

SPECIFICATION

TITLE OF THE INVENTION: REFRIGERATOR AND OPERATION METHOD DURING PRECOOLING OF REFRIGERATOR

5 TECHNICAL FIELD

[0001] The present disclosure relates to a refrigerator and an operation method during precooling of the refrigerator.

BACKGROUND

10 [0002] A refrigerator that can realize cryogenic cooling by using the Brayton cycle for a refrigeration cycle and can be used to, for example, cool superconducting equipment, liquefy various gases, or replace liquid nitrogen has been put into practical use in various technical fields such as medicine or food, and is attracting a great deal of attention.

[0003] An example of this type of refrigerator includes: a cooling part for cooling an object
15 to be cooled through heat exchange with a refrigerant; a low-stage compressor for compressing the refrigerant; an expander-integrated compressor including a middle-stage compressor for compressing the refrigerant and an expander for expanding the refrigerant, the compressor and the expander integrated into the expander-integrated compressor; a high-stage compressor for further compressing the refrigerant; and a refrigerant circulation line configured to feed the
20 refrigerant to the plurality of compressors, the expander, the cooling part, or the like described above and to circulate the refrigerant (see, for example, Patent Document 1). The expander-integrated compressor may be configured by integrating the high-stage compressor and the expander instead of the middle-stage compressor and the expander.

[0004] In the refrigerator configured as described above, for example, the refrigerant,
25 which is compressed single-stage by the low-stage compressor rotary driven by a motor, is cooled by a heat exchanger, and is sent to the middle-stage compressor to be further compressed by the middle-stage compressor rotary driven by a motor. The refrigerant compressed two-stage by the middle-stage compressor is cooled by the heat exchanger, and is further compressed

by the high-stage compressor rotary driven by a motor. The refrigerant compressed three-stage by the high-stage compressor is cooled by the heat exchanger, and then is further cooled by a cold recovery heat exchanger and sent to the expander, and the refrigerant itself is adiabatically expanded by the expander to low pressure and low temperature.

5 [0005] The low-pressure and low-temperature refrigerant is sent to the cooling part (heat exchanger) to cool the object to be cooled. Then, the refrigerant is sent to the cold recovery heat exchanger to cool a refrigerant to be sent to the expander, and returned to the low-stage compressor.

[0006] Further, the refrigerator of this type may include a buffer line part composed of: a
10 buffer line connected to a high-pressure line from the high-stage compressor to the expander and a low-pressure line from the expander to the low-stage compressor in the refrigerant circulation line; a buffer tank disposed on the buffer line; and valves (open-close valves) respectively disposed on a high-pressure line side and a low-pressure line side (an inlet side and an outlet side) of the buffer tank (see, for example, Patent Document 1).

15 [0007] In these refrigerators, if a change in heat load of the object to be cooled is detected by a heat load detecting means, the flow rate of the refrigerant in the refrigerant line is controlled by controlling the opening degrees of the valves disposed upstream and downstream of the buffer tank, thereby adjusting a refrigerating ability.

20 Citation List

Patent Literature

[0008]

Patent Document 1: WO2016/178272A1

25 SUMMARY

Technical Problem

[0009] Herein, in the conventional refrigerator including the compressor-integrated expander described above, when the refrigerator is stopped, a refrigerant pressure increases in

a refrigerant circulation line system as a refrigerant temperature rises, and in this state, the refrigerant pressure of the high-pressure line from the high-stage compressor to the expander and the refrigerant pressure of the low-pressure line from the expander to the low-stage compressor in the refrigerant circulation line are balanced (high and low pressures are equalized).

[0010] Therefore, in the pressure equalization state, the pressure on the low-pressure line side is higher than a pressure during a normal operation, it is likely that the pressure on the high-pressure line side rises excessively if the refrigerator undergoes a startup operation at the high refrigerant pressure, and since the motor-driven compressor-integrated expander is provided in particular, a motor load increases and it may be necessary to limit the number of rotations during operation depending on a motor capacity.

[0011] Further, when the refrigerator undergoes the startup operation at the high refrigerant pressure, a circulation path has a minimum cross section in a passage near an inlet of the expander where the density is highest under rated operating conditions, and thus an intake temperature of the expander tends to increase (the refrigerant density tends to decrease) during precooling. Then, surging of the compressor may be caused by a choke phenomenon at the inlet of the expander where the flow rate of refrigerant at that section is low. This surging during the startup operation also tends to occur, if the motor-driven compressor-integrated expander is provided and the pressure on the high-pressure line side rises excessively.

[0012] Thus, in the above-described conventional refrigerator, room for improvement is left in terms of suppressing that the high pressure rises significantly above the steady-state operating pressure and enabling a precooling operation with high operating efficiency by suppressing the excessive load on the motor or the occurrence of surging, in an initial operation period from startup to the precooling operation.

[0013] In view of the above problems, an object of the present disclosure is to provide a refrigerator and an operation method during precooling of the refrigerator which can suppress that the high pressure rises significantly above the steady-state operating pressure, suppress the excessive load on the motor or the occurrence of surging, and improve the operation efficiency

(cooling efficiency of the refrigerant, the cooling object), in the initial operation period from startup to the precooling operation.

Solution to Problem

5 [0014] One aspect of a refrigerator of the present disclosure includes: an expander-integrated compressor which includes a compressor for compressing a refrigerant, and an expander for expanding the refrigerant compressed by the compressor, the expander being coupled to the compressor via a rotational shaft drivable by a motor; a cooling part for cooling a cooling object with the refrigerant expanded by the expander; a refrigerant circulation line for
10 circulating the refrigerant, the refrigerant circulation line including a low-pressure line ranging from the expander to the low-stage compressor via the cooling part, an intermediate-pressure line ranging from the low-stage compressor to the high-stage compressor, and a high-pressure line ranging from the high-stage compressor to the expander; a bypass line which is connected at one end to a first connection portion disposed on the high-pressure line and is connected at
15 another end to a second connection portion disposed on the low-pressure line; and a bypass valve disposed on the bypass line and capable of adjusting a flow rate of the refrigerant flowing through the bypass line by adjusting an opening degree.

Further, it is desirable that the refrigerator also includes a buffer tank for recovering a refrigerant gas in the high-pressure line.

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Advantageous Effects

[0015] According to a refrigerator (and an operation method during precooling of the refrigerator) of the present disclosure, it is possible to effectively suppress, by using a buffer tank or a bypass line, that a high pressure rises significantly above a steady-state operating
25 pressure in an initial operation period from startup to precooling operation. Furthermore, it is also possible to control the opening degree and the rotation speed in the bypass line based on temperature detection instead of refrigerant flow rate detection. Thus, in the initial operation period from startup to the precooling operation, it is possible to suppress an excessive load on

a motor or occurrence of surging, and it is possible to improve operation efficiency (cooling efficiency of a refrigerant, a cooling object) by performing the stable precooling operation.

BRIEF DESCRIPTION OF DRAWINGS

5 [0016] FIG. 1 is a diagram showing an example of a refrigerator according to an embodiment of the present disclosure.

FIG. 2 is a flowchart showing an example of an operation method in an initial operation period from startup to a precooling operation (until the completion of the precooling operation) in an operation method during precooling of the refrigerator according to an embodiment of the
10 present disclosure.

FIG. 3 is a flowchart showing an example of a control operation of a buffer line part in the initial operation period from startup to the precooling operation (the completion of the precooling operation) in the operation method during precooling of the refrigerator according to an embodiment of the present disclosure.

15 FIG. 4 is a graph showing an example of a relationship between an operation time and a refrigerant temperature, and a relationship between the operation time and the opening degree of a bypass valve when the refrigerator and the operation method during precooling of the refrigerator are used according to an embodiment of the present disclosure.

FIG. 5 is a flowchart showing a bypass control operation in the initial operation period
20 from startup to the precooling operation, and is a flowchart showing an example of a control flow if stepwise (step) control is performed, in the operation method during precooling of the refrigerator according to an embodiment of the present disclosure.

FIG. 6 is a graph showing an example of a relationship between the refrigerant temperature and the opening degree of the bypass valve if the bypass control operation is
25 performed by the stepwise (step) control in the operation method during precooling of the refrigerator according to an embodiment of the present disclosure.

FIG. 7 is a flowchart showing the bypass control operation in the initial operation period from startup to the precooling operation, and is a flowchart showing an example of a control

flow if continuous (proportional) control is performed, in the operation method during precooling of the refrigerator according to an embodiment of the present disclosure.

FIG. 8 is a graph showing an example of the relationship between the refrigerant temperature and the opening degree of the bypass valve if the bypass control operation is performed by the continuous (proportional) control in the operation method during precooling of the refrigerator according to an embodiment of the present disclosure.

FIG. 9 is a graph showing an example of pressure fluctuation states of a high-pressure line, a low-pressure line, and a buffer tank in the initial operation period from startup to the precooling operation of the refrigerator according to the present disclosure.

DETAILED DESCRIPTION

[0017] Hereinafter, a refrigerator and an operation method during precooling of the refrigerator according to some embodiments of the present disclosure will be described with reference to FIGs. 1 to 9.

It is intended, however, that unless particularly specified, dimensions, materials, shapes, relative positions and the like of components described in the embodiments or shown in the drawings shall be interpreted as illustrative only and not intended to limit the scope of the present invention.

For instance, an expression of relative or absolute arrangement such as “in a direction”, “along a direction”, “parallel”, “orthogonal”, “centered”, “concentric” and “coaxial” shall not be construed as indicating only the arrangement in a strict literal sense, but also includes a state where the arrangement is relatively displaced by a tolerance, or by an angle or a distance whereby it is possible to achieve the same function.

For instance, an expression of an equal state such as “same”, “equal”, and “uniform” shall not be construed as indicating only the state in which the feature is strictly equal, but also includes a state in which there is a tolerance or a difference that can still achieve the same function.

Further, for instance, an expression of a shape such as a rectangular shape or a tubular

shape shall not be construed as only the geometrically strict shape, but also includes a shape with unevenness or chamfered corners within the range in which the same effect can be achieved.

On the other hand, an expressions such as “comprising”, “including”, “having”, “containing”, and “constituting” one constitutional element are not intended to be exclusive of other constitutional elements.

[0018] The present disclosure relates to a refrigerator that can realize cryogenic cooling by using the Brayton cycle for a refrigeration cycle and an operation method during precooling of the refrigerator, and in particular relates to a refrigerator that can perform suitable operation-related control in an initial operation period from startup to a precooling operation (until the completion of precooling) and an operation method during precooling of the refrigerator.

[0019] (Refrigerator)

More specifically, for example, as shown in FIG. 1, a refrigerator 1 of the present embodiment includes a cooling part (secondary side load heat exchanger) 2 for cooling a cooling object (in the present embodiment, a refrigerant R2 on a cooling object side by heat exchange with a refrigerant R1, a low-stage compressor C1 for compressing the refrigerant R1, a middle-stage compressor C2 for further compressing the refrigerant R1, and an expander-integrated compressor 7 integrating a high-stage compressor C3 for further compressing the refrigerant R1 and an expander T for expanding the refrigerant R1, and a refrigerant circulation line 8 for sequentially feeding and circulating the refrigerant R1 to the low-stage compressor C1, the middle-stage compressor C2, the high-stage compressor C3, the expander T, the cooling part 2, and the like.

[0020] In addition to the high-stage compressor C3 and the expander T, the expander-integrated compressor 7 includes a first motor 9 with an output shaft whose both ends are connected to the high-stage compressor C3 and the expander T, for rotary driving the output shaft, and thus the high-stage compressor C3 and the expander T about an axis.

[0021] Further, in the refrigerator 1 of the present embodiment, the low-stage compressor C1 and the middle-stage compressor C2 are also configured as an integrated type, and this

integrated compressor 10 includes a second motor 11 with an output shaft whose both ends are connected to the low-stage compressor C1 and the middle-stage compressor C2, for rotary driving the output shaft, and thus the low-stage compressor C1 and the middle-stage compressor C2 about the axis.

5 [0022] Further, the refrigerator 1 of the present embodiment is configured by connecting the low-stage compressor C1, the middle-stage compressor C2, the high-stage compressor C3, and the expander T in series on the refrigerant circulation line 8.

[0023] The refrigerant circulation line 8 constitutes a low-pressure line between the expander T and the low-stage compressor C1, and constitutes a high-pressure line between the
10 high-stage compressor C3 and the expander T. The refrigerant circulation line 8 constitutes an intermediate-pressure line between the low-stage compressor C1 and the high-stage compressor C3.

[0024] A first heat exchanger 12 for cooling the refrigerant discharged from the low-stage compressor C1 and a second heat exchanger 13 for cooling the refrigerant R1 discharged from
15 the middle-stage compressor C2 are disposed on a first intermediate-pressure line, and a third heat exchanger 14 for cooling the refrigerant discharged from the high-stage compressor C3 is disposed on the high-pressure line. Further, a cold recovery heat exchanger (regenerative heat exchanger) 15 is provided between the expander T and the third heat exchanger 14 on the high-pressure line.

20 [0025] The first heat exchanger 12, the second heat exchanger 13, and the third heat exchanger 14 cool the refrigerant R1 with, for example, cooling water w.

[0026] Further, the cooling part 2 is provided between the expander T and the cold recovery heat exchanger 15 on the low-pressure line. In the present embodiment, a cooling line is part of the low-pressure line.

25 [0027] In the present embodiment, the cooling object cooled with the refrigerant R1 sent to the heat exchanger of the cooling part 2 is the cooling object refrigerant (secondary refrigerant) R2, and the cooling object refrigerant R2 circulates through a cooling object-side circulation line 16 and is sequentially sent to the cooling part 2 to be cooled to a predetermined temperature.

[0028] In the refrigerator 1 of the present embodiment configured as described above, the refrigerant, which is compressed single-stage by the low-stage compressor C1 rotary driven by the second motor 11, is cooled by the first heat exchanger 12, and is sent to the middle-stage compressor C2 to be further compressed by the middle-stage compressor C2 rotary driven by the second motor 11. The refrigerant R1 compressed two-stage by the middle-stage compressor C2 is cooled by the second heat exchanger 13, and is further compressed by the high-stage compressor C3 rotary driven by the first motor 9. The refrigerant R1 compressed three-stage by the high-stage compressor C3 is cooled by the third heat exchanger 14, and then is further cooled by the cold recovery heat exchanger 15 and sent to the expander T, and is adiabatically expanded by the expander T, thereby generating cold energy. That is, the refrigerant itself is adiabatically expanded to low pressure and low temperature. The high-stage compressor C3 and the expander T are also coupled to the both ends of the output shaft of the first motor 9, which is a common power source, thereby achieving efficiency through contribution of power recovered by the expander T to compression power of the high-stage compressor C3.

[0029] Further, the low-pressure and low-temperature refrigerant R1 is sent to the heat exchanger of the cooling part 2, and this refrigerant cools the cooling object refrigerant R2 flowing through the cooling object-side circulation line 16 to a predetermined temperature. Then, the refrigerant R1 is sent to the cold recovery heat exchanger 15 to cool the refrigerant R1 to be sent to the expander T, and returned to the low-stage compressor C1.

[0030] As a side note, in the refrigerator 1, an example of the refrigerant R1 can include helium, neon, hydrogen, nitrogen, air, or hydrocarbon. The temperature of the refrigerant R1 can be extremely low temperatures of, for example, approximately -190°C to -200°C (83.15 to 73.15 K) on the inlet side of the expander T and approximately -210°C to -220°C (63.15 to 53.15 K) on the outlet side of the expander T.

[0031] Thus, the refrigerator 1 of the present embodiment can be used to, for example, cool superconducting equipment, liquefy various gases, or replace liquid nitrogen.

[0032] More specifically, as shown in FIG. 1, as an example of the cooling object cooled

by exchanging heat with the refrigerant R1 in the cooling part 2, liquid nitrogen (cooling object refrigerant R2) for cooling a superconducting equipment 20 such as a superconducting cable can be given.

In this case, for example, the cooling object-side circulation line (liquid nitrogen circulation line) 16 circulating among the cooling part 2, the superconducting equipment 20, and a reservoir tank 21 is provided, a circulation pump 22 is further provided on the cooling object-side circulation line 16, configuring such that the liquid nitrogen R2 cooled to the extremely low temperature in the cooling part 2 circulates to the superconducting equipment 20.

[0033] On the other hand, in the refrigerator 1, as described above, while the refrigerator is stopped, the refrigerant pressure increases as the refrigerant temperature rises, and in this state, the high and the low pressures are equalized. Therefore, if the refrigerator 1 undergoes a startup operation at the high refrigerant pressure, since the refrigerant pressure in the low-pressure line is high, the refrigerant pressure in the high-pressure line rises, resulting in an increase in load on the motor (11 (9)) and it may be necessary to limit the number of rotations during operation depending on a motor capacity.

Further, when the refrigerator 1 undergoes the startup operation at the high refrigerant pressure, it may be considered that a choke phenomenon occurs at the inlet of the expander T and surging occurs in the compressor (C1, C2, C3).

[0034] (Control flow of precooling process)

Meanwhile, a precooling operation process for the refrigerator 1 (the operation method during precooling of the refrigerator) of the present embodiment includes refrigerator precooling operation control, bypass control, and buffer tank refrigerant recovery control, as shown in FIGs. 1 and 2.

[0035] First, the refrigerator precooling operation control is to perform operation control from the startup to the completion of precooling of the refrigerator 1, and a control rotation speed is controlled such that a cooling velocity is kept constant based on a target temperature setting (T1, T2) and a measured temperature (T) at the inlet or the outlet of the expander T.

[0036] The bypass control is to control the opening degree of an open-close valve 32 on a bypass line 31 according to the measured temperature (T), and includes steps (step control) and continuous control. The open-close valve 32 is closed if the refrigerant R1 is cooled down to the target set temperature (T1), and the non-bypass control operation is performed.

5 [0037] Further, the buffer tank refrigerant recovery control is to recover the refrigerant R1 from the high-pressure line to a buffer tank 27 to reduce a load on the precooling operation of the refrigerator 1. An open-close valve 28 is opened if a pressure difference exceeds a set value, and the refrigerant R1 flows into the buffer tank 27 from the high-pressure line.

[0038] In these controls, the bypass control and the buffer tank refrigerant recovery control
10 are performed in parallel to the refrigerator precooling operation control, and they are the combination to undergo constant monitoring.

[0039] Hereinafter, the control contents will be described in more detail.

[0040] (Buffer line part)

The refrigerator 1 of the present embodiment is firstly provided with a buffer line part 25.

15 [0041] The buffer line part 25 includes: a buffer line 26 connected at one end to a third connection portion S3 between the cold recovery heat exchanger 15 and the third heat exchanger 14 on the high-pressure line and connected at another end to a fourth connection portion S4 between the low-stage compressor C1 and the cold recovery heat exchanger 15 on the low-pressure line; the buffer tank 27 disposed on the buffer line 26 to temporarily store the
20 refrigerant R1; the first open-close valve (high-pressure side buffer valve) 28 disposed on an inlet side of the buffer tank 27 (a high-pressure line side between the buffer tank 27 and the third connection portion S3); and a second open-close valve (low-pressure side buffer valve) 29 disposed on an outlet side of the buffer tank 27 (a low-pressure line side between the buffer tank 27 and the fourth connection portion S4).

25 [0042] By opening the first open-close valve 28 on the inlet side and depending on the opening degree of the first open-close valve 28, the refrigerant R1 is temporarily sent to the buffer tank 27 from the high-pressure line and stored in the buffer tank 27 by utilizing the pressure difference (differential pressure), making it possible to adjust the amount (flow rate)

of the refrigerant R1 flowing through the refrigerant circulation line 8. Further, by closing the first open-close valve 28 and opening the second open-close valve 29 on the outlet side, as well as depending on the opening degree of the second open-close valve 29, the refrigerant R1 is returned to the low-pressure line from the buffer tank 27 by utilizing the pressure difference, making it possible to adjust the amount of the refrigerant R1 flowing through the refrigerant circulation line 8.

[0043] (Bypass line part)

Further, the refrigerator 1 of the present embodiment includes a bypass line part 30.

[0044] The bypass line part 30 includes the bypass line 31 connected at one end to a first connection portion S1 between the third connection portion S3 and the third heat exchanger 14 on the high-pressure line and connected at another end to a second connection portion S2 between the low-stage compressor C1 and the fourth connection portion S4 on the low-pressure line; and the third open-close valve (bypass valve) 32 disposed on the bypass line 31.

There is no problem even if the positions of the connection portions of the buffer line part 25 with the high-pressure line and the low-pressure line of the bypass line part 30 are interchanged.

[0045] (Refrigerant state/power state detection means)

The refrigerant circulation line 8 is provided with, between the expander T and the cold recovery heat exchanger 15 on the high-pressure line, a first temperature sensor 33 for detecting the temperature of the refrigerant R1 flowing through between the expander T and the cold recovery heat exchanger 15 on the high-pressure line.

The refrigerant circulation line 8 is provided with, between the cooling part 2 and the expander T on the cooling line, a second temperature sensor 34 for detecting the temperature of the refrigerant R1 flowing through the above place.

25 The cooling object-side circulation line 16 is provided with a third temperature sensor (secondary refrigerant temperature sensor) 35 for detecting the temperature of the cooling object liquid nitrogen R2 cooled by the cooling part 2.

[0046] A first pressure sensor 36 for detecting the pressure of the refrigerant R1 in the high-

pressure line is provided on the high-pressure line of the refrigerant circulation line 8, for example, between the third connection portion S3 and the first connection portion S1.

The buffer tank 27 is provided with a second pressure sensor 37 for detecting the pressure inside the buffer tank 27.

5 [0047] The expander-integrated compressor 7 is provided with a first dynamometer 38 for detecting the driving state of the first motor 9, and thus the rotation speeds of the rotational shaft, the high-stage compressor C3, and the expander T.

The integrated compressor 10 is provided with a second dynamometer 39 for detecting the driving state of the second motor, and thus the rotation speeds of the rotational shaft, the
10 low-stage compressor C1, and the middle-stage compressor C2.

[0048] Furthermore, the refrigerator 1 of the present embodiment includes a controller (control device) 40 for controlling the drive of the first motor 9, the second motor 11, the opening degree (open/close drive) of the first open-close valve 28, the second open-close valve 29, the third open-close valve 32, in response to a detection result of each of the first temperature
15 sensor 33, the second temperature sensor 34, the third temperature sensor 35, the first pressure sensor 36, the second pressure sensor 37, the first dynamometer 38, and the second dynamometer 39.

[0049] <Buffer tank refrigerant recovery control: operation control in initial operation period by using buffer line part>

20 First, the precooling operation control for recovering the refrigerant by using the buffer tank will be described.

Thus, the amount of the refrigerant R1 flowing into and out of the refrigerant circulation line 8 by the buffer line part 25 can be controlled by adjusting the opening degree of the first open-close valve 28, the second open-close valve 29 with the controller 40. It is preferable
25 that the third open-close valve of the bypass line part 30 is provided, and the first open-close valve 28, the second open-close valve 29 is an electric-operated valve.

[0050] More specifically, if the refrigerator 1 (motor 9, 11) is operated in a state where the pressure in the system of the refrigerant circulation line 8 is high, surging occurs in the

compressor, making it difficult to increase the rotation speed.

[0051] To cope therewith, in the refrigerator 1 of the present embodiment, the buffer tank 27 is provided between the low-pressure line and the high-pressure line in order to increase the rotation speed of the refrigerator 1 at startup, and the excess refrigerant R1 is recovered so that the discharge pressure of the refrigerator 1 does not exceed a certain pressure.

[0052] Thus, since the controller 40 controls the open/close drive of the first open-close valve 28 and adjusts the opening degree of the first open-close valve 28 based on the detection result of the first pressure sensor 36, the second pressure sensor 37, the refrigerant R1 can flow in by using the refrigerant pressure difference between the high-pressure line and the buffer tank 27, and the excess refrigerant R1 can be recovered to the buffer tank 27 so that the discharge pressure of the refrigerator 1 does not exceed the certain pressure.

[0053] (Control at startup/start of precooling operation)

As shown in FIGs. 1, 2, and 3, when startup/start of the precooling operation is performed (Step 1) after the refrigerator 1 is stopped, if the refrigerant pressures between the high-pressure line and the low-pressure line are balanced at high pressure along with the stop of the refrigerator 1, the refrigerant is recovered to the buffer tank 27 in the buffer line part 25 (Step 2) based on the detection result of the first pressure sensor 36, the second pressure sensor 37 (Step 3).

[0054] At this time, the controller 40 obtains the differential pressure of the refrigerant pressures between the high-pressure line and the buffer tank 27 (Step 3) upon receiving the detection results of the first pressure sensor 36 and the second pressure sensor 37, confirms whether the refrigerant pressures of the high-pressure line and the buffer tank 27 are balanced at high pressure, for example, if the differential pressure of the refrigerant pressures is not less than a set value (threshold) such as 10 kPa (Step 4), performs open control of the first open-close valve 28 (Step 5), and recovers the refrigerant by the buffer line part 25 (Step 6).

[0055] That is, the differential pressure between the pressure in the buffer tank 27 and the refrigerant pressure in the high-pressure line is obtained, and if the differential pressure exceeds the preset set value (such as 10 kPa), the controller 40 performs open control of the first open-

close valve 28 in the state where the second open-close valve 29 is closed (Step 5).

[0056] The open control of the first open-close valve 28 is performed (Step 5), the refrigerant R1 is sent to and temporarily stored in the buffer tank 27 due to the pressure difference between the buffer tank 27 and the high-pressure line (Step 6), and the flow rate (pressure) of the refrigerant R1 flowing through the Brayton cycle is decreased.

Thus, it is possible to prevent an overload operation (an excessive motor load on the first motor 9, the second motor 11) due to the increase in pressure in the refrigerant circulation line 8 in initial precooling.

The refrigerant R1 is sent to and temporarily stored in the buffer tank 27, the flow rate (pressure) of the refrigerant R1 flowing through the Brayton cycle is decreased, and if the differential pressure of the refrigerant pressures falls below the set value (Step 7), close control of the first open-close valve 28 is performed (Step 8). Further, if the differential pressure of the refrigerant pressures falls below the set value in the aforementioned (Step 4), the closed state of the first open-close valve 28 is maintained (Step 8).

[0057] (Control during precooling operation)

As described above, if the differential pressure between the buffer tank 27 and the high-pressure line exceeds the set value such as 10 kPa, the refrigerant is recovered from the high-pressure line to the buffer tank via the first open-close valve, and the differential pressure between the buffer tank and the high-pressure line is reduced (Step 6, Step 7).

[0058] Thus, at the start of the precooling operation after the refrigerator 1 is stopped, the high-pressure refrigerant R1 is recovered to the buffer tank 27 if the differential pressure continues to exceed the installed value. However, if the pressure (discharge pressure) of the refrigerant R1 in the high-pressure line does not largely fluctuate along with the operation of the refrigerator 1, the differential pressure between the buffer tank 27 and the high-pressure line is reduced and is maintained in that state. That is, the refrigerant R1 is no longer exchanged between the buffer tank 27 and the high-pressure line, the refrigerant R1 does not increase or decrease in the refrigerant circulation line 8, and the pressure in the high-pressure line is maintained.

[0059] Conversely, at the start of the precooling operation after the refrigerator 1 is stopped, if the pressure (discharge pressure) of the refrigerant R1 in the high-pressure line largely fluctuates along with the operation of the refrigerator 1, the refrigerant R1 continues to be recovered to the capacity adjusting buffer tank 27 from the high-pressure line.

5 [0060] Thus, in the refrigerator 1 of the present embodiment, since the refrigerant circulation line 8 (refrigerant passage system) has the sealed structure, the excess refrigerant R1 can be stored in the buffer tank 27 at normal temperature. That is, during the precooling operation, as described above, it is possible to automatically adjust the recovery amount of the refrigerant R1 merely by performing the open/close drive control of the first open-close valve
10 28 based on the detection results of the first pressure sensor 36 and the second pressure sensor 37 without measuring the flow rate, and it is possible to set the suitable state where the excessive motor load does not occur and to maintain that state.

[0061] The embodiment is described in which the differential pressure of the refrigerant pressures is obtained from the pressure detection results from the aforementioned (Step 3) to
15 (Step 6), and if the differential pressure is not less than the set value (threshold), the controller 40 controls the open control of the first open-close valve 28 to recover the refrigerant by the buffer line part 25.

On the other hand, as another embodiment, if the pressure in the high-pressure line is not less than the set value (threshold) instead of the differential pressure, the open control of the
20 first open-close valve 28 may be performed to allow the buffer line part 25 to recover the refrigerant.

[0062] (Transition control to normal (steady) operation)

Then, after the startup of the refrigerator 1, the refrigerant R1 on the high-pressure line side is temporarily pressurized and the excess refrigerant is stored in the buffer tank 27.
25 However, as cooling advances, the pressures of the refrigerant R1 in the low-pressure line and the high-pressure line, and thus in the entire device/system of the refrigerator 1 drop and approach the pressure state during a normal operation. In other words, the operation progresses with the respective pressures of the low-pressure line and the high-pressure line

becoming the pressure during the normal operation, entering the state where the excessive motor load is not caused. The first open-close valve 28 is closed at the stage when the pressure becomes lower than the buffer mechanism pressure set value (Step 8).

[0063] On the other hand, some refrigerant R1 increases in density and decreases in capacity if cooled from normal temperature to 100K or less. More specifically, the temperature of the refrigerant R1 becomes 100 K or less in the equipment or piping from the cold recovery heat exchanger 15 to the expander T, from the expander T to the cooling part 2, from the cooling part 2 to the cold recovery heat exchanger 15, and the density of the refrigerant R1 increases, resulting in capacity shortage. Conversely, even during operation, since the refrigerant temperature from the outlet of the cold recovery heat exchanger 15 in the low-pressure line to the inlet of the cold recovery heat exchanger 15 in the high-pressure line via the compressor is near normal temperature, the refrigerant capacity of the refrigerant R1 does not change.

Thus, it is necessary to hold in the system an amount corresponding to the decrease in refrigerant capacity on the cooling line side, the high-pressure line side which is the low-temperature side.

[0064] Therefore, in the refrigerator 1 and the operation method for the refrigerator 1 of the present embodiment, the refrigerant R1 is preferentially stored in the buffer tank 27. For example, the refrigerant recovering first open-close valve 28 is opened under the condition where the pressure difference detected by the first pressure sensor 36 and the second pressure sensor 37 is not less than the preset set value such as 10 kPa, such that the excess refrigerant R1 is recovered to the buffer tank 27 in the initial operation period from startup to the precooling operation (until the completion of precooling), such as immediately after startup.

[0065] Further, in the refrigerator 1 and the operation method for the refrigerator 1 of the present embodiment, if the pressure of the high-pressure line is not less than the set value (threshold) instead of the pressure difference (differential pressure) detected by the first pressure sensor 36 and the second pressure sensor 37, it is also possible to perform the open control of the first open-close valve 28 to allow the buffer line part 25 to recover the refrigerant

(see FIG. 9 (the graph showing an example of the state of pressure fluctuation in the high-pressure line, the low-pressure line, the buffer tank 27 during the stepwise control of the bypass control operation)).

[0066] <Refrigerator precooling operation control/bypass control: operation control in initial operation period by using buffer line part>

Next, since the refrigerator 1 needs to cool the refrigerant R1 with a large temperature difference, for example, from normal temperature to 100 K or less, the refrigerant circulation line 8 is conventionally provided with a narrowed portion with a minimum cross section near the inlet of the expander T where the density is highest.

[0067] Herein, during the precooling operation, the intake temperature tends to increase, in other words, the refrigerant density tends to decrease, the refrigerant flow rate in the narrowed portion with the minimum cross section near the inlet of the expander T decreases, which causes surging in the compressor C1, C2, C3. Thus, during the precooling operation, it is necessary to secure a sufficient refrigerant flow rate so as to suppress the surging.

[0068] To achieve this, the refrigerator 1 of the present embodiment includes the bypass line part 30 composed of the bypass line 31 capable of returning the refrigerant R1 from the high-pressure line to the low-pressure line and the third open-close valve 32 of the bypass valve.

[0069] Thus, since the open control of the third open-close valve 32 is performed by the controller 40, the part of the refrigerant R1 compressed by the high-stage compressor C3 can be returned to the low-stage compressor C1 and thus the high-stage compressor C3 without being supplied to the expander T. Further, since the opening degree of the third open-close valve 32 is adjusted by the controller 40, the flow rate of the refrigerant returned to the compressor C1, C2, C3 can be adjusted.

[0070] Thus, in the refrigerator 1 of the present embodiment, during precooling, since the opening degree of the third open-close valve 32 is appropriately changed according to the operating state, it is possible to prevent the occurrence of surging and to reduce the refrigerant R1 which is not used for cooling, enabling efficient (high COP: Coefficient of Performance) operation in which power is not wasted.

[0071] Next, in the refrigerator 1 and the operation method during precooling of the refrigerator 1 of the present embodiment, as shown in FIG. 2 (FIG. 5, FIG. 7, FIG. 1), the opening degree of the third open-close valve 32 is controlled according to the temperature condition of the refrigerant R1 (Step 9), and the precooling operation control composed of the bypass control and the refrigerator precooling operation control using the bypass line part 30 is performed. Further, the refrigerator precooling operation control and the bypass control are performed in parallel with the aforementioned bypass control.

[0072] (Refrigerator precooling operation control)

First, in the refrigerator precooling operation control (Step 9), for example, the operation is performed for 10 minutes at 60% rotation speed (Step 10).

[0073] Further, the opening degree of the third open-close valve 32 is adjusted, controlled based on the refrigerant temperature detected by the first temperature sensor 33 disposed on the high-pressure line or the second temperature sensor 34 disposed on the cooling line.

[0074] At this time, the opening degree of the third open-close valve 32 is reduced stepwise or continuously by the bypass control while maintaining the cooling velocity (a rate of decrease in the refrigerant temperature) during precooling at the preset constant cooling velocity, such as 60 K/h, such that the opening degree of the third open-close valve 32 is set at 0% at the stage when the refrigerant R1 reaches the first target temperature (100 K in the present embodiment) (Step 11).

[0075] Then, the use of the bypass line part 30 (bypass control) is stopped at the stage when the expander outlet temperature reaches the first target temperature (100 K) (Step 12), and the control (non-bypass control) is performed so as to supply the entire amount of the refrigerant to the expander T (Step 13).

[0076] Further, after stopping the use of the bypass line part 30, the refrigerant rotation speed is controlled based on the refrigerant temperature on the outlet side of the expander T detected by the second temperature sensor 34 such that the refrigerant temperature is maintained at the second target temperature or less (67 K or less in the present embodiment) (Step 14).

[0077] That is, in the present embodiment, until the circulation of liquid nitrogen, which is

the cooling object refrigerant R2, is started in the liquid nitrogen circulation line which is the cooling object-side circulation line 16, the second temperature sensor 34 detects the refrigerant temperature on the outlet side of the expander T, and the refrigerant temperature on the outlet side of the expander T is used as a temperature control point to set the second target temperature at 67 K or less. This prevents liquid nitrogen from freezing in the cooling part 2.

[0078] After the circulation of liquid nitrogen is started in the liquid nitrogen circulation line, the temperature control point is switched to the third temperature sensor 35 near the superconducting cable or the like, and the operation of the refrigerator 1 is controlled based on the refrigerant temperature on the outlet side of liquid nitrogen detected by the third temperature sensor 35. Whereby, the precooling operation of the refrigerator 1 is completed (Step 15), and liquid nitrogen to be cooled can easily and accurately be cooled.

[0079] It has been confirmed that regardless of whether the detection result of either the first temperature sensor 33 or the second temperature sensor 34 is used to control the opening degree of the third open-close valve 32, the same technical effect can be obtained if there is no particular fluctuation in heat load. Thus, although the refrigerator 1 of the present embodiment includes the first temperature sensor 33 and the second temperature sensor 34, in some cases, the refrigerator 1 of the present embodiment includes only one of the temperature sensors, whereby it is possible to reduce the number of temperature monitoring points, temperature sensors.

[0080] (Bypass control)

On the other hand, in the refrigerator 1 and the operation method during precooling of the refrigerator 1 of the present embodiment, as shown in FIG. 2, FIG. 5, FIG. 7 (FIG. 1), in parallel with the above-described refrigerator precooling operation control, the bypass control (Step 16) is performed by controlling the opening degree of the third open-close valve 32 stepwise or continuously (step control or proportional control), thereby reducing the change in flow rate flowing to the expander T. That is, the fluctuation in cooling capacity when the opening degree fluctuates is suppressed, making it easier to control the cooling velocity.

[0081] More specifically, the first reason for controlling the cooling velocity to be constant

during the precooling operation control using the bypass line part 30 is that if the heat exchanger is rapidly cooled, damage may be caused by thermal deformation.

The second reason is that if the change in cooling temperature is large, a fluctuation in adjustment range of the opening degree of the third open-close valve 32 or rotation speed of the refrigerator increases, making stable operation difficult. That is, since the flow rate of the refrigerant flowing through the bypass line 31 also affects the operating efficiency, the cooling velocity is kept constant in order to perform efficient operation.

[0082] Based on this, in the operation method during precooling of the refrigerator 1 of the present embodiment, as described above, during precooling, the two controls, namely, the opening degree control of the third open-close valve 32 of the bypass valve in the bypass line part 30 and the rotation speed control of the refrigerator 1 are combined to perform temperature control to keep the cooling velocity constant.

[0083] Further, in the operation method during precooling of the refrigerator 1 of the present embodiment, since the opening degree of the third open-close valve 32 of the bypass line part 30 is adjusted without supplying part of the refrigerant R1 to the expander T, without using a flow meter, the refrigerant R1 is returned from the high-pressure line to the low-pressure line through the bypass line 31 while adjusting the flow rate, suppressing the occurrence of surging.

[0084] Meanwhile, if the third open-close valve 32 is opened too much, an excessive flow rate is supplied to the compressor and wasted power is consumed. As a result, it is impossible to perform effective operation.

Thus, in the operation method during precooling of the refrigerator 1 of the present embodiment, the adjustment control (step control or proportional control) of the opening degree of the third open-close valve 32 is performed stepwise or continuously so as to hold the flow rate at which surging does not occur, and the third open-close valve 32 is closed (0% opening degree) at the stage when a design flow rate of the expander T is approached.

[0085] Further, in the opening degree control of the third open-close valve 32 of the bypass line part 30, the flow rate of the refrigerant flowing through the two routes, namely, the expander

T and the bypass line 31 is adjusted to set the condition allowing for efficient operation. Thus, just with the adjustment control of the refrigerant flow rate by the bypass line part 30, it may be conceivable that high-precision control cannot necessarily be performed from the viewpoint of the temperature control of the refrigerant R1.

5 [0086] Based on this, in the precooling operation method during precooling of the refrigerator 1 of the present embodiment, as described above, in addition to controlling the opening degree of the third open-close valve 32 of the bypass line part 30, the rotation speed of the refrigerator 1 is controlled, thereby adjusting/modifying the cooling velocity such that the cooling velocity is constant.

10 That is, in the operation method during precooling of the refrigerator 1 of the present embodiment, according to the magnitude of divergence between the measured temperature and the set target temperature of the refrigerant R1, the rotation speed of the refrigerator 1 is controlled such that the cooling velocity is constant, making it possible to accurately control the refrigerant temperature.

15 [0087] Thus, in the operation method during precooling of the refrigerator 1 of the present embodiment, since the opening degree adjustment control of the third open-close valve 32 of the bypass line part 30 and the rotation speed control of the refrigerator 1 are used in combination, in the initial operation period from startup to the completion of precooling, it is possible to suitably suppress the occurrence of surging and to accurately cool the refrigerant R1
20 at the constant cooling velocity, and it is possible to perform efficient operation control.

[0088] Herein, in the operation method during precooling of the refrigerator 1 of the present embodiment, in order to suitably achieve the above-described technical effect, the opening degree of the third open-close valve 32 of the bypass line part 30 is adjusted stepwise or continuously in the bypass control (Step 16).

25 The operation method for the refrigerator 1 of the present embodiment will be described in detail by taking an example of using each of the stepwise opening degree control (step control) and the continuous opening degree control (proportional control) of the third open-close valve 32 of the bypass line part 30.

[0089] <Stepwise operation control (step operation control) using bypass line part>

First, a method for stepwise controlling the opening degree of the third open-close valve 32 of the bypass valve in the bypass line part 30 will be described.

[0090] In the stepwise opening degree adjustment control of the third open-close valve 32 of the bypass line part 30, as shown in FIG. 5, FIG. 6 (see FIG. 1, FIG. 2, FIG. 4), for example, the refrigerator precooling operation control (Step 9) sets the rotation speed at 60% of a maximum value (Step 10) and sets the opening degree of the third open-close valve 32 at 40% (Step 17). Further, the first temperature sensor 33 or the second temperature sensor 34 measures the temperature of the refrigerant R1 at startup (Step 18). Then, from the stage when the refrigerator 1 is started and the precooling operation is started, the opening degree of the third open-close valve 32 is changed stepwise according to the refrigerant temperature detected by the first temperature sensor 33 or the second temperature sensor 34 (Step 19).

[0091] In the stepwise operation control using the bypass line part 30, the start point and the end point of the temperature in each step decides the opening degree step (in the present embodiment, steps 1 to 6: FIG. 6) of the third open-close valve 32. For example, if the opening degree of the third open-close valve 32 is V01% assuming that a certain step temperature range is from T01 to T02, the opening degree V01% of the third open-close valve 32 is maintained in a state where a measured temperature Ta of the first temperature sensor 33 or the second temperature sensor 34 is $T02 < Ta \leq T01$.

[0092] Then, the refrigerant temperature gradually decreases, and at the stage when the measured temperature Ta reaches T02, the opening degree V02% ($V02 < V01$) of the third open-close valve 32 corresponding to a next step temperature range from T02 to T03 ($T03 < Ta \leq T02$) is maintained.

[0093] Thus, the steps (steps 1 to 6) are sequentially changed as the cooling temperature drops, and the opening degree of the third open-close valve 32 is switched to the opening degree one step lower each time the step is changed to the next step.

[0094] If the opening degree of the third open-close valve 32 is reduced stepwise by sequentially changing the steps, the flow rate of the refrigerant R1 flowing through the bypass

line 31 from the high-pressure line to the low-pressure line decreases stepwise. In accordance with such stepwise decrease in flow rate of the refrigerant R1, the amount of the refrigerant flowing from the low-stage compressor C1 side to the expander T side increases stepwise. Thus, the refrigerator 1 of the present embodiment uses the rotation speed control (refrigerator
5 precooling operation control) together so as to maintain the constant cooling velocity.

[0095] For example, in FIG. 5, 6, assuming that the rotation speed of the refrigerator at startup (at the start of rotation) is 60%, the opening degree of the third open-close valve 32 is 40%, and five steps are performed until the subsequent measured temperature of the refrigerant R1 by the first temperature sensor 33 or the second temperature sensor 34 reaches the first target
10 temperature of 100 K, the temperature range at 225 K, 190 K, 155 K, 120 K, 100 K and the opening degree of the third open-close valve 32 are set.

[0096] As described above, since the stepwise opening degree control of the third open-close valve 32 of the bypass line part 30 and the rotation speed control of the refrigerator 1 are used in combination, in the operation method during precooling of the refrigerator 1 of the
15 present embodiment, the opening degree of the third open-close valve 32 can be set for each temperature section of each step, and the rotation speed control (for example, rotation speed $N=60\%$ to 75%) can be performed by using PID control or the like such that the cooling velocity takes the preset constant set value (such as 60 K/h) in each divided temperature section.

Thus, the operation method during precooling of the refrigerator 1 of the present
20 embodiment allows for the stable precooling operation with little fluctuation in pressure or rotation speed of the refrigerator 1.

[0097] Further, at the stage when the first target temperature of 100 K is reached, the opening degree of the third open-close valve 32 becomes 0%, the operation control using the bypass line part 30 ends, and the process shifts to the non-bypass control operation (Step 20).
25 Since the process shifts to the non-bypass control operation, all of the refrigerant circulation amount flows from the compressor to the expander T.

[0098] Then, in the precooling operation of the non-bypass control operation, the rotation speed is controlled toward the second target temperature of 67 K which is the next target

temperature. At this time, until the second target temperature of 67 K, the rotation speed control (for example, rotation speed $N=75\%$ to 95%) is performed by using PID control or the like such that the cooling velocity takes the preset constant set value (such as 60 K/h) (Step 13). Further, control is performed so as to maintain the second target temperature until the second target temperature of 67 K is reached and the nitrogen circulation operation on which the load is applied is performed (Step 13, 14, 15).

The rotation speed control need not be limited to using PID (Proportional-Integral-Differential) control. For example, P (Proportional) control, PI (Proportional-Integral) control, or the like may of course be used.

[0099] Therefore, with the refrigerator 1 and the operation method during precooling of the refrigerator 1 of the present embodiment, since the stepwise opening degree adjustment control of the third open-close valve 32 of the bypass line part 30 and the rotation speed control of the refrigerator 1 are used in combination, in the initial operation period from startup to the completion of precooling, it is possible to suitably suppress the occurrence of surging and to accurately cool the refrigerant R1 at the constant cooling velocity, and it is possible to perform efficient operation control.

[0100] <Continuous operation control (proportional operation control) using bypass line part>

Next, a method for continuously controlling the opening degree of the third open-close valve 32 of the bypass valve in the bypass line part 30 will be described.

[0101] In the continuous opening degree adjustment control of the third open-close valve 32 of the bypass line part 30, as shown in FIG. 7, FIG. 8 (see FIG. 1, FIG. 2, FIG. 4), as with the stepwise opening degree adjustment control, for example, the refrigerator precooling operation control (Step 9) sets the rotation speed at 60% of the maximum value (Step 10) and sets the opening degree of the third open-close valve 32 at 40% (Step 17). Further, the first temperature sensor 33 or the second temperature sensor 34 measures the temperature of the refrigerant R1 at startup (Step 18). Then, from the stage when the refrigerator 1 is started and the precooling operation is started, the opening degree of the third open-close valve 32 is

changed continuously according to the refrigerant temperature detected by the first temperature sensor 33 or the second temperature sensor 34 (Step 20).

[0102] In the continuous operation control using the bypass line part 30, the start point and the end point of the temperature in each step decides the opening degree step (in the present embodiment, steps 1 to 6: FIG. 8) of the third open-close valve 32.

[0103] However, in the initial state of operation, priority is given to the operation at 60% rotation speed (Step 10) or the operation control at 40% opening degree of the third open-close valve (Step 17), and since the valve opening degree of 40% is maintained until the temperature of the refrigerant R1 is further cooled to 225 K in (Step 18), the continuous operation control is substantially started from (step 2).

[0104] For example, if a certain step temperature range is from T01 to T02, the opening degree of the third open-close valve 32 is gradually decreased from V01% to V02% between the step temperature range of T01 and T02.

That is, let Ta be the measured temperature of the refrigerant R1 by the first temperature sensor 33 or the second temperature sensor 34, the opening degree V% of the third open-close valve 32 is obtained by the following equation (1).

[0105] (Equation 1)

$$V\% = V01 - ((V01 - V02) / (T01 - T02)) \times (T01 - Ta) \dots (1)$$

Herein, $T02 < Ta < T01$ is satisfied.

[0106] The third open-close valve 32 is continuously controlled according to the opening degree thus obtained, and the steps (steps 1 to 6: FIG. 8) are sequentially changed according to the drop in cooling temperature associated with the continuous control.

[0107] If the opening degree of the third open-close valve 32 is reduced continuously by sequentially changing the steps, if the opening degree of the third open-close valve 32 is reduced continuously, the flow rate of the refrigerant R1 flowing through the bypass line 31 from the high-pressure line to the low-pressure line decreases continuously. The flow rate of the refrigerant flowing through the bypass line from the high-pressure line to the low-pressure line decreases continuously. Since the amount of the refrigerant flowing from the low-stage

compressor C1 side to the expander T side increases continuously in accordance with the continuous decrease in flow rate of the refrigerant, the refrigerator 1 of the present embodiment uses the rotation speed control (refrigerator precooling operation control) together so as to maintain the constant cooling velocity.

5 [0108] For example, in FIG. 7, 8, assuming that the rotation speed of the refrigerator at startup (at the start of rotation) is 60%, the opening degree of the third open-close valve 32 is 40%, and four steps of from step 2 to step 5 are performed until the subsequent measured temperature of the refrigerant R1 by the first temperature sensor 33 or the second temperature sensor 34 reaches the first target temperature of 100 K, the temperature range at 225 K, 190 K,
10 155 K, 120 K, 100 K and the opening degree of the third open-close valve 32 are continuously set according to Equation (1) for each temperature range.

[0109] As described above, since the continuous opening degree control of the third open-close valve 32 of the bypass line part 30 according to Equation (1) and the rotation speed control of the refrigerator 1 are used in combination, in the operation method during precooling of the
15 refrigerator 1 of the present embodiment, the opening degree of the third open-close valve 32 can be set for each temperature section of each step, and the rotation speed control (for example, rotation speed $N=60\%$ to 75%) can be performed by using PID control or the like such that the cooling velocity takes the preset constant set value (such as 60 K/h) in each divided temperature section.

20 Thus, the operation method during precooling of the refrigerator 1 of the present embodiment allows for the stable precooling operation with little fluctuation in pressure or rotation speed of the refrigerator 1.

[0110] Further, as with the stepwise opening degree control, at the stage when the first target temperature of 100 K is reached, the opening degree of the third open-close valve 32
25 becomes 0%, the operation control using the bypass line part 30 ends, and the process shifts to the non-bypass control operation (Step 13). Since the process shifts to the non-bypass control operation, all of the refrigerant circulation amount flows from the compressor C1, C2, C3 to the expander T.

[0111] Then, in the precooling operation of the non-bypass control operation, the rotation speed is controlled toward the second target temperature of 67 K which is the next target temperature. At this time, until the second target temperature of 67 K, the rotation speed control (for example, rotation speed N=75% to 95%) is performed by using PID control or the like such that the cooling velocity takes the preset constant set value (such as 60 K/h) (Step 13). Further, control is performed so as to maintain the second target temperature until the second target temperature of 67 K is reached and the nitrogen circulation operation on which the load is applied is performed (Step 13, 14, 15).

Also in the case where the continuous opening degree control is used, the rotation speed control need not be limited to using PID (Proportional-Integral-Differential) control. For example, P (Proportional) control, PI (Proportional-Integral) control, or the like may of course be used.

[0112] Therefore, with the refrigerator 1 and the operation method during precooling of the refrigerator 1 of the present embodiment, since the continuous opening degree adjustment control of the third open-close valve 32 of the bypass line part 30 and the rotation speed control of the refrigerator 1 are used in combination, in the initial operation period from startup to the completion of precooling, it is possible to suitably suppress the occurrence of surging and to accurately cool the refrigerant R1 at the constant cooling velocity, and it is possible to perform efficient operation control.

[0113] <Temperature cooling control during precooling>

The main point of the temperature cooling control during scheduled time (operation method during scheduled time) by the refrigerator 1 of the present embodiment including the bypass line part 30, the buffer line part 25 is summarized as follows.

[0114] 1) At startup, the operation is started with the predetermined rotation speed of the refrigerator being RPM (1) (the rotation speed of at least the expander T among the compressors C1, C2, C3 and the expander T being the predetermined rotation speed RPM (1)) and the opening degree of the third open-close valve 32, which is the bypass valve, of the bypass line part 30 being the predetermined opening degree V% (2) (startup operation step).

[0115] 2) Further, the refrigerant temperature on the inlet side of the expander T or the refrigerant temperature on the outlet side of the expander T is detected by the first temperature sensor 33 or the second temperature sensor 34. Then, until the refrigerant temperature on the inlet side of the expander T or the refrigerant temperature on the outlet side of the expander T reaches, for example, the first target temperature of 100 K from 190 K (225 K), the refrigerant R1 in the high-pressure line is flowed through the bypass line 31 to the low-pressure line while decreasing the opening degree V% of the third open-close valve 32 stepwise or continuously. Further, the refrigerant R1 is cooled from the startup temperature to the first target temperature while performing stepwise or continuous control of the opening degree V% of the third open-close valve 32 (bypass control operation step).

[0116] 3) Next, at the stage when the opening degree of the third open-close valve 32 becomes 0% (closed) and the refrigerant temperature reaches the first target temperature, based on the refrigerant temperature on the outlet side of the expander T detected by the second temperature sensor 34 (or the refrigerant temperature detected by the first temperature sensor 33), the refrigerant temperature is cooled from the first target temperature to the second target temperature (non-bypass control operation step).

[0117] 4) Further, when the bypass control operation step and the non-bypass control operation step are performed, the continuous adjustment control of the rotation speed of the refrigerator 1 is performed based on the refrigerant temperature detected by the temperature sensor 34, such that the cooling velocity is kept constant until at least the cooling target temperature (first target temperature, second target temperature) is reached (cooling velocity control step).

[0118] 5) Further, during from the startup to the precooling operation of the above-described 1) to 4), if the state is detected where the first pressure sensor 36 and the second pressure sensor 37 set the refrigerant pressure in the high-pressure line higher than the pressure in the buffer tank 27 by the preset set value (10 kPa) or greater, the first open-close valve 28 is opened and the refrigerant R1 is recovered to the buffer tank 27 by using the pressure difference (refrigerant recovery step).

[0119] 6) Then, by the control from startup to the precooling operation of the above-described 1) to 5), the precooling operation is completed at the stage when the refrigerant temperature is cooled to reach the second target temperature and becomes constant, and after the completion of the precooling operation, with the start of circulation of liquid nitrogen, the refrigerant temperature detection point by the first temperature sensor 33 or the second temperature sensor 34 is switched to the refrigerant temperature detection point on the cooling object-side circulation line 16 in the third temperature sensor 35 for detecting the temperature of the cooling object refrigerant R2, and the process shifts to the main cooling operation (main cooling operation switching step).

10 [0120] By thus controlling the scheduled operation from the startup of the refrigerator 1 to the transition to the main cooling operation, for example, as shown in FIG. 4, it is possible to cool the refrigerant R1 with a constant temperature gradient during precooling.

[0121] Further, since the opening degree adjustment of the third open-close valve 32 and thus the adjustment control of the refrigerant flow rate to be bypassed are controlled stepwise or continuously based on the detection value of the first temperature sensor 33 or the second temperature sensor 34 disposed near the inlet or near the outlet of the expander T, it is possible to accurately perform control without complicating the device configuration, compared to the case where the flow rate of the refrigerant R1 is detected.

15 [0122] Therefore, with the refrigerator 1 and the operation method during precooling of the refrigerator 1 of the present embodiment, surging can be avoided by controlling the flow rate of the refrigerant R1 without detecting the flow rate of the refrigerant R1, making it possible to improve safety while simplifying the device configuration. Further, precooling becomes possible where the compressor C1, C2, C3 or the expander T is operated at high rotation speed, making it possible to achieve smooth precooling operation.

20 [0123] Meanwhile, for example, if surging is to be avoid only by controlling the rotation speed, the rotation speed would steplessly be controlled. However, in order to steplessly control the rotation speed, the flow meter for measuring the refrigerant flow rate is used. Consequently, the device configuration is complicated. Further, it is also conceivable to keep

the opening degree of the third open-close valve 32 constant. In this case, however, the refrigerant R1 unnecessarily bypassed increases as the cooling progresses.

[0124] In the refrigerator 1 of the present embodiment, if the opening degree of the third open-close valve 32 is increased at an appropriate timing, the refrigerant R1 is released from the high-pressure line to the low-pressure line without recovering the refrigerant R1 to the buffer tank 27, making it possible to secure the flow rate of the refrigerant R1. Thus, it is possible to suppress surging of the compressor C1, C2, C3 during precooling, without necessarily including the buffer line part 25.

[0125] Herein, FIG. 9 is a graph showing an example of pressure fluctuation states of the high-pressure line, the low-pressure line, and the buffer tank 27 in the bypass control operation (during stepwise control).

Further, for example, in FIGs. 9 and 4, (a) represents the time when the refrigerator operation is started, (b) represents the end point (refrigerant temperature: time at 225 K) of step 1 in the initial operation control, (c) represents the end point (refrigerant temperature: time at 190 K) of step 2 in the stepwise or continuous operation control, and (d) represents the end point (refrigerant temperature: time at 100 K) of step 5 in the stepwise or continuous operation control.

[0126] Then, as shown in FIG. 9 (and FIG. 4), since the refrigerant pressure in the high-pressure line is high between (a) at the start of the refrigerator operation and (b) at the end point of step 1 (corresponding to step 1), the open control of the first open-close valve 28 is performed between (a) and (b) to recover the refrigerant by the buffer line part 25. That is, in the refrigerator 1 and the operation method for the refrigerator 1 of the present embodiment, the pressure in the high-pressure line is not less than the set value (threshold) between (a) and (b), and at this time, the open control of the first open-close valve 28 is performed to recover the refrigerant by the buffer line part 25.

The fluctuation in internal pressure of the buffer tank 27 between (a) and (b) is substantially the same as the fluctuation in refrigerant pressure in the high-pressure line (indicates the same behavior/tendency).

[0127] Next, between (b) at the end point of step 1 and (c) at the end point of step 2 (corresponding to step 2), the opening degree of the third open-close valve (bypass valve) 32 of the bypass line part 30 decreases (for example, decreases from 40% to 35%) and the bypass amount of the refrigerant is decreased. Thus, between (b) and (c), the amount of the refrigerant directed from the compressor C3 to the expander T increases, temporarily increasing the pressure in the high-pressure line.

[0128] Thus, in the refrigerator 1 and the operation method for the refrigerator 1 of the present embodiment, the pressure in the high-pressure line is not less than the set value (threshold), or in other words not less than the internal pressure of the buffer tank 27, between (b) and (c) (corresponding to step 2), and between (b) and (c), the open control of the first open-close valve 28 is performed to recover the refrigerant by the buffer line part 25. That is, the refrigerant is recovered in a region where the refrigerant pressure in the high-pressure line is higher than the internal pressure of the buffer tank 27.

[0129] Further, between (a) and (b), between (b) and (c), by performing control to increase the rotation speed so as to keep the cooling velocity constant (by controlling the rotation speed at 60% to 75% after the operation with the constant (40%) opening degree of the third open-close valve 32, 60% of the rotation speed (10 minutes), for example), the cooling velocity of the refrigerant is kept constant and the refrigerant pressure in the high-pressure line decreases along with such drop in refrigerant temperature.

[0130] Further, in the refrigerator 1 and the operation method for the refrigerator 1 of the present embodiment, the cooling operation is continued at the constant opening degree of the third open-close valve 32, between (a) and (b), that is, until the refrigerant temperature reaches approximately 225 K.

[0131] More specifically, if the valve control of the third open-close valve 32 is performed between (a) and (b), a disturbance occurs as seen between (b) and (c), and the fluctuation in refrigerant pressure in the high-pressure line and further the change in rotation speed occur, which may lead to a decrease in operating efficiency when the cooling velocity of the refrigerant kept constant.

Thus, in the refrigerator 1 and the operation method for the refrigerator 1 of the present embodiment, even when the stepwise or continuous operation control is performed, the third open-close valve 32 is maintained at the constant opening degree without changing the opening degree in step 1 between (a) and (b).

5 [0132] Then, in the refrigerator 1 and the operation method for the refrigerator 1 of the present embodiment, the recovery of the refrigerant in the buffer tank 27 is first performed during the initial operation (refrigerant temperature up to 225 K) between (a) and (b) to recover excess refrigerant, and secondly, subsequently performed such that the refrigerant can temporarily be recovered by the pressure increase of the refrigerant when the opening degree
10 of the third open-close valve 32 is changed.

[0133] (Adjustment control of refrigerator ability during normal operation)

In the present embodiment, the refrigerator ability is adjusted according to the condition of the heat load during the normal (steady) operation after transition control to the normal operation is performed.

15 When increasing the ability of the refrigerator 1, the open control of the second open-close valve 29 is performed to return the refrigerant R1 stored in the buffer tank 27 to a low-pressure line 8a.

When decreasing the ability of the refrigerator 1, the open control of the first open-close valve 28 is performed to recover the refrigerant R1 to the buffer tank 27.

20 [0134] At this time, in the refrigerator 1 of the present embodiment, the set temperature of the refrigerant R1 and the rotation speed of the refrigerator 1 (the rotation speeds of the first motor 9 and the second motor 11, and thus the respective compressors C1, C2, and C3) are used as the determination conditions for adjusting the refrigerator ability, that is, the determination conditions for the open/close drive control of the first open-close valve 28 and the second open-
25 close valve 29. Further, a third pressure sensor 41 is provided on the low-pressure line.

[0135] For example, the second open-close valve 29 is open if the refrigerant temperature detected by the first temperature sensor 33 (or the second temperature sensor 34) is not lower than the preset set temperature (pressure is insufficient) and the rotation speed of the refrigerator

is 100% (motor load is good), and is closed if the pressure in the buffer tank 27 is decreased by a certain pressure or the refrigerant temperature is not higher than the set temperature (refrigerant amount is excessive) and the rotation speed of the refrigerator is below 100% (motor load increases). The pressures in the high-pressure line, the buffer tank 27, and the low-pressure line are measured by the respective pressure sensors, and the refrigerant R1 is discharged or recovered on the condition of not less than the set differential pressure.

[0136] The first open-close valve 28 is open (the refrigerant amount in the refrigerant circulation line is reduced) if the refrigerant temperature detected by the first temperature sensor 33 (or the second temperature sensor 34) is not higher than the preset set temperature (refrigerant amount is excessive) and the rotation speed of the refrigerator falls below the preset threshold such as 98% (motor load is excessive), and is closed (refrigerant recovery is stopped) if the pressure in the buffer tank 27 is increased by a certain pressure or the refrigerant temperature is not lower than the set temperature (refrigerant amount decreases) and the rotation speed of the refrigerator increases (motor load decreases) and exceeds the threshold such as 98%.

[0137] Consequently, the capacity of the buffer tank 27 is limited, and it is necessary to adjust the recovery amount or recovery time of the refrigerant. However, since the open/close drive control of the first open-close valve 28 and the second open-close valve 29 is performed as described above, it is possible to adjust the recovery amount or recovery time of the refrigerant, and it is possible to adjust and maintain the refrigerant ability in the suitable state during normal operation.

[0138] The embodiments of the refrigerator and the operation method during precooling of the refrigerant of the present disclosure have been described above. However, the refrigerator and the operation method during precooling of the refrigerant of the present disclosure are not limited to the above-described embodiments, but can be modified as appropriate within a scope without departing from the gist of the present invention, including a modification or the like.

[0139] For example, in the present embodiment, the refrigerator is configured with the three compressors, namely, the low-stage compressor, the middle-stage compressor, and the high-

stage compressor. However, there is no need to limit the number of compressors in particular, as long as the refrigerator includes at least the low-stage compressor, the high-stage compressor.

[0140] Further, in the present embodiment, the one controller 40 controls the drive of the first motor 9, the second motor 11, the opening degree (open/close drive) of the first open-close valve 28, the second open-close valve 29, the third open-close valve 32, in response to the detection result of each of the first temperature sensor 33, the second temperature sensor 34, the third temperature sensor 35, the first pressure sensor 36, the second pressure sensor 37, the first dynamometer 38, and the second dynamometer 39. However, the number of controllers does not necessarily have to be one. That is, the refrigerator may be configured with a plurality of controllers for sharing the detection results of the respective sensors or the like and sharing the drive control of the respective motors, valves, or the like.

[0141] The embodiments of the refrigerator and the operation method during precooling of the refrigerator of the present disclosure function effectively not only at startup of the refrigerator from a state where pressures are equalized at normal temperature, but also at restart immediately after the refrigerator is stopped. In that case, even on the condition where the refrigerant temperature of the refrigerator or the temperature of the low-temperature equipment does not rise, the controller performs the refrigerator precooling operation control, the bypass control, the buffer tank refrigerant recovery control based on the measurement values of the various sensors, making it possible to start, continue the precooling operation without any trouble.

[0142] Lastly, the contents described in the above embodiments would be understood as follows, for instance.

[0143] (1) A refrigerator (refrigerator 1) according to one aspect of the present disclosure includes: an expander-integrated compressor (expander-integrated compressor 7) which includes a compressor (high-stage compressor C3) for compressing a refrigerant (refrigerant R1), and an expander (expander T) for expanding the refrigerant compressed by the compressor, the expander being coupled to the compressor via a rotational shaft drivable by a motor (first motor 9); a cooling part (cooling part 2) for cooling a cooling object (cooling object, liquid

nitrogen, secondary refrigerant R2) with the refrigerant expanded by the expander; a refrigerant circulation line (refrigerant circulation line 8) for circulating the refrigerant, the refrigerant circulation line including a low-pressure line ranging from the expander to the low-stage compressor (low-stage compressor C1) via the cooling part, an intermediate-pressure line ranging from the low-stage compressor to the high-stage compressor, and a high-pressure line ranging from the high-stage compressor to the expander; a bypass line (bypass line 31) which is connected at one end to a first connection portion (first connection portion S1) disposed on the high-pressure line and is connected at another end to a second connection portion (second connection portion S2) disposed on the low-pressure line; and a bypass valve (third open-close valve 32) disposed on the bypass line and capable of adjusting a flow rate of the refrigerant flowing through the bypass line by adjusting an opening degree.

[0144] In the refrigerator of the above (1), since the bypass valve undergoes the open control, the part of the refrigerant compressed by the high-stage compressor can be returned to the low-stage compressor and thus the high-stage compressor without being supplied to the expander. Further, since the opening degree of the bypass valve is adjusted, it is possible to change the flow rate of refrigerant returned to the compressor and thus the flow rate of the refrigerant flowing to the expander.

[0145] Thus, in the initial operation period from startup to the completion of precooling, since the opening degree of the bypass valve is appropriately changed according to the operating state, it is possible to prevent the occurrence of surging and to reduce the refrigerant which is not used for cooling, enabling efficient (high COP) operation in which power is not wasted.

[0146] (2) A refrigerator according to another aspect of the present disclosure is the refrigerator of the above (1) that includes: a temperature sensor (first temperature sensor 33) for detecting a temperature of the refrigerant flowing between the first connection portion and the expander of the high-pressure line; and a controller (controller 40, control device) for controlling the opening degree of the bypass valve and a rotation speed of the rotational shaft based on a detection result of the temperature sensor.

[0147] In the refrigerator of the above (2), since the opening degree adjustment of the

bypass valve and thus the adjustment control of the refrigerant flow rate to be bypassed are controlled based on the detection value of the temperature sensor for detecting the temperature of the refrigerant flowing between the first connection portion and the expander such as near the inlet of the expander, it is possible to accurately perform control without complicating the device configuration, compared to the case where the flow rate of the refrigerant is detected.

[0148] Therefore, surging can be avoided by controlling the flow rate of the refrigerant without detecting the flow rate of the refrigerant, making it possible to improve safety while simplifying the device configuration. Further, precooling becomes possible where the compressor or the expander is operated at high rotation speed, making it possible to achieve smooth precooling operation.

[0149] That is, in the initial operation period, compared to before, it is possible to suitably suppress the occurrence of surging and to accurately cool the refrigerant at the constant cooling velocity, and it is possible to perform efficient operation control.

[0150] (3) A refrigerator according to another aspect of the present disclosure is the refrigerator of the above (1) that includes: a temperature sensor (second temperature sensor 34) for detecting a temperature of the refrigerant between the cooling part and the expander of the low-pressure line; and a controller for controlling the opening degree of the bypass valve and a rotation speed of the rotational shaft based on a detection result of the temperature sensor.

[0151] In the refrigerator of the above (3), since the opening degree adjustment of the bypass valve and thus the adjustment control of the refrigerant flow rate to be bypassed are controlled based on the detection value of the temperature sensor for detecting the temperature of the refrigerant flowing between the cooling part and the expander such as near the outlet of the expander, it is possible to accurately perform control without complicating the device configuration, compared to the case where the flow rate of the refrigerant is detected.

[0152] Therefore, surging can be avoided by controlling the flow rate of the refrigerant without detecting the flow rate of the refrigerant, making it possible to improve safety while simplifying the device configuration. Further, precooling becomes possible where the compressor or the expander is operated at high rotation speed, making it possible to achieve

smooth precooling operation.

[0153] That is, in the initial operation period, compared to before, it is possible to suitably suppress the occurrence of surging and to accurately cool the refrigerant at the constant cooling velocity, and it is possible to perform efficient operation control.

5 [0154] (4) A refrigerator according to another aspect of the present disclosure is the refrigerator of the above (2) or (3), wherein the controller is configured to: control the bypass valve such that the opening degree is decreased stepwise until the temperature of the refrigerant detected by the temperature sensor reaches a preset first target temperature; and control the rotation speed such that a rate of decrease in the temperature of the refrigerant detected by the temperature sensor is maintained constant, in an initial operation period from a start of startup to a completion of a precooling operation of the refrigerator.

[0155] In the refrigerator of the above (4), in the initial operation period from startup to the completion of precooling, in addition to controlling the opening degree of the bypass valve, the rotation speed of the refrigerator (compressor, expander) is controlled, thereby
15 adjusting/modifying the cooling velocity to maintain the constant cooling velocity. Thus, it is possible to accurately control the refrigerant temperature.

[0156] Further, since the stepwise opening degree control of the bypass valve and the rotation speed control of the refrigerator are used in combination, the opening degree of the bypass valve can be set for each temperature section of each step, and the rotation speed can be
20 controlled such that the cooling velocity takes the preset constant set value in each divided temperature section.

Thus, the stable precooling operation with little fluctuation in pressure or rotation speed of the refrigerator is possible.

[0157] (5) A refrigerator according to another aspect of the present disclosure is the
25 refrigerator of the above (2) or (3), wherein the controller is configured to: control the bypass valve such that the opening degree is decreased continuously until the temperature of the refrigerant detected by the temperature sensor reaches a preset first target temperature; and control the rotation speed such that a rate of decrease in the temperature of the refrigerant

detected by the temperature sensor is maintained constant, in an initial operation period from a start of startup to a completion of a precooling operation of the refrigerator.

[0158] In the refrigerator of the above (5), in the initial operation period from startup to the completion of precooling, in addition to controlling the opening degree of the bypass valve, the rotation speed of the refrigerator (compressor, expander) is controlled, thereby adjusting/modifying the cooling velocity to maintain the constant cooling velocity. Thus, it is possible to accurately control the refrigerant temperature.

[0159] Further, since the continuous opening degree control of the bypass valve and the rotation speed control of the refrigerator are used in combination, the opening degree of the bypass valve can be set for each temperature section of each step, and the rotation speed can be controlled such that the cooling velocity takes the preset constant set value in each divided temperature section.

Thus, the stable precooling operation with little fluctuation in pressure or rotation speed of the refrigerator is possible.

[0160] (6) A refrigerator according to another aspect of the present disclosure is the refrigerator of the above (4) or (5), wherein the controller is configured to: control the bypass valve such that the opening degree becomes 0% at a stage when the temperature of the refrigerant detected by the temperature sensor reaches the first target temperature; and control the rotation speed such that the rate of decrease in the temperature of the refrigerant detected by the temperature sensor is maintained constant while maintaining the opening degree at 0% until the temperature of the refrigerant, which is detected by the temperature sensor and is lower than the first target temperature, reaches a second target temperature set lower than the first target temperature.

[0161] In the refrigerator of the above (6), at the stage when the first target temperature is reached, the opening degree of the bypass valve becomes 0%, the operation control using the bypass line ends, and the process shifts to the non-bypass control operation in which all the refrigerant circulation amount flows from the compressor to the expander. Then, in the precooling operation of the non-bypass control operation, the rotation speed is controlled such

that the cooling velocity is maintained constant toward the second target temperature which is the next target temperature.

Therefore, since the stepwise or continuous opening degree adjustment control of the bypass valve and the rotation speed control of the refrigerator are used in combination, in the initial operation period from startup to the completion of precooling, it is possible to suppress the occurrence of surging more effectively and to accurately cool the refrigerant at the constant cooling velocity, and it is possible to perform efficient operation control.

[0162] (7) A refrigerator according to another aspect of the present disclosure is the refrigerator of the above (6) that includes: a heat exchanger (cooling part, secondary side load heat exchanger 2) for exchanging heat between the refrigerant and a secondary refrigerant (cooling object refrigerant R2) for cooling the cooling object; and a secondary refrigerant temperature sensor (third temperature sensor 35) for detecting a temperature of the secondary refrigerant. The controller is configured to control the rotation speed based on a detection result of the secondary refrigerant temperature sensor, if the temperature of the refrigerant detected by the temperature sensor is lower than the second target temperature.

[0163] In the refrigerator of the above (7), the temperature detection point is switched from the temperature sensor to the secondary refrigerant temperature sensor at the stage when the second target temperature is reached, and the rotation speed is controlled based on the detection result of the secondary refrigerant temperature sensor. Thus, it is possible to smoothly shift from the precooling operation in the initial operation period to the normal (steady) operation.

[0164] (8) A refrigerator according to another aspect of the present disclosure is the refrigerator of any one of the above (1) to (7) that includes: a cold recovery heat exchanger (cold recovery heat exchanger 15) for cooling a refrigerant in the high-pressure line with a refrigerant having been used to cool the cooling object in the cooling part; a buffer line (buffer line 26) which is connected at one end to a third connection portion (third connection portion S3) disposed between the cold recovery heat exchanger and the expander of the high-pressure line, and is connected at another end to a fourth connection portion (fourth connection portion S4) disposed between the expander and the cooling part of the low-pressure line; a buffer tank

(buffer tank 27) disposed on the buffer line and capable of storing the refrigerant sent from the high-pressure line; a high-pressure side buffer valve (first open-close valve 28) disposed between the buffer tank and the third connection portion of the buffer line; a low-pressure side buffer valve (second open-close valve 29) disposed between the buffer tank and the fourth connection portion of the buffer line; a first pressure sensor (first pressure sensor 36) for detecting a pressure of the refrigerant between the first connection portion and the third connection portion of the high-pressure line; a second pressure sensor (second pressure sensor 37) for detecting an internal pressure of the buffer tank; and a controller for controlling opening degrees of the high-pressure side buffer valve and the low-pressure side buffer valve according to detection results of the first pressure sensor and the second pressure sensor.

[0165] In the refrigerator of the above (8), during from the startup to the precooling operation, if the state is detected where the first pressure sensor and the second pressure sensor set the refrigerant pressure in the high-pressure line higher than the pressure in the buffer tank by the preset set value or greater, the high-pressure side buffer valve is opened and the refrigerant can be recovered to the buffer tank by using the pressure difference.

Thus, it is possible to more effectively suppress the occurrence of excessive motor load, the occurrence of surging.

[0166] (9) An operation method during precooling of a refrigerator according to one aspect of the present disclosure is an operation method in an initial operation period from startup to a completion of precooling of a refrigerator that includes: an expander-integrated compressor which includes a compressor for compressing a refrigerant, and an expander for expanding the refrigerant compressed by the compressor, the expander being coupled to the compressor via a rotational shaft drivable by a motor; a cooling part for cooling a cooling object with the refrigerant expanded by the expander; a refrigerant circulation line for circulating the refrigerant, the refrigerant circulation line including a low-pressure line ranging from the expander to the low-stage compressor via the cooling part, an intermediate-pressure line ranging from the low-stage compressor to the high-stage compressor, and a high-pressure line ranging from the high-stage compressor to the expander; a bypass line which is connected at one end to a first

connection portion disposed on the high-pressure line and is connected at another end to a second connection portion disposed on the low-pressure line; a bypass valve disposed on the bypass line and capable of adjusting a flow rate of the refrigerant flowing through the bypass line by adjusting an opening degree; a temperature sensor for detecting a temperature of the refrigerant flowing between the first connection portion and the expander of the high-pressure line or a temperature of the refrigerant between the cooling part and the expander of the low-pressure line; and a controller for controlling the opening degree of the bypass valve and a rotation speed of the rotational shaft based on a detection result of the temperature sensor, the operation method during precooling of the refrigerator, including: a startup operation step of starting an operation by setting the rotation speed of the rotational shaft at a preset rotation speed lower than a rotation speed during a steady operation after the initial operation period and setting the opening degree of the bypass valve at a preset opening degree; a bypass control operation step of controlling, with the controller, such that the opening degree of the bypass valve is decreased stepwise until the temperature of the refrigerant detected by the temperature sensor reaches a preset first target temperature; a non-bypass control operation step of cooling, at a stage when the temperature of the refrigerant reaches the first target temperature, the refrigerant until the temperature of the refrigerant reaches a preset second target temperature from the first target temperature, at a 0-percent opening degree of the bypass valve; and a cooling velocity control step of controlling, with the controller, the rotation speed such that a rate of decrease in the temperature of the refrigerant is maintained constant at least in the bypass control operation step among the bypass control operation step and the non-bypass control operation step.

[0167] In the operation method during precooling of the refrigerator of the above (9), since the bypass valve undergoes the open control, the part of the refrigerant compressed by the high-stage compressor can be returned to the low-stage compressor and thus the high-stage compressor without being supplied to the expander. Further, since the opening degree of the bypass valve is adjusted, it is possible to change the flow rate of refrigerant returned to the compressor and thus the flow rate of the refrigerant flowing to the expander.

[0168] Thus, in the initial operation period from startup to the completion of precooling, since the opening degree of the bypass valve is appropriately changed according to the operating state, it is possible to prevent the occurrence of surging and to reduce the refrigerant which is not used for cooling, enabling efficient (high COP) operation in which power is not wasted.

5 [0169] Further, in the initial operation period from startup to the completion of precooling, in addition to controlling the opening degree of the bypass valve, the rotation speed of the refrigerator (compressor, expander) is controlled, thereby adjusting/modifying the cooling velocity to maintain the constant cooling velocity. Thus, it is possible to accurately control the refrigerant temperature.

10 [0170] Then, since the opening degree adjustment of the bypass valve and thus the adjustment control of the refrigerant flow rate to be bypassed are controlled based on the detection value of the first temperature sensor or the second temperature sensor disposed near the inlet or near the outlet of the expander, it is possible to accurately perform control without complicating the device configuration, compared to the case where the refrigerant flow rate is

15 detected.

[0171] Therefore, surging can be avoided by controlling the flow rate of the refrigerant without detecting the flow rate of the refrigerant, making it possible to improve safety while simplifying the device configuration. Further, precooling becomes possible where the compressor or the expander is operated at high rotation speed, making it possible to achieve

20 smooth precooling operation.

[0172] That is, in the initial operation period, compared to before, it is possible to suitably suppress the occurrence of surging and to accurately cool the refrigerant at the constant cooling velocity, and it is possible to perform efficient operation control.

[0173] (10) An operation method during precooling of a refrigerator according to another

25 aspect of the present disclosure is the operation method for the refrigerator of the above (9), wherein the bypass control operation step includes controlling, with the controller, such that the opening degree of the bypass valve is decreased stepwise until the temperature of the refrigerant detected by the temperature sensor reaches the preset first target temperature.

[0174] In the operation method during precooling of the refrigerator of the above (10), in the initial operation period from startup to the completion of precooling, in addition to controlling the opening degree of the bypass valve, the rotation speed of the refrigerator (compressor, expander) is controlled, thereby adjusting/modifying the cooling velocity to maintain the constant cooling velocity. Thus, it is possible to accurately control the refrigerant temperature.

[0175] Further, since the stepwise opening degree control of the bypass valve and the rotation speed control of the refrigerator are used in combination, the opening degree of the bypass valve can be set for each temperature section of each step, and the rotation speed can be controlled such that the cooling velocity takes the preset constant set value in each divided temperature section.

Thus, the stable precooling operation with little fluctuation in pressure or rotation speed of the refrigerator is possible.

[0176] (11) An operation method during precooling of a refrigerator according to another aspect of the present disclosure is the operation method for the refrigerator of the above (9), wherein the bypass control operation step includes controlling, with the controller, such that the opening degree of the bypass valve is decreased continuously until the temperature of the refrigerant detected by the temperature sensor reaches the preset first target temperature.

[0177] In the operation method during precooling of the refrigerator of the above (11), in the initial operation period from startup to the completion of precooling, in addition to controlling the opening degree of the bypass valve, the rotation speed of the refrigerator (compressor, expander) is controlled, thereby adjusting/modifying the cooling velocity to maintain the constant cooling velocity. Thus, it is possible to accurately control the refrigerant temperature.

[0178] Further, since the continuous opening degree control of the bypass valve and the rotation speed control of the refrigerator are used in combination, the opening degree of the bypass valve can be set for each temperature section of each step, and the rotation speed can be controlled such that the cooling velocity takes the preset constant set value in each divided

temperature section.

Thus, the stable precooling operation with little fluctuation in pressure or rotation speed of the refrigerator is possible.

[0179] (12) An operation method during precooling of a refrigerator according to another aspect of the present disclosure is the operation method for the refrigerator of any one of the above (9) to (11), wherein the refrigerator includes: a heat exchanger for exchanging heat between the refrigerant and a secondary refrigerant for cooling the cooling object; and a secondary refrigerant temperature sensor for detecting a temperature of the secondary refrigerant, and the controller includes a main cooling operation switching step of controlling the rotation speed based on a detection result of the secondary refrigerant temperature sensor, if the temperature of the refrigerant detected by the temperature sensor is lower than the second target temperature.

[0180] In the operation method during precooling of the refrigerator of the above (12), the temperature detection point is switched from the temperature sensor to the secondary refrigerant temperature sensor at the stage when the second target temperature is reached, and the rotation speed is controlled based on the detection result of the secondary refrigerant temperature sensor. Thus, it is possible to smoothly shift from the precooling operation in the initial operation period to the normal (steady) operation.

Reference Signs List

[0181]

- 1 Refrigerator
- 2 Cooling part (secondary side load heat exchanger)
- 7 Expander-integrated compressor
- 8 Refrigerant circulation line
- 9 First motor
- 10 Integrated compressor
- 11 Second motor

	12	First heat exchanger
	13	Second heat exchanger
	14	Third heat exchanger
	15	Cold recovery heat exchanger (regenerative heat exchanger)
5	16	Cooling object-side circulation line
	20	Superconducting equipment (cooling object)
	25	Buffer line part
	26	Buffer line
	27	Buffer tank
10	28	First open-close valve (high-pressure side buffer valve)
	29	Second open-close valve (low-pressure side buffer valve)
	30	Bypass line part
	31	Bypass line
	32	Third open-close valve (bypass valve)
15	33	First temperature sensor (temperature sensor)
	34	Second temperature sensor (temperature sensor)
	35	Third temperature sensor (secondary refrigerant temperature sensor)
	36	First pressure sensor
	37	Second pressure sensor
20	41	Third pressure sensor
	38	First dynamometer
	39	Second dynamometer
	40	Controller (control device)
	C1	Low-stage compressor
25	C2	Middle-stage compressor
	C3	High-stage compressor
	T	Expander
	R1	Refrigerant

- R2 Cooling object refrigerant (liquid nitrogen, secondary refrigerant, cooling object)
- S1 First connection portion
- S2 Second connection portion
- S3 Third connection portion
- 5 S4 Fourth connection portion
- w Cooling water

CLAIMS

[Claim 1] A refrigerator, comprising:

a low-stage compressor for compressing a refrigerant;

5 an expander-integrated compressor which includes a high-stage compressor for further compressing the refrigerant, and an expander for expanding the refrigerant compressed by the high-stage compressor, the expander being coupled to the high-stage compressor via a rotational shaft drivable by a motor;

a cooling part for cooling a cooling object with the refrigerant expanded by the expander;

10 a refrigerant circulation line for circulating the refrigerant, the refrigerant circulation line including a low-pressure line ranging from the expander to the low-stage compressor via the cooling part, an intermediate-pressure line ranging from the low-stage compressor to the high-stage compressor, and a high-pressure line ranging from the high-stage compressor to the expander;

15 a bypass line which is connected at one end to a first connection portion disposed on the high-pressure line and is connected at another end to a second connection portion disposed on the low-pressure line; and

a bypass valve disposed on the bypass line and capable of adjusting a flow rate of the refrigerant flowing through the bypass line by adjusting an opening degree.

20

[Claim 2] The refrigerator according to claim 1, comprising:

a cold recovery heat exchanger for cooling the refrigerant flowing through the high-pressure line with the refrigerant in the low-pressure line having passed through the cooling part, the cold recovery heat exchanger being disposed on the high-pressure line;

25 a temperature sensor for detecting a temperature of the refrigerant flowing between the cold recovery heat exchanger and the expander of the high-pressure line; and

a controller for controlling the opening degree of the bypass valve and a rotation speed of the rotational shaft based on a detection result of the temperature sensor.

[Claim 3] The refrigerator according to claim 1, comprising:

a temperature sensor for detecting a temperature of the refrigerant between the cooling part and the expander of the low-pressure line; and

5 a controller for controlling the opening degree of the bypass valve and a rotation speed of the rotational shaft based on a detection result of the temperature sensor.

[Claim 4] The refrigerator according to claim 2 or 3,

wherein the controller is configured to:

10 control the bypass valve such that the opening degree is decreased stepwise until the temperature of the refrigerant detected by the temperature sensor reaches a preset first target temperature; and control the rotation speed such that a rate of decrease in the temperature of the refrigerant detected by the temperature sensor is maintained constant, in an initial operation period from a start of startup to a completion of a precooling operation of the refrigerator.

15

[Claim 5] The refrigerator according to claim 2 or 3,

wherein the controller is configured to:

control the bypass valve such that the opening degree is decreased continuously until the temperature of the refrigerant detected by the temperature sensor reaches a preset first target
20 temperature; and control the rotation speed such that a rate of decrease in the temperature of the refrigerant detected by the temperature sensor is maintained constant, in an initial operation period from a start of startup to a completion of a precooling operation of the refrigerator.

[Claim 6] The refrigerator according to claim 4 or 5,

25 wherein the controller is configured to:

control the bypass valve such that the opening degree becomes 0% at a stage when the temperature of the refrigerant detected by the temperature sensor reaches the first target temperature; and control the rotation speed such that the rate of decrease in the temperature of

the refrigerant detected by the temperature sensor is maintained constant while maintaining the opening degree at 0% until the temperature of the refrigerant, which is detected by the temperature sensor and is lower than the first target temperature, reaches a second target temperature set lower than the first target temperature.

5

[Claim 7] The refrigerator according to claim 6, comprising:

a heat exchanger for exchanging heat between the refrigerant and a secondary refrigerant for cooling the cooling object; and

10 a secondary refrigerant temperature sensor for detecting a temperature of the secondary refrigerant,

wherein the controller is configured to:

control the rotation speed based on a detection result of the secondary refrigerant temperature sensor, if the temperature of the refrigerant detected by the temperature sensor is lower than the second target temperature.

15

[Claim 8] The refrigerator according to any one of claims 1 to 7, comprising:

a cold recovery heat exchanger for cooling a refrigerant in the high-pressure line with a refrigerant having been used to cool the cooling object in the cooling part;

20 a buffer line which is connected at one end to a third connection portion disposed between the cold recovery heat exchanger and the high-stage compressor of the high-pressure line, and is connected at another end to a fourth connection portion disposed between the low-stage compressor and the cold recovery heat exchanger of the low-pressure line;

a buffer tank disposed on the buffer line and capable of storing the refrigerant sent from the high-pressure line;

25 a high-pressure side buffer valve disposed between the buffer tank and the third connection portion of the buffer line;

a low-pressure side buffer valve disposed between the buffer tank and the fourth connection portion of the buffer line;

a first pressure sensor for detecting a pressure of the refrigerant between the first connection portion and the third connection portion of the high-pressure line;

a second pressure sensor for detecting an internal pressure of the buffer tank; and

a controller for controlling opening degrees of the high-pressure side buffer valve and the low-pressure side buffer valve according to detection results of the first pressure sensor and the second pressure sensor.

[Claim 9] The refrigerator according to claim 1, comprising:

a cold recovery heat exchanger for cooling the refrigerant flowing through the high-pressure line with the refrigerant having passed through the cooling part, the cold recovery heat exchanger being disposed on the high-pressure line;

a temperature sensor for detecting a temperature of the refrigerant flowing between the cold recovery heat exchanger and the expander of the high-pressure line; and

a controller for controlling the opening degree of the bypass valve and a rotation speed of the rotational shaft based on a detection result of the temperature sensor,

wherein the controller is configured to control the bypass valve such that the opening degree is decreased stepwise or continuously until the temperature of the refrigerant detected by the temperature sensor reaches a preset first target temperature, in an initial operation period from a start of startup to a completion of a precooling operation of the refrigerator.

[Claim 10] An operation method in an initial operation period from startup to a completion of precooling of a refrigerator that includes:

a low-stage compressor for compressing a refrigerant;

an expander-integrated compressor which includes a high-stage compressor for further compressing the refrigerant, and an expander for expanding the refrigerant compressed by the high-stage compressor, the expander being coupled to the high-stage compressor via a rotational shaft drivable by a motor;

a cooling part for cooling a cooling object with the refrigerant expanded by the expander;

a refrigerant circulation line for circulating the refrigerant, the refrigerant circulation line including a low-pressure line ranging from the expander to the low-stage compressor via the cooling part, an intermediate-pressure line ranging from the low-stage compressor to the high-stage compressor, and a high-pressure line ranging from the high-stage compressor to the expander;

a bypass line which is connected at one end to a first connection portion disposed on the high-pressure line and is connected at another end to a second connection portion disposed on the low-pressure line;

a bypass valve disposed on the bypass line and capable of adjusting a flow rate of the refrigerant flowing through the bypass line by adjusting an opening degree;

a temperature sensor for detecting a temperature of the refrigerant flowing between the cold recovery heat exchanger and the expander of the high-pressure line or a temperature of the refrigerant between the cooling part and the expander of the low-pressure line; and

a controller for controlling the opening degree of the bypass valve and a rotation speed of the rotational shaft based on a detection result of the temperature sensor, the operation method during precooling of the refrigerator, comprising:

a startup operation step of starting an operation by setting the rotation speed of the rotational shaft at a preset rotation speed lower than a rotation speed during a steady operation after the initial operation period and setting the opening degree of the bypass valve at a preset opening degree;

a bypass control operation step of controlling, with the controller, such that the opening degree of the bypass valve is decreased until the temperature of the refrigerant detected by the temperature sensor reaches a preset first target temperature;

a non-bypass control operation step of cooling, at a stage when the temperature of the refrigerant reaches the first target temperature, the refrigerant until the temperature of the refrigerant reaches a preset second target temperature from the first target temperature, at a 0-percent opening degree of the bypass valve; and

a cooling velocity control step of controlling, with the controller, the rotation speed such

that a rate of decrease in the temperature of the refrigerant is maintained constant at least in the bypass control operation step among the bypass control operation step and the non-bypass control operation step.

5 [Claim 11] The operation method during precooling of the refrigerator according to claim 10,
wherein the bypass control operation step includes controlling, with the controller, such
that the opening degree of the bypass valve is decreased stepwise until the temperature of the
refrigerant detected by the temperature sensor reaches the preset first target temperature.

10 [Claim 12] The operation method during precooling of the refrigerator according to claim 10,
wherein the bypass control operation step includes controlling, with the controller, such
that the opening degree of the bypass valve is decreased continuously until the temperature of
the refrigerant detected by the temperature sensor reaches the preset first target temperature.

15 [Claim 13] The operation method during precooling of the refrigerator according to any one of
claims 10 to 12,

wherein the refrigerator includes:

a heat exchanger for exchanging heat between the refrigerant and a secondary refrigerant
for cooling the cooling object; and

20 a secondary refrigerant temperature sensor for detecting a temperature of the secondary
refrigerant, and

wherein the controller includes:

a main cooling operation switching step of controlling the rotation speed based on a
detection result of the secondary refrigerant temperature sensor, if the temperature of the
25 refrigerant detected by the temperature sensor is lower than the second target temperature.