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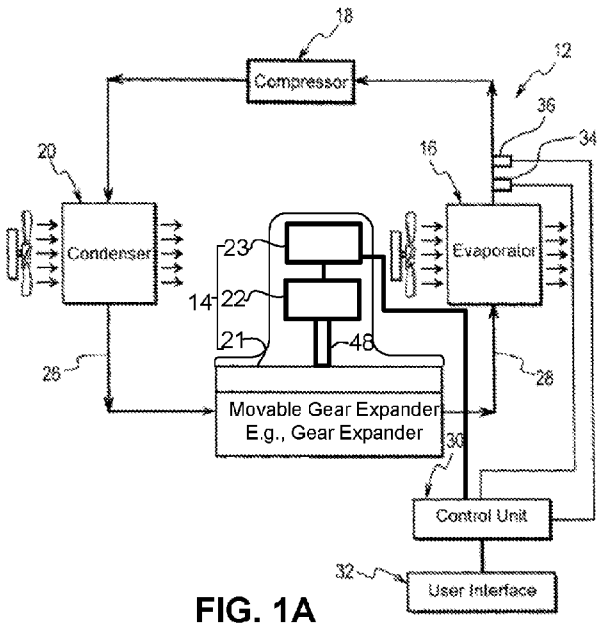


FIG. 1A

(57) **Abstract**: A refrigeration system includes an evaporator, a compressor fluidly connected to the evaporator to compress low-pressure refrigerant exiting the evaporator to high-pressure vapor refrigerant, a high-side heat exchanger fluidly connected to the compressor to receive the high pressure vapor refrigerant and dissipate heat therefrom, and an energy recovery device configured to extract work from the high pressure refrigerant flowing therethrough, the energy recovery device including a gear expander, a generator and a controller. The gear expander having a fluid inlet, a fluid outlet in fluid communication with the fluid inlet, and a mechanical power output for outputting mechanical power created by fluid passing between the fluid inlet and fluid outlet, the fluid inlet arranged between a high pressure output of the compressor and an inlet of the evaporator. The generator is mechanically coupled to the gear mechanical power output and operative to convert mechanical power produced by the gear to electrical power. The controller is electrically coupled to the generator, the controller configured to regulate electrical power produced by the generator and output the regulated electrical power.

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GEAR EXPANDER FOR ENERGY RECOVERY

RELATED APPLICATION DATA

This application claims priority of U.S. Provisional Application No. 62/115,411 filed on February 12, 2015, which is incorporated by reference in its entirety.

TECHNICAL FIELD

The present invention relates to an air conditioning and refrigeration systems. More specifically, the present invention relates to an air conditioning or refrigeration system with an energy recovery device that extracts work from expanding refrigerant moving from a high-pressure zone to a lower pressure zone of the air conditioning or refrigeration system.

BACKGROUND

Air conditioning and refrigeration systems utilize the phase changes of refrigerant fluids in order to extract heat from circulated air, and thus cool the air. A typical air conditioning or refrigeration system includes a compressor, a condenser, an expansion valve and an evaporator. The compressor compresses a cool vapor-phase refrigerant (e.g., Freon®, R410a, R404a) to heat the same, resulting in a hot, high-pressure vapor-phase refrigerant. This hot vapor-phase refrigerant runs through a condenser, typically a coil that dissipates heat. The condenser condenses the hot vapor-phase refrigerant into liquid refrigerant. The liquid refrigerant is regulated through the expansion valve, which expands the refrigerant to a cold, low-pressure saturated liquid-vapor-phase refrigerant. This

cold saturated liquid-vapor-phase refrigerant runs through the evaporator(s), typically a coil that absorbs heat from the space to be cooled.

Depending on the type of cooling system, various types of devices may be used to cool the refrigerant. As used herein, the term "high-side heat exchanger" includes condensers, gas coolers, vapor coolers, liquid coolers, and the like, as may be utilized by the type of cooling system.

Basically, the input energy for an air conditioning or refrigeration system is typically represented by the power required to operate the compressor that compresses refrigerant vapor. Much of the energy added to the system through the compression process is expelled as kinetic energy during the expansion phase when the pressure of the refrigerant rapidly drops. In order to increase the efficiency of air conditioning and refrigeration systems, attempts have been made to recover some of the energy released during the expansion process and to convert the recovered energy into useful work. For example, one proposal to improve energy efficiency of a vehicle air conditioning system is disclosed in U.S. Pat. No. 6,272,871. Generally, in this patent, the air conditioning system is provided with an energy recovery device that recovers energy generated during operation of the air conditioning system. Specifically, the air conditioning system utilizes a vane-type expander (similar to a vane type compressor, but operating in reverse) to extract energy from normal operation of the air conditioning system. In this air conditioning system, the expanding refrigerant is used to rotate the vane-type expander that is connected to a shaft from which mechanical and/or electrical energy can be extracted.

SUMMARY

It has been discovered that air conditioning and refrigeration systems employing rotating expansion devices (such as vane-type expanders configured as energy recovery devices) may exhibit suction losses, which can impede rotational motion and reduce efficiency. The geometries of some vane-type expanders can also cause expanded refrigerant to be partially re-compressed before exiting the expander. Additionally, the high number and complexity of parts that comprise vane-type expanders introduces additional cost and potential points of failure.

In view of these operational limitations of rotating expansion devices such as vane-type expanders, one aspect of the present invention is to utilize a movable expander in an air conditioning or refrigeration system that can reduce and/or eliminate the suction loss that occurs in energy recovery devices that utilize a vane-type expander in a refrigeration system. A drive system, such as an electrical generator and controller, are operatively coupled to the energy recovery device to extract fluid energy from the system and convert the fluid (mechanical) energy into electrical energy, which may be stored in a storage device (e.g., a battery), provided to other devices via a common bus, or sold back to the power company.

According to one aspect of the invention, . A refrigeration system includes: at least one evaporator; at least one compressor fluidly connected to the at least one evaporator to compress low-pressure refrigerant vapor exiting the at least one evaporator to high-pressure vapor refrigerant; at least one high-side heat exchanger fluidly connected to the at least one compressor to receive

the high pressure refrigerant vapor and dissipate heat therefrom; an energy recovery device configured to extract work from the high pressure refrigerant flowing therethrough, the energy recovery device including a gear expander, a generator and a controller, the gear expander having a fluid inlet, a fluid outlet in fluid communication with the fluid inlet, and a mechanical power output for outputting mechanical power created by fluid passing between the fluid inlet and fluid outlet, the fluid inlet arranged between a high pressure output of the at least one compressor and an inlet of the at least one evaporator, the generator mechanically coupled to the gear mechanical power output and operative to convert mechanical power produced by the gear to electrical power, and the controller operatively coupled to the generator, the controller configured to regulate a speed of the generator to control electrical power produced by the generator.

Optionally, the controller is configured to regulate a load placed on the gear expander based on at least one of refrigerant mass flow or refrigeration cycle control.

Optionally, the controller is configured to control parameters of the refrigeration cycle.

Optionally, the controller is configured to regulate the speed of the generator based on at least one of refrigerant superheat, hot gas flow from the compressor discharge, flash gas separation, flash gas cooling, or evaporator defrost.

Optionally, the controller is configured to control a flow rate of high pressure vapor refrigerant exiting the at least one high-side heat exchanger and

entering the energy recovery device based on at least one of pressure and temperature of the refrigeration system.

Optionally, the gear expander fluid inlet is fluidly connected to an outlet of the at least one high-side heat exchanger to receive high pressure refrigerant exiting the at least one high-side heat exchanger, and the gear expander fluid outlet is fluidly connected to an inlet of the at least one evaporator to deliver low pressure refrigerant thereto.

Optionally, the gear expander fluid inlet is fluidly connected to an outlet of the at least one compressor to receive high pressure vapor refrigerant exiting the at least one compressor, and the gear expander fluid outlet is fluidly connected to an inlet or an outlet of the at least one evaporator.

Optionally, the gear expander fluid inlet is fluidly connected to an outlet of the at least one high-side heat exchanger, and a gear expander fluid outlet is fluidly connected to an inlet of a flash gas separator or directly to the at least one evaporator.

Optionally, the controller is configured to regenerate electrical power produced by the generator to an AC or DC electrical bus.

Optionally, the controller comprises a variable speed drive controller.

Optionally, the generator is hermetically sealed.

Optionally, a chamber of the gear expander includes an inner rotor and an outer rotor, a rotation axis of the inner rotor being offset from a rotation axis of the outer rotor such that rotational movement of the outer rotor drives the inner rotor, the inner rotor defining the output of the gear expander.

Optionally, the energy recovery device further includes a rotatable shaft connected to the inner rotor of the gear expander.

Optionally, the rotatable shaft of the energy recovery device is configured and arranged to extract work from rotational movement of the inner rotor.

Optionally, the inner rotor rotates the rotatable shaft in a first direction about a center rotational axis of the rotatable shaft in response to at least one of a phase change or a pressure change of the flow of a refrigerant from the high pressure refrigerant at the inlet to the low pressure refrigerant at the outlet.

Optionally, the energy recovery device further includes a rotatable shaft connected to the outer rotor of the gear expander.

Optionally, the rotatable shaft of the energy recovery device is configured and arranged to extract the work from rotational movement of the outer rotor.

Optionally, the outer rotor rotates the rotatable shaft in a first direction about a center rotational axis of the rotatable shaft in response to at least one of a phase change or a pressure change of the flow of a refrigerant from the high pressure refrigerant at the inlet to the low pressure refrigerant at the outlet.

Optionally, the system includes a control unit operatively connected to the controller, wherein control of the generator is performed in at least one of the control unit or the controller.

Optionally, the gear expander comprises ceramic components.

Optionally, the outer rotor and the inner rotor of the gear expander are formed from ceramic material.

Optionally, components of the gear expander comprise friction-reducing coatings.

According to another aspect of the invention, a method is provided for recovering energy from a refrigeration system that includes at least one evaporator, at least one compressor fluidly connected to the at least one evaporator to compress low-pressure refrigerant vapor exiting the at least one evaporator to high-pressure vapor refrigerant, at least one high-side heat exchanger fluidly connected to the at least one compressor to receive the high pressure refrigerant vapor and dissipate heat therefrom, an energy recovery device configured to extract work from the high pressure refrigerant flowing therethrough, the energy recovery device including a gear expander, a generator and a controller, the gear expander having a fluid inlet, a fluid outlet in fluid communication with the fluid inlet, and a mechanical power output for outputting mechanical power created by fluid passing between the fluid inlet and fluid outlet, the fluid inlet arranged between a high pressure output of the at least one compressor and an inlet of the at least one evaporator, the generator mechanically coupled to the gear mechanical power output and operative to convert mechanical power produced by the gear to electrical power. The method includes regulating, via the controller, a speed of the generator to control electrical power produced by the generator.

Optionally, regulating includes regulating a load placed on the gear expander based on at least one of refrigerant mass flow or refrigeration cycle control.

Optionally, regulating includes regulating the speed of the generator based on at least one of refrigerant superheat, hot gas flow from the compressor discharge, flash gas separation, flash gas cooling, or evaporator defrost.

Optionally, regulating includes controlling a flow rate of high pressure vapor refrigerant exiting the at least one high-side heat exchanger and entering the energy recovery device based on at least one of pressure change or pressure and temperature of the refrigeration system.

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BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of this invention will now be described in further detail with reference to the accompanying drawings.

FIG. 1A is a schematic system diagram of a refrigeration system equipped with an energy recovery device in accordance with an illustrated embodiment.

FIG. 1B is a schematic system diagram of a CO_2-based refrigeration system equipped with an energy recovery device in accordance with an illustrated embodiment.

FIG. 2 is a simplified schematic view of the energy recovery device including a movable (gear) expander.

FIG. 3 is a simplified cross sectional view of the movable expander as seen along section line 3-3 in FIG. 2 showing the high pressure line entering the movable expander and the low pressure line exiting the movable expander.

FIG. 4 is a simplified cross sectional view of the movable expander as seen along section line 4-4 in FIG. 3 showing the flow path of refrigerant through the movable expander.

FIG. 5 is a simplified cross sectional view of the movable expander as seen along section line 5-5 in FIG. 4 showing a ring gear and a center gear that define expansion cavities in the movable expander.

FIG. 6 is a simplified cross sectional view of the movable expander as seen along section line 6-6 in FIG. 4 illustrating the chambers through which refrigerant passes through the movable expander to generate torque.

FIG. 7 is a schematic diagram illustrating an energy recovery device in accordance with the present disclosure.

FIG. 8 is a schematic diagram illustrating redistribution of electrical power via a common AC or DC bus in accordance with the present disclosure.

FIG. 9 is a block diagram illustrating a method for generating a speed reference based on refrigerant super heat.

FIG. 10 is a block diagram illustrating a method for generating a speed reference based on refrigerant pressure.

FIG. 11 is a control block diagram illustrating a regulation scheme for controlling a load placed on the generator.

DETAILED DESCRIPTION

Selected embodiments will now be explained with reference to the drawings. It will be apparent to those skilled in the art from this disclosure that the following descriptions of the embodiments are provided for illustration only and not for the purpose of limiting the invention as defined by the appended claims and their equivalents.

Referring initially to FIG. 1A, a refrigeration system 12 is equipped with an energy recovery device 14 in accordance with an illustrated embodiment. The energy recovery device 14 extracts energy (work) from expansion of refrigerant as the refrigerant moves from a high-pressure zone of the refrigeration system 12 to a low-pressure zone of the refrigeration system 12. As shown schematically in FIG. 1A, in addition to the energy recovery device 14, the refrigeration system 12 also includes an evaporator 16, a compressor 18 and a high-side heat exchanger 20.

In the illustrated embodiment, the energy recovery device 14 basically includes a movable expander 21, a generator 22 and a drive controller 23. More particularly, in the illustrated embodiment, the movable expander 21 is a gear expander. The movable expander 21 is configured and arranged to extract energy (work) from expansion of the refrigerant as the refrigerant moves from a high-pressure zone of the refrigeration system 12 to a low-pressure zone of the refrigeration system 12. While the refrigeration system 12 is especially suitable for use in supermarkets, convenience stores, or other places where a refrigerated space is desired, the refrigeration system 12 is also suitable for use in HVAC applications.

In the illustrated embodiment of FIGS. 1A, 2 and 4, the generator 22 is driven by the movable expander 21 to produce electricity which can be stored in a battery (not shown), used to power other systems, or sold back to the power company. While the generator 22 is illustrated as being rotated by the energy recovered by the movable expander 21, it will be apparent to those skilled in the refrigeration field that the recovered energy can be used to rotate other devices

as needed and/or desired, depending on the application of the refrigeration system 12.

The components of the refrigeration system 12 will now be described in more detail. Basically, the energy recovery device 14 and the compressor 18 divide the refrigerant circuit into a high pressure line 26 and a low pressure line 28. The evaporator 16 is disposed in the low pressure line 28, while the high-side heat exchanger 20 is disposed in a high pressure line 26. The compressor 18 is disposed between the beginning of the high pressure line 26 and the end of the low pressure line 28.

In one embodiment, the energy recovery device 14 is disposed between the end of the high pressure line 26 and the beginning of the low pressure line 28. Thus, the outlet side of the energy recovery device 14, the low pressure line 28 with the evaporator 16, and the inlet side of the compressor 18 generally define a low-pressure zone of the refrigeration system 12. On the other hand, the outlet side of compressor 18, the high pressure line 26 with the high-side heat exchanger 20, and the inlet side of the energy recovery device 14 generally define a high-pressure zone of the refrigeration system 12.

In another embodiment, the energy recovery device 14 is disposed between the high pressure outlet of the compressor 18 and the inlet of the high-side heat exchanger. In this configuration, the outlet side of an expansion valve (arranged between an outlet of the high-side heat exchanger 20 and an inlet of the evaporator 16), the inlet and outlet of the evaporator 16, and the inlet side of the compressor 18 generally define a low-pressure zone of the refrigeration system 12. On the other hand, the outlet side of compressor 18, the inlet and

outlet of the energy recovery device 14, the inlet and outlet of the high-side heat exchanger 20 and the inlet of the expansion valve generally define a high-pressure zone of the refrigeration system 12. Alternatively, the energy recovery device 14 is disposed between the high pressure outlet of the compressor 18 and the inlet or outlet of the evaporator 16.

The evaporator 16 is a conventional element of the refrigeration system 12 and serves to absorb heat outside the evaporator 16. The evaporator 16 can include a blower or fan which forces air past the evaporator 16 for improved heat transfer. Heat in the moving air is in turn absorbed by low-pressure refrigerant within the evaporator 16. Optimally, the refrigerant within the evaporator 16 is in a liquid-vapor state and exits in the vapor state after absorbing heat. The low pressure line 28 fluidly connects the energy recovery device 14 to the evaporator 16 and also fluidly connects the evaporator 16 to the compressor 18.

The compressor 18 is fluidly connected to the evaporator 16 to compress low-pressure vapor refrigerant exiting the evaporator 16 to high-pressure vapor refrigerant that is directed to the high-side heat exchanger 20. In other words, the low-pressure refrigerant exiting the evaporator 16 is directed to the compressor 18 via the low pressure line 28. The compressor 18 preferably compresses the refrigerant in a conventional manner into high-pressure refrigerant in the vapor state. The high-pressure refrigerant compressed by the compressor 18 exits the compressor 18 via the high pressure line 26. Thus, the high pressure line 26 is further fluidly connected to the high-side heat exchanger 20 in a conventional manner.

As mentioned above, the high-side heat exchanger 20 is fluidly connected to the compressor 18 to receive the high pressure refrigerant and dissipate heat therefrom. The high-side heat exchanger 20 can include a blower or fan that forces air past the high-side heat exchanger 20 for improved heat transfer. Hence, the high-pressure refrigerant within the high-side heat exchanger 20 is cooled by airflow in a conventional manner or by other means not shown here. The cooled high-pressure refrigerant is then directed to the energy recovery device 14 via the high pressure line 26. More specifically, the high-pressure refrigerant drives the movable expander 21 and thus the generator 22, which is coupled to the movable expander 21 via rotatable shaft 48. In this manner, the mechanical energy of the refrigeration system is converted to electrical energy.

The refrigeration system 12 further includes a control unit 30 for controlling the drive controller 23 (and thus the generator 22) based on the operational state of the system. The control unit 30 is operatively connected to the drive controller 23 to control the flow of power through the generator 22 based on, for example, pressure and temperature of the refrigerant. An effect of such control of the generator 22 is that the flow rate of high pressure refrigerant exiting the high-side heat exchanger 20 and entering the movable expander 21 of the energy recovery device 14 is also regulated, and energy losses produced by the refrigeration system are recovered. The control unit 30 preferably includes a microcomputer with a refrigeration control program that controls the refrigeration system 12 in accordance with the refrigeration control program. The control unit 30 also preferably includes other conventional components such as an input interface circuit, an output interface circuit, and storage devices such as

a ROM (Read Only Memory) device and a RAM (Random Access Memory) device. It will be apparent to those skilled in the art from this disclosure that the precise structure and algorithms for the control unit 30 can be any combination of hardware and software that will carry out the functions of the air conditioning or refrigeration system 12 as needed and/or desired.

In addition to the secondary function of controlling the drive controller 23 and generator 22, a primary function of the control unit 30 is to provide a cold evaporator temperature that is at its setpoint, determined by the application, while ensuring that the refrigerant entering the compressor 18 is in the vapor phase. This facilitates good compression behavior at the compressor 18 and A/C cooling performance. It is noted that while a separate drive controller 23 and control unit 30 are shown, the features can be combined in a single controller, e.g., within the drive controller 23 or within control unit 30, if desired.

A conventional user interface 32 is provided for allowing the user to input the desired settings that the control unit 30 uses to operate the components of the refrigeration system 12. In other words, the conventional user interface 32 is operatively coupled to the control unit 30 for the user to control the operation of the refrigeration system 12 in a conventional manner.

The refrigeration system 12 further includes a pressure sensor 34 and a temperature sensor 36. The control unit 30 is operatively connected to the pressure sensor 34 and the temperature sensor 36. The pressure sensor 34 and the temperature sensor 36 are, for example, mounted to the low pressure line 28 downstream of the evaporator 16. The pressure sensor 34 detects refrigerant pressure within the low pressure line 28. The temperature sensor 36 detects

temperature within the low pressure line 28. Signals from the pressure sensor 34 and the temperature sensor 36 are processed by the control unit 30. In response to measured pressure and/or temperature conditions, the control unit 30 regulates power flow through the generator 22 to maintain a desired pressure condition within the low pressure line 28 and/or desired temperature proximate the evaporator 16.

Novel aspects of the system may also be employed to CO_2-based refrigeration systems. With reference to FIG. 1B, illustrated is an exemplary CO_2-based refrigeration system that includes the energy recovery device 14, a liquid/vapor tank 25 (also referred to as a flash gas separator), a valve 27, an evaporator 16, a compressor 18 and a gas cooler (e.g., a high-side heat exchanger or other cooling device) 20.

The compressor 18 is fluidly connected to an outlet of the evaporator 16 to compress low-pressure vapor refrigerant exiting the evaporator 16 to high-pressure vapor refrigerant. The compressor 18 compresses the refrigerant in a conventional manner into high-pressure refrigerant in the vapor state, which exits the compressor 18 and is provided to the high-side heat exchanger 20. The compressed refrigerant passes through the high-side heat exchanger 20 where it is cooled. The cooled high-pressure refrigerant exits the high-side heat exchanger 20 and is provided to an inlet of the energy recovery device 14 (e.g., an inlet of the movable expander) to drive the movable expander 21 and thus the generator 22, which again is coupled to the movable expander 21 via rotatable shaft 48. In this manner, the mechanical energy losses of the CO_2 refrigeration system are converted to electrical energy. An outlet of the energy recovery

device is fluidly connected to the liquid/vapor tank 25, where both vapor and liquid are stored. Liquid exits a bottom portion of the liquid/vapor tank 25 and is provided to an inlet of the evaporator 16. In addition, valve 27 is fluidly connected between a top portion of the liquid/vapor tank 25 and the inlet of the compressor 18, thereby allowing vapor to bypass the evaporator 16.

Turning now to FIGS. 2 to 6, the energy recovery device 14 of the illustrated embodiment will now be discussed in more detail. In the illustrated embodiment, the movable expander 21 is a gear expander which comes from a class of gears known as epitrochoidial. The movable expander 21 has a housing 40 with a gear expander chamber 42 (best seen in Fig. 3), an inlet 44 and an outlet 46. The inlet 44 fluidly connects the high pressure line 26 to the gear expander chamber 42, while the outlet 46 fluidly connects the low pressure line 28 to the gear expander chamber 42. A rotatable output shaft 48 is rotatably supported relative to the housing 40 by generator shaft bearings 50. In the illustrated embodiment, the housing 40 includes a first housing part 40a and a second housing part 40b, with the rotatable output shaft 48 protruding out of the second housing part 40b for attachment to an input of the generator 22.

Inside the gear expander chamber 42, the movable expander 21 is provided with an inner rotor 54, an outer rotor 56 and a flow control plate 58. The rotatable output shaft 48 is fixedly connected to the inner rotor 54 so that they rotate together as a single unit. The output shaft 48 extracts work from the movement of the movable expander 21 due to the refrigerant phase change and/or refrigerant pressure change in the movable expander 21, causing the output shaft 48 to turn, which in turn drives generator 22. Basically, the output

shaft 48 is configured and arranged to extract the work from rotational movement of the inner rotor gear 54. In particular, the inner rotor 54 engages the outer rotor 56 such that inner rotor 54 rotates the output shaft 48 in response to a phase change of the flow of refrigerant from the high pressure refrigerant at the inlet 44 to the low pressure refrigerant at the outlet 46. The inner rotor 54 and the outer rotor 56 are disposed in the gear expander chamber 42 such that the inner rotor 54 has its axial end faces coplanar with respective axial end faces of the outer rotor 56.

The outer rotor 56 is rotatably supported in the first housing part 40a by an outer rotor bearing 60. Thus, the outer rotor 56 rotates inside of the first housing part 40a. As seen in FIG. 5, the outer rotor 56 has an interior surface that defines a gear-shaped inner cavity 62 comprising nine teeth. The inner rotor 54 is disposed within the gear-shaped inner cavity 62, with a rotation axis A1 of the inner rotor 54 being offset from a rotation axis A2 of the outer rotor 56 such that rotational movement of the outer rotor 56 drives the inner rotor 54. Since the outer rotor 56 has nine teeth, the inner rotor 54 is provided with eight teeth. Other gear configurations/ratios are possible, e.g., 4/5, 7/8. In other words, if the outer rotor 56 has N number of teeth then the inner rotor 54 will have N-1 number of teeth. The teeth of the inner rotor 54 are meshed with the teeth of the outer rotor 56 to divide the gear-shaped inner cavity 62 of the outer rotor 56 into a plurality of isolated expansion cavities C1 to C8. As shown in in FIG. 6, the contact points between the inner rotor 54 and the outer rotor 56 to divide the gear-shaped inner cavity 62 into the isolated expansion cavities C1 to C8. Thus, the inner rotor 54 and the outer rotor 56 are arranged to define the isolated

expansion cavities C1 to C8 that move as the inner rotor 54 and the outer rotor 56 rotate.

As the outer rotor 56 rotates, lobes of the outer rotor 56 that conform in shape and size with the concave portions between the teeth of the inner rotor 54 make contact with the inner rotor 54 causing it to rotate. By connecting the inner rotor 54 to the output shaft 48, work can be extracted from the refrigeration system 12. The rotors 54 and 56 are oriented such that high pressure refrigerant enters the gear-shaped inner cavity 62 between the outer rotor 56 and the inner rotor 54 at the point where the volume between the rotors 54 and 56 is smallest. Upon further rotation of the rotors 54 and 56, as the volume between the rotors 54 and 56 nears a maximum value, the refrigerant is allowed to expand before exiting the housing 40. The rotors 54 and 56 are arranged within the gear expander chamber 42 with respect to the axis of the output shaft 48 such that a first axial side of the rotors 54 and 56 receives high pressure refrigerant entering the gear expander chamber 42 of the movable expander 21 and such that the first axial side of the rotors 54 and 56 discharges low pressure refrigerant exiting the gear expander chamber 42 of the movable expander 21. However, it should be understood that the rotors 54 and 56 could alternatively be arranged within the gear expander chamber 42 such that high pressure refrigerant enters into and exits from opposite axial sides of the rotors 54 and 56 (e.g., in conjunction with a reversal of fluid direction).

The flow control plate 58 controls the flow refrigerant into and out of the gear-shaped inner cavity 62 between the outer rotor 56 and the inner rotor 54. In particular, the flow control plate 58 is fixed to the housing 40, and is basically

provided with a first refrigerant input port 58a and a refrigerant output port 58b. The first refrigerant input port 58a constitutes a first flow interface. The refrigerant output port 58b constitutes a second flow interface. The second flow interface (e.g., the refrigerant output port 58b) has a cross-sectional area that is larger than a cross-sectional area of the first flow interface (e.g., the first refrigerant input port 58a).

The first flow interface (e.g., the first refrigerant input port 58a) is disposed between the inlet 44 of the housing 40 and the gear expander chamber 42. Thus, the high pressure refrigerant continuously enters the gear expander chamber 42 through the first flow interface during operation of the refrigeration system 12 and as controlled by control unit 30.

The second flow interface (e.g., the refrigerant output port 58b) is disposed between the outlet 46 of the housing 40 and the gear expander chamber 42. Thus, the low pressure refrigerant exits the gear expander chamber 42 through the second flow interface. The refrigerant output port 58b is shaped to give the refrigerant a maximum opportunity to exit the gear expander chamber 42 of the housing 40 before the rotors 54 and 56 come together again. In other words, the refrigerant output port 58b is shaped to avoid recompressing the expanded refrigerant. The second flow interface (e.g., the refrigerant output port 58b) spans at least two of the isolated expansion cavities C1 to C8 at a given time such that low pressure refrigerant is discharged from the at least two of the plurality of isolated expansion cavities C1 to C8 from the gear expander chamber 42 through the second flow interface (e.g., the refrigerant output port 58b).

The first refrigerant input port 58a defines a flow path that permits refrigerant to flow into the gear expander chamber 42. The first refrigerant input port 58a at the first flow interface fluidly connects the inlet 44 of the housing 40 to the gear expander chamber 42 to deliver high pressure refrigerant to the gear expander chamber 42. More specifically, the first refrigerant input port 58a is arranged to continually deliver high pressure refrigerant to one of the plurality of isolated expansion cavities.

Rotating surfaces of the gears and surfaces contacting the gears may or may not have material enhancements to reduce wear and frictional loss, and may or may not be formed from ceramic materials.

Referring now to Fig. 7, a schematic diagram is provided showing a configuration of the energy recovery device 14 and control unit 30. More specifically, the energy recovery device 14 includes the movable expander 21, generator 22, drive controller 23, where a control unit 30 is operatively coupled to the drive controller 23 of the energy recovery device 14. As described herein, the movable expander 21 converts fluid energy in the refrigeration system into mechanical power (e.g., rotational mechanical power). The generator shaft is connected to the inner rotor of the movable expander of the movable expander 21, and a second end coupled to an input shaft of the generator 22. As the movable expander 21 provides the rotational mechanical energy to the generator 22, the generator 22 produces electrical power. The drive controller 23 or the like is electrically connected to the generator 22, which may be an AC or DC machine, and regulates the electrical power output by the generator 22. In addition the control unit 30 regulates the drive controller 23 based on system

input. The drive controller 23 can regenerate power provided by the generator to an AC or DC bus for use by other devices, such as fans, blowers, compressors, heaters, lights, etc., as shown in Fig. 8. Alternatively or additionally, the electrical power may be stored for future use (e.g., in a battery), and/or sold back to the power company.

Preferably, the generator 22 and/or drive controller 23 are hermetically sealed (as shown in Figs. 1 and 2), and the drive controller is an AC or DC variable speed four-quadrant drive controller that has regeneration capability during overhauling operation. The drive controller 23 may employ conventional power devices, such as SCRs, IGBTs, and the like, and is operatively coupled to the control unit 30 that controls operation of the power devices to regulate power produced by the generator 22 and thus the load placed on the movable expander 21. The drive controller 23 preferably includes a microcomputer with a drive control program that controls the power devices in accordance with the drive control program. The drive controller 23 also preferably includes other conventional components such as an input interface circuit, an output interface circuit, and storage devices such as a ROM (Read Only Memory) device and a RAM (Random Access Memory) device. It will be apparent to those skilled in the art from this disclosure that the precise structure and algorithms for the controller can be any combination of hardware and software that will carry out drive control functions as needed and/or desired.

Exemplary drive controllers that may be utilized include Texas Instruments TMS320C242 or Freescale an1914. The drive controller 23 may or may not be sensorless, may or may not use current feedback control, may or

may not use encoder feedback control, may or may not use hall sensor feedback control, may or may not use V/Hz control, and may or may not use back EMF control.

In operation, the drive controller 23 is configured to regulate (maintain) generator speed during an overhauling condition. As the speed of the generator 22 is regulated, a speed of the movable expander 21, via the mechanical coupling between the generator 22 and movable expander 21, is also regulated. Such speed regulation of the movable expander 21 can be used to control refrigerant mass flow, refrigeration cycle control points (e.g., evaporator super heat, hot gas flow from compressor discharge, evaporator defrost, pressure set points, or other applicable points).

Referring now to FIGS. 9 and 10, flow diagrams 100 and 200 illustrating exemplary methods for generating a speed reference signal for controlling a speed of the generator 22 based on refrigerant super heat (FIG. 9) and refrigerant pressure (FIG. 10). The flow diagrams include a number of process blocks arranged in a particular order. As should be appreciated, many alternatives and equivalents to the illustrated steps may exist and such alternatives and equivalents are intended to fall with the scope of the claims appended hereto. Alternatives may involve carrying out additional steps or actions not specifically recited and/or shown, carrying out steps or actions in a different order from that recited and/or shown, and/or omitting recited and/or shown steps. Alternatives also include carrying out steps or actions concurrently or with partial concurrence.

Beginning with the method of Fig. 9, at step 102 the super heat of the refrigerant in the system 12 is calculated. Calculation of the refrigerant super heat may be performed using conventional techniques known by the person having ordinary skill in the art. For example, the pressure at the output of the evaporator 16 may be measured using pressure sensor 34, and the temperature corresponding to the measured pressure can be determined from pressure-temperature tables for the particular refrigerant. Also, the actual temperature of the refrigerant at the output of the evaporator 16 may be measured using temperature sensor 36. The refrigerant super heat then may be determined based on the difference between the measured temperature and the temperature derived from the pressure measurement. Alternatively, the superheat may be determined based on two temperature measurements, one at the inlet of the evaporator, the other at the exit.

Next at block 104 the super heat as calculated at block 102 may be compared to a high super heat threshold. Such high super heat threshold may be stored in memory of the control unit 30, for example, and/or may be settable via user interface 32. If at block 106 the calculated super heat is greater than the high super heat threshold, the method moves to block 108 where the generator speed reference is increased. Such increase, for example, may be an incremental increase (e.g., a predetermined step). Upon increasing the generator speed reference, the method moves to block 102 and repeats.

Moving back to block 106, if the calculated refrigerant super heat is not greater than the high super heat threshold, the method moves to block 110 where the calculated refrigerant super heat is compared to a low super heat

threshold. Like the high super heat threshold, the low super heat threshold may be stored in memory of the control unit 30 and/or settable via user interface 32. If the calculated refrigerant super heat is less than the low super heat threshold, the method moves to block 114 where the generator speed reference is decreased, for example, by a predetermined step. The method then moves back to block 102 and repeats.

Moving back to block 112, if the calculated refrigerant super heat is not less than the low super heat threshold, the method moves to block 116 where the generator speed reference is maintained at its present value. The method then moves back to block 102 and repeats.

Accordingly, by implementing the method illustrated in Fig. 9 the optimal energy from the system may be extracted while maintaining the refrigerant super heat at a desired value.

Referring briefly to FIG. 10, this illustrates another method for generating a speed reference for the generator 22. The method of FIG. 10 is similar to the method of FIG. 9 and therefore only the differences will be discussed.

The method of FIG. 10 generates a speed reference for the generator 22 based on refrigerant pressure. Thus, at block 202 the refrigerant pressure is determined, for example, from a measurement made by pressure sensor 34. The remainder of the method in FIG. 10 is the same as that of FIG. 9 except that the high and low thresholds correspond to refrigerant pressure instead of refrigerant super heat.

Referring now to FIG. 11, illustrated is a control block diagram 300 showing a simple speed regulator 302 for regulating the speed of the generator

22, and a speed reference generator 304 for generating the speed reference used by the speed regulator 302.

The speed reference generator 304 creates a speed reference in a manner similar to that described in FIGS. 9 and 10. However, instead of incrementing/decrementing the speed reference signal the regulator of Fig. 11 implements a proportional-plus-integral (PI) controller to provide enhanced operation. For example, a refrigerant super heat setpoint or a refrigerant pressure setpoint may be entered at block 306, for example, by a user through the user interface 32. In this regard, the user may simply type in the desired refrigerant super heat setpoint or refrigerant pressure setpoint using a keypad, touch screen, or the like on the user interface 32. The actual refrigerant super heat or refrigerant pressure may be determined at block 308 as described with respect to FIGS. 9 and 10, e.g., by pressure and/or temperature measurement of the refrigerant using pressure and temperature sensors 34 and 36. An error signal then is calculated at the output of summing junction 310 based on the difference between the refrigerant setpoint value and the refrigerant feedback value. The error signal is provided to a proportional-plus-integral (PI) controller 312, which outputs a speed reference signal for the generator 22 based on a combination of a proportional component and an integral component. In this regard, the PI controller 312 may apply a proportional gain Kp to the error signal to generate the proportional component, and an integral gain Ki to an integrator that integrates the error signal to generate the integral component. While a PI controller is illustrated, other types of controllers may be implemented without departing from the scope of the invention.

The generator speed reference as output by the speed reference generator 304 is provided to the speed regulator 302 at block 314. The speed regulator 302 operates in a manner similar to that of the speed reference generator 304. In this regard, a speed feedback signal is determined at block 316, for example, based on a speed feedback device coupled to the shaft 48 of the generator 22. The speed feedback device may be a tachometer, an encoder, a resolver, or any other device that may be used to provide data indicative of generator speed. While use of a speed feedback device is discussed, other methods of determining the speed may be used without departing from the scope of the invention. For example, the speed of the generator may be inferred based one or more of measured generator voltage, field current, generator frequency, etc.

An error signal is provided at the output of summing junction 318 based on a difference between the speed reference signal and the speed feedback signal. The error signal from the summing junction 318 then is provided to PI controller 320, which generates, for example, a current reference signal based on a combination of a proportional component and an integral component as discussed above with respect to the speed reference generator 304. The current reference signal at block 322 then is provided to the drive controller 23. The drive controller 23 regulates the current output of the generator 22 based on the provided current reference signal. In this regard, the current (and thus the load on the generator 22) is varied to regulate the desired parameter (e.g., refrigerant super heat, refrigerant pressure, flow, etc.) while recovering energy from the system.

While only selected embodiments have been chosen to illustrate the present invention, it will be apparent to those skilled in the art from this disclosure that various changes and modifications can be made herein without departing from the scope of the invention as defined in the appended claims. For example, the size, shape, location or orientation of the various components can be changed as needed and/or desired. Components that are shown directly connected or contacting each other can have intermediate structures disposed between them.

The functions of one element can be performed by two, and vice versa. The structures and functions of one embodiment can be adopted in another embodiment. It is not necessary for all advantages to be present in a particular embodiment at the same time. Every feature which is unique from the prior art, alone or in combination with other features, also should be considered a separate description of further inventions by the applicant, including the structural and/or functional concepts embodied by such features. The terms of degree such as "substantially", "about" and "approximately" as used herein mean a reasonable amount of deviation of the modified term such that the end result is not significantly changed. Thus, the foregoing descriptions of the embodiments according to the present invention are provided for illustration only, and not for the purpose of limiting the invention as defined by the appended claims and their equivalents.

CLAIMS

1. A refrigeration system comprising:

at least one evaporator;

at least one compressor fluidly connected to the at least one evaporator to compress low-pressure refrigerant vapor exiting the at least one evaporator to high-pressure vapor refrigerant;

at least one high-side heat exchanger fluidly connected to the at least one compressor to receive the high pressure refrigerant vapor and dissipate heat therefrom;

an energy recovery device configured to extract work from the high pressure refrigerant flowing therethrough, the energy recovery device including a gear expander, a generator and a controller,

the gear expander having a fluid inlet, a fluid outlet in fluid communication with the fluid inlet, and a mechanical power output for outputting mechanical power created by fluid passing between the fluid inlet and fluid outlet, the fluid inlet arranged between a high pressure output of the at least one compressor and an inlet of the at least one evaporator,

the generator mechanically coupled to the gear mechanical power output and operative to convert mechanical power produced by the gear to electrical power, and

the controller operatively coupled to the generator, the controller configured to regulate a speed of the generator to control electrical power produced by the generator.

2. The system as set forth in claim 1, wherein the controller is configured to regulate a load placed on the gear expander based on at least one of refrigerant mass flow or refrigeration cycle control.

3. The system according to any one of claims 1-2, where the controller is configured to control parameters of the refrigeration cycle.

4. . The system according to any one of claims 1-3 , wherein the controller is configured to regulate the speed of the generator based on at least one of refrigerant superheat, hot gas flow from the compressor discharge, flash gas separation, flash gas cooling, or evaporator defrost.

5. The system as set forth in any one of claims 1-4, wherein the controller is configured to control a flow rate of high pressure vapor refrigerant exiting the at least one high-side heat exchanger and entering the energy recovery device based on at least one of pressure and temperature of the refrigeration system.

6. The system as set forth in any one of claims 1-5, wherein the gear expander fluid inlet is fluidly connected to an outlet of the at least one high-side heat exchanger to receive high pressure refrigerant exiting the at least one high-side heat exchanger, and the gear expander fluid outlet is fluidly connected to an inlet of the at least one evaporator to deliver low pressure refrigerant thereto.

7. The system as set forth in any one of claims 1-5, wherein the gear expander fluid inlet is fluidly connected to an outlet of the at least one compressor to receive high pressure vapor refrigerant exiting the at least one compressor, and the gear expander fluid outlet is fluidly connected to an inlet or an outlet of the at least one evaporator.

8. The system as set forth in any one of claims 1-5, wherein the gear expander fluid inlet is fluidly connected to an outlet of the at least one high-side heat exchanger, and a gear expander fluid outlet is fluidly connected to an inlet of a flash gas separator or directly to the at least one evaporator.

9. The system as set forth in any one of claims 1-8, wherein the controller is configured to regenerate electrical power produced by the generator to an AC or DC electrical bus.

10. The system as set forth in any one of claims 1-9, wherein the controller comprises a variable speed drive controller.

11. The system according to any one of claims 1-10 wherein the generator is hermetically sealed.

12. The system as set forth in any one of claims 1-11, wherein a chamber of the gear expander includes an inner rotor and an outer rotor, a rotation axis of the inner rotor being offset from a rotation axis of the outer rotor such that

rotational movement of the outer rotor drives the inner rotor, the inner rotor defining the output of the gear expander.

13. The system as set forth in claim 12, wherein the energy recovery device further includes a rotatable shaft connected to the inner rotor of the gear expander.

14. The system as set forth in claim 13, wherein the rotatable shaft of the energy recovery device is configured and arranged to extract work from rotational movement of the inner rotor.

15. The system as set forth in any one of claims 13-14, wherein the inner rotor rotates the rotatable shaft in a first direction about a center rotational axis of the rotatable shaft in response to at least one of a phase change or a pressure change of the flow of a refrigerant from the high pressure refrigerant at the inlet to the low pressure refrigerant at the outlet.

16. The system as set forth in any one of claims 12-15, wherein the energy recovery device further includes a rotatable shaft connected to the outer rotor of the gear expander.

17. The system as set forth in claim 16, wherein the rotatable shaft of the energy recovery device is configured and arranged to extract the work from rotational movement of the outer rotor.

18. The system as set forth in any one of claims 16-17, wherein the outer rotor rotates the rotatable shaft in a first direction about a center rotational axis of the rotatable shaft in response to at least one of a phase change or a pressure change of the flow of a refrigerant from the high pressure refrigerant at the inlet to the low pressure refrigerant at the outlet.

19. The system as set forth in any one of claims 1-18, further comprising a control unit operatively connected to the controller, wherein control of the generator is performed in at least one of the control unit or the controller.

20. The system according to any one of claims 1-19, wherein the gear expander comprises ceramic components.

21. The system according to claim 20, wherein the outer rotor and the inner rotor of the gear expander are formed from ceramic material.

22. The system according to any one of claims 1-21, wherein components of the gear expander comprise friction-reducing coatings.

23. A method for recovering energy from a refrigeration system that includes at least one evaporator, at least one compressor fluidly connected to the at least one evaporator to compress low-pressure refrigerant vapor exiting the at least one evaporator to high-pressure vapor refrigerant, at least one high-side heat

exchanger fluidly connected to the at least one compressor to receive the high pressure refrigerant vapor and dissipate heat therefrom, an energy recovery device configured to extract work from the high pressure refrigerant flowing therethrough, the energy recovery device including a gear expander, a generator and a controller, the gear expander having a fluid inlet, a fluid outlet in fluid communication with the fluid inlet, and a mechanical power output for outputting mechanical power created by fluid passing between the fluid inlet and fluid outlet, the fluid inlet arranged between a high pressure output of the at least one compressor and an inlet of the at least one evaporator, the generator mechanically coupled to the gear mechanical power output and operative to convert mechanical power produced by the gear to electrical power, the method comprising regulating, via the controller, a speed of the generator to control electrical power produced by the generator.

24. The method as set forth in claim 23, wherein regulating includes regulating a load placed on the gear expander based on at least one of refrigerant mass flow or refrigeration cycle control.

25. The method according to any one of claims 23-24 , wherein regulating includes regulating the speed of the generator based on at least one of refrigerant superheat, hot gas flow from the compressor discharge, flash gas separation, flash gas cooling, or evaporator defrost.

26. The method as set forth in any one of claims 23-25, wherein regulating includes controlling a flow rate of high pressure vapor refrigerant exiting the at least one high-side heat exchanger and entering the energy recovery device based on at least one of pressure change or pressure and temperature of the refrigeration system.

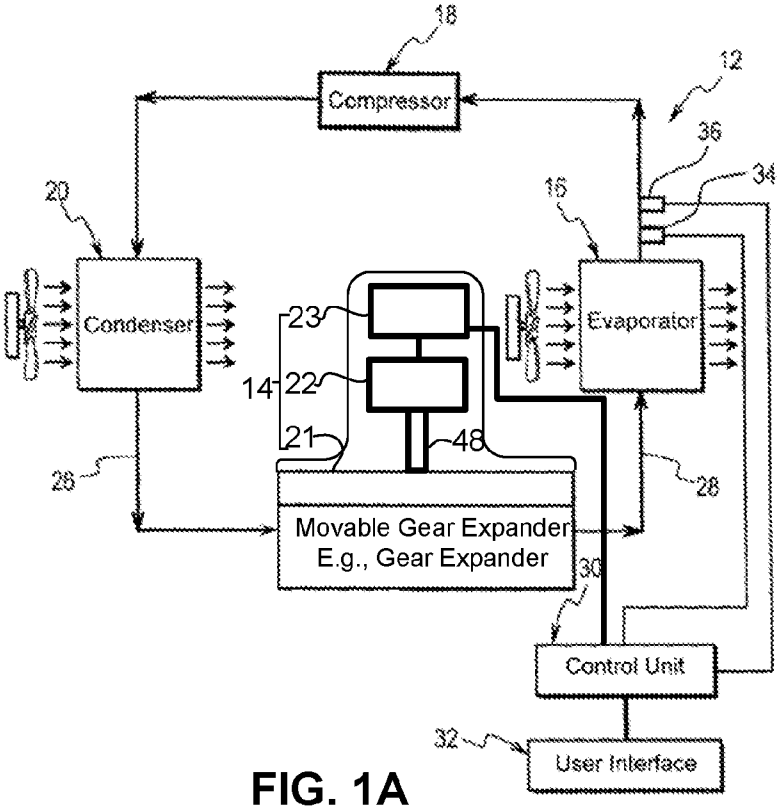

18
Compressor
12
36
34
20
16
Condenser
Evaporator
23
14
22
21
48
26
28
Movable Gear Expander
E.g., Gear Expander
30
Control Unit
32
User Interface

FIG. 1A

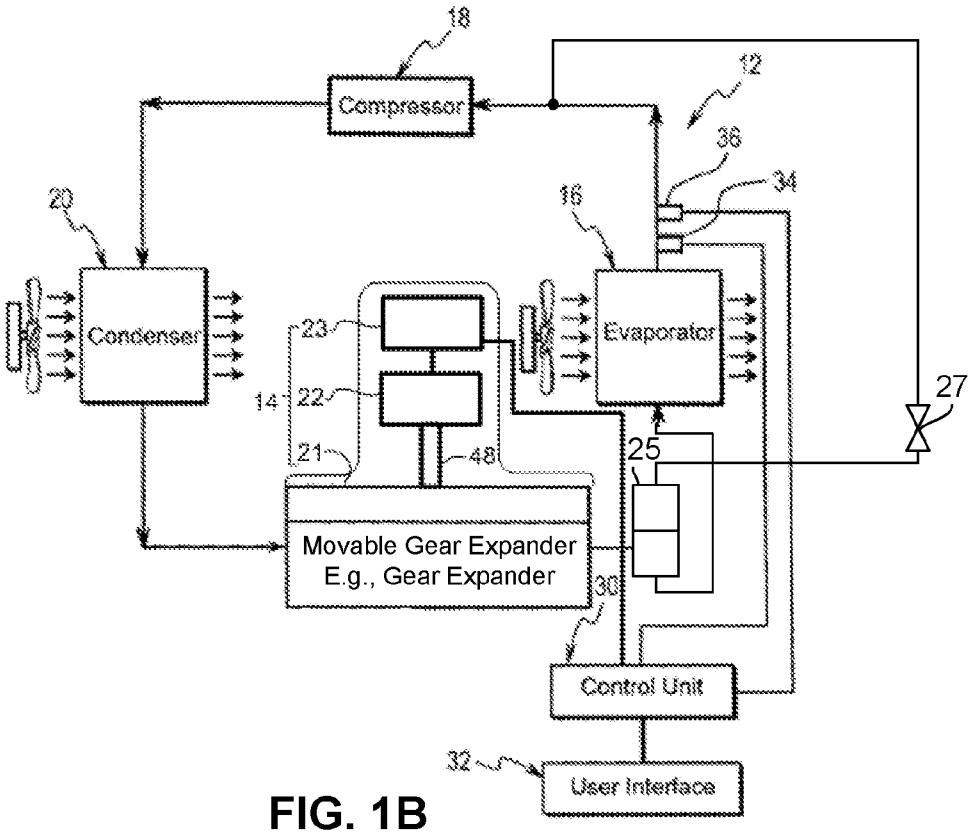

18
Compressor
12
36
34
20
16
Condenser
Evaporator
23
14
22
21
48
27
25
Movable Gear Expander
E.g., Gear Expander
30
Control Unit
32
User Interface

FIG. 1B

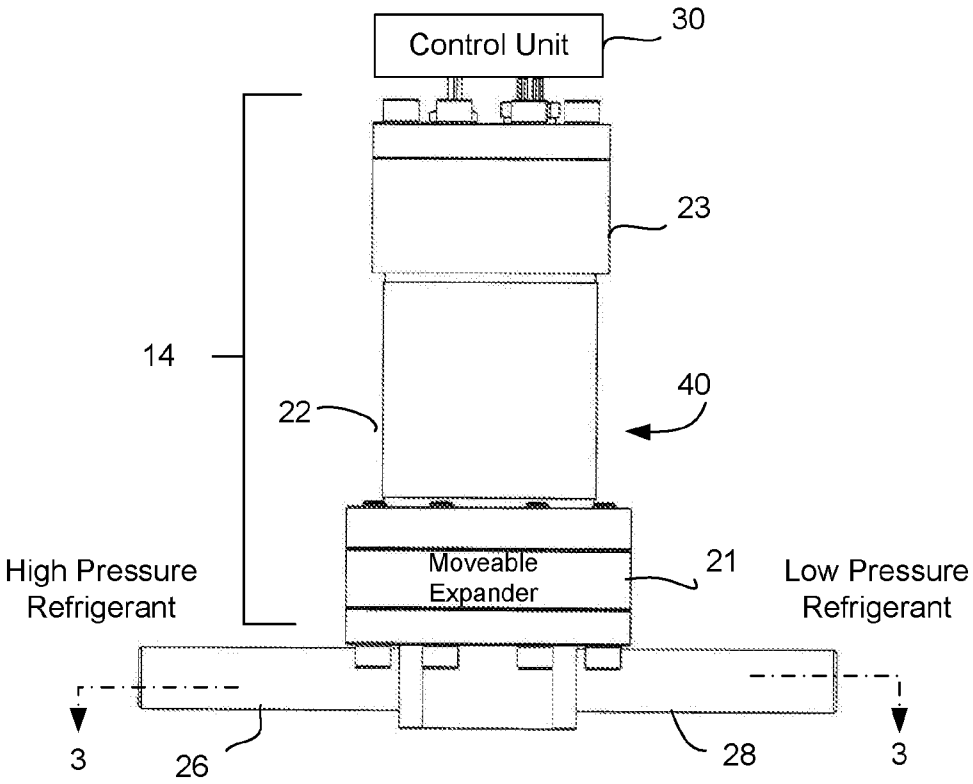

Control Unit
30
23
14
40
22
21
Moveable
Expander
High Pressure
Refrigerant
Low Pressure
Refrigerant
3
26
28
3

FIG. 2

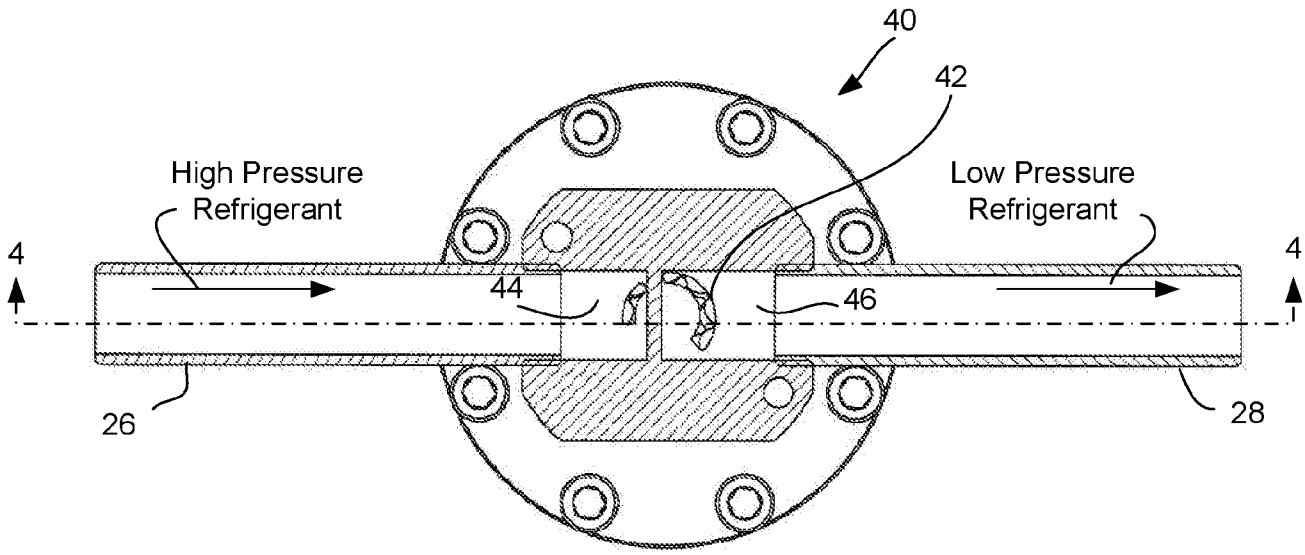

40
42
High Pressure
Refrigerant
Low Pressure
Refrigerant
4
44
46
4
26
28

FIG. 3

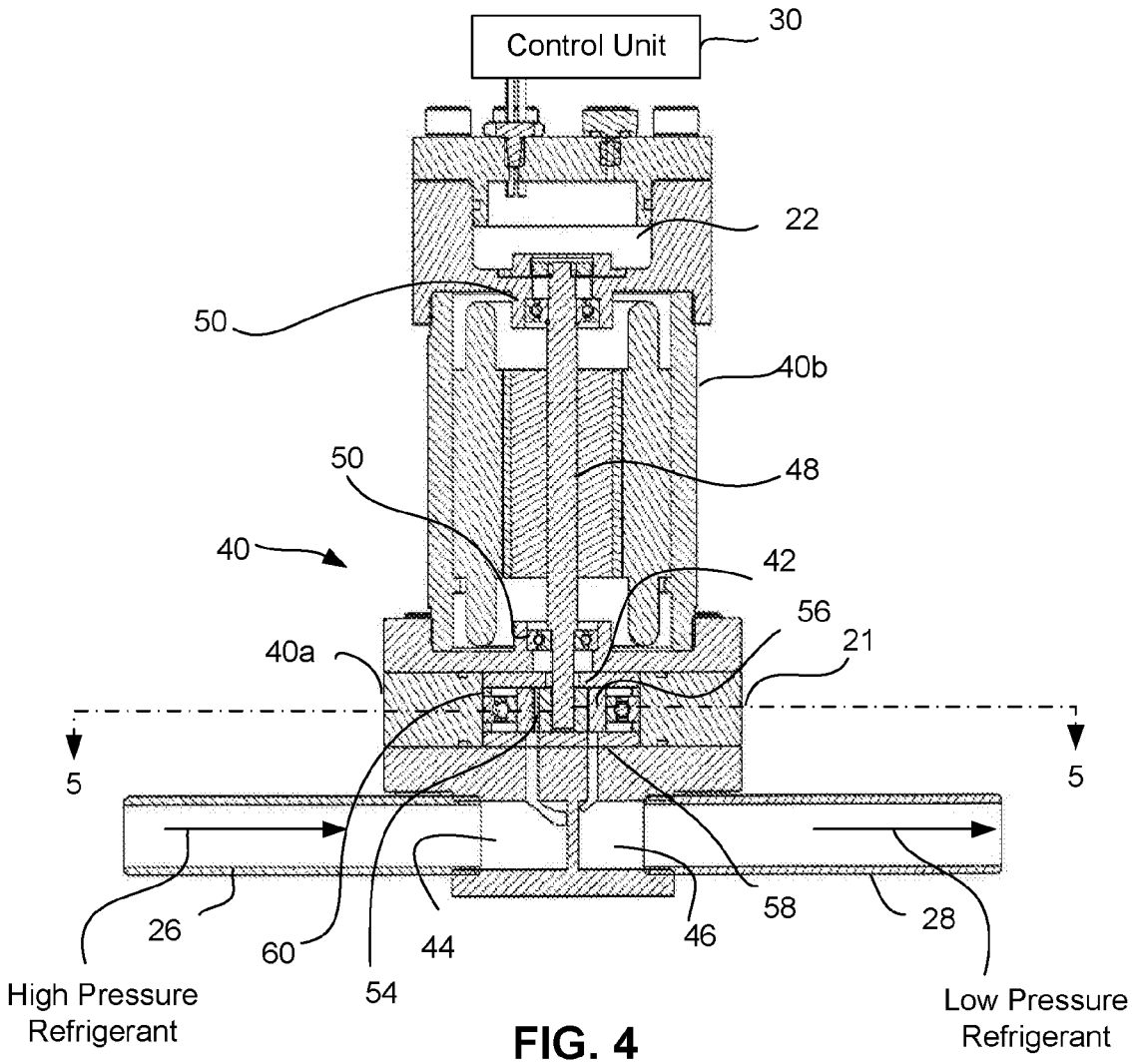

Control Unit
30
22
50
40b
50
48
40
42
56
21
40a
5
5
26
60
54
44
46
58
28
High Pressure
Refrigerant
Low Pressure
Refrigerant

FIG. 4

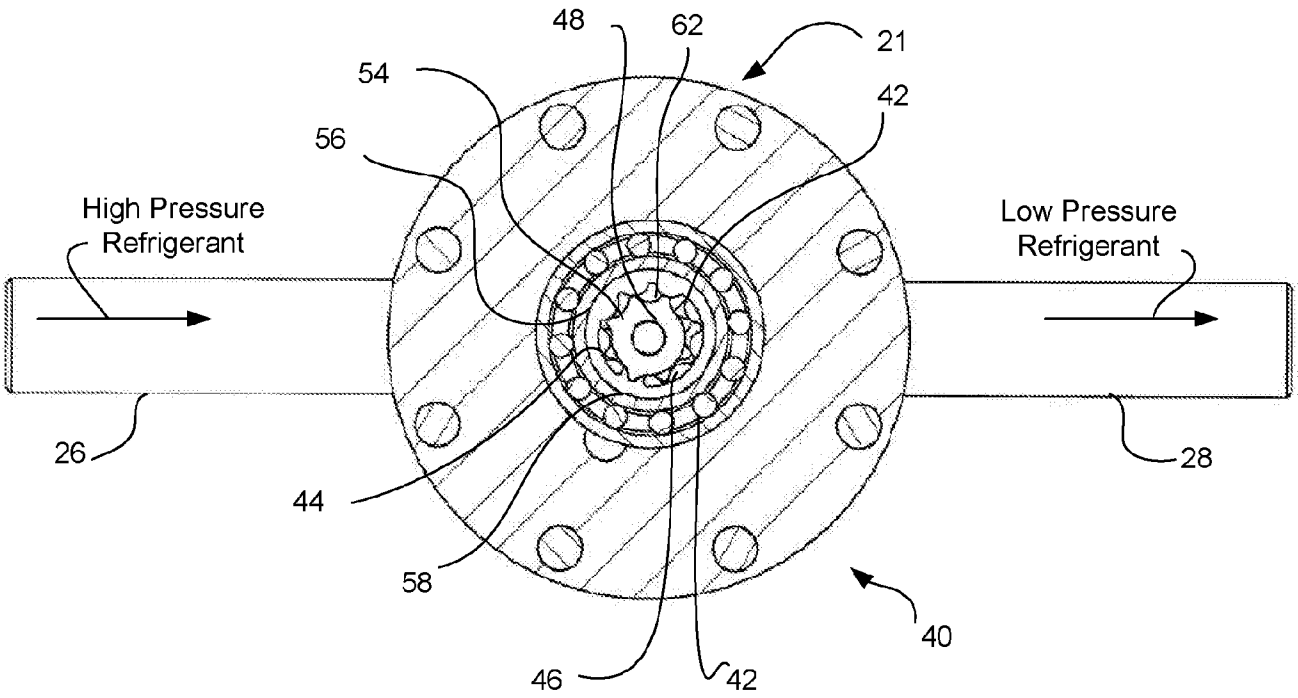

48
62
21
54
42
56
High Pressure
Refrigerant
Low Pressure
Refrigerant
26
28
44
58
40
46
42

FIG. 5

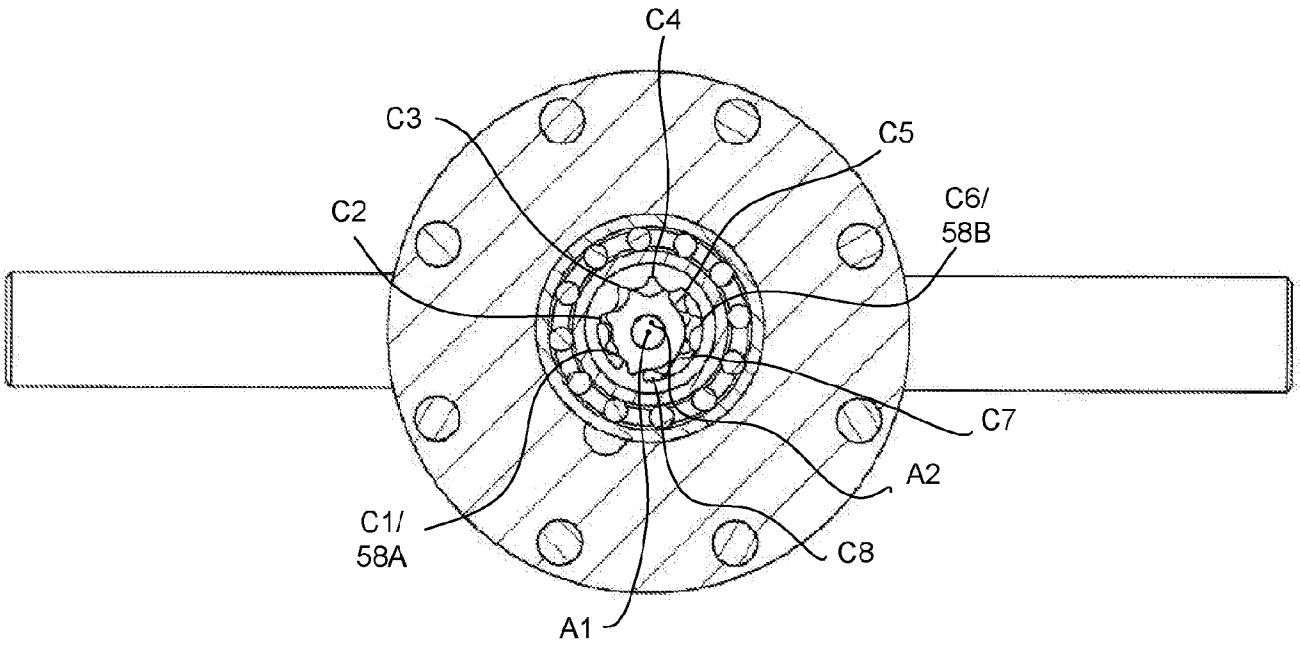

C4
C3
C5
C2
C6/
58B
C7
A2
C1/
58A
C8
A1

FIG. 6

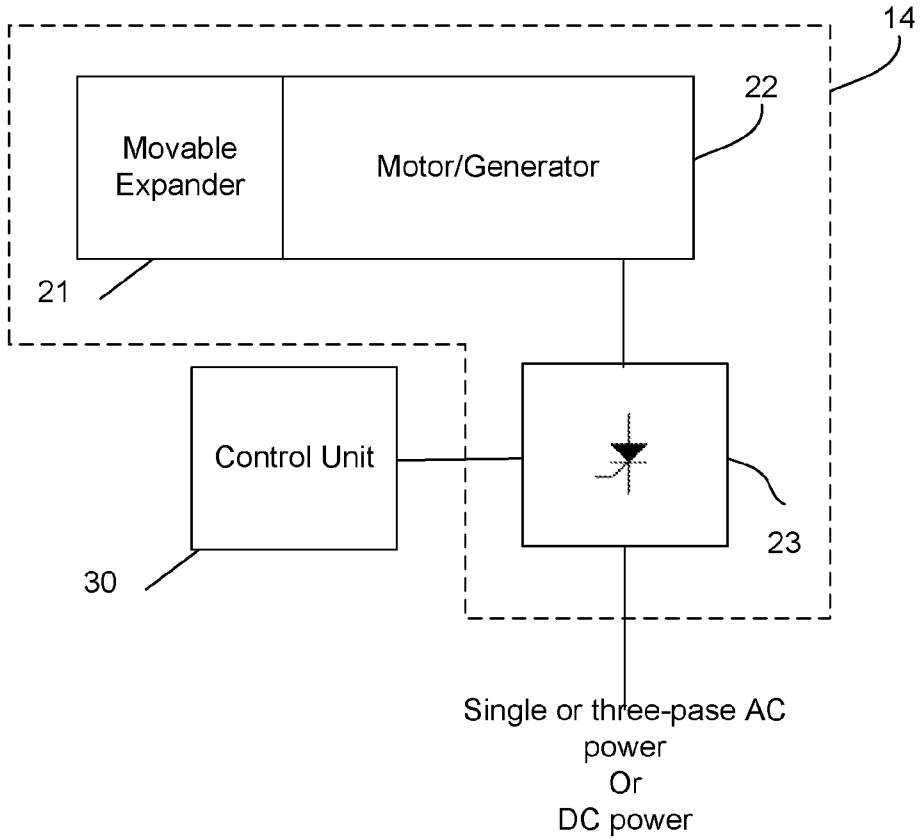

14
22
Movable Expander
Motor/Generator
21
Control Unit
23
30
Single or three-pase AC power
Or
DC power

FIG. 7

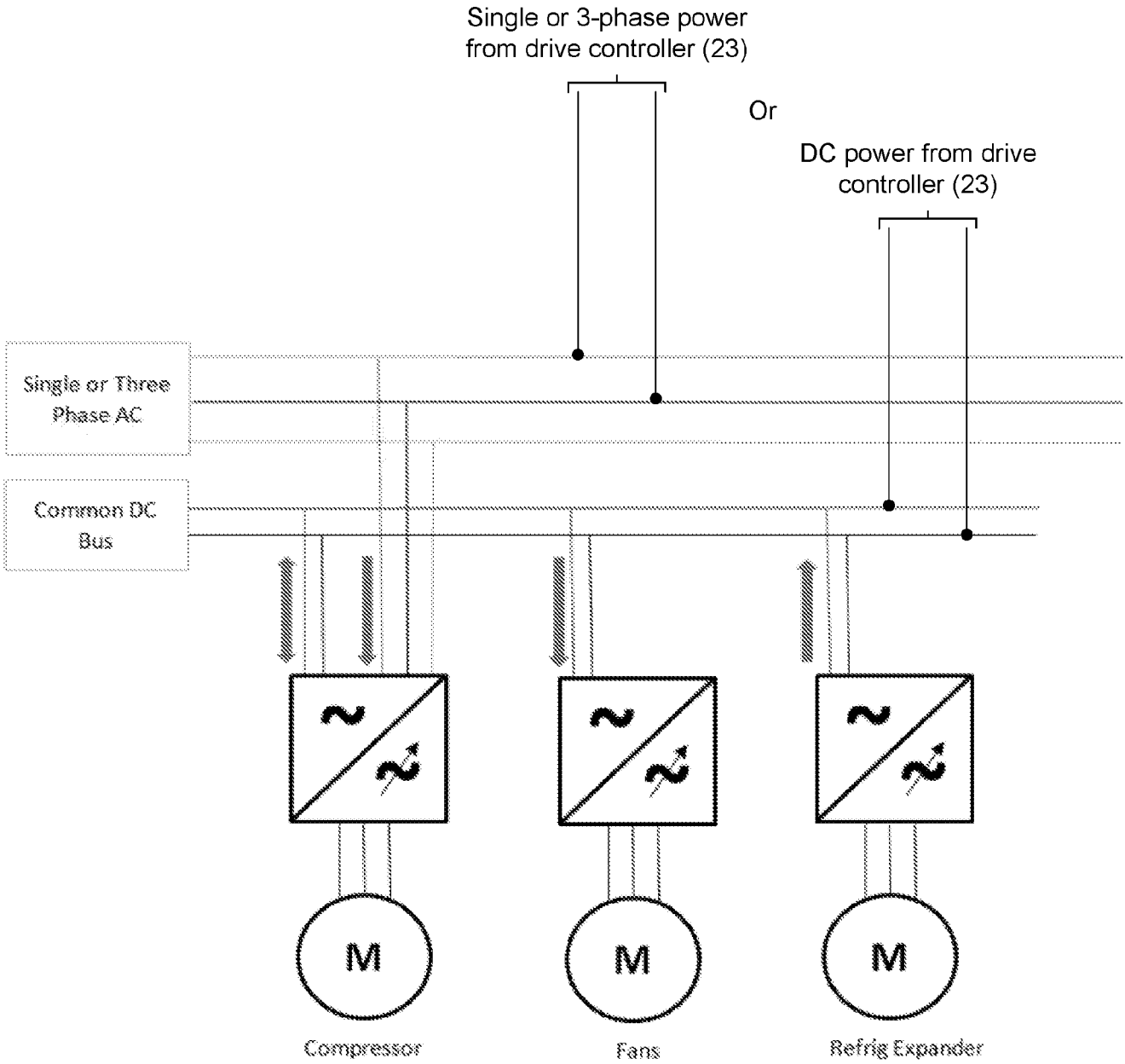

Single or 3-phase power
from drive controller (23)
Or
DC power from drive
controller (23)
Single or Three
Phase AC
Common DC
Bus
M
M
M
Compressor
Fans
Refrig Expander

FIG. 8

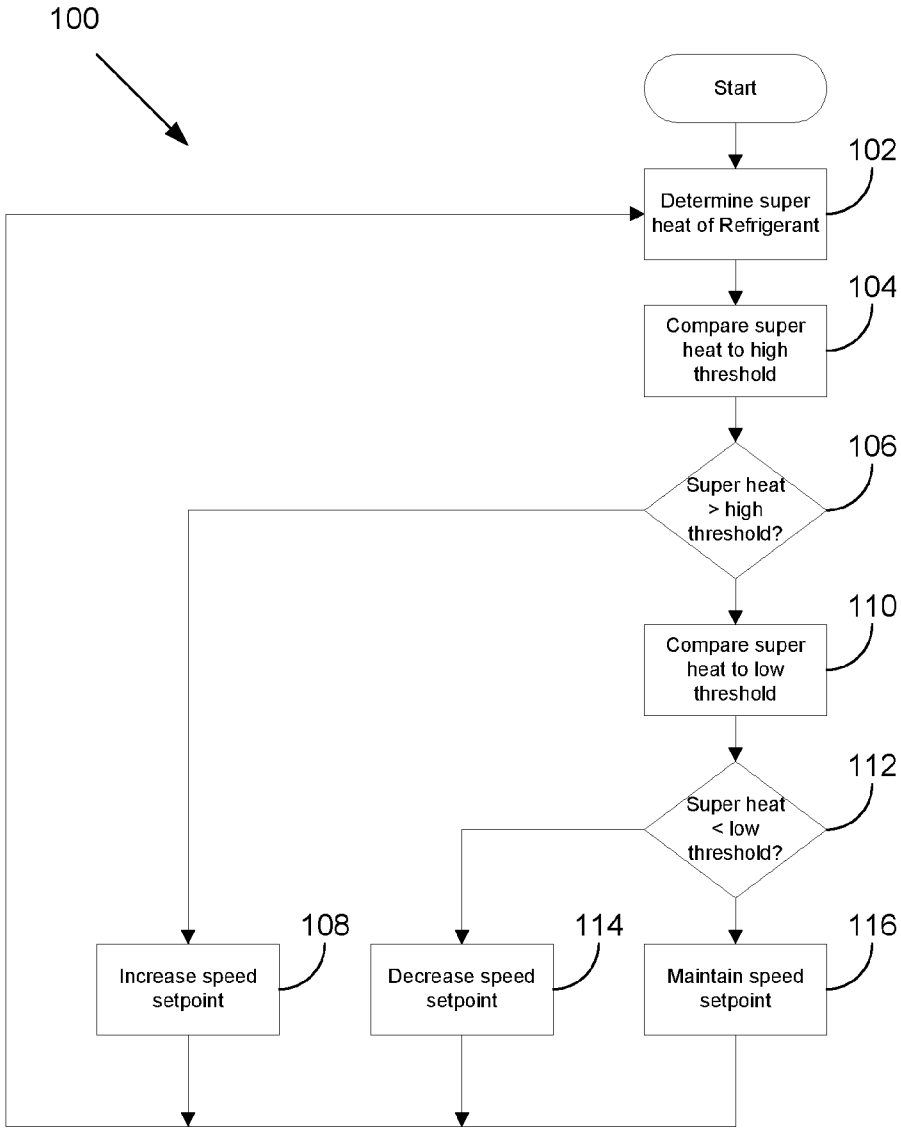

100
Start
102
Determine super heat of Refrigerant
104
Compare super heat to high threshold
106
Super heat > high threshold?
110
Compare super heat to low threshold
112
Super heat < low threshold?
108
Increase speed setpoint
114
Decrease speed setpoint
116
Maintain speed setpoint

FIG. 9

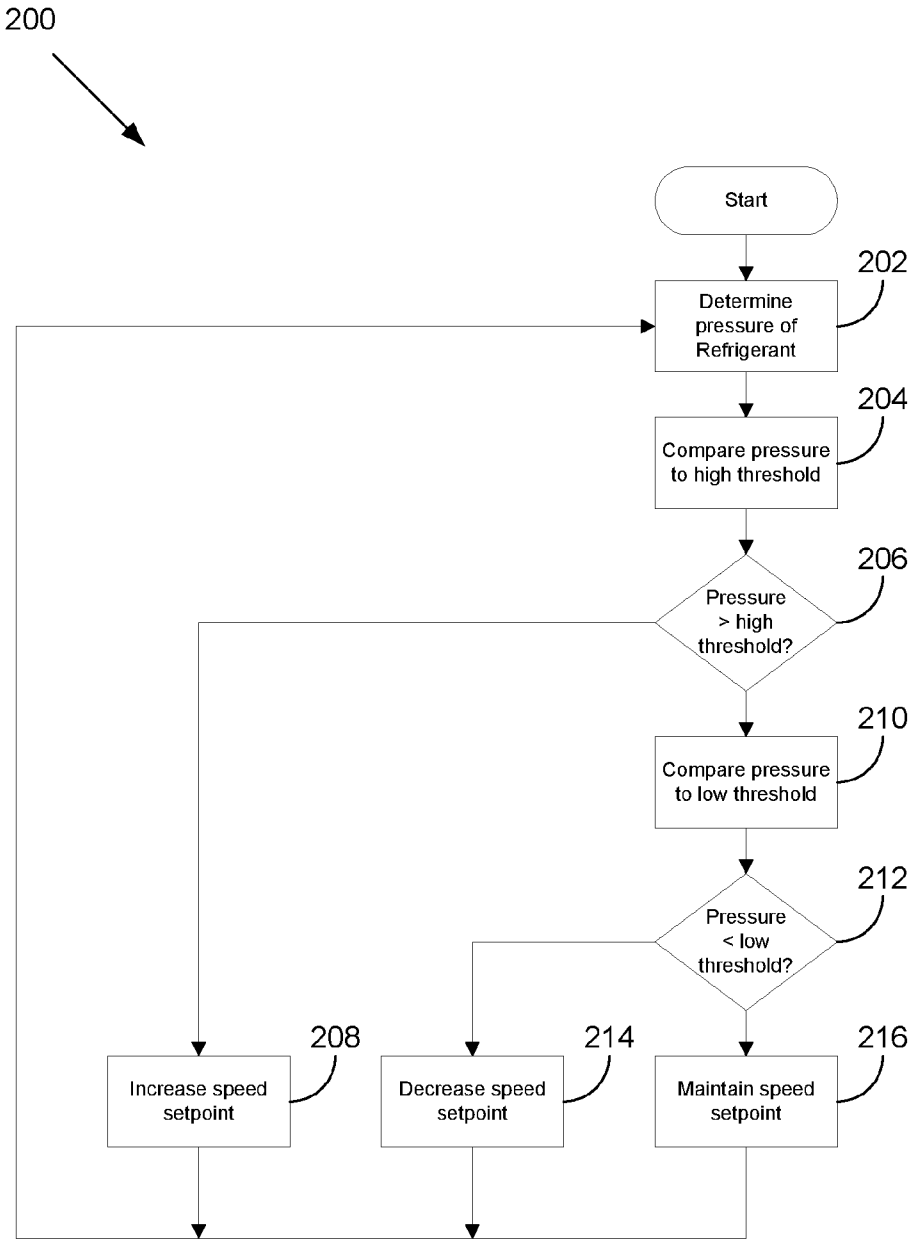

200
Start
202
Determine pressure of Refrigerant
204
Compare pressure to high threshold
206
Pressure > high threshold?
210
Compare pressure to low threshold
212
Pressure < low threshold?
208
Increase speed setpoint
214
Decrease speed setpoint
216
Maintain speed setpoint

FIG. 10

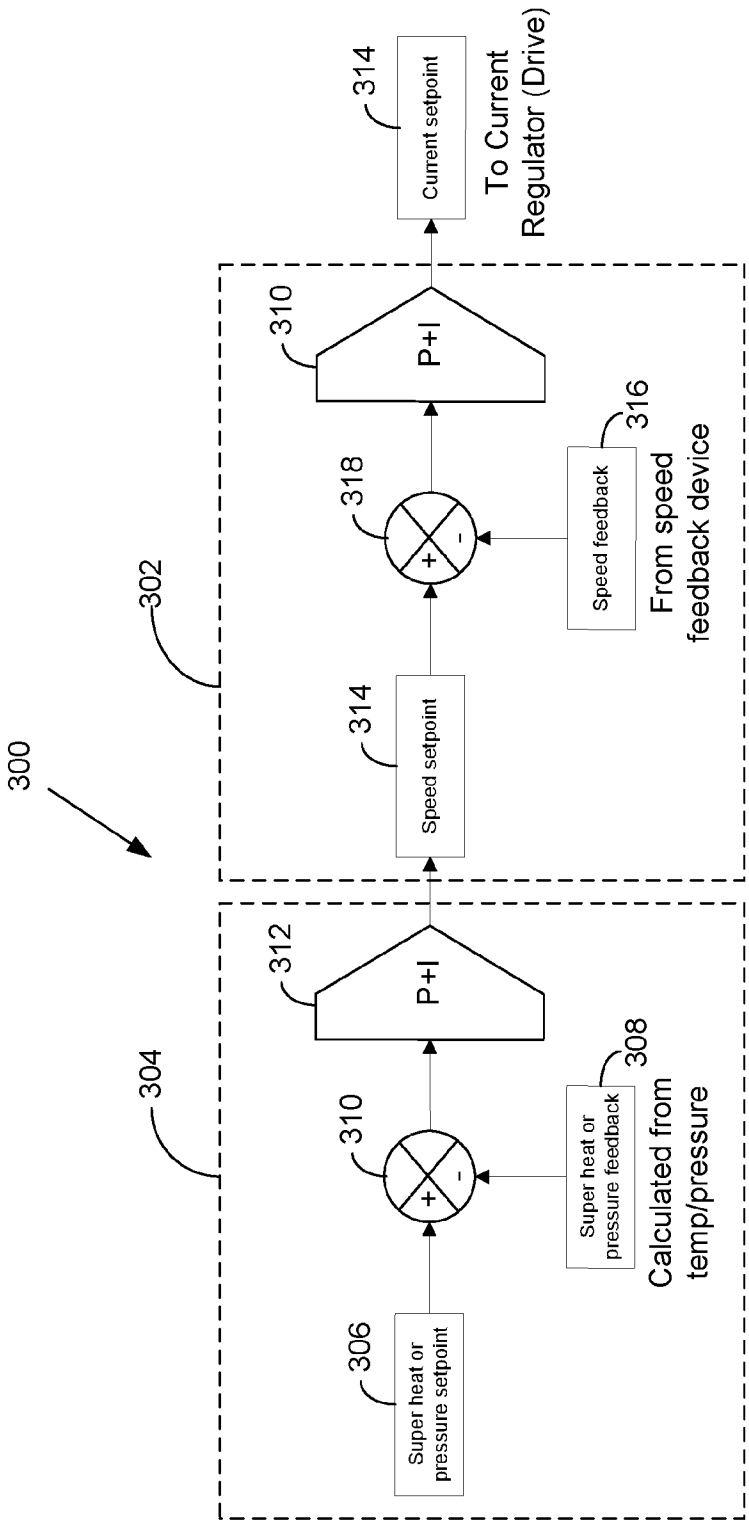

300
302
304
306
Super heat or pressure setpoint
308
Super heat or pressure feedback
Calculated from temp/pressure
310
312
P+I
314
Speed setpoint
316
Speed feedback
From speed feedback device
318
314
Current setpoint
To Current Regulator (Drive)

FIG. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2016/017647

A. CLASSIFICATION OF SUBJECT MATTER
INV. F25B11/02 F25B9/06
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F25B F01K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2000 249411 A (AISIN SEIKI) 14 September 2000 (2000-09-14) abstract; figures 1,2,7 paragraphs [0011], [0023] - [0027], [0052] - [0056]	1-26
X	US 2014/102098 A1 (BOWAN BRETT A [US] ET AL) 17 April 2014 (2014-04-17) paragraphs [0028], [0029], [0030], [0036], [0037], [0049]; figure 1	1-5,7-26
X	US 2014/083098 A1 (DAVIDSON CHAL S [US] ET AL) 27 March 2014 (2014-03-27) paragraphs [0037], [0057], [0111]; figure 1	1-26

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 April 2016	02/05/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Ritter, Christoph

1

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2016/017647

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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X	WO 2006/120819 A1 (MATSUSHITA ELECTRIC IND CO LTD [JP]; MATSUI KEIZO; MATSUYAMA TETSUYA) 16 November 2006 (2006-11-16) abstract; figures	1-3
A	WO 2013/141805 A1 (ENERGIHUSET FOERSAELJNINGS AB HARDY HOLLINGWORTH [SE]) 26 September 2013 (2013-09-26) the whole document	1-26
A	US 2010/251766 A1 (RAUCH JEREMIAH JAMES [US] ET AL) 7 October 2010 (2010-10-07) paragraphs [0034], [0036], [0037]; claim 1	1-26

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2016/017647

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