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- (71) **Applicant (for all designated States except US):** ENER-FUEL, INC. [US/US]; 1501 Northpoint Parkway, Suite 101, West Palm Beach, FL 33407 (US).
- (72) **Inventors; and**
- (75) **Inventors/Applicants (for US only):** BETTS, Daniel, Augusto [US/US]; 7643 NW 70th Ave., Parkland, FL 33067 (US). GAROZZO-VALENCIA, Gaelle, Laura [US/US]; 5505 N. Military Trl. #312, Boca Raton, FL 33496 (US). FUCHS, Michel [US/US]; 1019 Bedford Ave., Palm Beach Gardens, FL 33403 (US).
- (74) **Agents:** HILMERT, Laura, J. et al.; Armstrong Teasdale LLP, 7700 Forsyth Blvd., Suite 1800, St. Louis, MO 63105 (US).
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(54) **Title:** FUEL CELL-COUPLED HEATING AND REFRIGERATION SYSTEM

FIG. 1A

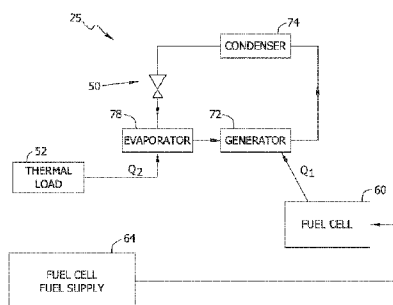
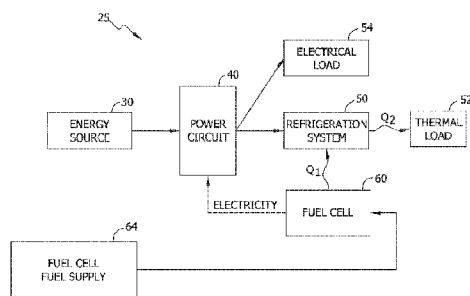


FIG. 1B



(57) **Abstract:** Disclosed are fuel cell coupled refrigeration systems and to the use of fuel cells to provide thermal energy to a refrigeration system. More particularly, a heat exchanger couples, directly or indirectly, to a fuel cell and a heat driven refrigeration system to transfer at least a portion of thermal energy generated by the fuel cell to the refrigeration system, thereby driving a refrigeration cycle of the refrigeration system.



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FUEL CELL-COUPLED HEATING AND REFRIGERATION SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present application claims the benefit of U.S. Provisional Patent Application Serial No. 61/492,318 filed on June 1, 2011, entitled "Fuel Cell Coupled Refrigeration System for Power, Heating and Cooling Applications", the entire disclosure of which is expressly incorporated by reference herein.

FIELD OF THE DISCLOSURE

[0002] The present disclosure relates to the use of a fuel cell, and in particular a proton exchange membrane (PEM) fuel cell, to power a heat driven refrigeration system for use in regulating the ambient temperature of an environment.

BACKGROUND OF THE DISCLOSURE

[0003] Heating and cooling systems of different types are commonly used to control ambient temperatures of internal spaces of buildings and vehicles and to cool refrigeration volumes such as transport trailers, refrigerators and freezers. Generally, heating and cooling systems consume electrical or mechanical energy to drive a heating and cooling cycle. Some systems, for example heat pumps, include valves adapted to switch the flow of refrigerant through heat exchangers, referred to as condensers and evaporators, so that the system can provide heating or cooling depending on the outdoor temperature. For convenience, systems configured to provide heating or cooling by changing the state of a fluid medium to transfer heat will be referred to as refrigeration systems.

[0004] Air cooling and vapor-compression are two common refrigeration systems. In air cooling systems, a fan or series of fans causes ambient air to flow over or through the target space. The air absorbs heat and transfers the heat to an external space. However, the cooling capacity depends on the air temperature of the ambient air, which can vary widely. As a result, air cooling may be unreliable, particularly in tropical and desert environments.

[0005] In a vapor-compression refrigeration system, the system transfers heat through a fluid refrigerant that is periodically cycled through a condenser and an evaporator. The cooling effect is provided when the refrigerant enters the evaporator, where the refrigerant's phase changes from a liquid-vapor mixture to a saturated-vapor at low pressure. The refrigerant then passes into a compressor where pressure of the refrigerant is increased as it is mechanically compressed and the refrigerant is transformed into a superheated-vapor. From the compressor, the refrigerant enters into the condenser where the heat picked up in the evaporator is rejected to the atmosphere, and the refrigerant changes back to a saturated-liquid. The refrigerant then returns to its initial liquid-vapor state after passing through an expansion valve. The energy input to drive the cycle is provided in the refrigerant compression stage. Vapor-compression systems are more reliable than air cooling systems but consume more energy and are generally heavier.

[0006] Accordingly, there is a need in the art for a more energy-efficient, effective means of powering refrigeration systems. It would be further advantageous if the thermal and electrical energy to be provided to a refrigeration system was provided at a highly efficient, consistent manner, with little to no gas emissions.

SUMMARY OF THE DISCLOSURE

[0007] The present disclosure is directed to a fuel cell coupled refrigeration system and to the use of fuel cells to provide thermal energy to a refrigeration system. For example, a heat exchanger couples, directly or indirectly, to a fuel cell and a heat driven refrigeration system to transfer at least a portion of thermal energy generated by the fuel cell to the refrigeration system, thereby driving a refrigeration cycle of the refrigeration system. In some embodiments, the heat exchanger may further be coupled with an electric heating device such to transfer at least a portion of the thermal energy generated by the electric heating device to the refrigeration system as an alternative or supplemental thermal energy source from the fuel cell.

[0008] In one embodiment the present disclosure is directed to a fuel cell coupled refrigeration system comprising: a fuel cell operable to generate thermal energy; a heat driven refrigeration system comprising a refrigerant for being driven

through a refrigeration cycle; and a heat exchanger thermally coupled to the fuel cell to receive at least a portion of the thermal energy to drive the refrigeration cycle of the refrigeration system.

[0009] In another embodiment the present disclosure is directed to a heat exchanger for a heat driven refrigeration system. The heat exchanger comprises: a generator comprising an inlet fluidly coupled to an outlet, the inlet adapted to receive a refrigeration fluid at an inlet temperature and the outlet adapted to discharge the refrigeration fluid at a discharge temperature greater than the inlet temperature; and a fuel cell thermally coupled to the generator, the fuel cell adapted to heat the generator and the refrigeration fluid circulating therein.

[0010] In another embodiment the present disclosure is directed to a method of driving a refrigeration cycle of a heat driven refrigeration system to cool an ambient environment. The method comprises: heating a refrigerant using thermal energy produced by a fuel cell to form a heated refrigerant gas having a pressure higher than the refrigerant prior to heating; and cooling the heated refrigerant gas in a condenser to form a liquid refrigerant having a pressure lower than the heated refrigerant gas, wherein the heated refrigerant gas absorbs heat from the ambient environment as it is cooled.

[0011] It has been unexpectedly discovered that using thermal energy generated by fuel cells to drive refrigeration cycles of a refrigeration system provides both functional and financial benefits to the user, particularly homeowners. Particularly, the average energy output of the fuel cell is decreased as the electrical load of the HVAC system is decreased or eliminated, compared to the conventional electrically driven heating, ventilation, and air conditioning (HVAC) system, enabling a higher efficiency fuel cell operation. Note that fuel cell efficiency for a given fuel cell stack increases as its power level decreases. Further, surplus electrical energy generated by the fuel cell can additionally be used to power the electrical grid of a building or residence, providing alternative or supplemental electrical energy during periods when electrical costs are highest for utilities (e.g., summer months).

[0012] Accordingly, the fuel cell coupled refrigeration system of the present disclosure can be used as an upgrade or alternative to the conventional HVAC system, which is a high cost appliance, to provide for more energy-efficient heating and cooling.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The above-mentioned and other disclosed features, and the manner of attaining them, will become more apparent and will be better understood by reference to the following description of disclosed embodiments taken in conjunction with the accompanying drawings, wherein:

[0014] FIG. 1A is a block diagram of a fuel cell coupled refrigeration system including a fuel cell, a heat driven refrigeration system, and a heat exchanger according to one embodiment of the disclosure;

[0015] FIG. 1B is a block diagram of fuel cell coupled refrigeration system including a fuel cell, a heat driven refrigeration system, a heat exchanger, and an additional energy source according to one embodiment of the disclosure;

[0016] FIG. 2 is a schematic diagram depicting an absorption refrigeration system thermally coupled with a fuel cell according to yet another embodiment of the disclosure;

[0017] FIG. 3 is a schematic diagram depicting the fuel cell coupled refrigeration system of FIG. 2 thermally coupled with an air pump directing excess heat to a heat load according to another embodiment of the disclosure;

[0018] FIG. 4 is a schematic diagram depicting a vapor-compression refrigeration system thermally coupled to a liquid cooled fuel cell with an auxiliary cooling system according to a yet further embodiment of the disclosure;

[0019] FIG. 5 is a schematic diagram depicting an absorption refrigeration system thermally coupled to a fuel cell and an auxiliary liquid cooling system according to a further embodiment of the disclosure;

[0020] FIG. 6 is a schematic diagram depicting the ejector refrigeration system fluidly coupled to a fuel cell according to yet another embodiment of the disclosure;

[0021] FIG. 7 is a schematic diagram depicting a compressor fluidly coupled to a fuel cell coupled refrigeration system according to another embodiment of the disclosure;

[0022] FIG. 8 is a schematic diagram depicting a vapor-compression refrigeration system thermally coupled to a fuel cell and an auxiliary cooling system according to a further embodiment of the disclosure;

[0023] FIG. 9 is a schematic diagram depicting an absorption refrigeration system thermally coupled to a liquid cooled fuel cell with an auxiliary liquid cooling system according to a yet further embodiment of the disclosure;

[0024] FIG. 10 is a block diagram of a fuel cell coupled refrigeration system including a heat driven refrigeration system, a fuel cell and a battery cell stack according to another embodiment of the disclosure; and

[0025] FIGS. 11 and 12 are block diagrams of a fuel cell coupled refrigeration system in a mobile application according to a further embodiment of the disclosure, further including heating and cooling devices.

[0026] Corresponding reference characters indicate corresponding parts throughout the several views. Although the drawings represent embodiments of various features and components according to the present disclosure, the drawings are not necessarily to scale and certain features may be exaggerated in order to better illustrate and explain the present invention. The exemplification set out herein illustrates embodiments of the disclosure, and such exemplifications are not to be construed as limiting the scope of the invention in any manner.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0027] The present disclosure is directed to a fuel cell coupled refrigeration system and a method in which thermal energy from the fuel cell is applied to the

refrigeration system. Thermal energy generated by the fuel cell can be used to drive a refrigeration cycle of the refrigeration system in an energy-efficient operation as an alternative or as a supplement to conventional electrically driven refrigeration systems. Exemplary refrigeration systems include absorption and ejector refrigeration systems. The fuel cell coupled refrigeration systems of the present disclosure can further be used with vapor-compression refrigeration systems to provide sole or supplemental thermal energy to drive the system.

[0028] These and other features of the fuel cell coupled refrigeration systems and methods of the present disclosure, as well as some of the many optional variations and additions, are described in detail hereafter.

[0029] As used herein, the term “heat driven refrigeration system” refers to a heating and cooling refrigeration cycle that eliminates the need for a mechanical compressor and instead uses a thermal energy source to drive the cycle. Exemplary heat driven refrigeration systems include absorbent and ejector refrigeration systems.

[0030] As used herein, the term “refrigeration cycle” refers to a model of moving heat from one location (“source”) at a lower temperature to another location (“heat sink”) at a higher temperature using mechanical work or thermal work.

[0031] As used herein, the term “thermal load” refers to any component or device suitable to supply or receive heat. Exemplary thermal loads include electronic components, passenger cabins, battery compartments, electronic circuits, storage compartments, ice makers, dehumidifiers, and the like. The foregoing and later described embodiments describe heat transfer devices which may be referred to as heat exchangers (e.g., evaporators, condensers and generators).

[0032] As used herein, the term “generator” refers to a heat transfer device which thermally couples, directly or indirectly, a refrigeration system and a fuel cell such that excess heat from the fuel cell may heat the refrigerant of the refrigeration system. In one embodiment according to the disclosure, a generator includes a body. Embedded in the body are a refrigerant circuit and a heating device. The heating device is configured to heat the refrigerant in the refrigerant circuit. The body may comprise a number of integrated components. A fuel cell coupled refrigeration

system may be referred to herein as a heat driven refrigeration system. Heat transfer devices may be liquid-to-liquid, gas-to-gas, surface-to-liquid and surface to gas heat transfer devices. Air is an exemplary gas.

[0033] As used herein, the term “evaporator” is a component that is thermally coupled, directly or indirectly, to a thermal load to remove heat therefrom.

[0034] The foregoing embodiments and additional embodiments of the disclosure will now be described with reference to the figures. Referring to FIG. 1A, a general embodiment of a fuel cell coupled refrigeration system 25 according to the disclosure includes a heat driven refrigeration system 50 thermally coupled to a thermal load 52 and to a fuel cell 60, and a fuel cell fuel supply 64. Excess heat from fuel cell 60 is applied, via heat exchanger (i.e., generator as shown in FIG. 1A) 72, to increase the temperature of a refrigerant (not shown) flowing in refrigeration system 50 and at least partially increases the pressure of the refrigerant. Refrigeration system 50 provides or removes thermal energy to or from thermal load 52 to heat or cool thermal load 52.

[0035] As shown in FIG. 1B, in some embodiments, an additional energy source 30, provides energy through power circuit 40 to one or both of refrigeration system 50 and electrical load 54. Exemplary additional energy sources include mechanical, direct current (DC) and alternating current (AC) energy sources. Exemplary mechanical power sources include belts and gears driven by engines, hydraulic turbines and other non-electrical sources of energy. Exemplary AC energy sources include generators and an AC power grid. Exemplary DC energy sources include energy storage devices, fuel cells and solar arrays.

[0036] For example, in one embodiment of the present disclosure, fuel cell coupled refrigeration system 25 is comprised in a building. Energy source 30 comprises an electrical power grid providing AC power to refrigeration system 50, in this case a vapor-compression refrigeration system, through power circuit 40.

[0037] In a reliability mode of operation, electrical energy produced by fuel cell 60 is supplied to refrigeration system 50 to operate refrigeration system 50 even if power from energy source 30 is unavailable. The DC energy from fuel cell 60 is

inverted into AC energy and the AC energy is supplied to refrigeration system 50. In another example, energy source 30 supplements the DC energy supplied from fuel cell 60 to operate refrigeration system 50.

[0038] In yet another example, fuel cell coupled refrigeration system is comprised in an electric vehicle and energy source comprises a mechanical energy source driving the compressor of a vapor-compression refrigeration system. In a further example, fuel cell coupled refrigeration system is comprised in an electric vehicle and refrigeration system comprises an absorption or ejection refrigeration system.

[0039] Typically the fuel cell coupled refrigeration systems of the present disclosure include heat driven refrigeration systems including absorption refrigeration and ejector refrigeration systems. Absorption refrigeration relies on the use of a liquid media (the “adsorbent”) such as water or lithium bromide that is capable of adsorbing a large amount of a refrigerant at low temperature and pressure. The refrigerant, for example ammonia, sulfur dioxide, water or a hydrocarbon as known in the art, passes through a condenser, an expansion valve and an evaporator in the same way as in the vapor-compression system described above. The compressor is replaced by an adsorber, a pump and a generator. As the refrigerant passes through the adsorber, it is adsorbed by the adsorbent and heat is released to the environment. The refrigerant and the adsorbent then enter a pump where the pressure of the mixture increases to the generator’s pressure. The mixture is heated in the generator to separate the high-pressure refrigerant from the adsorbent.

[0040] Ejector refrigeration is a thermally driven refrigeration cycle that also relies on heat input rather than mechanical means to drive the cycle. The ejector refrigeration system consists of two loops, the refrigeration loop and the power loop. In the power loop, the liquid refrigerant is pumped into a generator where an external heat source (e.g., fuel cell and/or electric heating device) vaporizes the refrigerant resulting in high pressure vapor called the primary fluid. The primary fluid expands through the ejector’s nozzle and increases its velocity. This creates a vacuum in the refrigeration loop which draws in the vapor from the evaporator called the secondary fluid. The secondary fluid enters the ejector’s diffuser where the velocity decreases

and the pressure recovers. The secondary fluid goes through a condenser where heat is rejected to the environment. The condensed liquid is partly pumped back to the generator completing the power loop. The remaining condensed liquid is drawn into an expansion valve where the pressure is lowered. The liquid enters the evaporator where the low pressure created by the primary fluid allows the secondary fluid to evaporate at very low temperature and thereby provide the cooling effect. The secondary fluid then enters the ejector completing the refrigeration cycle.

[0041] Referring to FIGS. 2-9, exemplary embodiments according to the disclosure of fuel cell coupled refrigeration systems are provided. Referring to FIG. 2, in one embodiment a fuel cell coupled refrigeration system 100 comprises an absorption system 400 including a heat exchanger 152, such as an evaporator having a heat receiving surface 416, coupled to a thermal load 402, an adsorber 424, a pump 428, at least one generator 430, 432, a condenser 440 and an expansion valve 442. The system 100 also comprises an exemplary fuel cell system, illustratively fuel cell 410, thermally coupled to generators 430 and 432. Heat output by fuel cell 410 provides thermal energy to generators 430 and 432 to drive the refrigeration cycle of absorption system 400 as described above.

[0042] In one embodiment, an electric heating device 220 drives the refrigeration cycle when fuel cell 410 does not generate sufficient heat to do so. An additional unexpected advantage of coupling the electric heating device 220 and fuel cell 410 is that this allows decoupling of the thermal and electrical loads from the fuel cell. That is, when a separate electrical load provides electrical energy to electric heating device 220, heat produced from electric heating device 220 combines with heat produced by fuel cell 410 to drive the refrigeration cycle. When no separate electrical load is provided, however, electrical energy produced by fuel cell 410 can drive electric heating device 220, while heat produced from fuel cell 410 may still be used to drive the refrigeration cycle. It should be recognized that although described herein as an electric heating device, any other heating device as known in the refrigeration art can be used as a supplemental or alternative thermal energy source to the fuel cell for providing heat to drive the refrigeration cycle.

[0043] Generators 430 and 432 may be manufactured applying known heat exchange principles based on contact surface and fluid flow control to maximize the transfer of heat generated by fuel cell 410 to the fluid mixture circulating through the generator to cause the mixture to separate into its absorbent and refrigerant constituents. Another method of achieving heat transfer may be through boiling or phase change heat transfer in the generator 430, 432. Heat is transferred by heat transfer surface 416 from thermal load 402 and evaporated by the heat exchanger (evaporator) 152 thereby cooling thermal load 402.

[0044] In one embodiment (not shown), fuel cell 410 also functions as a heat source for a heat load in addition to heating generators 430 and 432. A separate heat exchanger may be used to extract heat from fuel cell 410 for heating purposes. For example, in one embodiment, a dual purpose heat exchanger is provided configured with separate heat transfer conduits. One conduit extracts heat for use with refrigeration system 400 when refrigeration is required and another conduit extracts heat for heating of thermal load 402 when heating is required.

[0045] In one particularly suitable embodiment, the fuel cell comprises at least one proton exchange membrane (PEM) fuel cell designed to convert fuel such as pure hydrogen or a hydrogen-rich gas stream and an oxidant such as air in an electrochemical reaction that generates water vapor, electrical power and waste heat. Each cell includes a PEM membrane disposed between bipolar plates. Fuel cells may operate at different temperatures. Low-temperature PEM fuel cells operate between 60°C and 80°C. High-temperature PEM fuel cells may operate between 95°C and 180°C and reject heat at about 150°C. Typically, absorption refrigeration can be achieved with heat at a temperature of about 60°C. Similarly, thermal compression or isochoric compression of typical air cooling system refrigerants can be achieved with heat at a temperature of about 60°C. The temperature differential between the rejected heat and the generator, which determines the heat transfer efficiency, also determines the size of the exchange surface required to transfer heat from a typical PEM fuel cell to a generator. Thus, the size of the generator to exchange heat with a low-temperature PEM fuel cell is much larger than the size of a generator used with a high-temperature PEM fuel cell to achieve the same heat transfer rate. Furthermore, at the temperatures at which the high-temperature PEM fuel cells operate, it is

possible to transfer enough heat to run a compact generator utilizing the external surfaces of the fuel cells rather than having to circulate fluid through the bipolar plates. The ability to extract sufficient heat from the external surfaces simplifies and enables construction of an integrated fuel cell/generator structure.

[0046] In another embodiment, however, heat exchange may be improved by circulating fluid through the biopolar plates to increase the contact surface. This configuration enables the use of low-temperature PEM fuel cells with fuel cell coupled refrigeration systems as described in the present disclosure.

[0047] Referring to FIG. 3, in another embodiment, a fuel cell coupled refrigeration system 100 is provided comprising an air pump or fan 456 forcing air to flow through fuel cell 410. The forced air absorbs heat produced by fuel cell 410 and transfers the heat to the environment or to a thermal load. For example, thermal load 454 is shown in FIG. 3 receiving heat from the forced air.

[0048] In one embodiment, the fuel cell coupled refrigeration system 100 is configured to control the temperature of one or more compartments (not shown). When heating is desired, the fuel cell coupled refrigeration system 100 transfers heat from fuel cell 410 to the compartments.

[0049] In some embodiments, the fuel cell coupled refrigeration systems include auxiliary cooling systems. Embodiments of fuel cell coupled refrigeration systems including auxiliary cooling systems according to the disclosure are described with reference to FIGS. 4 and 5. In FIG. 4, an auxiliary cooling system 446 includes a heat exchanger 444, a radiator 448 and a pump 452.

[0050] For example, in an electric vehicle application, pump 452 is powered by an energy storage system (not shown) which is in turn powered by fuel cell 410. A refrigerant is circulated in a cooling loop through auxiliary cooling system 446 to cool, at least partially, fuel cell 410. In one embodiment, generator 430 and heat exchanger 444 are integrated in a dual purpose generator. In an alternative embodiment, separate heat exchange components are independently coupled to the fuel cell 410. If the refrigeration system 100 is not in operation, auxiliary cooling system 446 cools fuel cell 410. If some refrigeration is desired, absorption

refrigeration system 400 and auxiliary cooling system 446 may be selectively operated by an energy management system to maximize the efficiency of the fuel cell coupled refrigeration system 100. In a further embodiment, generator 430 also includes heating device 220.

[0051] In FIG. 5, an auxiliary cooling system 460 includes heat exchanger 444, radiator 448, pump 452, and a liquid cooled fuel cell 466 thermally coupled to a second heat exchanger 464. A refrigerant is circulated through cooling system 460 to cool fuel cell 466. The refrigerant may be circulated through fuel cells to draw heat from fluid channels disposed within the fuel cell bipolar plates or around their periphery. Heat is then transferred from the refrigerant to generator 430 by heat exchanger 444. Alternatively, heat is removed from the refrigerant by radiator 448. In the arrangements described with reference to FIGS. 4 and 5, the auxiliary cooling system 446, 460 supplements fuel cell thermal management utilizing a liquid refrigerant such as water, ethylene glycol, propylene glycol or mineral oil. The auxiliary cooling system 460 provides operational flexibility by enabling fuel cell 410, 466 to operate independently from the absorption refrigeration system 400, 480. Auxiliary cooling is particularly useful when radiator 448 can discharge absorbed heat to a heat load (not shown).

[0052] Referring to FIG. 6, in another embodiment of a fuel cell coupled refrigeration system according to the disclosure, an ejector refrigeration system 670 is provided. Ejector refrigeration system 670 comprises a refrigerant reservoir 672, expansion valve 642, heat exchanger 652, a pump 674 pumping refrigerant through the fuel cell coupled refrigeration system 500, an ejector 676 having an ejector nozzle 680, and condenser 640. The power loop includes pump 628 to pump the refrigerant therethrough and fuel cell 610 thermally coupled to heat exchangers 678 and 679. After exiting the power loop, the refrigerant is mixed with secondary fluid exiting refrigeration system 670 and heat is removed therefrom.

[0053] In a variation thereof (not shown), an auxiliary cooling system is provided as described with reference to FIGS. 4 and 5. During operation, refrigerant is pumped into the power loop from reservoir 672 to heat exchangers 678 and 679. The excess heat produced by fuel cell 610 vaporizes the refrigerant which maintains

the fuel cell temperature within an optimal range, for example, at temperatures of from about 120°C to about 150°C. The vaporized refrigerant enters ejector nozzle 680 at high pressure and is throttled to high velocity. This increase in velocity draws the secondary fluid in the refrigerant loop into ejector 676. The same refrigerant used as the primary fluid is also used for the secondary fluid. The secondary fluid first enters expansion valve 642 which opens only if below a certain pressure, for example below about 8 and 10 mbar absolute. The refrigerant flows into evaporator 652 and pump 674 before entering ejector 676. Pump 674 is added to achieve a deeper vacuum thereby causing the refrigerant to boil at lower temperature. In one embodiment, the refrigerant is water and the boiling point of the water is decreased to between 50°C and 80°C. The fluid mixture exiting from ejector 676 is routed to condenser 640 which rejects the heat picked up by the refrigerant to the atmosphere. The refrigerant then returns to reservoir 672.

[0054] In one variation, electric heating device 700 is provided as an alternative/supplemental heat source to drive the refrigeration cycle of ejector refrigeration system 670. In one example, heating device 700 and fuel cell 610 are cycled to alternatively drive the refrigeration cycle, at least sometimes. In another example, heating device 700 and fuel cell 610 are operated concurrently, at least sometimes, to drive the refrigeration cycle. It should be recognized that by having the electric heating device 700, the fuel cell power output and heat generation can be decoupled from the heating load and the electrical load as described above, enabling greater operational flexibility.

[0055] In other embodiments of a fuel cell coupled refrigeration system according to the disclosure, as shown in FIG. 7, the refrigeration system 300 comprises a compressor 310. The compressor 310 may be powered by electrical energy (e.g., alternating or direct current) (not shown). In one variation, Q_1 , such as is provided by fuel cell 314, is used to induce isochoric compression of the refrigerant to reduce an energy requirement of the compressor 310. In one embodiment, the system 300 is operable to increase a pressure of a portion of the refrigerant downstream of the compressor. In a form thereof, the pressure is increased by heating the portion of the refrigerant in a substantially constrained volume. By heating in a substantially constrained volume, pressure increases. In another embodiment, heating can also be

applied in a not-substantially constrained volume so long as heating increases the pressure of the refrigerant, for example by controlling feed and discharge flow rates such that the pressure is not relieved as a result of decreased flows.

[0056] In yet another embodiment, the pressure is increased by expanding steam (not shown) generated by fuel cell 314 to compress the refrigerant. As the steam increases in a constrained space, the refrigerant is compressed and its pressure increases. Increasing the pressure reduces an energy requirement of compressor 310. Thus, for the same amount of heating or cooling demanded of system 300, less electrical energy is consumed as a result of the application of thermal energy from fuel cell 314 to refrigeration system 300. In one embodiment, fuel cell 314 is operated between 60°C and 180°C. More particularly, in one embodiment, a low temperature PEM fuel cell is operated between 60°C and 80°C. In another embodiment, an intermediate temperature PEM fuel cell is operated between 90°C and 150°C. In yet another embodiment, a high temperature PEM fuel cell is operated between 100°C and 180°C.

[0057] In one suitable embodiment, a method according to the disclosure includes retrofitting a vapor-compression refrigeration system, such as system 300, by adding generator 316 and fuel cell 314 to transfer excess heat from the fuel cell 314 to the refrigerant.

[0058] Referring to FIGS. 8 and 9, exemplary embodiments of a fuel cell coupled vapor-compression refrigeration system 1000 according to the disclosure are provided. Fuel cell coupled refrigeration system 1000 includes vapor-compression refrigeration system 480 coupled to a generator 430 to heat the refrigerant. As shown in FIG. 8, generator 430 is coupled upstream of a compressor 482, between compressor 482 and condenser 440. In another variation, generator 430 is coupled downstream of compressor 482. For example, generator 430 may be coupled downstream of compressor 482 between heat exchanger 152 and compressor 482. As illustrated in FIGS. 8 and 9, vapor-compression refrigeration system 480 comprises, respectively, auxiliary cooling systems 446 and 460. In a further variation, system 480 does not include an auxiliary cooling system. In all of the above variations and examples, generator 482 compresses the refrigerant, and generator 430 raises the

temperature of the refrigerant such that the energy consumed by compressor 482 is reduced when generator 430 operates relative to when it does not.

[0059] As noted above, alternative/supplemental energy sources may be included in the fuel cell coupled refrigeration systems of the present disclosure. Referring to FIG. 10, a schematic diagram of a fuel cell coupled refrigeration system according to an embodiment of the disclosure, including a fuel cell system 100, a heat driven refrigeration system 150, and a battery system 160, is provided to power a load 104. Fuel cell system 100 includes a fuel cell 110, a fuel cell management system (FMS) 140, and a fuel reservoir 130 containing fuel for the fuel cell 110. In the present embodiment, fuel cell system 100 includes a fluid conduit 120 thermally coupled to fuel cell 110 to extract heat therefrom and having an inlet 122 and a discharge outlet 124. When fuel cell system 100 operates, the fluid passing through fluid conduit 120 is heated and the heated fluid then flows to refrigeration system 150. In a variation thereof, a heat exchanger 152 (e.g., generator) of refrigeration system 150 is physically and thermally coupled to fuel cell system 100 to extract heat from surfaces of fuel cell 110. FMS 140 is communicatively coupled by a signal line 191 to an energy management system 178 and receives a demand signal therethrough. The demand signal causes FMS 140 to control fuel cell system 100 to provide fuel to fuel cell 110 in relation to the amount of energy required by energy management system 178 to enable an electrochemical reaction in fuel cell 110. Electrical power produced by the electrochemical reaction is provided via power lines 171 and 172 to battery system 160. FMS 140 includes a power conditioner (not shown) which converts the voltage of electrical energy generated by fuel cell 110 to a voltage compatible with battery system 160. Electrical power is provided via power lines 173 and 174 from battery system 160 to load 104. Exemplary loads include propulsion systems in mobile applications, computing systems of telecommunication systems or mobile systems, and any other compatible electrical system.

[0060] In particularly suitable embodiments, fuel cell 110 is electrically coupled in parallel with battery cell stack 162 and load 104. In this configuration, fuel cell 110 can participate in powering the electrical load 104 in conjunction with battery system 160. In cases where load 104 is lower than fuel cell 110 power output, fuel cell 110 can recharge battery cell stack 162 while providing power to load 104.

[0061] In the present embodiment, heat exchanger 152 is configured to receive heat from battery system 160. Refrigeration system 150 further includes a fluid supply line 154 fluidly coupled to inlet 122 and a fluid return line 156 fluidly coupled to discharge outlet 124. A primary fluid circulates through refrigeration system 150, fluid supply line 152, fluid conduit 120 and fluid return line 156 driven by a fluid pump (not shown) or by density changes caused by temperature variations in the refrigerant. As the primary fluid passes through fluid conduit 120 it receives heat from fuel cell 110 and then refrigeration system 150 discharges the heat to the environment or to a heat load. The heat received by refrigeration system 150 drives its cooling cycle as explained above and below with reference to FIGS. 2-9. Refrigeration system 150 also extracts heat from battery system 160 with heat exchanger 152. In one variation of the present embodiment, fluid conduit 120 is comprised by a generator (not shown), and the generator is integrated with fuel cell 110. While the fuel cell coupled refrigeration system depicted in FIG. 10 has been described with reference to a battery system, the invention is not so limited. In one variation of the fuel cell coupled refrigeration system with additional energy source as depicted in FIG. 10, the system comprises any electrical energy storage device.

[0062] In another variation of the present embodiment, the primary fluid is thermally coupled to an electric heating device 200 having a fluid conduit 203 between an inlet 202 and a discharge outlet 204. In one example, heating device 200 comprises a plurality of electric heating bands 206 configured to heat fluid conduit 203 and fluid passing therethrough. Heating device 200 is powered by power lines 175 and 176 which are supplied power by battery cell stack 162 of battery system 160 or directly by the fuel cell 110. A switching device 210 is controlled by energy management system 178 with a control signal supplied via a signal line 192 to engage or disengage heating device 200. Exemplary switching devices include relays and contactors.

[0063] As explained further below with reference to FIGS. 11 and 12, according to various embodiments disclosed herein it is advantageous to enable operation of refrigeration system 150 even when fuel cell system 100 is not producing electric power. At such times, battery system 160 powers heating device 200 to produce sufficient heat to drive the refrigeration cycle. When the charge level of

battery system 160 is sufficiently reduced, e.g. below a no-load charge threshold, an energy management system (not shown), as known in the art, engages fuel cell system 100 to recharge battery system 160, thereby also producing sufficient heat to drive the refrigeration cycle, and disengages heating device 200. In one example, an energy management system engages fuel cell system 100 when its charge level is below 90%. In another example, an energy management system engages fuel cell system 100 when its charge level is below 80%. The no-load charge threshold is a design choice dependant on the sizes and response times of the integrated system components.

[0064] The no-load charge threshold can depend on application specific variables. Thus, multiple conditional no load charge thresholds may be applicable under varying conditions. In one example, after the batteries are sufficiently charged the fuel cell system is disengaged and the heating device is engaged to keep the refrigeration system working, to cool the batteries for example. Once the batteries reach a no-load charge threshold, the fuel cell system re-engages to charge the batteries, the heating device disengages, and the fuel cell heat drives the refrigeration cycle. The fuel cell system and the heating device may cycle on and off as described herein for other purposes as well.

[0065] In a further embodiment of a fuel cell coupled refrigeration system according to the disclosure, the fuel cell coupled refrigeration system is comprised in an electric vehicle. The electric vehicle comprises an electric propulsion system and an integrated energy management system. Exemplary propulsion systems comprise wheels or propellers driven by one or more electric motors. Exemplary motors include regenerating motors. The fuel cell coupled refrigeration system, such as shown in FIG. 10, further provides electric power to the propulsion system. In one variation, the refrigeration system is coupled to a thermal load of the electric vehicle and the fuel cell coupled refrigeration system includes a comfort cycling feature. Accordingly, when the vehicle is parked, the fuel cell refrigeration system cycles to provide comfort. In one example, comfort is provided by heating an electric vehicle cabin while the propulsion system of the electric vehicle is disengaged. Heating may be provided by the fuel cells or by an auxiliary heating device powered by an energy storage system. In one example, heating is provided by the fuel cells and the no-load threshold is set below a cooling no-load threshold to enable the fuel cells to generate

more heat than would be generated if an optimal efficiency threshold were chosen. In another example, comfort is provided by cooling the electric vehicle cabin while the propulsion system of the electric vehicle is disengaged. When the electric vehicle is parked, the heating device and the fuel cell coupled refrigeration system cycle and the refrigeration system cools the cabin.

[0066] An embodiment according to the disclosure of a fuel cell coupled refrigeration system as in FIG. 10 in a mobile application is depicted in FIGS. 11 and 12. Referring to FIG. 11, an exemplary schematic diagram of an electric vehicle 300 is shown comprising a plurality heating sources and a plurality of cooling sources powered by fuel cell system 100, battery system 160 and refrigeration system 150. Some heating and cooling sources may be available, for example, if a vehicle is retrofitted with a fuel cell coupled refrigeration system. Battery system 160 is located in a battery compartment 304. An auxiliary heating source, denoted as heating device 306, is provided for heating a cabin 302 where a driver and passengers may be seated. Auxiliary cooling sources include auxiliary fuel cell cooling system 310 and compressor refrigeration system 308.

[0067] In view of the above, it will be seen that the several advantages of the disclosure are achieved and other advantageous results attained. As various changes could be made in the above systems and methods without departing from the scope of the disclosure, it is intended that all matter contained in the above description and shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

[0068] When introducing elements of the present disclosure or the various versions, embodiment(s) or aspects thereof, the articles “a”, “an”, “the” and “said” are intended to mean that there are one or more of the elements. The terms “comprising”, “including” and “having” are intended to be inclusive and mean that there may be additional elements other than the listed elements.

WHAT IS CLAIMED IS:

1. A fuel cell coupled refrigeration system comprising:

a fuel cell operable to generate thermal energy;

a heat driven refrigeration system comprising a refrigerant for being driven through a refrigeration cycle; and

a heat exchanger thermally coupled to the fuel cell to receive at least a portion of the thermal energy to drive the refrigeration cycle of the refrigeration system.
2. The fuel cell coupled refrigeration system of claim 1 wherein the heat exchanger is a generator and the fuel cell is coupled with the generator.
3. The fuel cell coupled refrigeration system of claim 2 further comprising a condenser, and wherein the condenser is fluidly coupled to the generator.
4. The fuel cell coupled refrigeration system of claim 3 further comprising an evaporator, and wherein the evaporator is fluidly coupled to the condenser and the generator.
5. The fuel cell coupled refrigeration system of claim 1 wherein the heat driven refrigeration system further comprises an absorption system comprising a liquid media.
6. The fuel cell coupled refrigeration system of claim 5 wherein the refrigerant is selected from the group consisting of ammonium, sulfur dioxide, water, and hydrocarbon.
7. The fuel cell coupled refrigeration system of claim 1 further comprising an electric heating device thermally coupled with the heat exchanger, and wherein the heat exchanger receives thermal energy from at least one of the fuel cell and the electric heating device.

8. The fuel cell coupled refrigeration system of claim 7 wherein the electric heating device is configured to receive power from a battery cell stack cooled by the fuel cell coupled refrigeration system.
9. The fuel cell coupled refrigeration system of claim 1 wherein the heat exchanger comprises a first heat exchanger being a condenser and a second heat exchanger being an evaporator, and wherein the heat driven refrigeration system further comprises a compressor fluidly coupled to the condenser.
10. The fuel cell coupled refrigeration system of claim 9 wherein the compressor is thermally coupled to the fuel cell.
11. A heat exchanger for a heat driven refrigeration system, the heat exchanger comprising:
 - a generator comprising an inlet fluidly coupled to an outlet, the inlet adapted to receive a refrigeration fluid at an inlet temperature and the outlet adapted to discharge the refrigeration fluid at a discharge temperature greater than the inlet temperature; and
 - a fuel cell thermally coupled to the generator, the fuel cell adapted to heat the generator and the refrigeration fluid circulating therein.
12. The heat exchanger of claim 11 wherein the refrigerant comprising a refrigerant selected from ammonium, sulfur dioxide, water, and hydrocarbon.
13. The heat exchanger of claim 11 further comprising an electric heating device coupled to the generator.
14. The heat exchanger of claim 11 wherein the fuel cell is a high-temperature proton exchange membrane fuel cell.
15. A method of driving a refrigeration cycle of a heat driven refrigeration system to cool an ambient environment, the method comprising:

heating a refrigerant using thermal energy produced by a fuel cell to form a heated refrigerant gas having a pressure higher than the refrigerant prior to heating; and

cooling the heated refrigerant gas in a condenser to form a liquid refrigerant having a pressure lower than the heated refrigerant gas, wherein the heated refrigerant gas absorbs heat from the ambient environment as it is cooled.

16. The method of claim 15 wherein the fuel cell is a high-temperature proton exchange membrane fuel cell.
17. The method of claim 15 further comprising absorbing the refrigerant into a liquid media prior to heating the refrigerant.
18. The method of claim 17 further comprising evaporating the refrigerant prior to absorbing the refrigerant into a liquid media.
19. The method of claim 15 further comprising compressing the refrigerant prior to heating the refrigerant.
20. The method of claim 15 comprising further heating the refrigerant using thermal energy produced by an electric heating device.

FIG. 1A

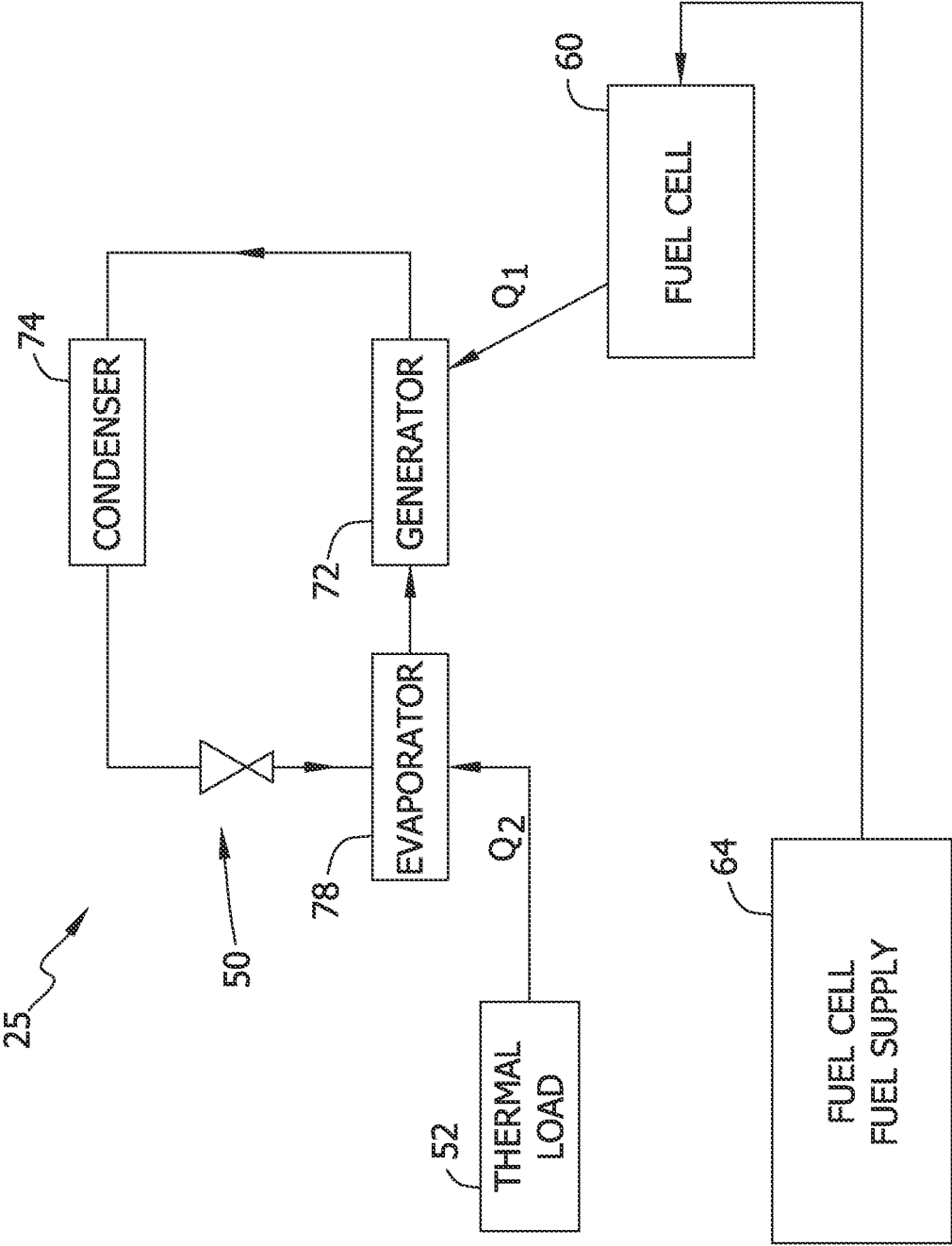


FIG. 1B

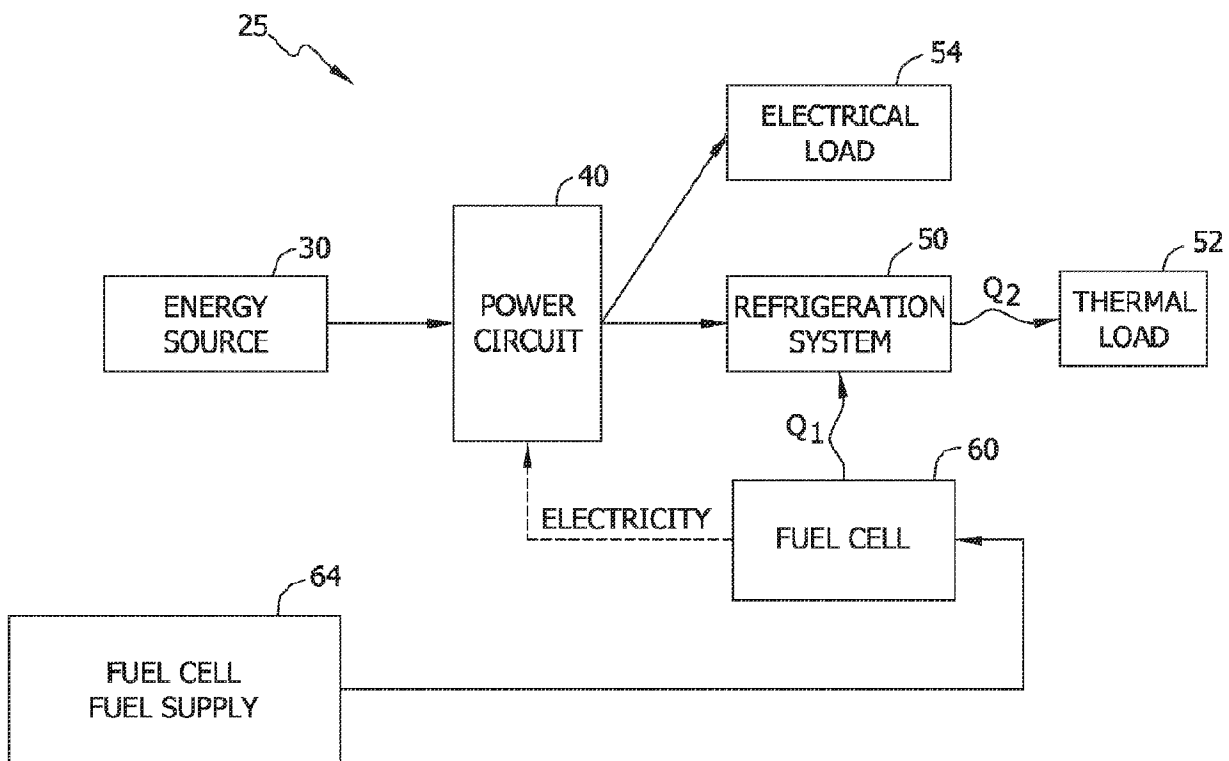


FIG. 2

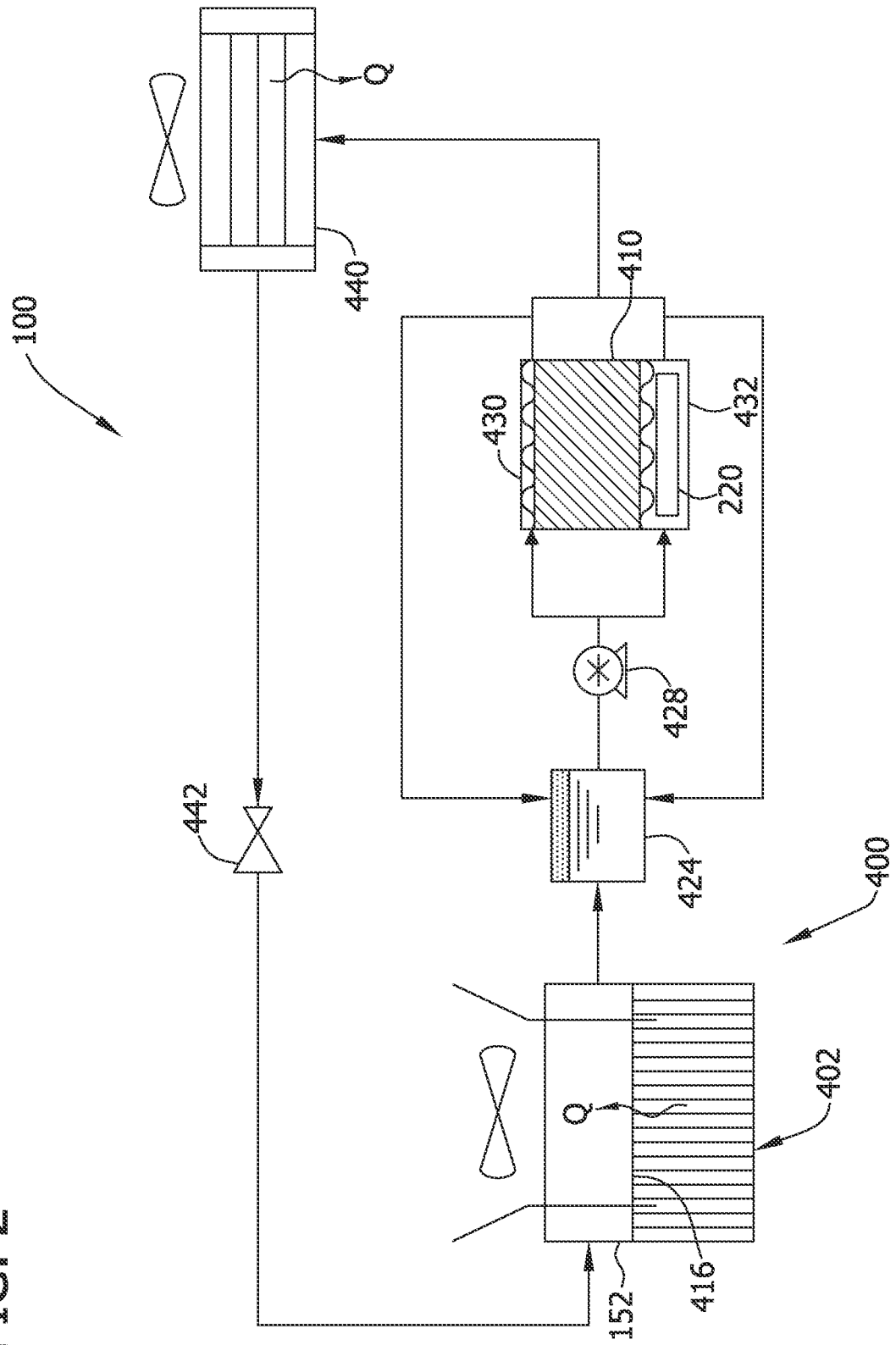
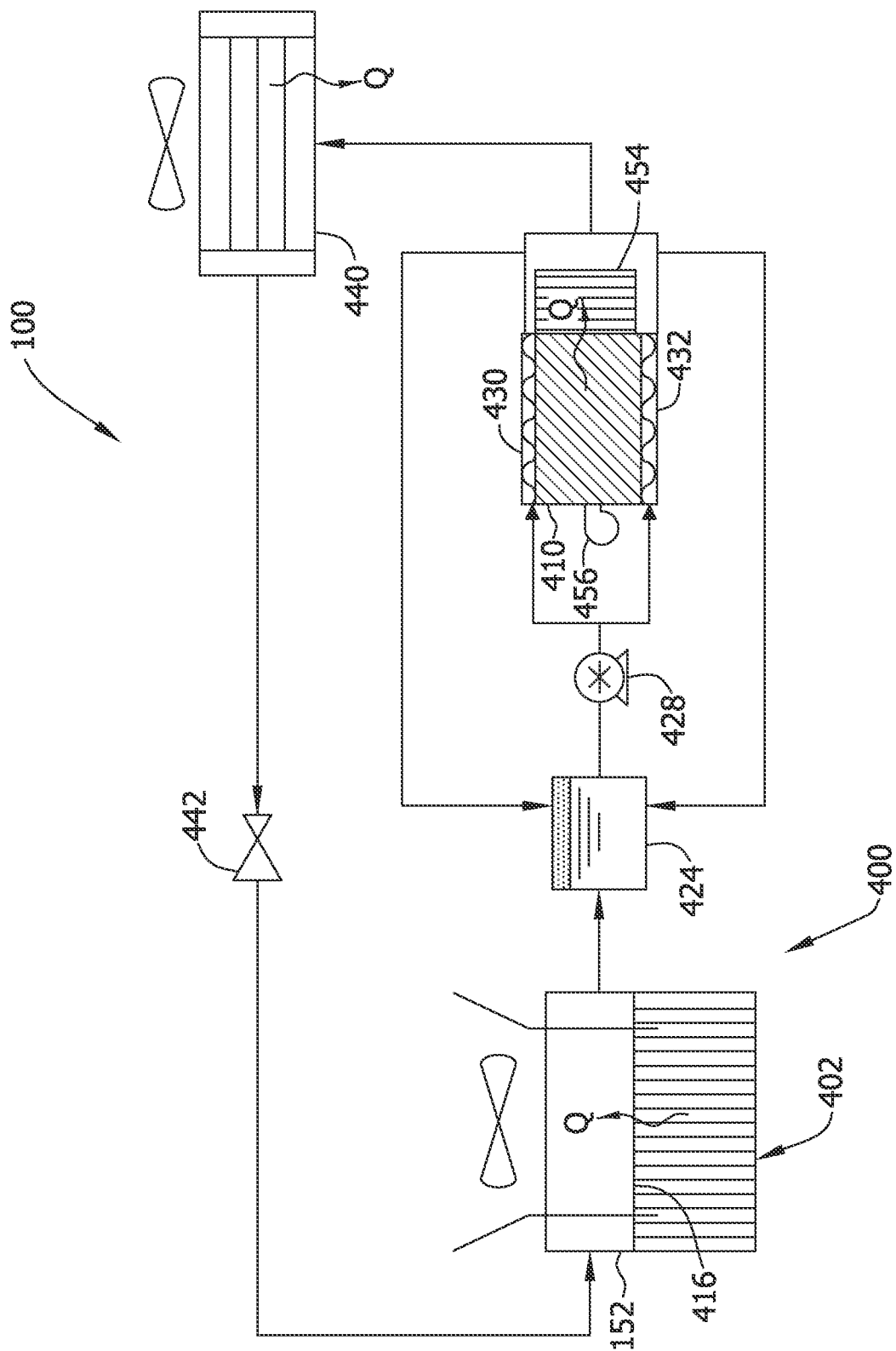


FIG. 3



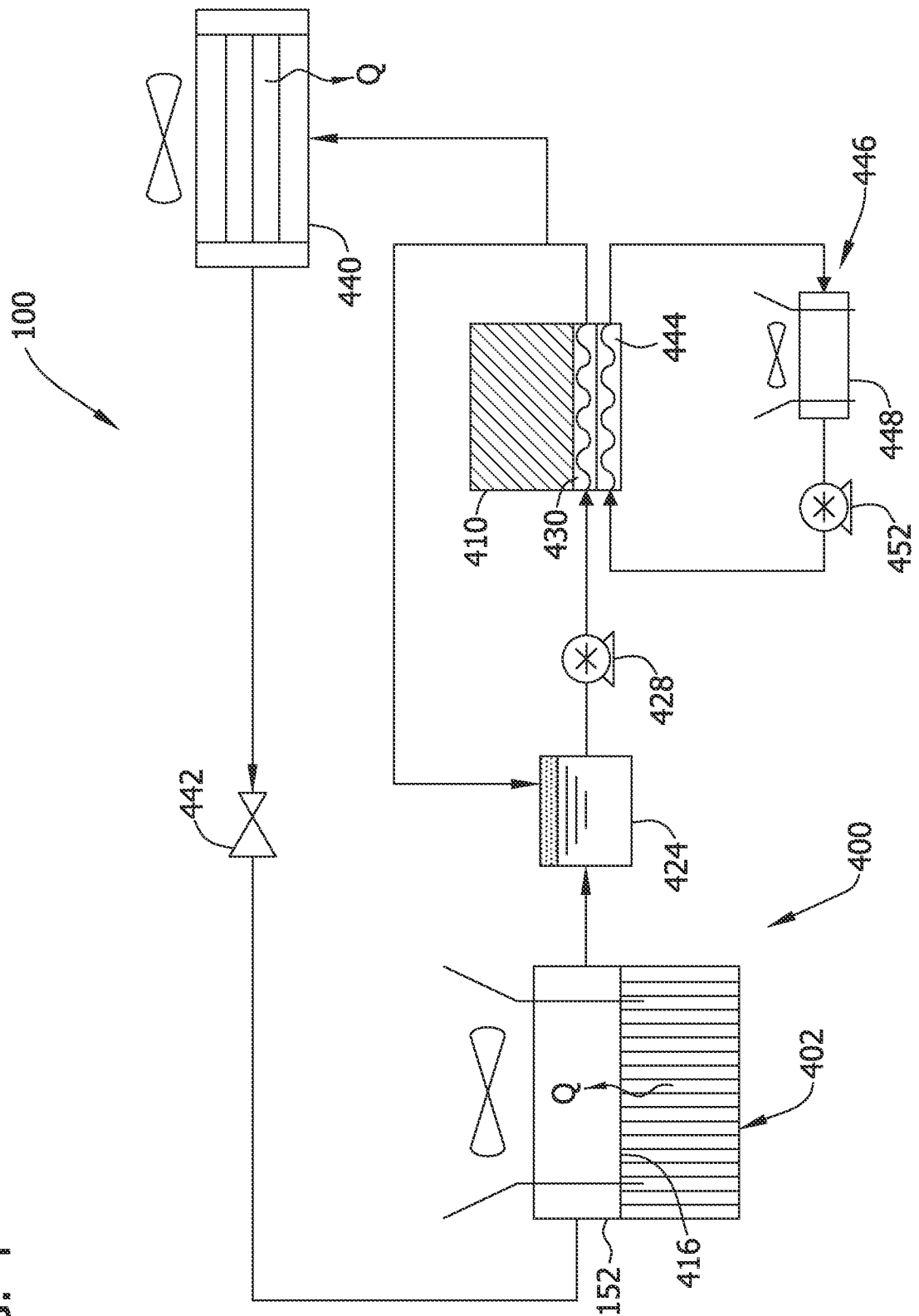


FIG. 5

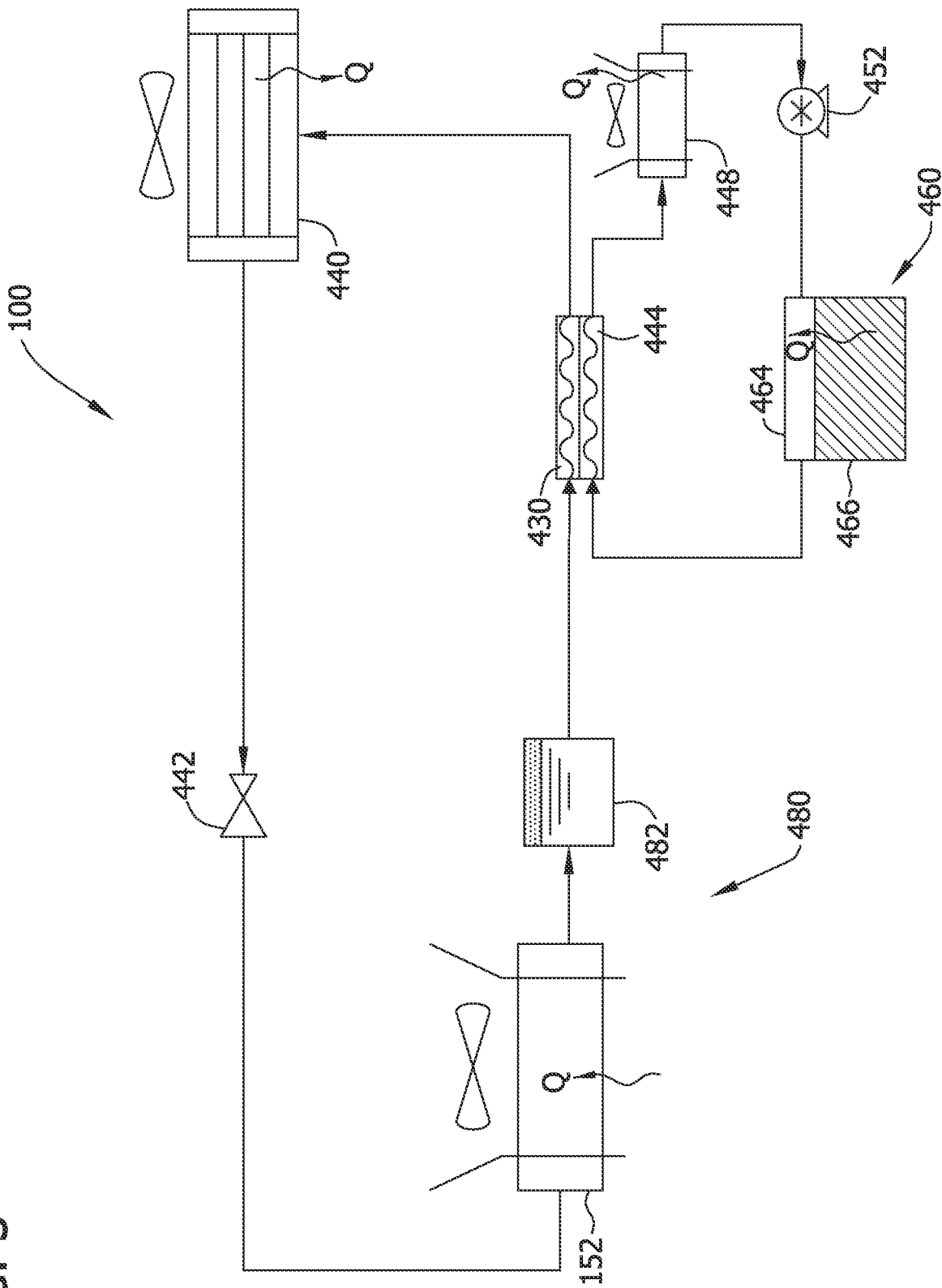
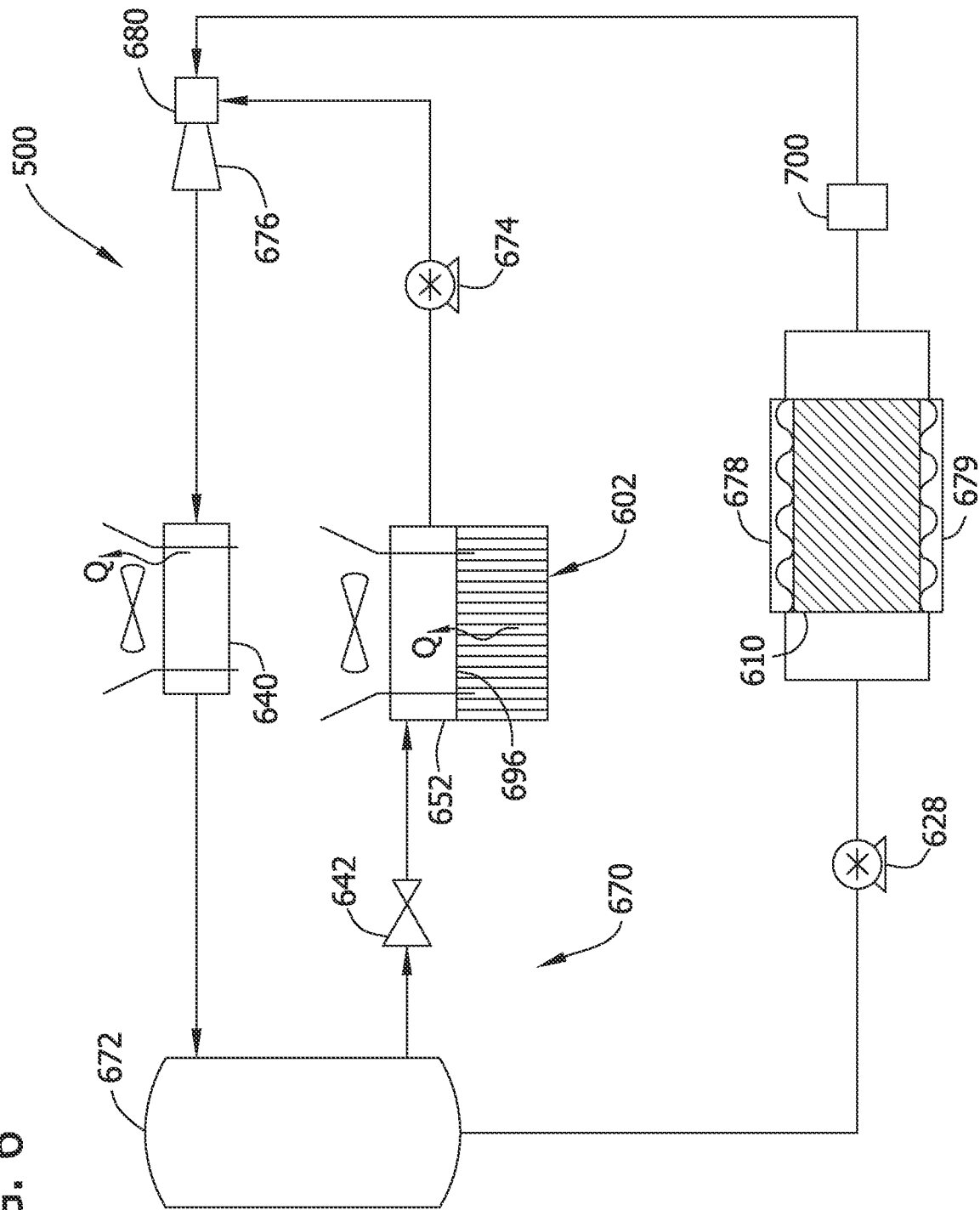


FIG. 6



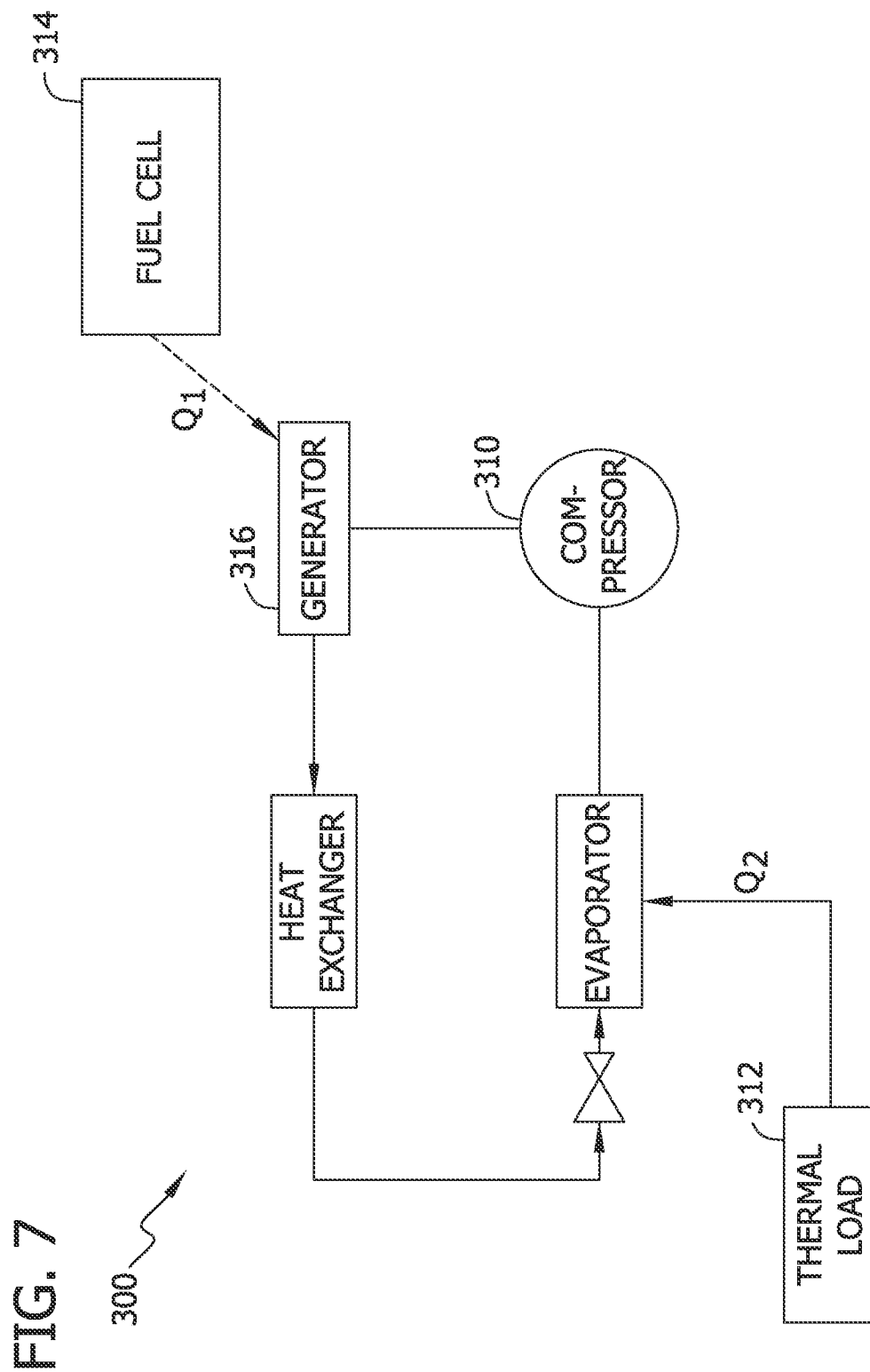


FIG. 8

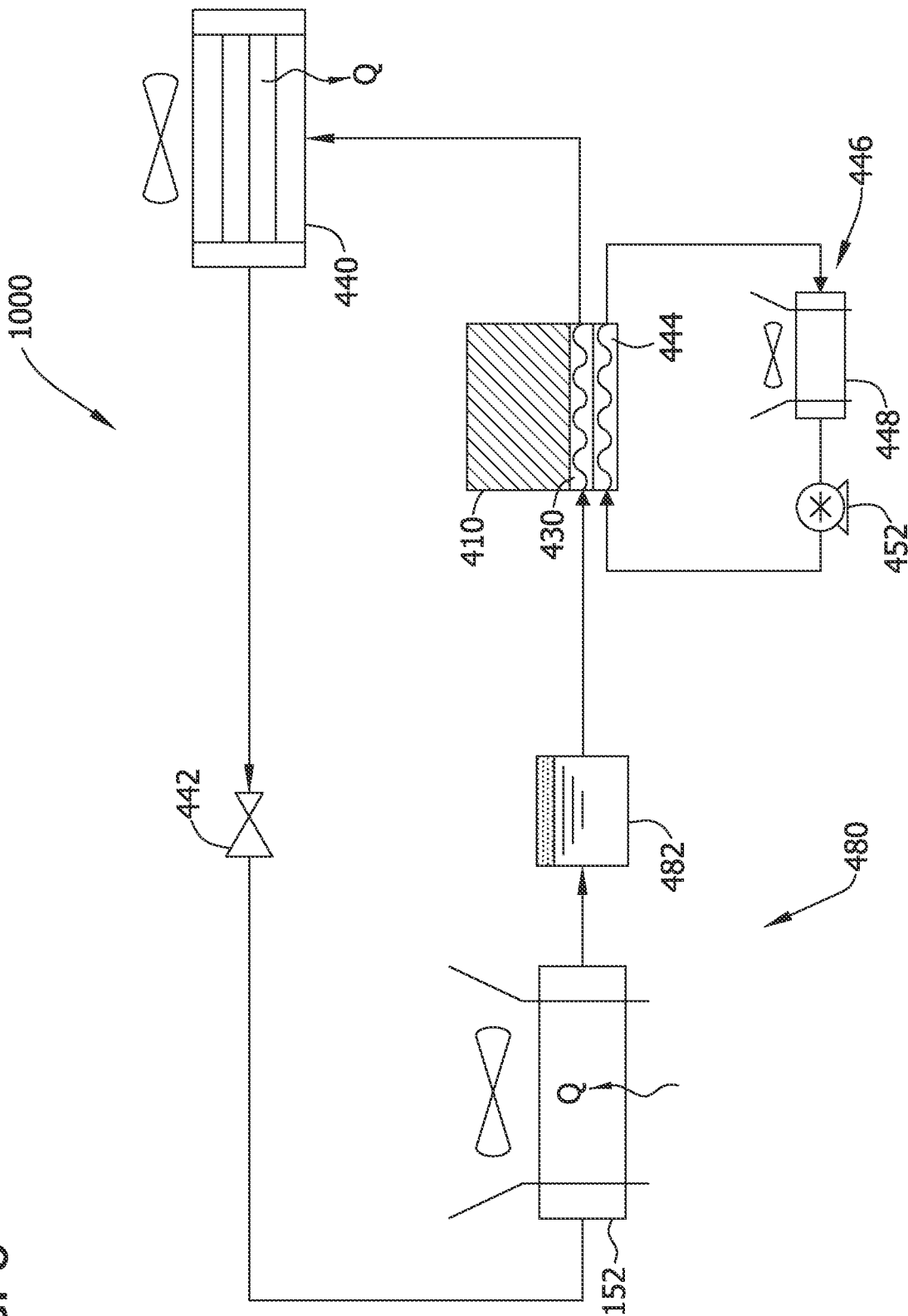


FIG. 9

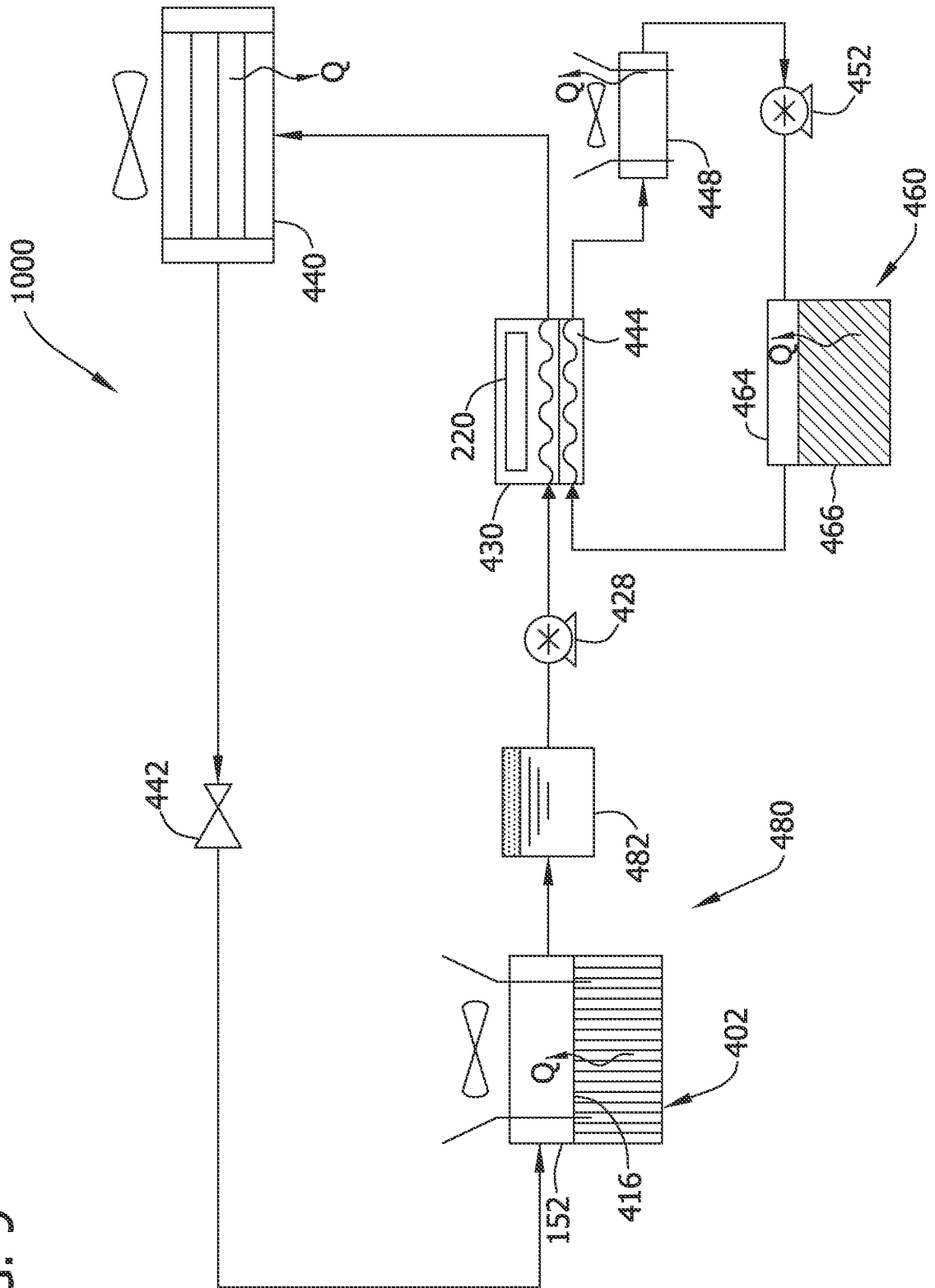


FIG. 10

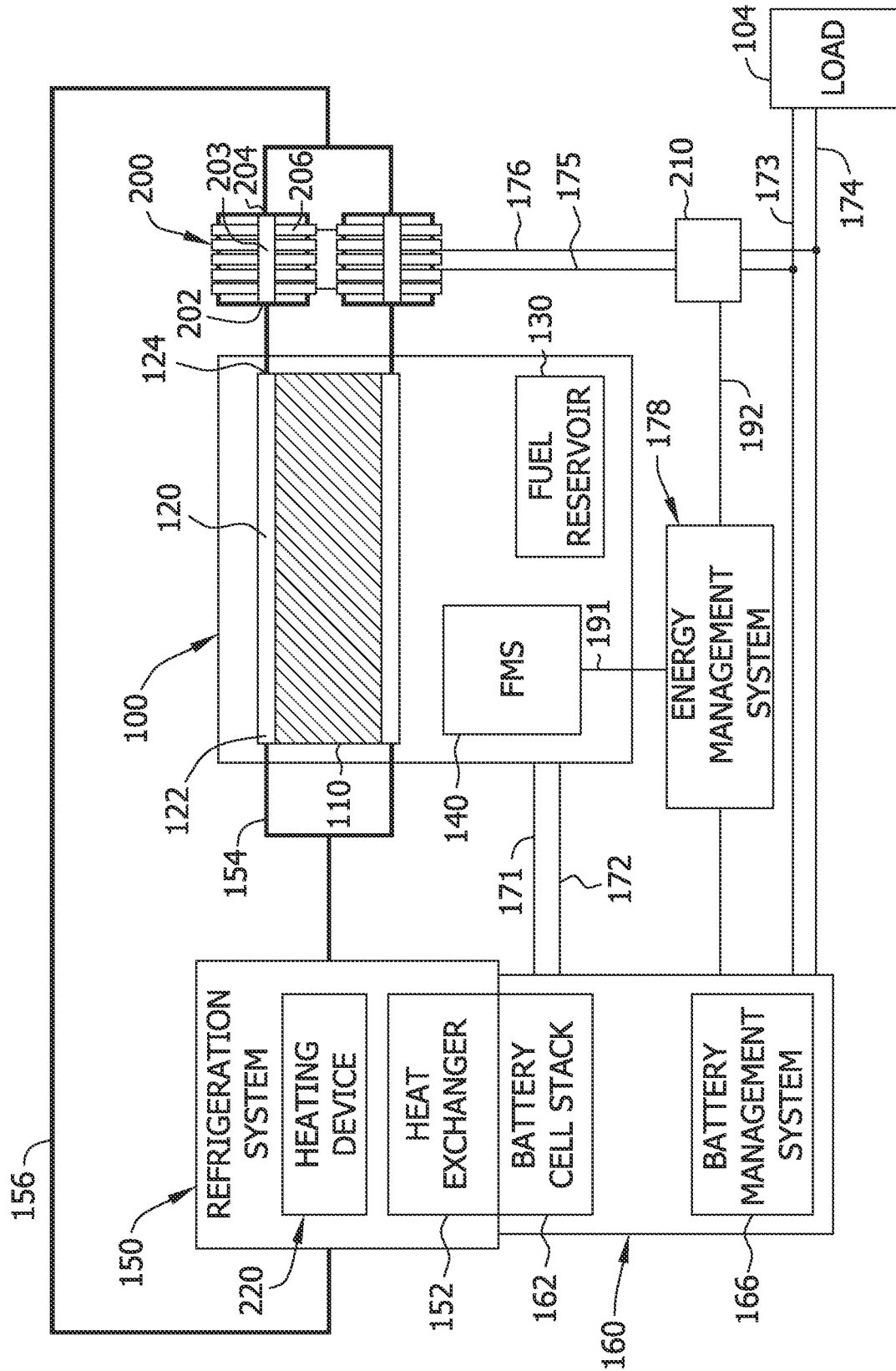


FIG. 11

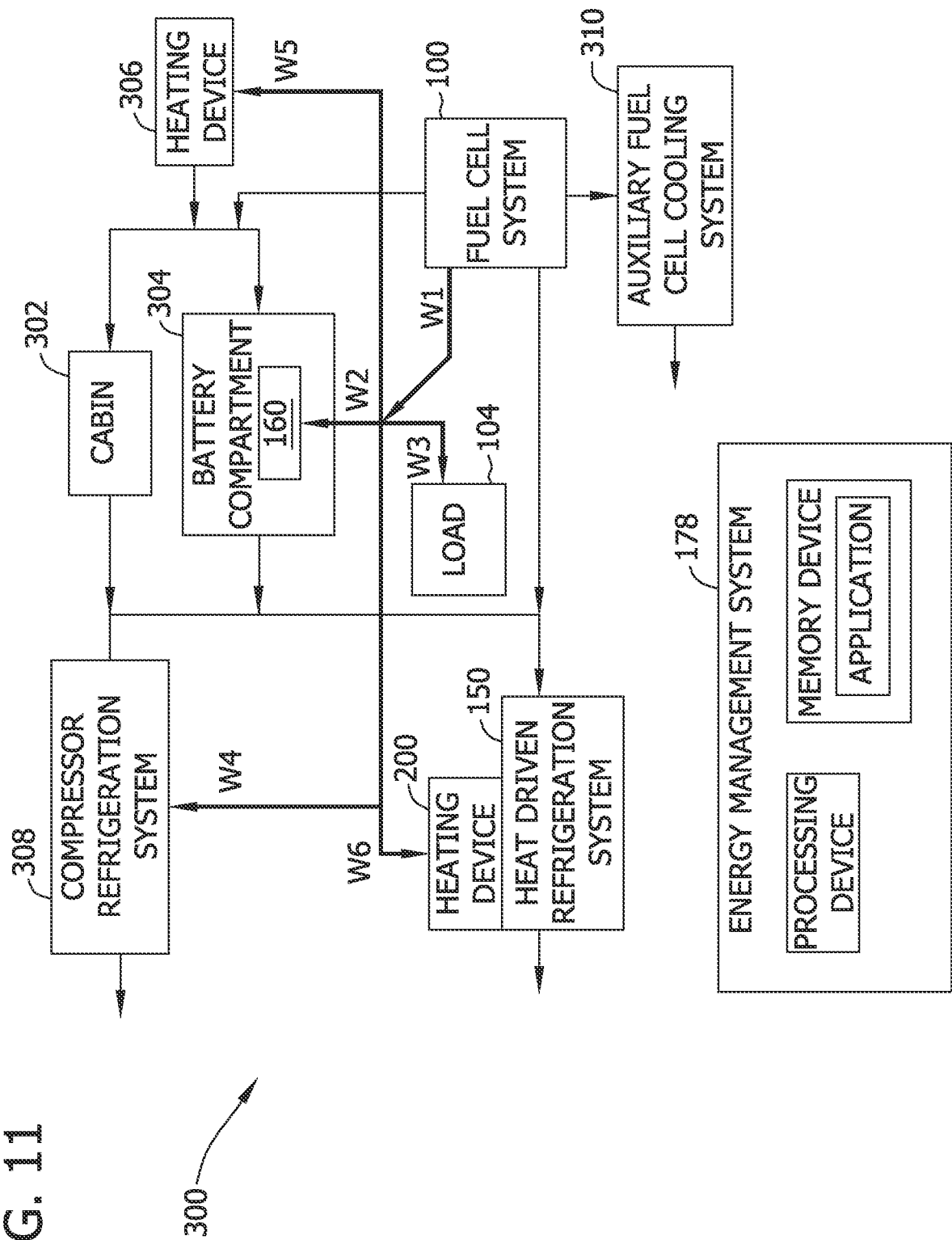


FIG. 12

