) is configured to compare a measured temperature of the cold head (102) measured by the temperature sensor (204) with a temperature threshold and operate the cooler in a case where the measured temperature of the cold head (102) exceeds the temperature threshold.

5. The pulse tube cryocooler (100) according to claim 1, wherein the forced cooling device (200) includes a cooling fan disposed to be separated from the cold head (102).

6. The pulse tube cryocooler (100) according to claim 1, wherein at most 1/4 of a total length of the pulse tube (110a, 110b) in an axial direction extends inside the radiator (150) .

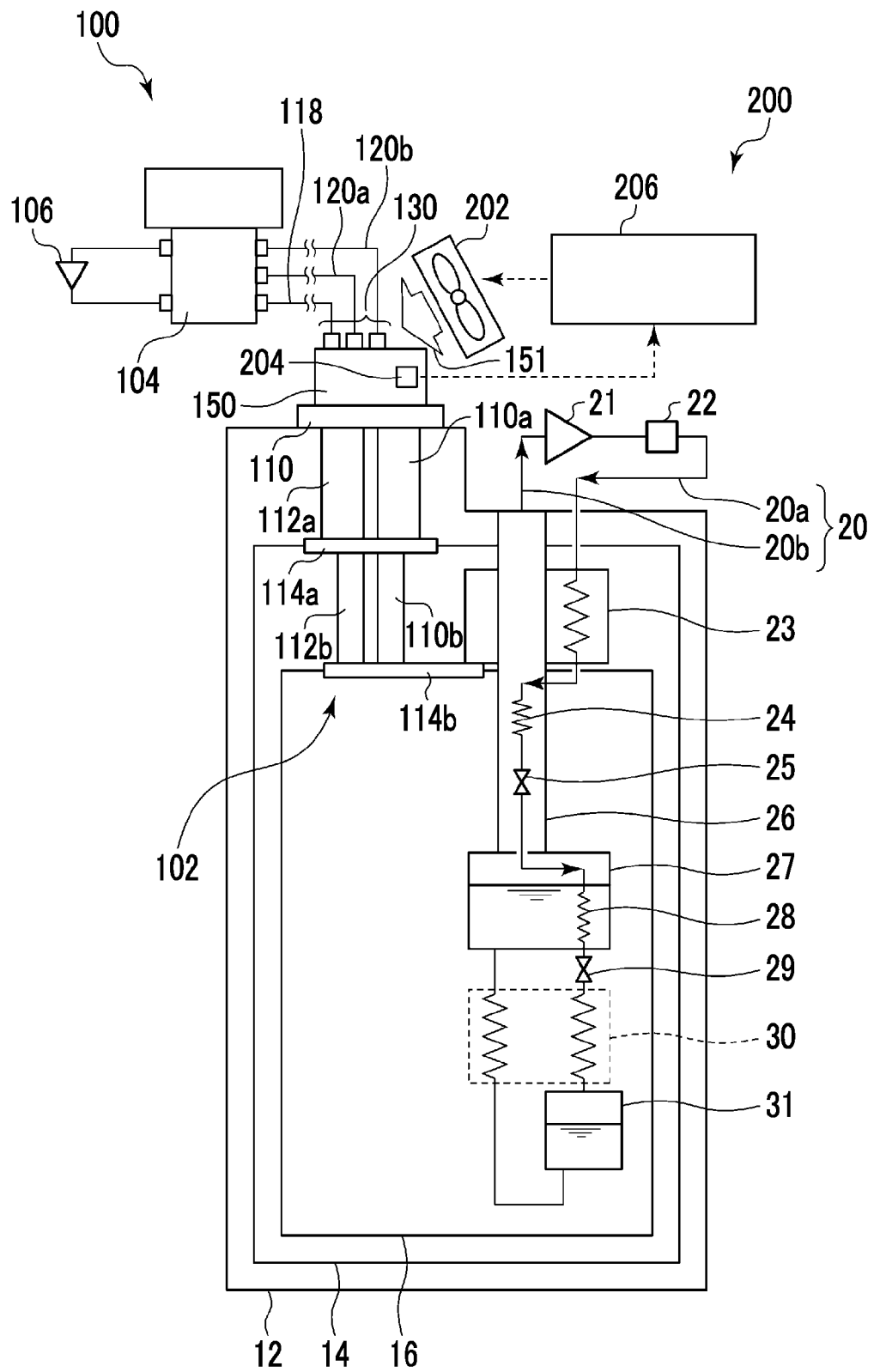
7. The pulse tube cryocooler (100) according to claim 1, wherein the radiator (150) includes a radiating fin that extends in an axial direction of the pulse tube (110a, 110b), and the forced cooling device (200) includes a cooling fan disposed upward or obliquely upward of the radiating fin.

8. The pulse tube cryocooler (100) according to any one of claims 1 to 7, further comprising: a valve unit disposed to be separated from the cold head (102) and connected to the high-temperature end of the pulse tube (110a, 110b) by a pipe.

9. A method for cooling down a pulse tube cryocooler (100) that includes a cold head (102) including a pulse tube (110a, 110b) and a radiator (150) thermally coupled to a high-temperature end of the pulse tube (110a, 110b), the method comprising:

performing cool-down of the pulse tube cryocooler (100) from an ambient temperature to a cryogenic temperature; and
forcedly cooling the radiator (150) in the cool-down of the pulse tube cryocooler (100).

FIG. 1



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FIG. 2

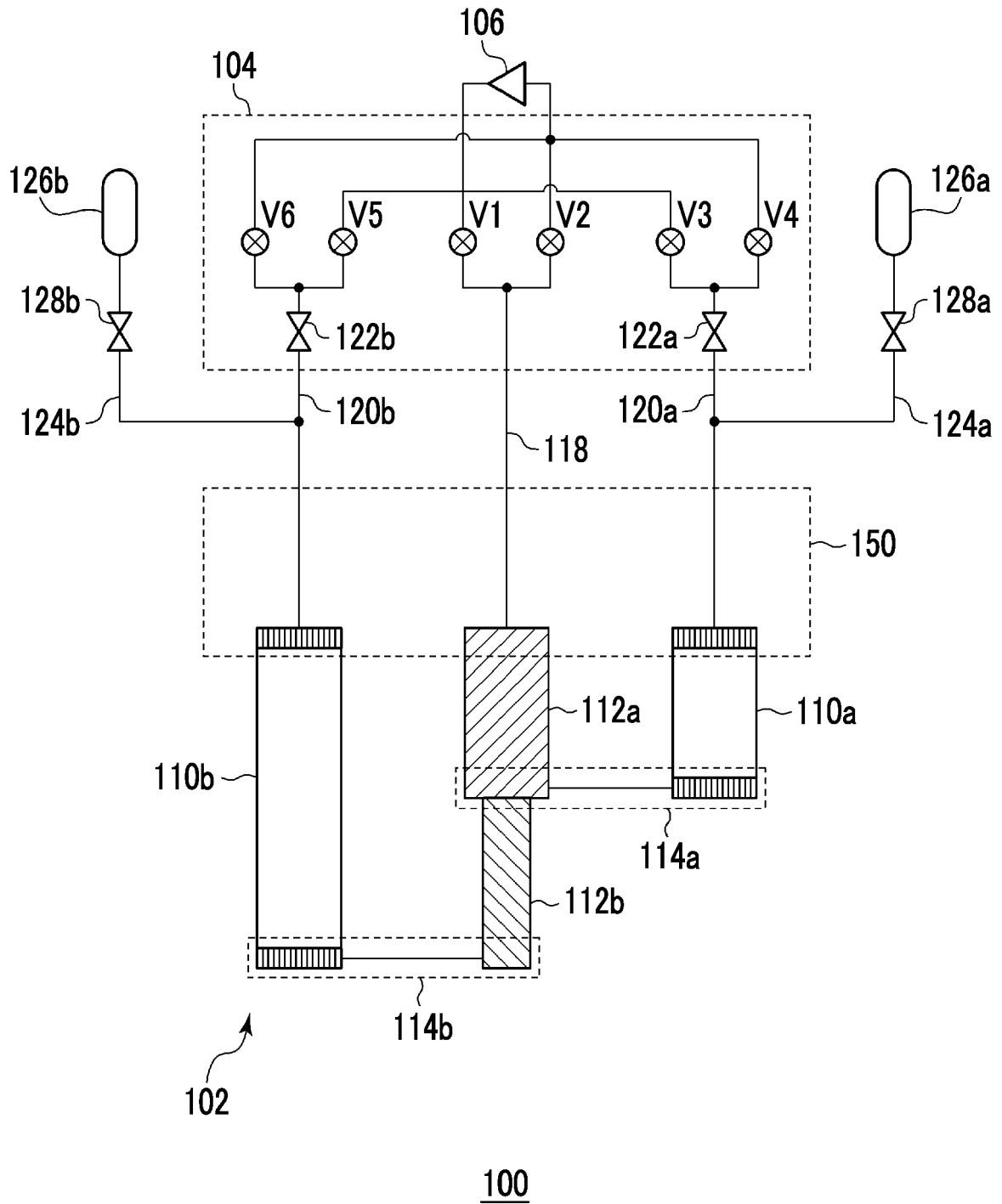


FIG. 3

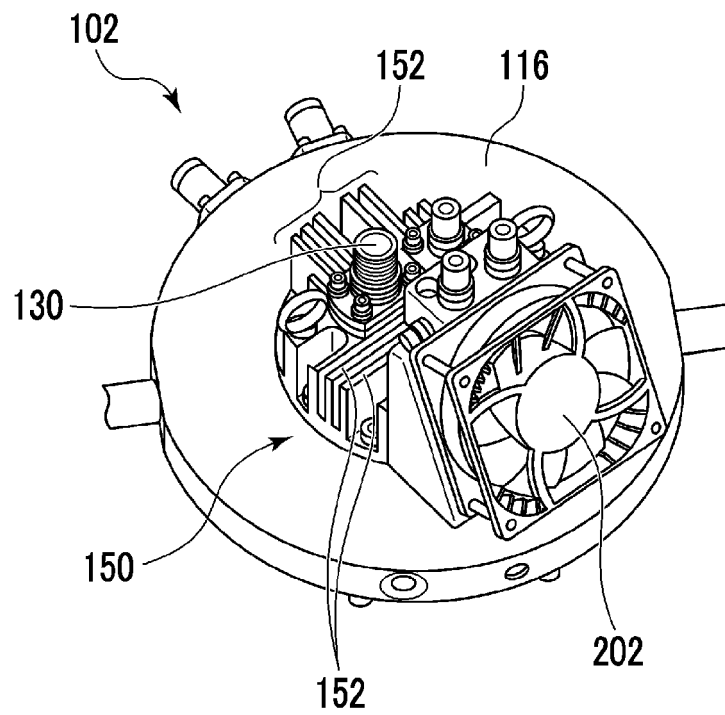
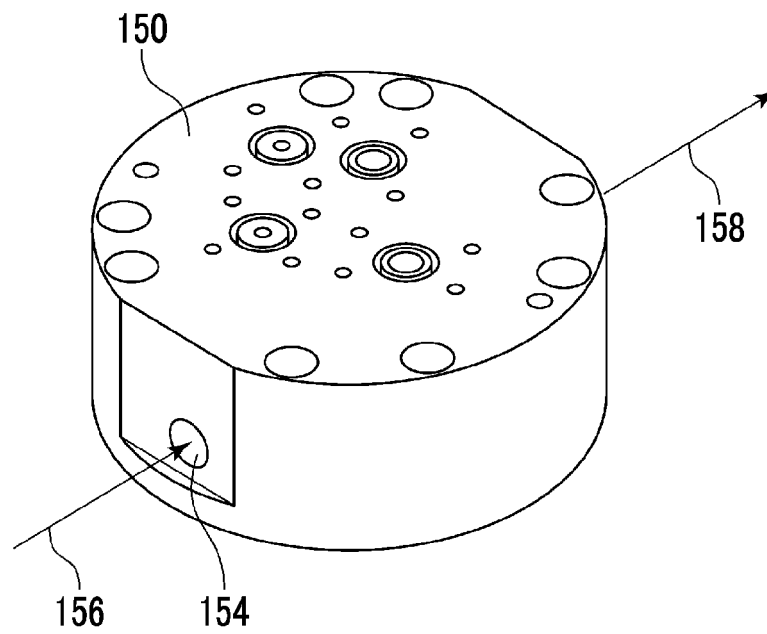


FIG. 4



200



EUROPEAN SEARCH REPORT

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Place of search Munich		Date of completion of the search 23 April 2024	Examiner Lucic, Anita
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