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(54) **HEAT PUMP**

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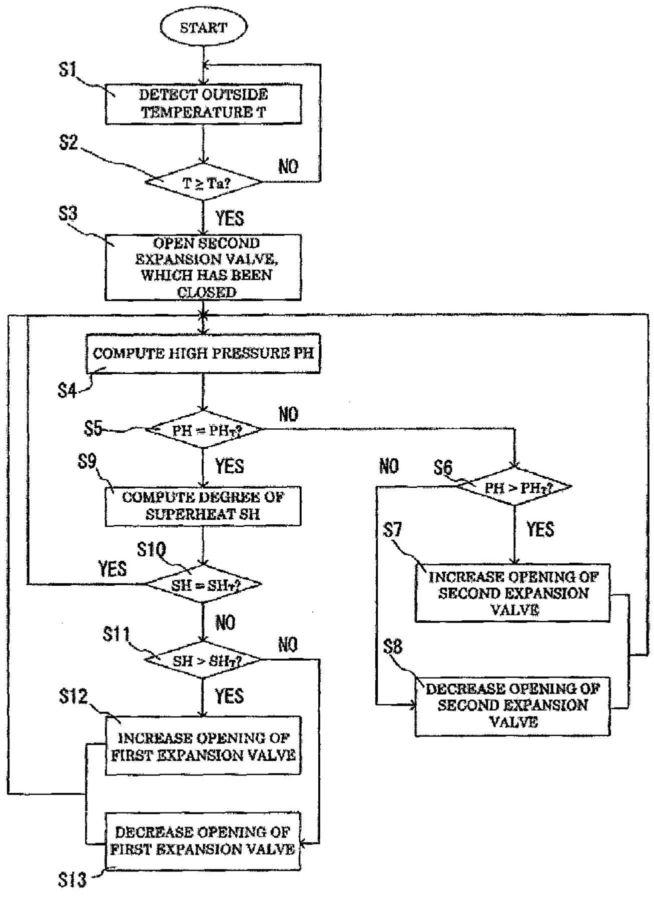
(57) **ABSTRACT**

A heat pump of the present invention has a compressor and an expander coupled with a common axis of rotation, a first throttling device disposed in a circulation passage of refrigerant, and a second throttling device disposed in a bypass passage diverted from the expander. A control device controls the openings of these throttling devices. The control device executes a first controlling in which the opening of the first throttling device is adjusted in order to bring a high pressure PH in a refrigeration cycle close to a predetermined value determined based on a value at which the coefficient of performance (COP) of the heat pump is optimized, and after the first controlling is completed, it executes a second controlling in which the opening of the second throttling device is adjusted in order to bring a degree of superheat SH close to a predetermined positive value. This ensures smooth and stable operations of the heat pump.



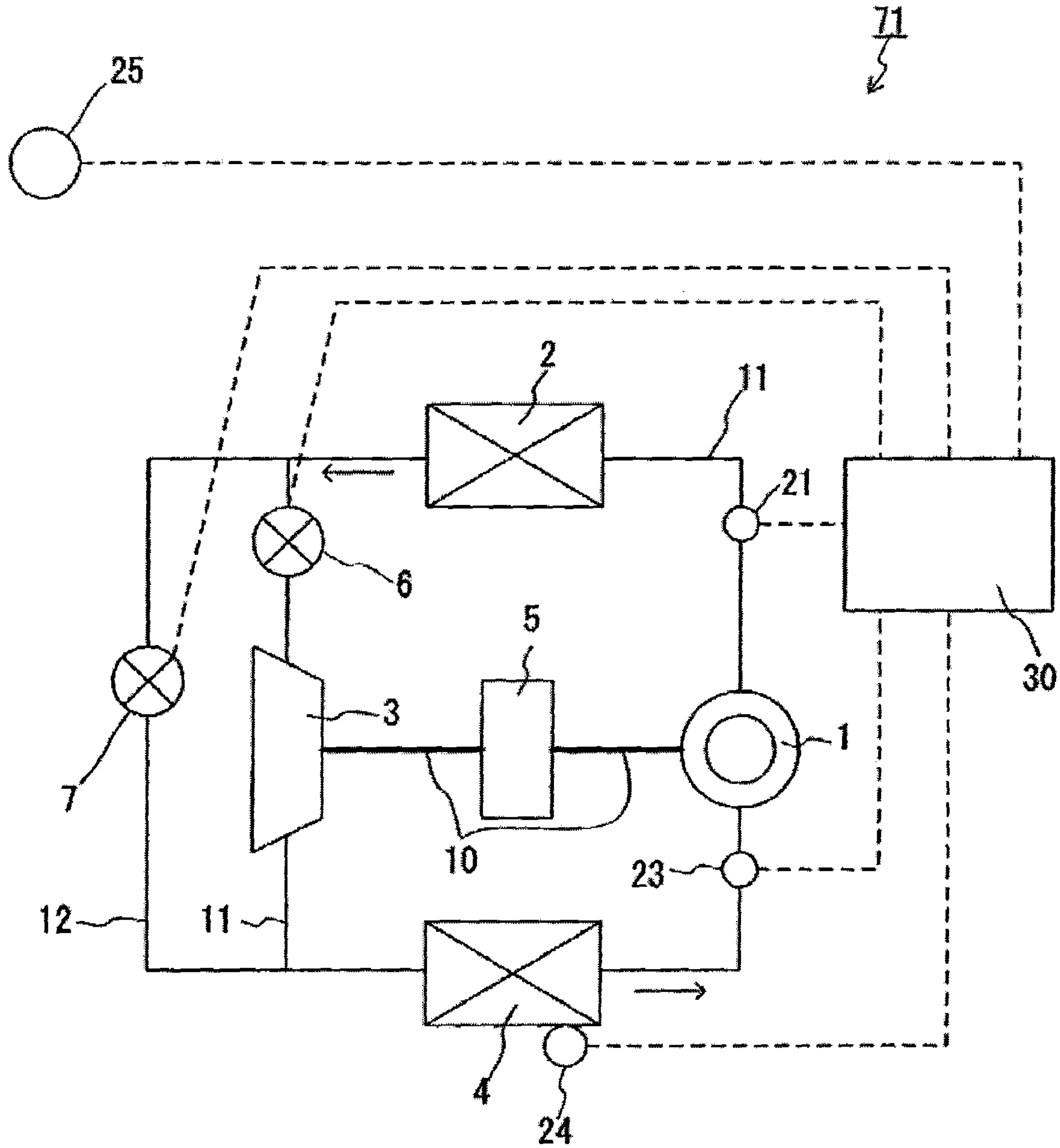


FIG. 1

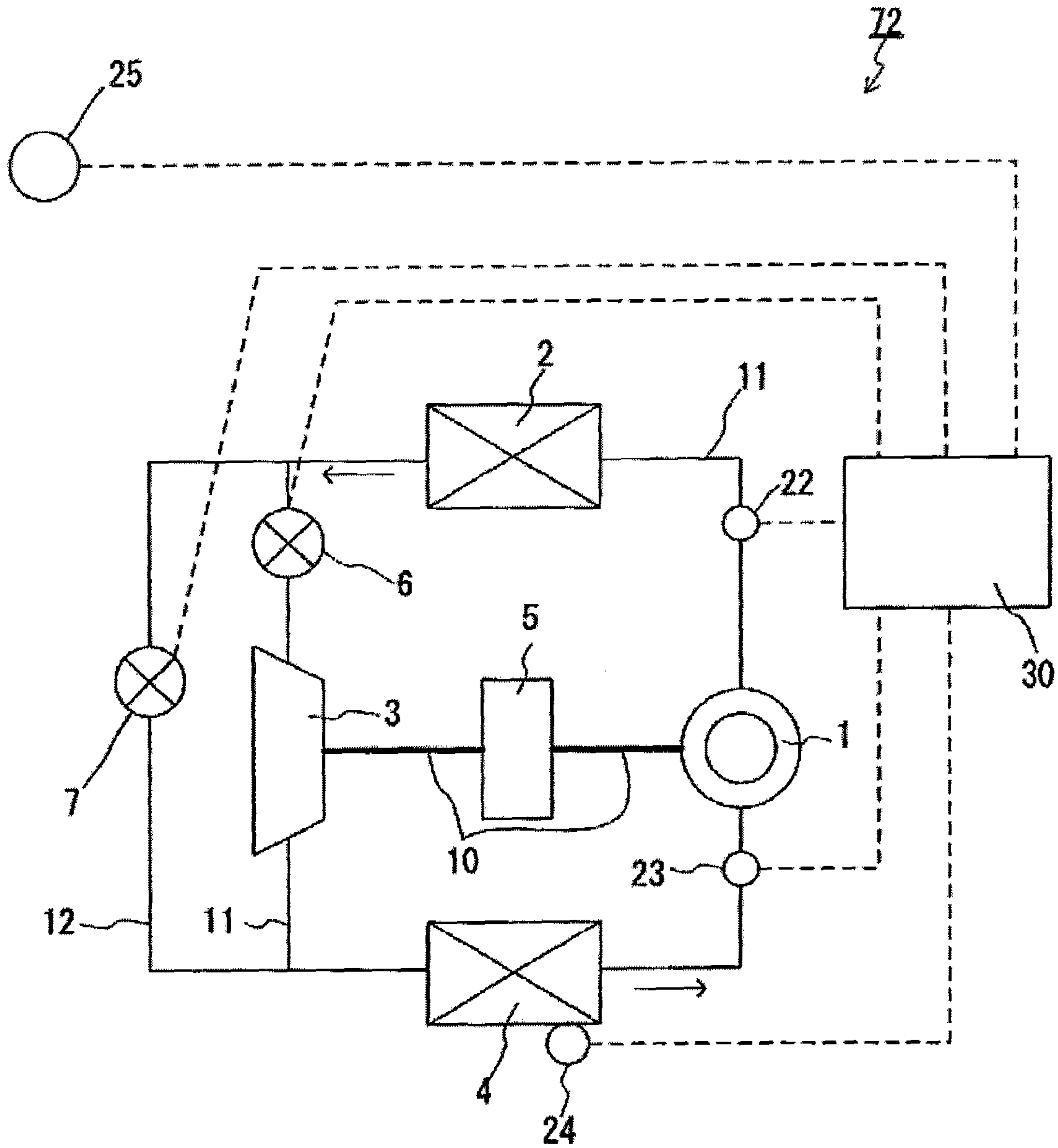


FIG. 2

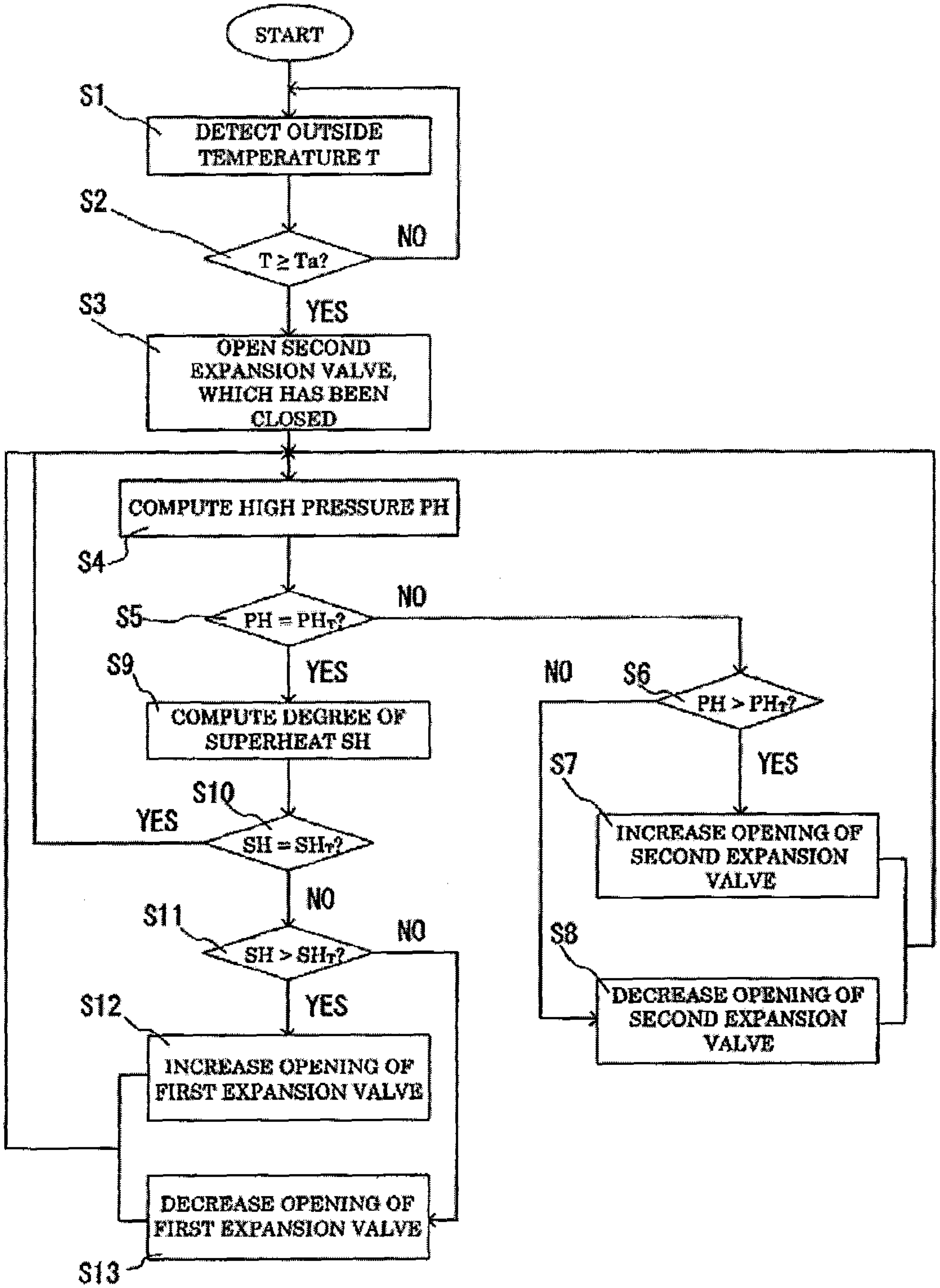

START
S1
DETECT OUTSIDE TEMPERATURE T
S2
T ≥ Ta?
NO
YES
S3
OPEN SECOND EXPANSION VALVE, WHICH HAS BEEN CLOSED
COMPUTE HIGH PRESSURE PH
S4
S5
PH = PHT?
NO
YES
S9
COMPUTE DEGREE OF SUPERHEAT SH
S10
SH = SHT?
YES
NO
S11
SH > SHT?
NO
YES
S12
INCREASE OPENING OF FIRST EXPANSION VALVE
DECREASE OPENING OF FIRST EXPANSION VALVE
S13
S6
PH > PHT?
NO
YES
S7
INCREASE OPENING OF SECOND EXPANSION VALVE
S8
DECREASE OPENING OF SECOND EXPANSION VALVE

FIG. 3

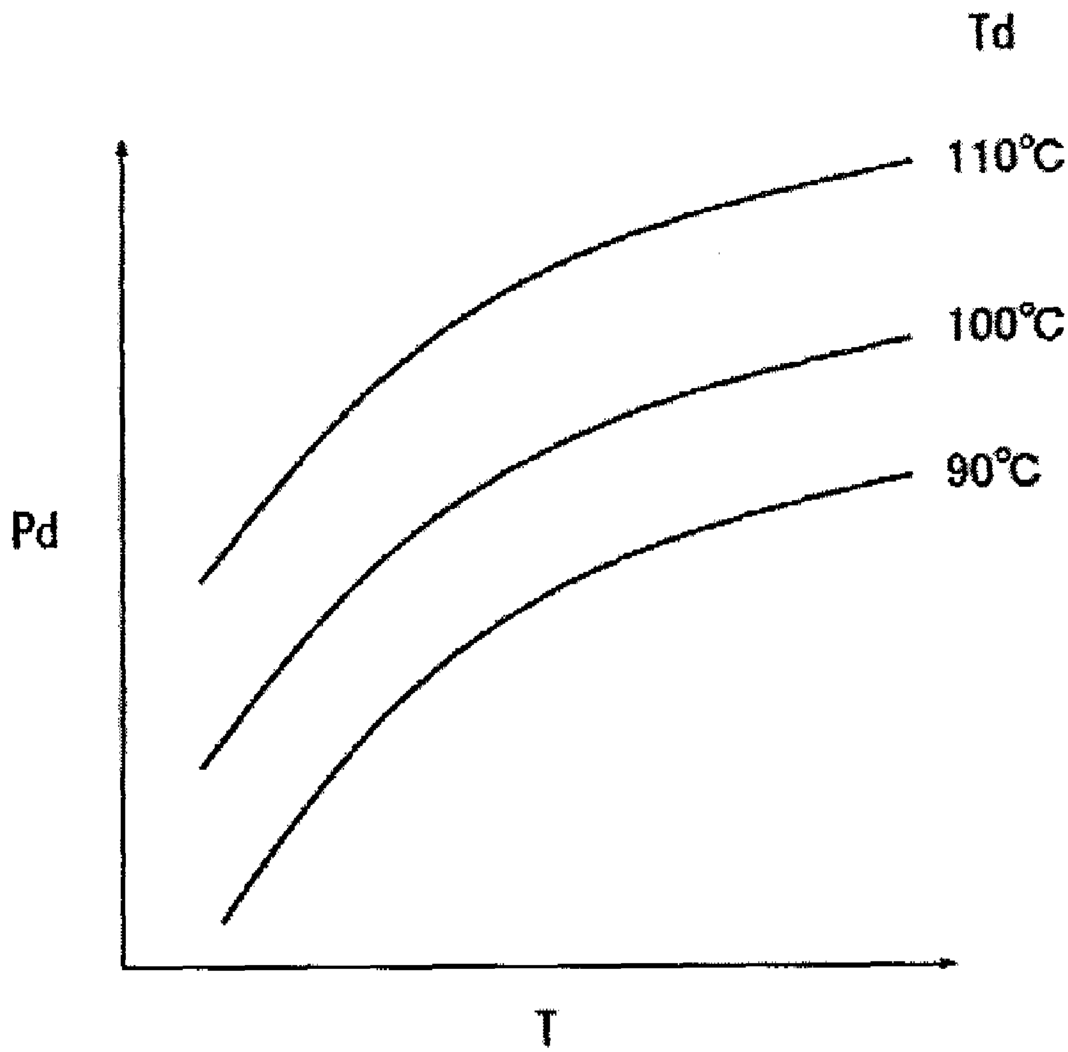


FIG. 4

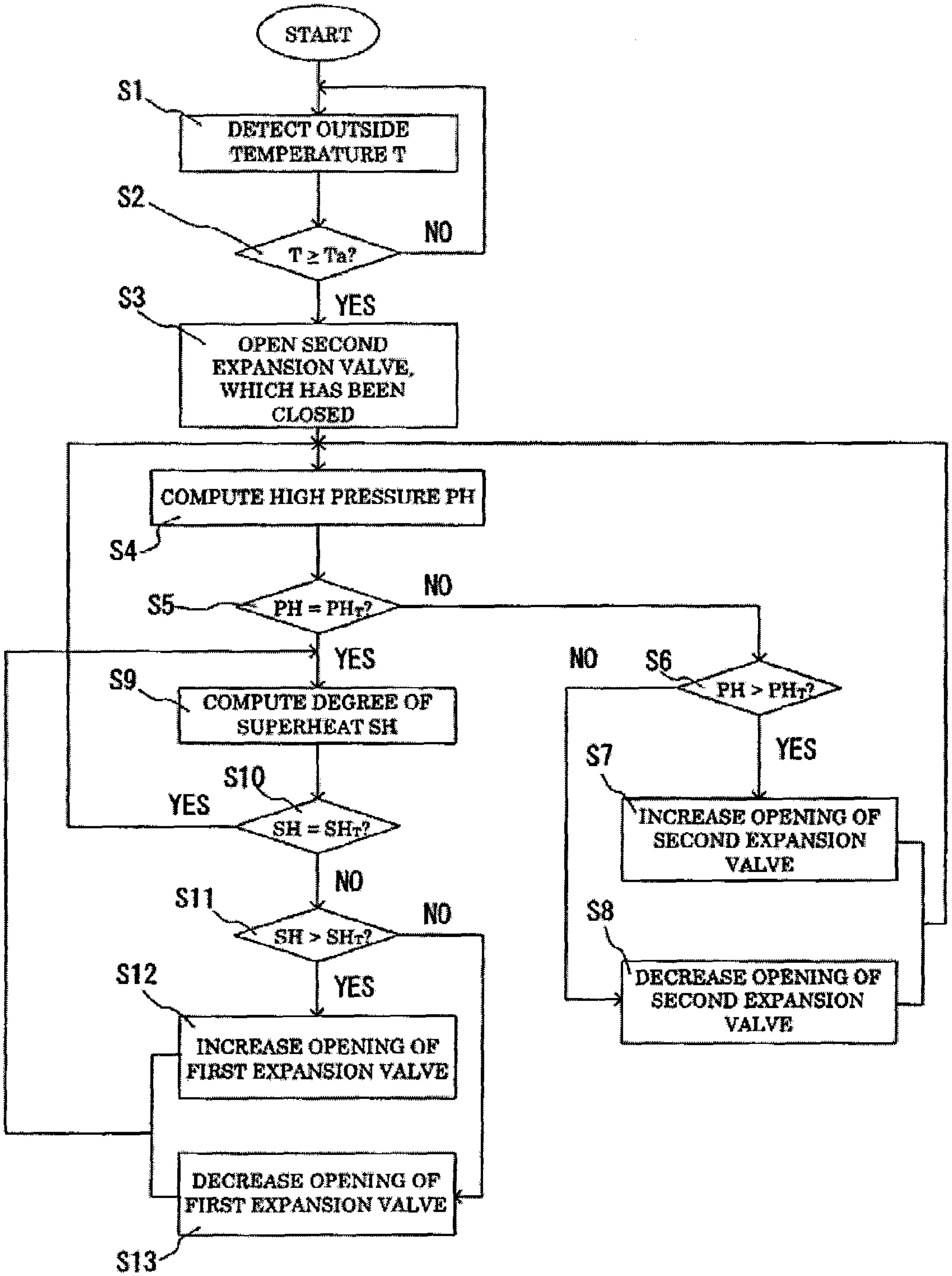
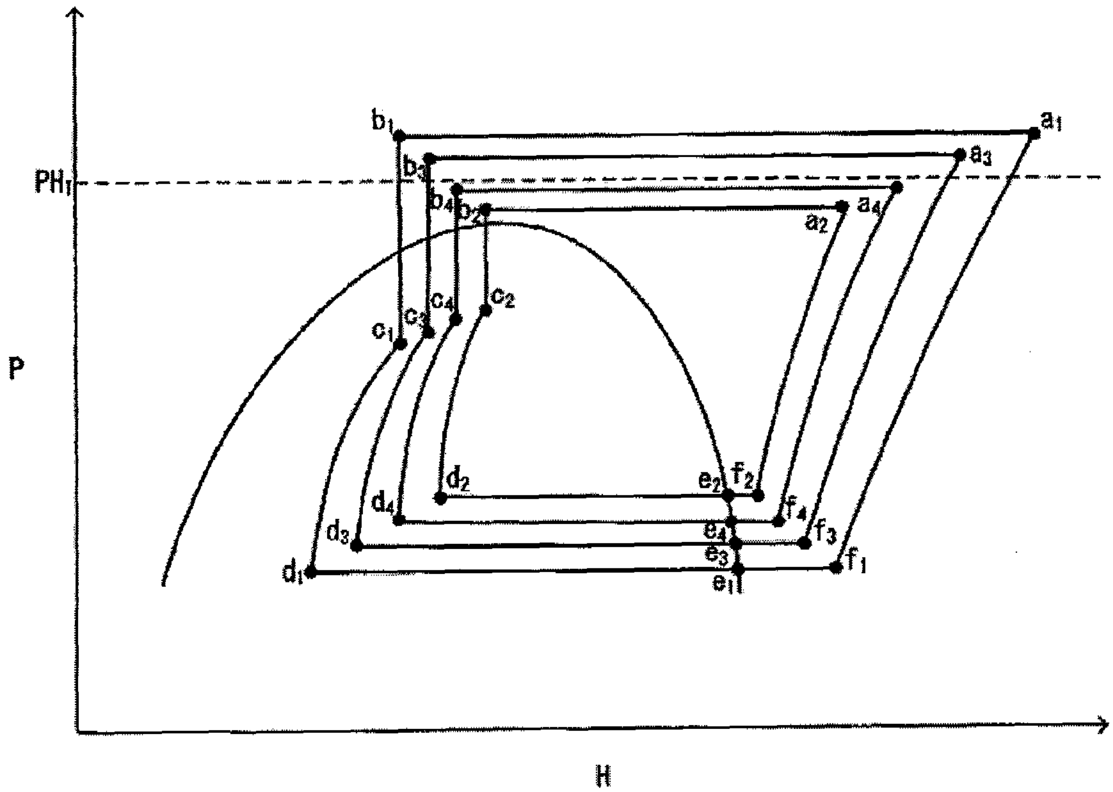

START
S1
DETECT OUTSIDE TEMPERATURE T
S2
T ≥ Ta?
NO
YES
S3
OPEN SECOND EXPANSION VALVE, WHICH HAS BEEN CLOSED
COMPUTE HIGH PRESSURE PH
S4
S5
PH = PH$_T$?
NO
YES
S6
PH > PH$_T$?
NO
YES
S7
INCREASE OPENING OF SECOND EXPANSION VALVE
S8
DECREASE OPENING OF SECOND EXPANSION VALVE
S9
COMPUTE DEGREE OF SUPERHEAT SH
S10
SH = SH$_T$?
YES
NO
S11
SH > SH$_T$?
NO
YES
S12
INCREASE OPENING OF FIRST EXPANSION VALVE
DECREASE OPENING OF FIRST EXPANSION VALVE
S13

FIG. 5



P
H
PH1
a1
a2
a3
a4
b1
b2
b3
b4
c1
c2
c3
c4
d1
d2
d3
d4
e1
e2
e3
e4
f1
f2
f3
f4

FIG. 6

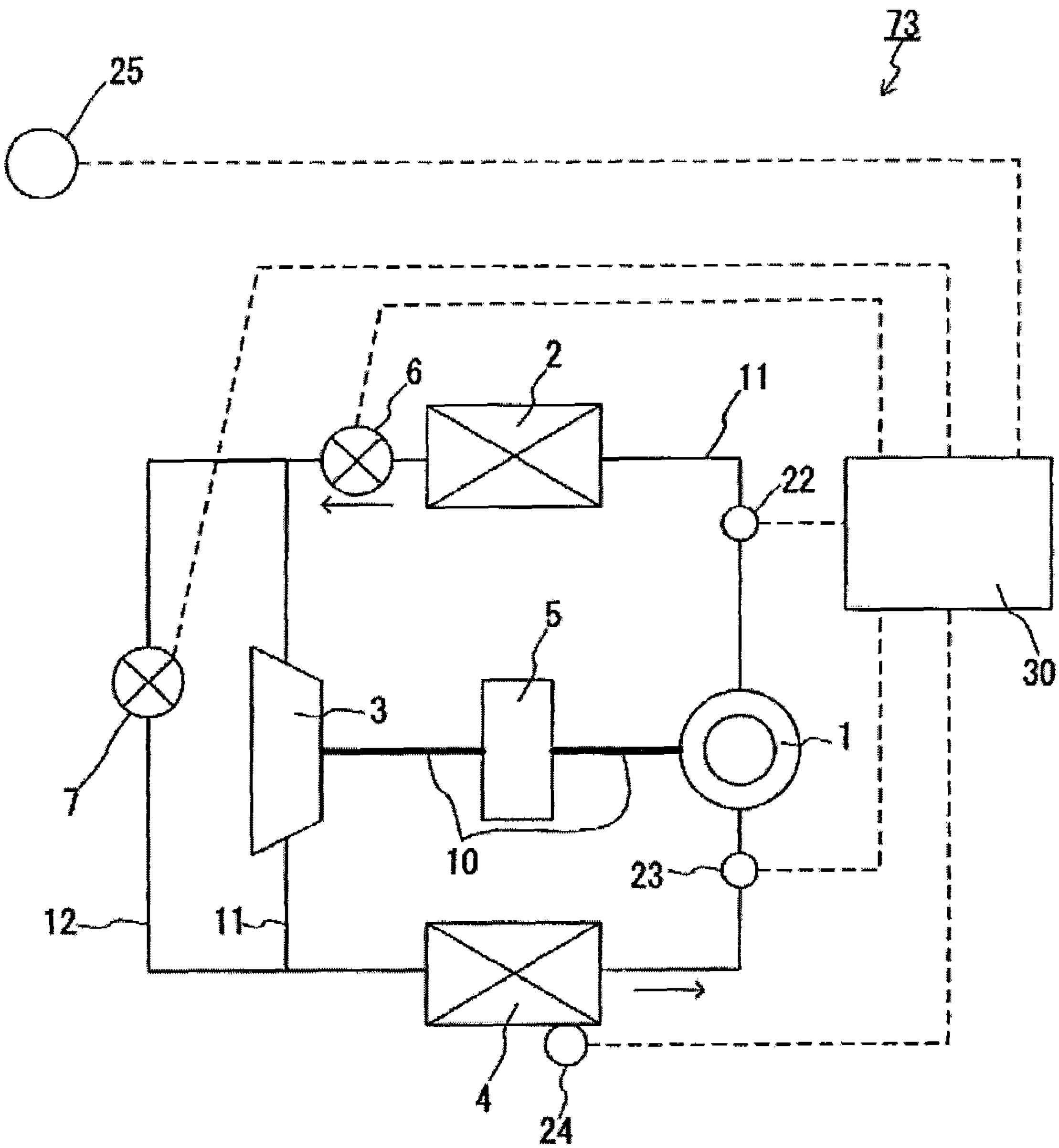


FIG. 7

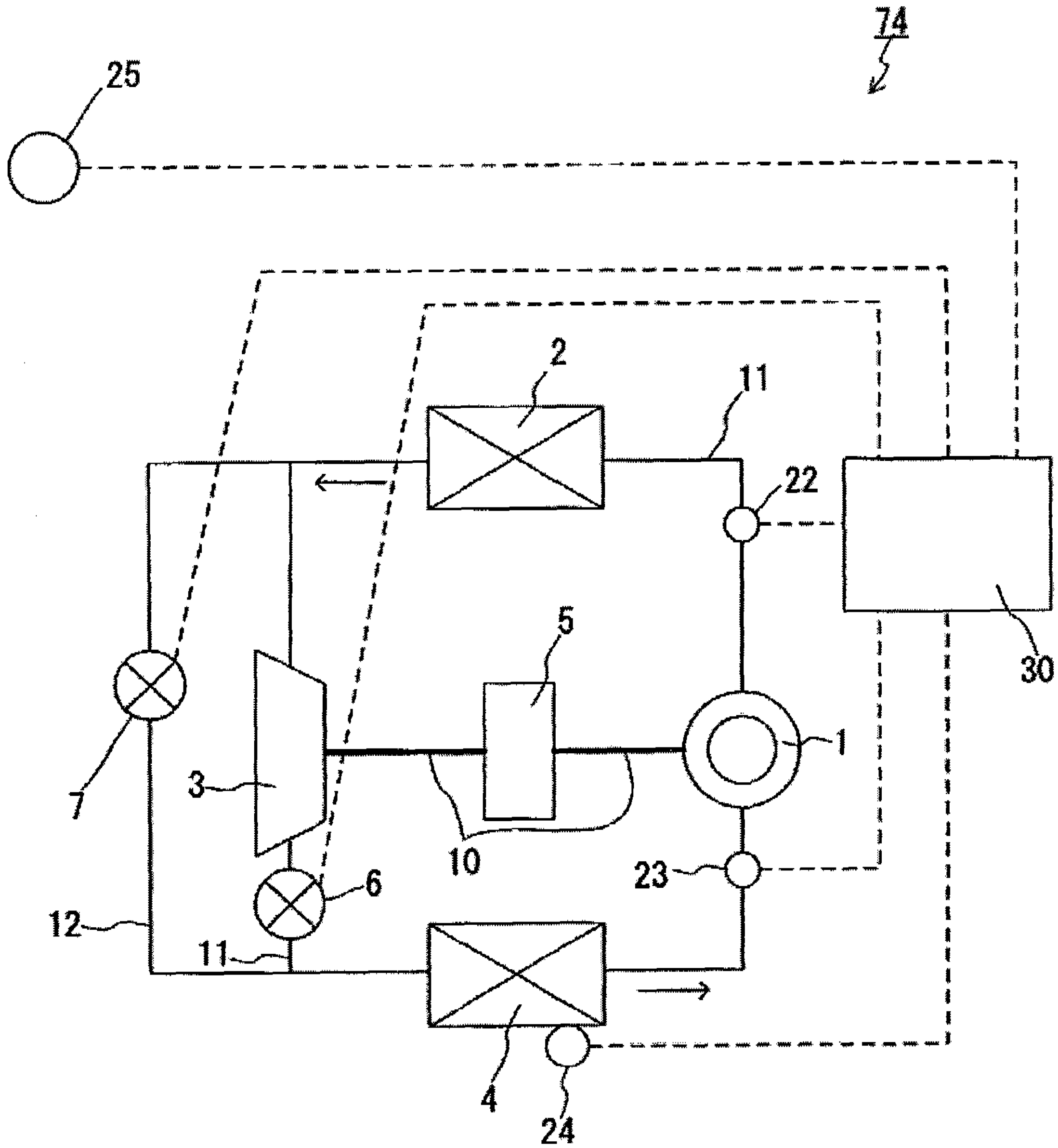


FIG. 8

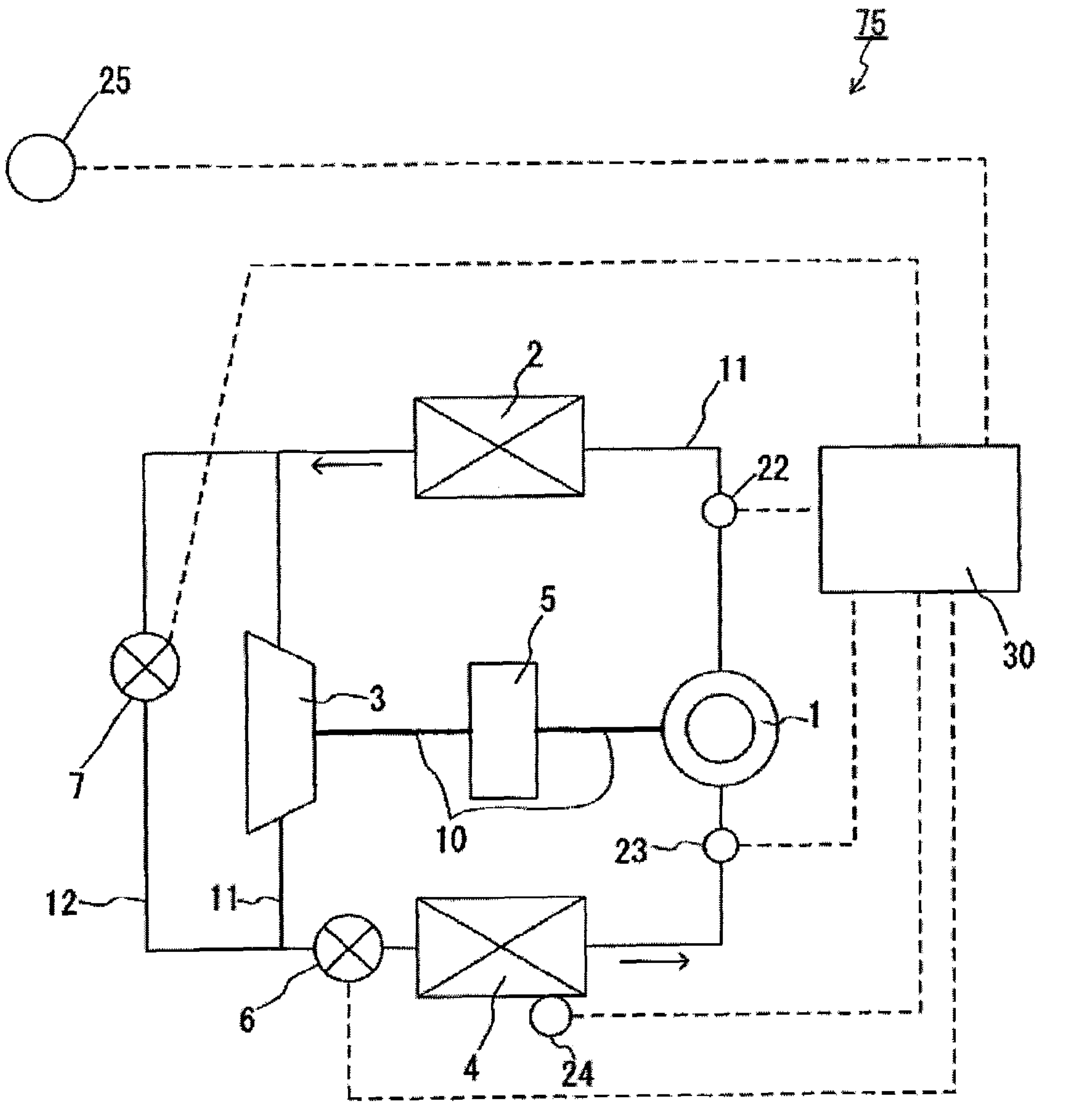


FIG. 9

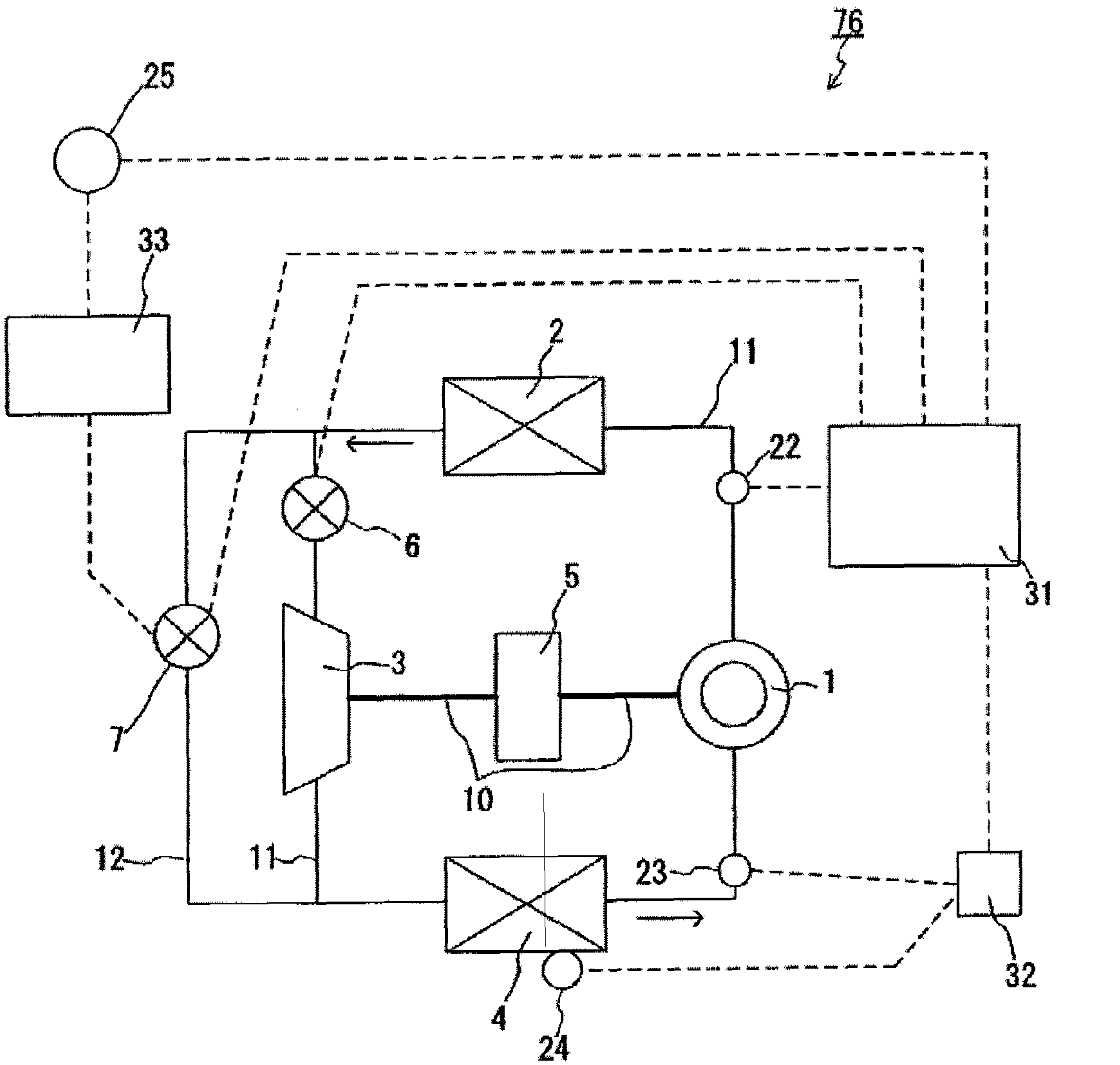


FIG. 10

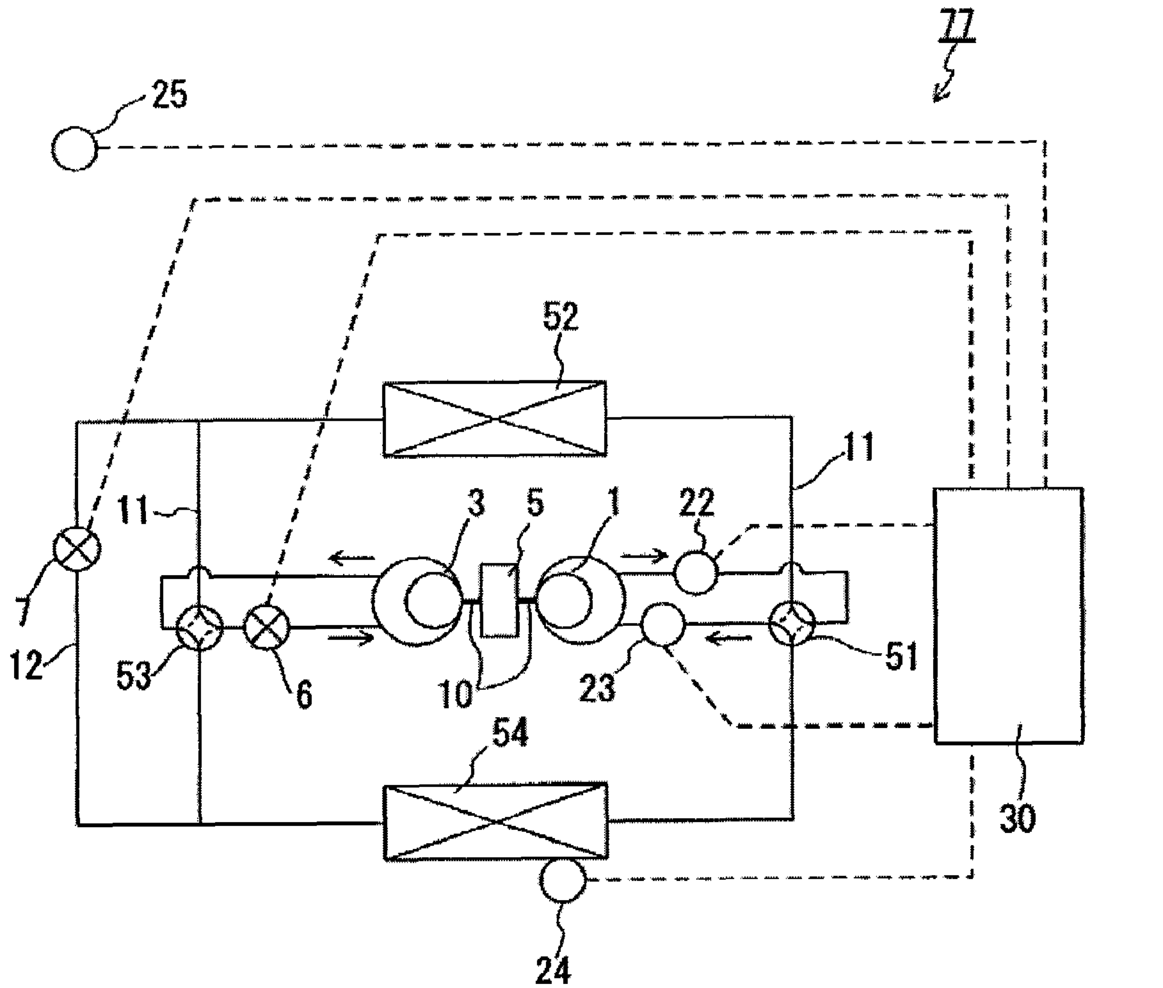


FIG. 11

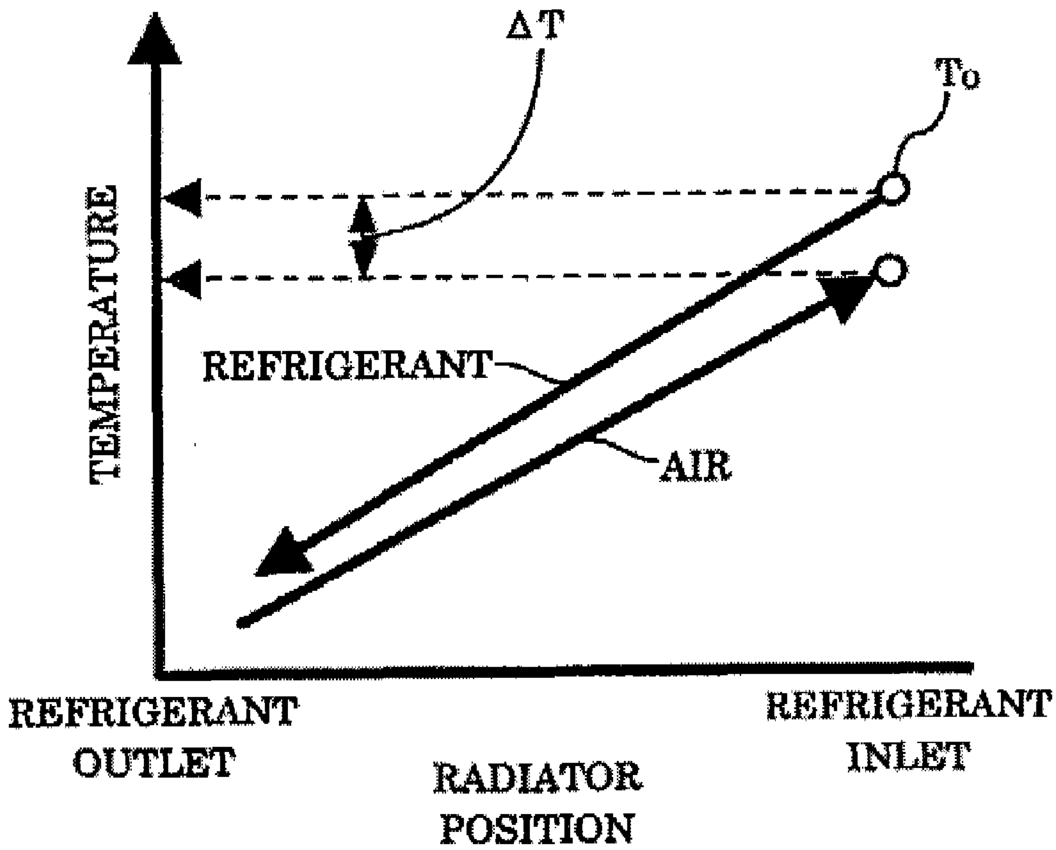

ΔT
To
TEMPERATURE
REFRIGERANT
AIR
REFRIGERANT OUTLET
RADIATOR POSITION
REFRIGERANT INLET

FIG. 12

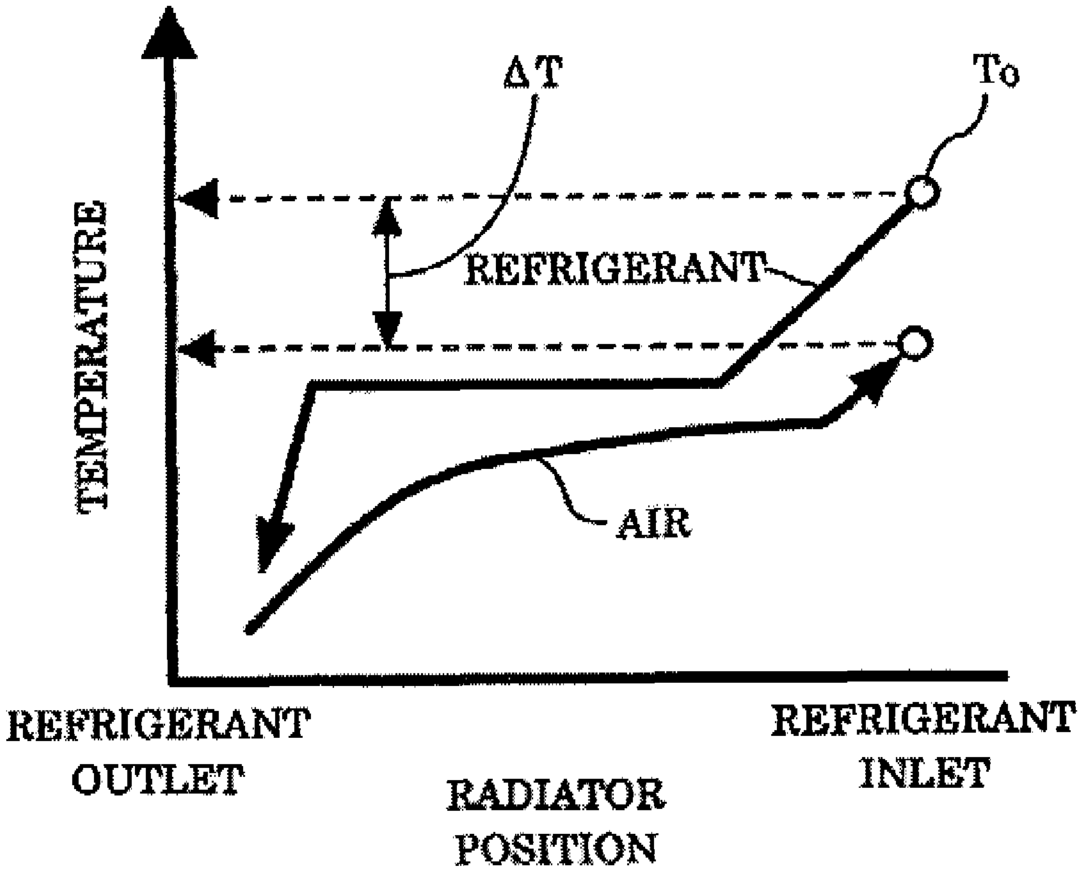

ΔT
To
TEMPERATURE
REFRIGERANT
AIR
REFRIGERANT OUTLET
RADIATOR POSITION
REFRIGERANT INLET

FIG. 13

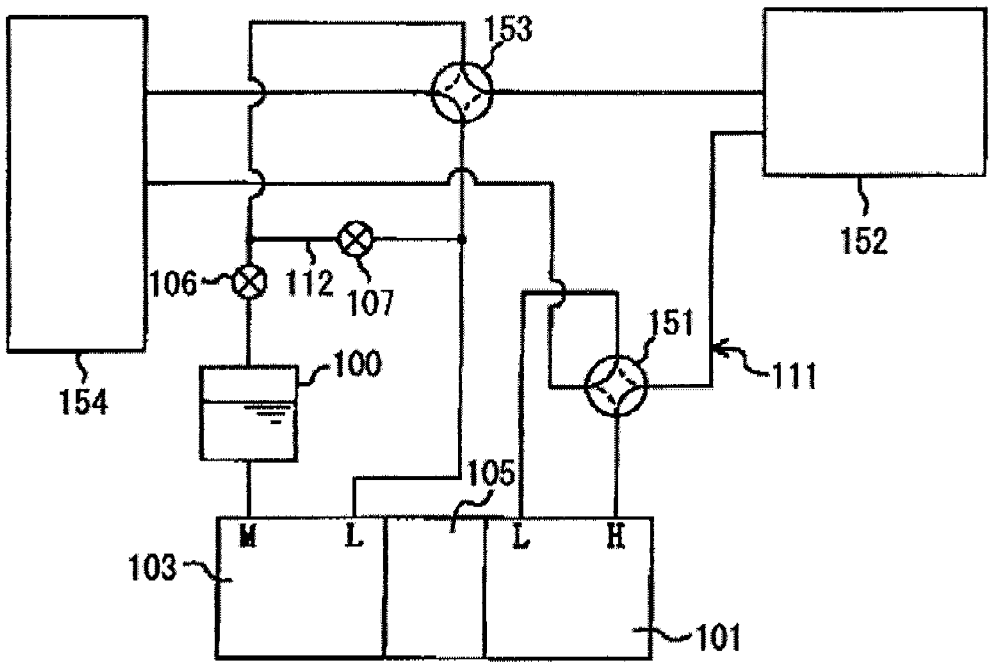

153
152
106
112
107
151
111
100
154
105
M
L
L
H
103
101

FIG. 14

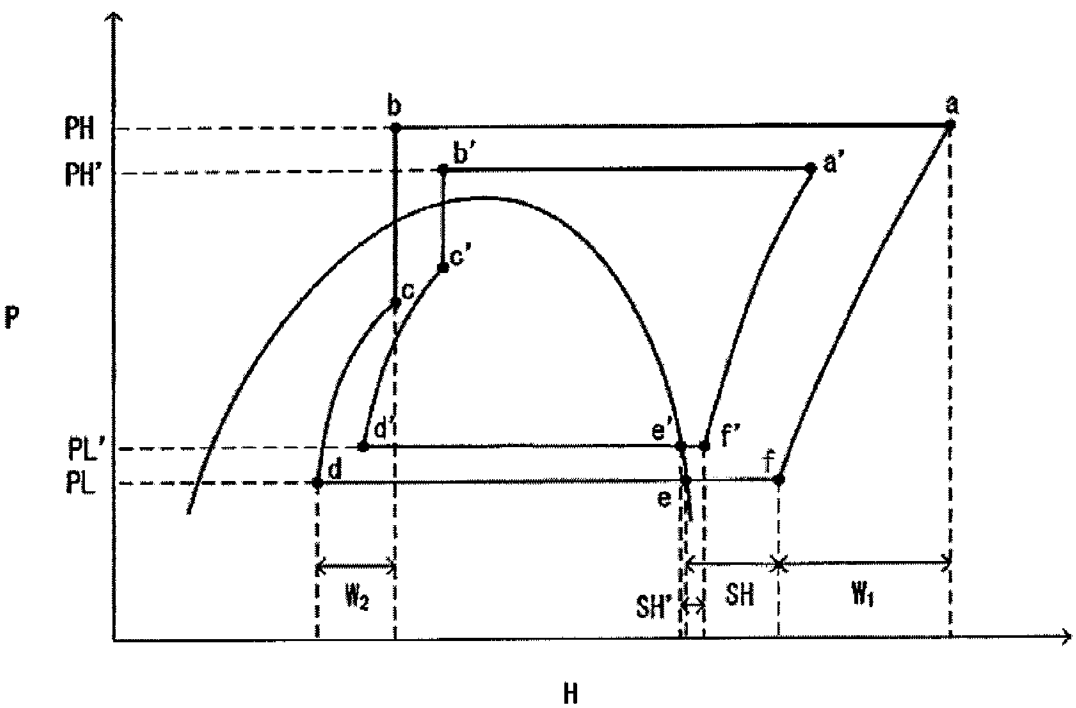

PH
PH'
P
PL'
PL
b
a
b'
a'
c'
c
d'
e'
f'
f
d
e
W2
SH'
SH
W1
H

FIG. 15

HEAT PUMP

[0001] This application is a continuation of prior pending International Application Number PCT/JP2005/022655, filed on Dec. 9, 2005, which designated the United States.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates to heat pumps useful for hot water heaters, air-conditioners, and the like, and more particularly to a heat pump furnished with a mechanism for recovering energy with an expander.

[0004] 2. Description of the Related Art

[0005] A heat pump employing an expander in place of an expansion valve can recover the expansion energy of refrigerant as electric power or mechanical power. As the expander, in many cases a positive displacement expander is used that has a space with a variable capacity for introducing and expanding the refrigerant therein. The energy recovery with the expander has a significant value, particularly in the transcritical cycle of carbon dioxide in which the high pressure reaches a supercritical state of the refrigerant.

[0006] Because of its structure, the expander cannot recover energy unless the refrigerant passes through it in a predetermined direction. The heat pump used for an air-conditioner, however, requires that the refrigerant should flow in opposite directions when in a cooling operation and when in a heating operation because it is necessary to use the heat exchanger installed indoors as a radiator during the heating operation but as an evaporator during the cooling operation.

[0007] JP 2001-66006A discloses a heat pump capable of energy recovery with an expander in both cooling and heating operations. This heat pump is designed so that the refrigerant can flow through the expander in the same direction in both cooling and heating operations by switching in a four-way valve. Furthermore, in this heat pump, the expander and the compressor are connected to a common axis of rotation. In other words, they are directly coupled, in order to use the energy recovered by the expander directly for operating the compressor.

[0008] In the heat pump in which the expander and the compressor are directly coupled, the expander and the compressor operate at the same rotational speed and therefore it is impossible to vary the ratio between the displacement of the expander and the displacement of the compressor according to operation conditions. In other words, the heat pump of this type has the constraint of constant density ratio. For that reason, the heat pump in which the expander and the compressor are coupled directly has difficulty in performing a smooth operation according to operation conditions, although it has good efficiency in energy recovery. JP 2003-121018A discloses a heat pump that alleviates this difficulty.

[0009] As illustrated in FIG. **14**, JP 2003-121018A discloses, as in JP 2001-66006A, a heat pump in which two four-way valves **151** and **153** are disposed in piping **111** so that refrigerant can flow in the same direction through an expander **103** and a compressor **101** during both cooling and heating operations by switching in the four-way valves **151** and **153** (cf FIG. **4** in the publication). In an air-conditioner employing this heat pump, the passages shown by solid lines in the four-way valves **151** and **153** are selected during heating so that an indoor heat exchanger **152** functions as a radiator and an outdoor heat exchanger **154** functions as an evaporator. In this air-conditioner, the passages shown by dashed lines in the four-way valves **151** and **153** are selected during cooling so that the indoor heat exchanger **152** functions as an evaporator and the outdoor heat exchanger **154** functions as a radiator. In this heat pump, the expander **103** and the compressor **101** are coupled directly so that they share a single rotation shaft, and this rotation shaft is driven by a motor **105**.

[0010] In the heat pump disclosed in JP 2003-121018A, an expansion valve (bypass valve) **107** is disposed in a bypass circuit **112** disposed in parallel with the expander **103**, and an expansion valve **106** is also disposed in series with the expander **103**. The opening of the expansion valve **106** or the expansion valve **107** is controlled according to the operation condition. A receiver **100** prevents excessive flow of the refrigerant into the expander **103** by temporarily reserving the refrigerant.

[0011] As discussed above, although the heat pump in which the expander and the compressor are coupled directly is advantageous in energy recovery, it cannot change the displacement ratio between the expander and the compressor according to operation conditions. For example, if the expander is designed based on the standard condition in a cooling operation, the displacement of the expander will be too large in a heating operation with respect to the required value. For that reason, in the heat pump disclosed in JP 2003-121018A, the expansion valve **107** is fully closed during a heating operation, while the opening of the expansion valve **106** is controlled as appropriate. On the other hand, during a cooling operation, the displacement of the expander **103** may become less than the required value. When this is the case, the expansion valve **106** is fully opened, while the opening of the expansion valve **107** is controlled as appropriate.

[0012] In this way, the heat pump disclosed in JP 2003-121018A avoids the constraint of constant density ratio and makes possible smooth cycling operations according to operation conditions by adjusting the opening of one of the expansion valves **106** and **107** while keeping the opening of the other one in a fully opened or fully closed state.

[0013] FIG. **15** is a Mollier diagram illustrating the refrigeration cycle of the heat pump shown in FIG. **14**. The horizontal axis H represents enthalpy while the vertical axis P represents pressure. The refrigerant discharged from the compressor **101** and being in state a of a high pressure PH radiates heat at the indoor heat exchanger **152** or at the outdoor heat exchanger **154**, which functions as the radiator, and reaches state b. The refrigerant undergoes isentropic expansion at the expansion valve **106**, reaching state c, and then undergoes isenthalpic expansion in the expander **103**, reaching state d of a low pressure PL. While absorbing heat at the outdoor heat exchanger **154** or the indoor heat exchanger **152**, which functions as the evaporator, the refrigerant goes beyond the intersection point (state e) with the saturated vapor line and reaches state f, which is a superheated vapor state; thereafter, it flows into the compressor **101** again. In this heat pump, the energy corresponding to an enthalpy difference W_2 between state c and state d is recovered by the expander **103**. Therefore, it is sufficient for this heat pump to input, basically, a mechanical power corresponding to the difference (W_1-W_2), obtained by subtracting the enthalpy difference W_2 from an enthalpy difference W_1 that is the enthalpy difference between state a and state f, into the compressor **101**.

SUMMARY OF THE INVENTION

[**0014**] As described above, in the heat pump disclosed in JP 2003-121018A, when the displacement of the expander **103** becomes less than the required value, the expansion valve **107** is opened to allow a portion of the refrigerant to flow into the bypass circuit **112**. However, as the flow rate of the refrigerant flowing in the bypass circuit **112** is increased, the difference between the high pressure PH and the low pressure PL in the refrigeration cycle reduces, and correspondingly, the degree to which the refrigerant flowing into the compressor **101** is superheated (degree of superheat) also decreases.

[**0015**] This change also is shown in FIG. **15**. When the opening of the expansion valve **107** is increased, a refrigeration cycle (a to f) shifts to a refrigeration cycle (a' to f'). In accordance with this shift, the high pressure lowers from PH to PH' and the low pressure rises from PL to PL', as shown in FIG. **15**. The enthalpy difference between state f and state e, which corresponds to the degree of superheat of the refrigerant, accordingly decreases from SH to SH'.

[**0016**] When the degree of superheat SH of the refrigerant reduces, it becomes difficult to perform a stable operation and at the same time ensure the reliability of the compressor **101**. The reason is that, when the degree of superheat SH is low, a portion of the refrigerant remaining in a liquid state flows into the compressor **101**, and liquid compression, which should be avoided, may take place in the compressor **101**.

[**0017**] In the control process disclosed in JP 2003-121018A, the openings of the expansion valves **106** and **107** are adjusted for ensuring smooth operations, and as a result, the high pressure PH is varied. However, the high pressure PH in a refrigeration cycle affects the coefficient of performance (COP) of the heat pump, and therefore, it is desirable that the control of the expansion valves should be conducted appropriately not just from the viewpoint of ensuring smooth operations but also from the viewpoint of improving the coefficient of performance.

[**0018**] It should be noted here that the coefficient of performance (COP) is a dimensionless numerical value representing the ratio of the energy obtained relative to the energy put into the heat pump.

[**0019**] It is therefore an object of the present invention to enable efficient operations in a heat pump in which the expander and the compressor are coupled directly, and at the same time ensure the reliability of the compressor.

[**0020**] A heat pump according to the present invention includes: a compressor; a radiator; an expander; an evaporator; a piping that forms a circulation passage in which refrigerant circulates through the compressor, the radiator, the expander, and the evaporator in that order, and a bypass passage in which the refrigerant flows from the radiator to the evaporator without flowing through the expander; a first throttling device having a variable opening and disposed in the circulation passage between the radiator and the expander or between the expander and the evaporator; a second throttling device having a variable opening and disposed in the bypass passage; and a control device for adjusting the opening of the first throttling device and the opening of the second throttling device. In this heat pump, the compressor and the expander are connected to a common rotation shaft, and rotate at the same rate. The compressor and the expander may be connected to a single-piece rotation shaft or a multi-piece rotation shaft.

[**0021**] Further, in the heat pump of the present invention, the control device executes a first controlling in which, when the difference between a high pressure PH of the refrigerant circulating in the circulation passage and a predetermined value PH_T determined based on a value at which the coefficient of performance of the heat pump is optimized is outside a predetermined range PH_{DR}, the opening of the second throttling device is varied so that the absolute value of the difference between the pressure PH and the predetermined value PH_T becomes smaller. After completing the first controlling, the control device executes a second controlling in which, when the difference between a degree of superheat SH of the refrigerant flowing into the compressor and a predetermined positive value SH_T is outside a predetermined range SH_{DR}, the opening of the first throttling device is varied so that the absolute value of the difference between the degree of superheat SH and the predetermined value SH_T becomes smaller.

[**0022**] In the present invention, when the second throttling is adjusted to attempt an improvement in the coefficient of performance while ensuring smooth cycling operations, the first throttling device subsequently is adjusted to control the degree of superheat of the refrigerant. This controlling allows even the heat pump in which the compressor and the expander are coupled directly to perform smooth and efficient operations according to operation conditions while ensuring the reliability of the compressor.

BRIEF DESCRIPTION OF THE DRAWINGS

[**0023**] FIG. **1** is a diagram illustrating one example of the configuration of a heat pump according to the present invention.

[**0024**] FIG. **2** is a diagram illustrating another example of the configuration of the heat pump according to the present invention.

[**0025**] FIGS. **3** is a flowchart illustrating one example of the control process executed by the control device.

[**0026**] FIG. **4** is a graph illustrating the relationship between outside air temperature T and discharged refrigerant pressure Pd from the compressor, at respective discharged refrigerant temperatures Td.

[**0027**] FIG. **5** is a flowchart illustrating another example of controlling executed by the control device.

[**0028**] FIG. **6** is a Mollier diagram illustrating changes in the refrigeration cycle, originating from control processes executed by the control device.

[**0029**] FIG. **7** is a diagram illustrating yet another example of the configuration of the heat pump according to the present invention.

[0030] FIG. **8** is a diagram illustrating still another example of the configuration of the heat pump according to the present invention.

[0031] FIG. **9** is a diagram illustrating yet another example of the configuration of the heat pump according to the present invention.

[0032] FIG. **10** is a diagram illustrating still another example of the configuration of the heat pump according to the present invention.

[0033] FIG. **11** is a diagram illustrating an example of the configuration of a heat pump, according to the present invention, equipped with a four-way valve.

[0034] FIG. **12** is a graph illustrating the relationship between the position of refrigerant in the radiator and the temperature of refrigerant when using a chlorofluorocarbon as the refrigerant.

[0035] FIG. **13** is a graph illustrating the relationship between the position of refrigerant in the radiator and the temperature of refrigerant when using carbon dioxide as the refrigerant.

[0036] FIG. **14** is a diagram illustrating the configuration of a conventional heat pump.

[0037] FIG. **15** is a Mollier diagram illustrating changes in the refrigeration cycle, originating from the control process executed by the conventional heat pump.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0038] Hereinbelow, preferred embodiments of the present invention are described with reference to the drawings. In the following description, the same components and steps may be designated with the same reference numerals to avoid repetitive description.

[0039] FIG. **1** illustrates a configuration diagram of one embodiment of the heat pump according to the present invention. This heat pump **71** is provided with a compressor **1**, a radiator **2**, an expander **3**, and an evaporator **4**, as the primary constituent components for carrying out the fundamental functions of a heat pump. These components are connected by a piping **11** that forms a circulation passage in which refrigerant circulates through the compressor **1**, the radiator **2**, the expander **3**, and the evaporator **4**, in that order. One end of a piping **12** is connected to the piping **11** between the radiator **2** and the expander **3**, while the other end thereof is connected to the piping **11** between the expander **3** and the evaporator **4**. The piping **12** forms a bypass passage in which the refrigerant flows from the radiator **2** to the evaporator **4** without flowing through the expander **3**.

[0040] The refrigerant circulates in the direction indicated by the arrows in FIG. **1**, and at the radiator **2**, it radiates heat absorbed at the evaporator **4**. Thereby, this system functions as a heat pump for pumping up heat from the evaporator **4** to the radiator **2**. The compressor **1** and the expander **3** are coupled to a common rotation shaft **10** (a common axis of rotation). The compressor **1** is operated by mechanical power given from an electric motor **5** connected to the shaft **10** and mechanical power recovered by the expander **3**. A heat pump in which the compressor **1** and the expander **3** are coupled directly and rotated at the same number of revolutions has the constraint of constant density ratio. The number of revolutions of the expander **3** cannot be controlled independently from the number of revolutions of the compressor **1**. To avoid this constraint, a bypass passage of refrigerant is formed in the heat pump **71** by the piping **12**, and an expansion valve **7** is disposed in the bypass passage.

[0041] In the heat pump **71**, a first expansion valve **6**, which serves as the first throttling device, is disposed between the radiator **2** and the expander **3**, and a second expansion valve **7**, which serves as the second throttling device, is disposed in the bypass passage. In terms of the relationship with the expander **3**, the first expansion valve **6** is disposed in series with the expander **3**, while the second expansion valve **7** is disposed in parallel with the expander **3**. The openings of the expansion valves **6** and **7** can be controlled by a control device (controller) **30**. When the controller **30** sets the opening of the second expansion valve **7** to be minimum (in other words, to be in a fully closed state), the circulating refrigerant does not flow in the bypass passage but the entire refrigerant flows into the expander **3**.

[0042] In the heat pump **71**, a temperature sensor (first temperature sensing means) **23** for measuring the temperature of the refrigerant flowing into the compressor **1** is disposed between the evaporator **4** and the compressor **1**, and the evaporator **4** is provided with a temperature sensor (second temperature sensing means) **24** for detecting the temperature of the refrigerant in the evaporator **4**. By identifying the temperature of the refrigerant flowing into the compressor **1** and the temperature at which the refrigerant evaporates in the evaporator (refrigerant evaporation temperature), it is possible to calculate the degree of superheat SH of the refrigerant. Thus, in order to specify the degree of superheat SH, the heat pump further may have a first temperature sensing means for detecting the temperature of the refrigerant flowing into the compressor and a second temperature sensing means for detecting the temperature of the refrigerant in the evaporator.

[0043] The heat pump **71** also is furnished with a temperature sensor **25** for measuring outside air temperature T. As will be described later, as the outside air temperature T rises, the necessity of increasing the opening of the second expansion valve **7** intensifies. Thus, the heat pump further may have a third temperature sensing means for detecting the temperature outside the system. Specifically, an appropriate example of "the temperature outside the system" includes the temperature of a medium that flows into the radiator **2** and is heated there, such as the temperature of outside air or the temperature of the water flowing into the radiator.

[0044] The heat pump **71** is provided with a pressure sensor **21** disposed between the compressor **1** and the radiator **2**, for measuring pressure Pd of the refrigerant discharged from the compressor **1**. The pressure Pd corresponds to the high pressure PH in the refrigeration cycle. Thus, in order to specify the pressure PH, the heat pump further may have a pressure sensing means for detecting the pressure of the refrigerant discharged from the compressor.

[0045] The high pressure PH in the refrigeration cycle can be calculated from measurement values other than the pressure Pd. For example, it is possible to calculate the pressure PH from temperatures T and Td by measuring an outside air temperature T and a temperature Td of the refrigerant discharged from the compressor **1**. Installing a temperature sensor is less expensive than installing a pressure sensor. Moreover, when a pressure sensor is installed, refrigerant tends to leak easily from the location at which the pressure sensor is mounted. For these reasons, it is desirable that only temperature sensors be used to specify the pressure PH.

[0046] An example of the heat pump for implementing this calculation is illustrated in FIG. **2**. In a heat pump **72**, a temperature sensor **22** for measuring the temperature Td of the refrigerant discharged from the compressor **1** is disposed between the compressor **1** and the radiator **2**, in place of the pressure sensor **21**. Thus, in order to specify the pressure PH, the heat pump further may have a third temperature sensing means for detecting a temperature outside the system and a fourth temperature sensing means for detecting a temperature of the refrigerant discharged from the compressor.

[0047] All of the pressure sensor **21** and the temperature sensors **22**, **23**, **24**, and **25** are connected to the controller **30**, and in response to signals from these sensors, the controller **30** adjusts the openings of the expansion valves **6** and **7**. Conventionally known sensors may be used for these sensors. For example, the temperature sensors may be thermistors.

[0048] Hereinbelow, controlling of the heat pump **72** (cf. FIG. **2**) by the controller **30** will be described. The following illustrates a control process in the case that the cylinder volume of the expander **3** (to be precise, the ratio of the cylinder volume of the compressor **1** to the cylinder volume of the expander **3**) is determined based on a winter cycle condition. In this case, as the atmospheric temperature (outside air temperature T) outside the system rises, a required value for the displacement of the expander **3** increases, and when the outside air temperature T reaches a predetermined temperature, the required value exceeds the displacement of the expander **3**. In other words, when the outside air temperature T becomes higher than a predetermined value, the volume flow rate of the refrigerant flowing into the expander **3** becomes greater than the cylinder volume.

[0049] The number of revolutions of the expander **3**, which is directly coupled to the compressor, cannot be controlled separately from the number of revolutions of the compressor **1**. For this reason, when the required value becomes too large, it becomes necessary to open the second expansion valve **7** and allow a portion of the refrigerant to flow into the bypass passage, to ensure a smooth operation. Nevertheless, when a portion of the refrigerant flows into the bypass passage, the high pressure PH in the refrigeration cycle lowers, and the degree of superheat SH of the refrigerant flowing into the compressor **1** decreases correspondingly. The decrease of the degree of superheat SH may cause the refrigerant in a liquid state to flow into the compressor, making it impossible to ensure the reliability of the compressor. Moreover, as the high pressure PH lowers, the coefficient of performance (COP) of the heat pump changes correspondingly.

[0050] In the control process described below referring to FIG. **3**, the high pressure PH is controlled to be an appropriate value and the degree of superheat SH of the refrigerant also is controlled.

[0051] First, an outside air temperature T is input by a signal from the temperature sensor **25** (step **1**: S**1**). Next, the outside air temperature T is compared to a predetermined temperature Ta, and if the outside air temperature T is equal to or higher than the temperature Ta, the process proceeds to step **3**, whereas if the outside air temperature T is lower than the temperature Ta, the process returns to step **1** (step **2**: S**2**). If the outside air temperature T is equal to or higher than the temperature Ta, the second expansion valve **7**, which has been closed, is opened, and a portion of the refrigerant flows into the piping **12**, which forms the bypass passage (step **3**: S**3**).

[0052] At step **3**, the second expansion valve **7** may be opened to a predetermined opening, or the second expansion valve **7** may be opened to an opening corresponding to the temperature difference (T−Ta). The temperature Ta preferably may be determined based on, for example, the ratio of the cylinder volume of the expander **3** to the cylinder volume of the compressor **1**.

[0053] Herein, if the outside air temperature T is lower than the temperature Ta, the second expansion valve **7** is fully closed so that the whole amount of the refrigerant flows into the expander **3**. This control process is advantageous for enhancing the energy recovery efficiency by the expander **3**. However, this is merely illustrative, and a portion of the refrigerant may be introduced into the bypass passage prior to the execution of step **3**. In this case, step **3** is not a control process in which "the second expansion valve that has been closed is opened", but it is a control process in which "the opening of the second expansion valve is increased".

[0054] Subsequently, a high pressure PH in the refrigeration cycle is calculated based on the signals from the temperature sensors **22** and **25** (step **4**: S**4**). In the case of the heat pump **71** equipped with the pressure sensor **21**, a value obtained by the sensor **21** may be used as it is. Next, the pressure PH is compared to a predetermined target pressure PH_T, and if the pressure PH does not match the target pressure PH_T, the process moves to steps **6** and onward, whereas if they match, the process moves to steps **9** and onward (step **5**: S**5**).

[0055] The high pressure PH can be calculated, for example, based on the relationship diagram shown in FIG. **4**. Once the outside air temperature T and the temperature of the refrigerant discharged from the compressor (discharge refrigerant temperature of the compressor) Td are determined, it is possible to obtain the pressure of the refrigerant discharged from the compressor (discharge refrigerant pressure of the compressor) Pd.

[0056] The target pressure PH_T is determined based on a value at which the coefficient of performance of the heat pump is optimized. A pressure value at which the coefficient of performance of a heat pump is optimized varies depending on the heating capability of the radiator (which is a value such as 4.5 kW, 6.0 kW, etc, in the case of a hot water heater), the outside air temperature (which corresponds to incoming water temperature in the case of a hot water heater), and the like. A typical factor that affects the coefficient of performance is the outside air temperature. It is recommended that the target pressure PH_T be determined by measuring a value at which the coefficient of performance is optimized through an experiment in advance, and defining the target pressure PH_T as a function of a predetermined variable (for example, outside air temperature) based on the result of the experiment.

[0057] It is desirable that the target pressure PH_T be set at a value that matches a value (optimum value) at which the coefficient of performance of the heat pump is optimized in the operation conditions applied to the heat pump; however, the target pressure PH_T need not precisely or always match the optimum value. For example, it is possible to set one target pressure PH_T for outside air temperatures in a predetermined range. In this case, the target pressure PH_T varies in a stepwise manner depending on the changes of the outside air temperature or incoming water temperature. The relationship between the target pressure PH_T and a predetermined variable, represented by outside air temperature, is input to the controller **30** in advance, and the target pressure PH_T is determined based on the variable determined according to an operation condition.

[0058] If the pressure PH and the target pressure PH_T are not equal, it is determined whether or not the pressure PH is greater than the target pressure PH_T (step **6**: S**6**). Then, if it is found that the pressure PH is greater than the target pressure PH_T, the opening of the second expansion valve **7** is increased (step **7**: S**7**), whereas if it is found that the pressure PH is less than the target pressure PH_T, the opening of the second expansion valve **7** is decreased (step **8**: S**8**).

[0059] When the process goes through step **7**, the pressure PH reduces, whereas when the process goes through step **8**, the pressure PH rises. Thereafter, the process returns to step **4**, at which the pressure PH is calculated again, and the calculated pressure PH is compared to the target pressure PH_T at step **5**. Thus, the loop control of steps **4** to **8** is repeated until the pressure PH matches the target pressure PH_T.

[0060] In this loop control, it is recommended that the degree of variation of the opening in step **7** or **8** be kept very small. The reason is that, if the opening is changed greatly at one time, it becomes difficult for the pressure PH to converge on the target pressure PH_T.

[0061] If a match between the pressure PH and the target pressure PH_T is verified at step **5**, the control of the high pressure PH in the refrigeration cycle (first controlling) is suspended temporarily, and controlling of the degree of superheat SH of refrigerant (second controlling) is executed.

[0062] In the second controlling, the degree of superheat SH is calculated first (step **9**: S**9**). In the heat pump **72**, the degree of superheat SH is calculated based on the temperature measured by the temperature sensor **23**, referring to the saturated vapor line of the refrigerant (specifically, referring to the refrigerant evaporation temperature measured by the temperature sensor **24**). Next, the degree of superheat SH is compared to a predetermined target degree of superheat SH_T, and if the degree of superheat SH does not match the target degree of superheat SH_T, the process moves to steps **11** and onward, whereas if they match, the process returns to step **4** (step **10**: S**10**).

[0063] Although the predetermined value SH_T that is the target degree of superheat may be determined as appropriate depending on the type of heat pump, the type of refrigerant, expected use conditions, and so forth, and a value within a range higher than 0° C. but lower than or equal to 20° C. is generally suitable. The degree of superheat can be expressed as a temperature difference, as mentioned above, but the above-mentioned temperature difference is, to be precise, the difference between the temperature of the superheated refrigerant and the temperature indicated by the intersection point with the saturated vapor line at the pressure of that refrigerant (the boiling point at that pressure).

[0064] In order to ensure the reliability of the compressor, it is desirable that the degree of superheat SH be higher than a certain degree. However, if the degree of superheat SH is too high, the mechanical power to be input to the compressor will be too large. When taking these into account, it is preferable that the predetermined value SH_T be equal to or higher than 5° C., and more preferably 10° C. or lower. Controlling the degree of superheat SH within an appropriate range ensures the reliability of the compressor **1** and at the same time prevents the input of mechanical power to the compressor **1** from becoming larger than is necessary. Appropriate controlling of the degree of superheat SH serves not only to ensure the reliability of the compressor **1** but also to further improve the coefficient of performance of the heat pump.

[0065] If the degree of superheat SH and the target degree of superheat SH_T are not equal, it is determined whether or not the degree of superheat SH is higher than the target degree of superheat SH_T (step **11**: S**11**). Then, if the degree of superheat SH is found to be higher than the target degree of superheat SH_T, the opening of the first expansion valve **6** is increased (step **12**: S**12**), whereas if the degree of superheat SH is found to be less than the target degree of superheat SH_T, the opening of the first expansion valve **6** is decreased (step **13**: S**13**).

[0066] When the process goes through step **12**, the degree of superheat SH reduces, whereas when the process goes through step **13**, the degree of superheat SH rises. For the same reason as explained concerning steps **7** and **8**, it is recommended that the degree of variation of the opening(s) in step **12** or **13** be kept very small. This is because the degree of superheat SH reliably should be brought closer to the target degree of superheat SH_T by way of step **12** or step **13**.

[0067] After executing step **12** or **13**, the process returns to step **4** to perform the control of the pressure PH again. Thus, in the control process shown in FIG. **3**, after completing the control of the degree of superheat SH (second controlling), controlling of the high pressure PH (first controlling) is further executed.

[0068] If it is necessary to control only the high pressure PH, the control process as disclosed in JP 2003-121018A will be sufficient, in which the opening of one of the expansion valves is adjusted while the other one is kept in a fully opened or fully closed state. In contrast, in the control process shown in FIG. **3**, after completing the first controlling, in which the opening of the second expansion valve **7** is adjusted appropriately, the opening of the first expansion valve **6** is adjusted in the second controlling while the opening of the second expansion valve **7** is being kept as it is (in other words, without varying the opening of the second expansion valve **7**).

[0069] In the heat pumps **71** and **72** as well, the control process in which the opening of the first expansion valve **6** is adjusted while the second expansion valve **7** is kept fully closed may be executed in a temperature range in which the volume flow rate of the refrigerant flowing into the expander

3 is smaller than the cylinder volume of the expander **3**, although not shown in FIG. **3**. This control process may be executed between step **2** to step **1** when the process returns from step **2** to step **1**.

[**0070**] In the control process shown in FIG. **3**, the control of the pressure PH is completed after verifying a match between the pressure PH and the target pressure PH_T, and then the process proceeds to the control of the degree of superheat SH; on the other hand, the control of the degree of superheat SH is completed without verifying a match between the degree of superheat SH and the target degree of superheat SH_T, and then the process returns to the control of the pressure PH. This is because appropriate controlling of the high pressure PH in the refrigeration cycle is considered more important. However, this is merely illustrative, and in the control of the degree of superheat SH as well, it is possible to verify a match between the degree of superheat SH and the target degree of superheat SH_T and thereafter complete the control. A flowchart for executing this control process is illustrated in FIG. **5**.

[**0071**] In the example of the control process shown in FIG. **5**, after completing step **12** or **13**, the process returns to step **9** and the control process continues. In this case, the second controlling also is a loop control that is repeated until the degree of superheat SH matches the target value SH_T. When a loop control is employed, it may be appropriate that the decision in step **10** should be made, not as to whether or not the degree of superheat SH matches a target value, but rather as to whether or not the difference between the degree of superheat SH and the target value SH_T falls within a predetermined range SH_{DR}. The rest of the steps in the control process shown in FIG. **5** are executed in the same manner as in the example of the control process of FIG. **3**.

[**0072**] Various modifications may be made to the control of the pressure PH and the control of the degree of superheat SH other than the modification illustrated in FIG. **5**. It should be noted that the control process of the present invention is not limited to the examples of control processes shown in FIGS. **3** and **5**.

[**0073**] For example, in the foregoing, the subject of decision was a match between the pressure PH and the target pressure PH_T, in other words, whether or not the difference between the pressure PH and the target pressure PH_T is zero; however, in place of this, it also is possible to make the decision as to whether the difference between the pressure PH and the target pressure PH_T falls within a predetermined range PH_{DR}. In this case, in place of step **5**, a decision may be made as to whether or not the difference between the pressure PH and the target pressure PH_T falls within the predetermined range PH_{DR}. The decision as to whether or not the difference falls within the predetermined range PH_{DR} need not be made by directly calculating the difference, but it may be made by, for example, calculating a ratio and determining whether or not the ratio falls within a predetermined range PH_{DR} that is converted for the ratio. The control of the degree of superheat SH also may be conducted in a similar manner.

[**0074**] Although the predetermined ranges PH_{DR} and SH_{DR} may be set as appropriate depending on, for example, the use of the heat pump, it is desirable that they should be in a very limited range. An example of the predetermined range PH_{DR} is preferably from −1.2 MPa to 1.2 MPa, and more preferably from −0.8 MPa to 0.8 MPa, as expressed by a value obtained by subtracting the target pressure PH_T (MPa) from the pressure PH (MPa). It is preferable that the predetermined range SH_{DR} be within a range higher than $-(SH_T)$° C. but lower than or equal to 20° C., and more preferably a range higher than $-(SH_T)$° C. but lower than or equal to 10° C., as expressed by a value obtained by subtracting the target degree of superheat SH_T (° C.) from the degree of superheat SH (° C.); however, the predetermined range SH_{DR} may be set to be a value exceeding 0° C. in order that the just-mentioned value does not become negative. In the case that the target degree of superheat SH_T is 10° C., the range "higher than $-(SH_T)$° C. but lower than or equal to 20° C." means a range "higher than −10° C. but lower than or equal to 20° C.".

[**0075**] In addition, for example, a step of determining whether or not the second expansion valve **7** is fully closed may be added after step **8**, and if it is determined that the second expansion valve **7** is fully closed in the additional step, the process may return to step **1**. If it is determined that the second expansion valve **7** is not fully closed in the additional step, the control process returns to step **4** and is repeated.

[**0076**] Moreover, for example, step **9** may be executed subsequent to step **3** in order to execute the control of degree of the superheat SH prior to the control of the pressure PH. In this case, the degree of superheat SH is controlled first, then the pressure PH is controlled, and thereafter the degree of superheat SH is controlled again. Depending on the use and design of the heat pump, the control process may be started from step **4** or **9** without executing steps **1** to **3**.

[**0077**] As has been described above, the controller (control device) **30** executes the control of pressure (first controlling) in which, if the difference between a high pressure PH of the refrigerant and a predetermined target value PH_T is outside a predetermined range PH_{DR}, the opening of the second expansion valve (second throttling device) **7** is varied so that the absolute value of the difference between the pressure PH and the predetermined value PH_T becomes smaller (so that the pressure PH is brought closer to the predetermined value PH_T) (S**4** to S**8**).

[**0078**] Then, after completing the first controlling, the controller **30** executes the control of the degree of superheat (second controlling) in which, if the difference between a degree of superheat SH of the refrigerant flowing into the compressor and a predetermined positive value SH_T is outside a predetermined range SH_{DR}, the opening of the first expansion valve (first throttling device) **6** is varied so that the absolute value of the difference between the degree of superheat SH and the predetermined value SH_T becomes smaller (so that the degree of superheat SH is brought closer to the predetermined value SH_T) (S**9** to S**13**).

[**0079**] In the first controlling, it is preferable that the control device vary the opening of the second throttling device so that the difference between the pressure PH and the predetermined value PH_T falls within the predetermined range PH_{DR}. In the second controlling, the control device may vary the opening of the first throttling device so that the difference between the degree of superheat SH and the predetermined value SH_T falls within the predetermined range SH_{DR}.

[**0080**] In an example of the control process described above, the control device further may execute the first controlling after completing the second controlling, if the difference between the pressure PH and the predetermined value PH_T is outside the predetermined range PH_{DR}. The purpose is to control the pressure PH again, taking into account the variation of the pressure PH resulting from the second controlling.

[0081] As illustrated in the foregoing, a specific controlling may be as follows; in the first controlling, when the pressure PH is higher than the predetermined value PH_T and the difference between the pressure PH and the predetermined value PH_T is outside the predetermined range PH_{DR}, the opening of the second throttling device is increased; and when the pressure PH is lower than the predetermined value PH_T and the difference between the pressure PH and the predetermined value PH_T is outside the predetermined range PH_{DR}, the opening of the second throttling device is decreased.

[0082] In addition, in the second controlling, when the degree of superheat SH is higher than the predetermined value SH_T and the difference between the degree of superheat SH and the predetermined value SH_T is outside the predetermined range SH_{DR}, the opening of the first throttling device is increased; and when the degree of superheat SH is lower than the predetermined value SH_T and the difference between the degree of superheat SH and the predetermined value SH_T is outside the predetermined range SH_{DR}, the opening of the first throttling device is decreased.

[0083] In the control processes shown in FIGS. **3** and **5**, the respective values of the pressure PH and the degree of superheat SH are specified explicitly, and the expansion valves are adjusted based on the specified values to control the pressure PH and the degree of superheat SH. The control of the pressure PH and the degree of superheat SH may be carried out indirectly using alternative parameters associated with the pressure PH or the degree of superheat SH.

[0084] For example, by measuring a ratio RV of the volume flow rate of the refrigerant flowing into the compressor **1** to the volume flow rate of the refrigerant flowing into the expander **3**, it is possible to execute the control of the high pressure PH based on the ratio RV and a ratio RC of the volume of the expander **3** to the volume of the compressor **1**. The magnitude relationship between the ratio RV and the ratio RC is an alternative parameter RP associated with the high pressure PH, and with this parameter, it also is possible to set a control target R_{PT} associated with the target pressure PH_T.

[0085] Thus, in the just-described control process, the control device may determine whether or not the difference between the pressure PH and the predetermined value PH_T is within the predetermined range PH_{DR} by comparing a predetermined characteristic RP associated with the pressure PH and a predetermined value RP_T concerning the characteristic RP, the predetermined value RP_T being associated with the predetermined value PH_T, without directly comparing the pressure PH and the predetermined value PH_T.

[0086] FIG. **6** illustrates the changes in the refrigeration cycle resulting from the just-described control process. The initial refrigeration cycle (a_1 to f_1) shifts to a refrigeration cycle (a_2 to f_2) when the opening of the second expansion valve **7** is increased in the first controlling in order to reduce the high pressure that is higher than the target pressure PH_T. This refrigeration cycle then shifts to a refrigeration cycle (a_3 to f_3) when the opening of the first expansion valve **6** is decreased in the second controlling in order to ensure a relatively high degree of superheat. This refrigeration cycle further shifts to a refrigeration cycle (a_4 to f_4) when the opening of the second expansion valve **7** is increased in the first controlling that is executed again, in order to reduce the high pressure.

[0087] It should be noted that, as shown in FIG. **6**, when the high pressure in the refrigeration cycle is in a supercritical state, the difference between the low pressure and the high pressure in the refrigeration cycle is large, and the expander **3** contributes greatly to the energy recovery function. To achieve this, it is advisable that the heat pump may be configured such that the compressor compresses the refrigerant so that the refrigerant discharged from the compressor is in a supercritical state.

[0088] The configurations to which the present invention is applicable are not limited to the illustrative examples of FIGS. **1** and **2**. For example, although the piping **12** forms a bypass passage that bypasses the expander **3** and the first expansion valve **6** in the configurations of FIGS. **1** and **2**, it also is possible to employ a heat pump **73** in which the piping **12** is connected to the piping **11** so as to form a bypass passage that bypasses only the expander **3** (see FIG. **7**). Alternatively, it also is possible to employ a heat pump **74** in which the first expansion valve **6** is disposed downstream of the expander **3**, not upstream of the expander **3** (see FIG. **8**). Furthermore, it also is possible to employ a heat pump **75** in which the piping **12** forms a bypass passage that bypasses only the expander **3**, and the first expansion valve **6** is disposed downstream of the expander **3** (see FIG. **9**). These configurations are likewise capable of appropriately controlling the high pressure PH and the degree of superheat SH by applying the same control processes as described above.

[0089] Moreover, a plurality of controllers may share the function of the controller **30**. In a heat pump **76**, illustrated in FIG. **10**, a first controller **31** serves the function to adjust the openings of the first expansion valve **6** and the second expansion valve **7** in order to control the pressure PH and the degree of superheat SH (S**4** to S**8** and S**10** to S**13**), a second controller **32** serves the function to calculate the degree of superheat SH in response to the signals from the temperature sensors **23** and **24** (S**9**), and a third controller **33** serves to execute the control process of measuring an outside air temperature T and opening the second expansion valve **7** based on the measurement result (S**1** to S**3**).

[0090] Furthermore, it also is possible to employ a heat pump in which four-way valves **51** and **53** are provided. A heat pump **77**, illustrated in FIG. **11**, can be used as an air-conditioner in which a heating operation and a cooling operation can be switched from one to the other by switching in the four-way valves **51** and **53**. During the heating operation, the passages indicated by the solid lines are selected in the four-way valves **51** and **53**, so an indoor heat exchanger **52** functions as the radiator while an outdoor heat exchanger **54** functions as the evaporator. During the cooling operation, the passages indicated by the dashed lines are selected in the four-way valves **51** and **53**, so the outdoor heat exchanger **54** functions as the radiator while the indoor heat exchanger **52** functions as the evaporator. In this heat pump **77** as well, the high pressure PH and the degree of superheat SH can be controlled appropriately if the control processes illustrated above are applied thereto.

[0091] In the control processes illustrated above, the pressure Pd (PH) of the refrigerant discharged from the compressor is measured, or the temperature of the refrigerant discharged from the compressor is measured, in order to calculate the pressure PH. By utilizing this, abnormality management of the heat pump may be performed. The abnormality management can be executed as follows. In a heat pump having a configuration as illustrated above, if the pressure PH exceeds a predetermined limit pressure and/or if the temperature of the refrigerant discharged from the compressor **1** exceeds a predetermined limit temperature, the controller **30** recognizes the abnormality and performs adjustment to increase the opening(s) of the first expansion valve **6** and/or the second expansion valve **7** to a predetermined opening or greater. Here, it is preferable that the predetermined opening be set at an opening that exceeds the control ranges determined in the first controlling and the second controlling. Such an action makes it possible to reduce the pressure and temperature of the refrigerant quickly.

[0092] Even if the high pressure PH or the temperature of the refrigerant reaches an abnormal value due to an abrupt change in the operation condition or some other cause, the just-described control process makes it possible to eliminate the abnormal value in a short time. It should be noted that although the limit pressure and limit temperature may vary depending on such factors as the refrigerant and the configuration of the heat pump, illustrative examples of the limit pressure and the limit temperature may be given as 12 MPa and 115° C., respectively, in the case of using carbon dioxide as the refrigerant.

[0093] In order to execute the abnormality management as described above, it is preferable that, in the heat pump of the present invention, if the pressure PH exceeds a predetermined limit pressure or if the temperature of the refrigerant discharged from the compressor exceeds a predetermined limit temperature, the control device greatly varies at least one opening selected from the opening of the first throttling device and the opening of the second throttling device beyond the variation ranges of the openings in the first controlling and the second controlling.

[0094] FIGS. **12** and **13** show temperature changes of refrigerant and air (heated medium) in the evaporator in cases where carbon dioxide is used as the refrigerant and the high pressure in the refrigeration cycle is set to exceed the critical pressure of carbon dioxide (FIG. **12**) and where a fluorocarbon is used as the refrigerant (FIG. **13**). In both cases, the refrigerant flows into the radiator at a temperature T_0, and heats the air by heat exchange with the air. The temperature difference ΔT in the case of using carbon dioxide as the refrigerant is greater than the temperature difference ΔT in the case of using fluorocarbon as the refrigerant. This is because carbon dioxide does not undergo a phase change in the radiator, unlike fluorocarbons. Carbon dioxide is suitable as the refrigerant for heating the heated medium to a high temperature.

[0095] The present invention has great utility value as it achieves an improvement in the heat pump, which is useful for air-conditioners, hot water heaters, dish dryers, garbage drying disposers, and the like.

[0096] The invention may be embodied in other forms without departing from the spirit or essential characteristics thereof. The embodiments disclosed in this application are to be considered in all respects as illustrative and not limiting. The scope of the invention is indicated by the appended claims rather than by the foregoing description, and all changes which come within the meaning and range of equivalency of the claims are intended to be embraced therein.

What is claimed is:

1. A heat pump comprising:

a compressor; a radiator; an expander; and an evaporator;

a piping that forms a circulation passage in which refrigerant circulates through the compressor, the radiator, the expander, and the evaporator in that order, and a bypass passage in which the refrigerant flows from the radiator to the evaporator without flowing through the expander;

a first throttling device having a variable opening and disposed in the circulation passage between the radiator and the expander or between the expander and the evaporator;

a second throttling device having a variable opening and disposed in the bypass passage; and

a control device for adjusting the opening of the first throttling device and the opening of the second throttling device, wherein

the compressor and the expander are connected to a common rotation shaft; and

the control device executes a first controlling in which, when the difference between a high pressure PH of the refrigerant circulating in the circulation passage and a predetermined value PH_T determined based on a value at which a coefficient of performance of the heat pump is optimized is outside a predetermined range PH_{DR}, the opening of the second throttling device is varied so that the absolute value of the difference between the pressure PHI and the predetermined value PH_T becomes smaller; and

after completing the first controlling, the control device executes a second controlling in which, when the difference between a degree of superheat SH of the refrigerant flowing into the compressor and a predetermined positive value SH_T is outside a predetermined range SH_{DR}, the opening of the first throttling device is varied so that the absolute value of the difference between the degree of superheat SH and the predetermined value SH_T becomes smaller.

2. The heat pump according to claim 1, wherein, in the first controlling, the control device varies the opening of the second throttling device so that the difference between the pressure PH and the predetermined value PH_T falls within the predetermined range PH_{DR}.

3. The heat pump according to claim 1, wherein, in the second controlling, the control device varies the opening of the first throttling device so that the difference between the degree of superheat SH and the predetermined value SH_T falls within the predetermined range SH_{DR}.

4. The heat pump according to claim 1, wherein, after completing the second controlling, the control device further executes the first controlling when the difference between the pressure PH and the predetermined value PH_T is outside the predetermined range PH_{DR}.

5. The heat pump according to claim 1, wherein, in the first controlling,

when the pressure PH is higher than the predetermined value PH_T and the difference between the pressure PH and the predetermined value PH_T is outside the predetermined range PH_{DR}, the opening of the second throttling device is increased, and

when the pressure PH is lower than the predetermined value PH_T and the difference between the pressure PH and the predetermined value PH_T is outside the predetermined range PH_{DR}, the opening of the second throttling device is decreased.

6. The heat pump according to claim 1, wherein, in the second controlling,

when the degree of superheat SH is higher than the predetermined value SH_T and the difference between the degree of superheat SH and the predetermined value SH_T is outside the predetermined range SH_{DR}, the opening of the first throttling device is increased, and

when the degree of superheat SH is lower than the predetermined value SH_T and the difference between the degree of superheat SH and the predetermined value SH_T is outside the predetermined range SH_{DR}, the opening of the first throttling device is decreased.

7. The heat pump according to claim 1, wherein the predetermined value SH_T is set at a numerical value that is within a range higher than 0° C. but lower than or equal to 20° C.

8. The heat pump according to claim 1, further comprising, in order to specify the degree of superheat SH, a first sensor for detecting a temperature of the refrigerant flowing into the compressor, and a second sensor for detecting a temperature of the refrigerant in the evaporator.

9. The heat pump according to claim 1, further comprising a pressure sensor for detecting a pressure of the refrigerant discharged from the compressor in order to specify the pressure PH.

10. The heat pump according to claim 1, further comprising, in order to specify the pressure PH, a third sensor for detecting a temperature outside the heat pump system, and a fourth sensor for detecting a temperature of the refrigerant discharged from the compressor.

11. The heat pump according to claim 1, wherein the control device determines whether or not the difference between the pressure PH and the predetermined value PH_T is within the predetermined range PH_{DR} by comparing a predetermined characteristic RP associated with the pressure PH and a predetermined value RP_T concerning the characteristic RP, the predetermined value RP_T being associated with the predetermined value PH_T, without directly comparing the pressure PH and the predetermined value PH_T.

12. The heat pump according to claim 1, wherein, when the pressure PH exceeds a predetermined limit pressure or when the temperature of the refrigerant discharged from the compressor exceeds a predetermined limit temperature, the control device varies at least one opening selected from the opening of the first throttling device and the opening of the second throttling device beyond the variation ranges of the openings in the first controlling and the second controlling.

13. The heat pump according to claim 1, wherein the compressor compresses the refrigerant so that the refrigerant discharged from the compressor is in a supercritical state.

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