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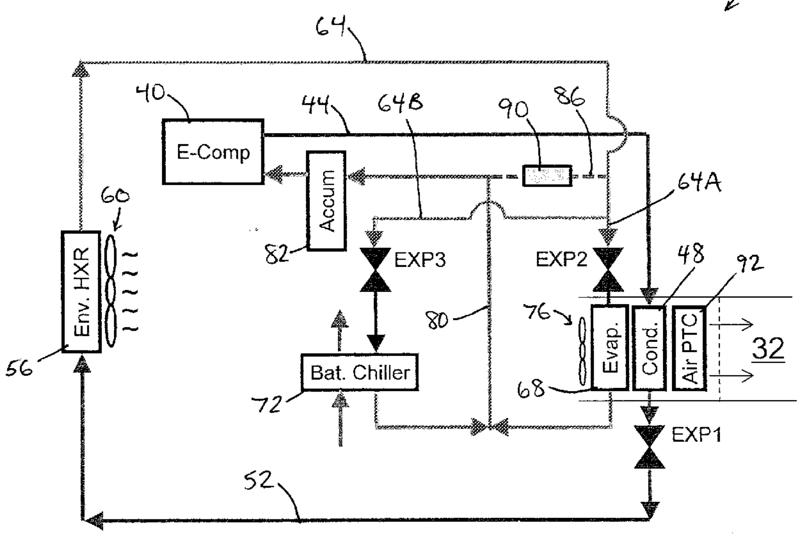
(54) **Title:** ELECTRIC VEHICLE THERMAL MANAGEMENT SYSTEM

Cabin & Battery Cooling

FIG. 1



(57) **Abstract:** An electric vehicle thermal management system includes a refrigeration system having an electrically-driven compressor, a cabin heater, a cabin cooler, first, second, and third expansion valves, an environmental heat exchanger, a battery chiller, a connector line, a valve, and refrigerant. The battery chiller is positioned between the third expansion valve and the compressor. When opened by the valve, the connector line selectively connects the environmental heat exchanger with the compressor, bypassing the second and third expansion valves. A bypass device controls selective activation of the cabin heater. Cabin cooling is provided in a first mode and cabin heating is provided in a second mode operating as a heat pump. The first expansion valve independently controls refrigerant expansion to the environmental heat exchanger and is further operable to pass refrigerant without expansion. The second expansion valve independently controls refrigerant expansion to the cabin cooler and is further operable to block refrigerant.

[Continued on next page]

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ELECTRIC VEHICLE THERMAL MANAGEMENT SYSTEM

BACKGROUND

[0001] The present invention relates to electric vehicles and thermal management for both the vehicle cabin and vehicle powertrain equipment. Vehicles designed to be driven partially or fully electrically can lack the availability of sufficient waste heat from an internal combustion engine to provide cabin heating. Although limited solutions exist in the art for thermal management in electric vehicles, some systems lack advanced features, while others are particularly complicated and costly to implement.

SUMMARY

[0002] In one aspect, the invention provides an electric vehicle thermal management system including a refrigeration system. The refrigeration system includes an electrically-driven compressor, a cabin heater, a cabin cooler, first, second, and third expansion valves, an environmental heat exchanger, a battery chiller, a connector line, a valve, and a circulating refrigerant. The battery chiller is positioned between a downstream side of the third expansion valve and an inlet of the compressor. The connector line is provided between a downstream side of the environmental heat exchanger and the inlet of the compressor to selectively bypass the second and third expansion valves, and the valve is operable to selectively open and close the connector line. An air handling unit has a fan operable to blow air across the cabin cooler to the cabin. A bypass device is operable in both a first configuration in which the cabin heater is active for transferring heat to the cabin and a bypass configuration in which the bypass device blocks the cabin heater from transferring heat to the cabin. The refrigeration system is configurable to selectively provide cabin cooling in a first mode operating as an air conditioning system to transfer thermal energy from the refrigerant to ambient at the environmental heat exchanger and to provide cabin heating in a second mode operating as a heat pump to absorb thermal energy into the refrigerant from ambient at the environmental heat exchanger. The first expansion valve is operable to independently control the expansion of the refrigerant to the environmental heat exchanger and is further operable to pass the refrigerant to the environmental heat exchanger without expansion. The second expansion valve is operable to independently control the expansion of the refrigerant to the cabin cooler and is further operable to block the refrigerant from flowing into the cabin cooler from the environmental heat exchanger.

[0003] In another aspect, the invention provides an electric vehicle thermal management system including a refrigeration system. The refrigeration system includes an electrically-driven compressor, a cabin heater, a cabin cooler, an environmental heat exchanger, a battery chiller, first, second, and third expansion valves, a connector line, a valve, and a circulating refrigerant. The battery chiller is positioned between a downstream side of the third expansion valve and an inlet of the compressor. The first expansion valve is positioned between the cabin heater and the environmental heat exchanger and has at least a first configuration operable to restrict a flow of refrigerant for expansion to the environmental heat exchanger and a second bypass configuration operable to pass a flow of refrigerant to the environmental heat exchanger without expansion. The second expansion valve is positioned immediately upstream of the cabin cooler and has at least a first configuration operable to restrict a flow of refrigerant for expansion to the cabin cooler and a second closed configuration operable to block a flow of refrigerant. The third expansion valve is positioned immediately upstream of the battery chiller and has at least a first configuration operable to restrict a flow of refrigerant for expansion to the battery chiller and a second closed configuration operable to block a flow of refrigerant. The connector line is provided between a downstream side of the environmental heat exchanger and the inlet of the compressor to selectively bypass the second and third expansion valves, and the valve is operable to selectively open and close the connector line. An air handling unit has a fan operable to blow air across the cabin cooler to the cabin. A bypass device is operable in both a first configuration in which the cabin heater is active for transferring heat to the cabin and a bypass configuration in which the bypass device blocks the cabin heater from transferring heat to the cabin. The thermal management system is operable to selectively provide all of the following operating modes by switching the first expansion valve between the first and bypass configurations, switching the second expansion valve between the first and closed configurations, switching the third expansion valve between the first and closed configurations, switching the connector line between open and closed, and switching the bypass device between the first configuration and the bypass configuration: a combined cabin and battery cooling mode, a cabin cooling mode, a battery cooling mode, a cabin heating mode, a cabin cooling with defogging mode, and a cabin heating with defogging mode.

[0004] In another aspect, the invention provides an electric vehicle including a thermal management system as described above.

[0005] In yet another aspect, the invention provides a method of switching between modes of a thermal management system in an electric vehicle. The method includes switching amongst all of a first mode for cabin and battery cooling, a second mode for cabin cooling, a third mode for battery cooling, a fourth mode for cabin heating, a fifth mode for defrosting an environmental heat exchanger, a sixth mode for defogging with cabin cooling, and a seventh mode for defogging with cabin heating by independently controlling a bypass device, three expansion valves and a shut-off valve to control the flow of refrigerant between an electrically-driven compressor, a cabin heater, a cabin cooler, a battery chiller, and the environmental heat exchanger. In some aspects, the three expansion valves and the shut-off valve are the only refrigerant valves provided in the thermal management system.

[0006] Other aspects of the invention will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Fig. 1 schematically illustrates a thermal management system of an electric vehicle according to one embodiment of the present invention. The thermal management system is illustrated in a first mode for cabin and battery cooling.

[0008] Fig. 2 schematically illustrates the thermal management system of Fig. 1 in a second mode for cabin cooling.

[0009] Fig. 3 is schematically illustrates the thermal management system of Fig. 1 in a third mode for battery cooling.

[0010] Fig. 4 schematically illustrates the thermal management system of Fig. 1 in a fourth mode for cabin heating.

[0011] Fig. 5 schematically illustrates the thermal management system of Fig. 1 in a fifth mode for defrosting an environmental heat exchanger.

[0012] Fig. 6 schematically illustrates the thermal management system of Fig. 1 in a sixth mode for defogging with cabin cooling.

[0013] Fig. 7 schematically illustrates the thermal management system of Fig. 1 in a seventh mode for defogging with cabin heating.

[0014] Fig. 8 is a plan view of the thermal management system of Fig. 1 arranged in an electric vehicle.

[0015] Fig. 9 illustrates an air handling unit of the thermal management system having a bypass device movable to selectively deactivate a cabin heater.

DETAILED DESCRIPTION

[0016] Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways.

[0017] Fig. 1 illustrates a thermal management system 20 for an electric vehicle 24 (Fig. 8). The electric vehicle 24 can be a battery-electric (i.e., all electric) vehicle (BEV), a plug-in hybrid electric vehicle (PHEV), or a hybrid electric vehicle (HEV). As such, the electric vehicle 24 includes at least one electric traction motor 25 for propulsion of the vehicle. For example, as shown in Fig. 8, the electric traction motor 25 can be mechanically coupled directly or indirectly to rotate one or more wheels 27 of the vehicle 24. The electric vehicle 24 may in some constructions include a combustion engine. However, in partial- or full-electric driving modes, drive power requirements from the combustion engine are reduced or eliminated. In other constructions, the electric vehicle 24 has no combustion engine whatsoever, or at least no combustion engine operable for propulsion of the vehicle. In order to power the electric traction motor 25, a battery pack 28 is included in the vehicle 24. The battery pack 28 may require cooling (or heating) under certain circumstances. In addition, a cabin 32 of the vehicle 24 for one or more occupants must be provided with climate control for occupant comfort. The thermal management system 20 selectively combines battery pack cooling with cabin climate control by implementing heat pump functionality in a layout that enables numerous different modes of operation depending upon vehicle operating conditions, ambient conditions, and climate control requirements of the cabin occupant(s). The heat pump operates a vapor-compression refrigeration cycle upon a working fluid, or "refrigerant".

[0018] The basic system components and layout of the thermal management system 20 are described with reference to Fig. 1. A compressor 40 is provided to compress gaseous refrigerant to a higher pressure and higher temperature than the entering refrigerant. The compressor 40 can be electrically operated (e.g., by an electric motor) rather than through a power-take-off device from a combustion engine. A compressor discharge line 44 extends from an outlet of the compressor 40 to an inlet of a cabin heater 48 (i.e., condenser) positioned in an air handling unit of a heating, ventilation, and air conditioning (HVAC) system in communication with the cabin 32. The air handling unit, shown in further detail in Fig. 9, also includes additional heating and cooling elements of the thermal management system 20 as described below. A first expansion valve EXP1 is positioned directly between an outlet of the cabin heater 48 and an inlet of an environmental heat exchanger 56 operable to transfer thermal energy from the refrigerant to the ambient environment or vice versa, depending on the operational mode and ambient conditions. The first expansion valve EXP1 can be immediately downstream of the cabin heater 48 and immediately upstream of the environmental heat exchanger 56. As used in this context herein, "direct" and "immediate" do not refer to a particular proximal distance, but rather the fact that there are no intermediate valves or other refrigeration cycle elements (e.g., compressor, heat exchange coils) therebetween. Although the first expansion valve EXP1 is capable of restricting or metering a flow of refrigerant to induce a pressure drop in the refrigerant, the first expansion valve EXP1 also has a configuration that does not restrict or meter the refrigerant flow, but rather passes the refrigerant without expanding it to a lower pressure. This is not to say that the flow restriction and corresponding pressure drop are zero, but rather, relatively minimized and not providing a significant expansion effect. For example, the refrigerant temperature, which corresponds directly to refrigerant pressure, may drop less than 5 Kelvin when in the unrestricted or open configuration. An inlet line 52 extends from the first expansion valve EXP1 to the inlet of the environmental heat exchanger 56. A fan 60 can be provided to enhance heat transfer by generating a flow of air through the environmental heat exchanger 56.

[0019] An outlet line 64 extends from an outlet of the environmental heat exchanger 56 to direct refrigerant to one or more cooling coils (i.e., evaporators). In particular, the outlet line 64 from the environmental heat exchanger 56 can diverge into two branches, including a first branch 64A that supplies refrigerant to a cabin cooler 68 (i.e., evaporator 68) through a second expansion valve EXP2, and a second branch 64B that supplies refrigerant to a battery chiller 72 (i.e., evaporator 72) through a third expansion valve EXP3. The second expansion valve EXP2 is arranged directly upstream of the cabin cooler 68, and the third expansion valve EXP3 is arranged directly upstream of the battery chiller 72. The battery chiller 72 may be part of a battery subsystem of the thermal management system 20 operable to cool the battery cells of the battery pack 28 directly or through an additional coolant fluid flowing in a separate coolant loop through the battery chiller 72. Such a coolant loop can include one or more pumps, valves, etc. (not shown) to control the coolant flow. The battery subsystem can alternately or additionally provide air cooling via a fan, and may additionally be provided with an electric heater to heat the battery pack 28 in low temperature conditions. The battery subsystem can thus selectively cool (or heat) the battery pack 28 to maintain its temperature within a predetermined operating range. It is also noted that the battery chiller 72 may also be arranged to draw heat from power electronics (not shown) associated with the battery pack 28.

[0020] A fan 76 of the HVAC air handling unit can be provided to drive a flow of air through the cabin cooler 68. Separate outlet line branches from outlets of the cabin cooler 68 and the battery chiller 72 are joined together to form a common compressor return line 80 leading to an inlet of the compressor 40. An accumulator 82 is provided along the compressor return line 80 to accumulate liquid and vapor phase refrigerant and pass the vapor phase refrigerant to the compressor 40. Between the compressor return line 80 and the outlet line 64 from the environmental heat exchanger 56, a connector line 86 with a valve, referred to herein as the shut-off valve 90, can selectively establish and block fluid communication for refrigerant flow. In some constructions, the shut-off valve 90 is a 2-position valve that is either open or closed. The shut-off valve 90 may also be a 3-port two position valve capable of passing refrigerant to the battery chiller 72 and the cabin cooler 68 in a first position and capable of passing refrigerant to the accumulator 82 in a second position. Of all the components that receive the circulating refrigerant, the thermal management system 20 can in some constructions be limited to exactly four valves, which are the shut-off valve 90 and the three expansion valves EXP1, EXP2, EXP3 (at least two of which can effectively be closed or turned off and at least one of which can effectively provide pass-through flow without expansion).

[0021] Each of the expansion valves EXP1, EXP2, EXP3 can be implemented as an electronic expansion valve (EEV), a thermal expansion valve (TXV) with internal shut-off or bypass valves, a thermal expansion valve (TXV) and external shut-off or bypass valves, fixed expansion orifices with electronic shut-off or bypass valves, or any combination of EEVs, TXVs, orifices and shut-off or bypass valves. In particular, the first expansion valve EXP1 has at least two configurations, including a first configuration operable to meter the flow of refrigerant to induce a pressure drop and operate as an expansion valve, and a second configuration that is fully open so as to avoid operating as an expansion valve (e.g., by further opening a restriction orifice or opening an additional unrestricted bypass conduit). This is not to say that the flow restriction and corresponding pressure drop are zero, but rather, relatively minimized and not providing a significant expansion effect. For example, the refrigerant temperature, which corresponds directly to refrigerant pressure, may drop less than 5 Kelvin when in the second configuration. Further, each of the second and third expansion valves EXP2, EXP3 has at least two configurations, including a first configuration operable to meter the flow of refrigerant to induce a pressure drop and operate as an expansion valve, and a second closed configuration that blocks the flow of refrigerant. For the case of TXVs, the second and third expansion valves EXP2, EXP3 may rely on the mechanical action of the TXV to block the flow of refrigerant when there is no fluid flow through the battery chiller 72 or cabin evaporator 68. Additional configurations and modes can be provided in some constructions. For example, all three of the expansion valves EXP1, EXP2, EXP3 can have identical constructions providing at least three configurations (i.e., metering as an expansion valve, fully open, and fully closed according to the above descriptions) even if the thermal management system 20 does not utilize every configuration of every expansion valve. In this way, the thermal management system 20 can be constructed using only expansion valves of a single identical construction, rather than requiring multiple unique constructions of expansion valves.

[0022] Fig. 9 schematically illustrates the HVAC air handling unit in which the cabin heater and chiller 48, 68 are located. In addition to these respective refrigeration elements, an electric heater 92 (e.g., a positive temperature coefficient resistive heater, labeled "Air PTC" in the drawings) can be provided and operable, when energized by an electrical source, to heat the air delivered to the cabin 32 by the fan 76 through the HVAC air handling unit. A bypass device or bypass flap 94 is provided for manipulating air flow in the air handling unit downstream of the cabin cooler 68 and upstream of both the cabin heater 48 and the electric heater 92. In a first or open position of the bypass flap 94 as shown in solid in Fig. 9, the cabin heater and cooler 48, 68 and the electric heater 92 are in the HVAC airflow circuit between the fan 76 and the cabin 32. When moved to a second or bypass position as shown in dashed lines in Fig. 9, the bypass flap 94 blocks the cabin heater 48 and the electric heater 92 from the air flow between the fan 76 and the cabin 32. Thus, as will be apparent from the additional description below, it is possible to avoid heating the cabin 32 with the cabin heater 48 without stopping the flow of hot refrigerant through the cabin heater 48. The bypass flap 94 is one example of a bypass device that can selectively put the cabin heater 48 into and out of a heat transfer circuit with the air for the cabin 32. In other constructions, the bypass device can include a bypass passage and a refrigerant valve movable between a first position that directs the refrigerant through the cabin heater 48 and a second or bypass position in which refrigerant is transferred from the compressor discharge line 44 to the inlet line 52 to the environmental heat exchanger 56 without passing through the cabin heater 48 (i.e., bypassing the cabin heater 48). The cabin heater 48 refrigerant bypass functionality may also be included as a third port in the first expansion valve EXP1. A bypass line is schematically illustrated by the dashed line between the compressor discharge line 44 to the inlet line 52 in Fig. 9. By either construction, the bypass device is operable in both a first configuration in which the cabin heater 48 is active for transferring heat to the cabin 32 and a bypass configuration in which the bypass device blocks the cabin heater 48 from transferring heat to the cabin 32.

[0023] The thermal management system 20 is illustrated in Fig. 1 in a first mode for providing cooling to both the cabin 32 and the battery pack 28. During the first mode of operation, refrigerant flows through the various elements of the system 20 in accordance with the directional arrows of Fig. 1. The shut-off valve 90 is in the closed position to prevent refrigerant flow through the connector line 86. The first expansion valve EXP1 located between the cabin heater 48 and the environmental heat exchanger 56 is in the full open or bypass position. In this position, the hot, high-pressure refrigerant delivered from the compressor 40 is passed through the cabin heater 48 to the environmental heat exchanger 56 where it is cooled by ambient airflow, optionally aided by the operation of the fan 60. The bypass flap 94 can be in the second or bypass position as shown in Fig. 9 so that the fan 76 does not blow air across the cabin heater 48 into the cabin 32. The condensed refrigerant, after being cooled at the environmental heat exchanger 56, is delivered to the second and third expansion valves EXP2, EXP3 through the first and second branches 64A, 64B of the outlet line 64. The second and third expansion valves EXP2, EXP3 are open (i.e., not closed or shut off) with a restricted opening, and each is operable to induce a pressure drop and expand the refrigerant from high pressure to low pressure. Refrigerant flow exiting both the cabin cooler 68 and the battery chiller 72 is combined to the compressor return line 80 to return to the compressor 40 through the accumulator 82.

[0024] Fig. 2 schematically illustrates the thermal management system 20 in a second mode for cabin cooling. In the second mode, the refrigerant is not utilized to cool the battery pack 28. For example, the driver of the vehicle may request air conditioning on a hot day immediately upon entering the vehicle, prior to the battery pack 28 reaching the maximum allowable operating temperature. In order to achieve the second mode for cabin cooling only, the third expansion valve EXP3 is in a fully closed configuration. Thus, refrigerant does not flow through the battery chiller 72. The remaining elements of the thermal management system 20 are configured as in the first mode described above. Refrigerant from the outlet line 64 flows only through the second expansion valve EXP2 to the cabin cooler 68 before returning to the compressor return line 80 for recirculation through the compressor 40, the cabin heater 48, the first expansion valve EXP1 (in full open or bypass configuration), and the environmental heat exchanger 56.

[0025] Fig. 3 schematically illustrates the thermal management system 20 in a third mode for battery cooling. In the third mode, the refrigerant is not utilized to cool the cabin 32. For example, when ambient conditions are modest and the driver does not request air conditioning, the battery pack 28 may reach a maximum allowable operating temperature due to heavy use in the driving cycle or charging. In order to achieve the third mode for battery cooling only, the second expansion valve EXP2 is in a fully closed configuration. Thus, refrigerant does not flow through the cabin cooler 68. The remaining elements of the thermal management system 20 are configured as in the first mode described above. Refrigerant from the outlet line 64 flows only through the third expansion valve EXP3 to the battery chiller 72 before returning to the compressor return line 80 for recirculation through the compressor 40, the cabin heater 48, the first expansion valve EXPl (in full open or bypass configuration), and the environmental heat exchanger 56.

[0026] Fig. 4 schematically illustrates the thermal management system 20 in a fourth mode for cabin heating. In the fourth mode, the first expansion valve EXPl is utilized for metering refrigerant (not fully-open or bypassed), and the second and third expansion valves EXP2, EXP3 are closed. Thus, there is no flow of refrigerant through the cabin cooler 68 or the battery chiller 72 to the compressor return line 80. Rather, low pressure refrigerant flows to the compressor 40 through the shut-off valve 90 in the connector line 86, which is in the open position. From the compressor 40, high pressure, high temperature refrigerant is delivered to the cabin heater 48. Heat is transferred into the cabin 32 from the cabin heater 48 such that the vapor-phase refrigerant condenses into liquid, and warm liquid refrigerant flows to the first expansion valve EXPl, where it is expanded to a lower temperature and lower pressure. Depending on the type of refrigerant, condensation may not occur, and the cabin heater 48 may be referred to as a gas cooler with respect to the gaseous refrigerant therein. From the first expansion valve EXPl, the refrigerant flows to the environmental heat exchanger 56, which in this mode acts as an evaporator coil where a portion of the liquid refrigerant may vaporize to gaseous phase as heat is absorbed from ambient. From the environmental heat exchanger 56, the refrigerant flows back to the inlet of the compressor 40 through the open shut-off valve 90 and the accumulator 82. Thus, in the fourth mode the thermal management system 20 is operated as a heat pump to provide the cabin 32 with heat absorbed from ambient at the environmental heat exchanger 56. Since ambient conditions may vary drastically, cabin heating capability can be further increased by also operating the electric heater 92 in the HVAC air handling unit. Regardless of whether the electric heater 92 is operated to supplement the heat pump in the fourth mode, the air flap 94 is in the first or open position as shown in solid in Fig. 9 so that the cabin heater 48 and the electric heater 92 are in the HVAC airflow circuit between the fan 76 and the cabin 32. Although the cabin cooler 68 is also in the HVAC airflow circuit, the second expansion valve EXP2 being closed prevents the cabin cooler 68 from cooling the air delivered to the cabin 32.

[0027] Fig. 5 schematically illustrates the thermal management system 20 in a fifth mode for defrosting the environmental heat exchanger 56. In lower ambient temperatures, during heat pump operation according to the fourth mode illustrated in Fig. 4, the environmental heat exchanger 56 may become partially covered in ice which impedes airflow and heat transfer capability. Periodically, or upon sensing that the performance of the environmental heat exchanger 56 is reduced due to ice, the thermal management system 20 will temporarily switch to the fifth mode as shown in Fig. 5. In the defrost mode, the first expansion valve EXP1 is set to the fully open or bypass position so that the hot refrigerant is not metered or expanded, but rather higher pressure, warm refrigerant is passed to the environmental heat exchanger 56, thus providing heating for de-icing or defrosting. To maximize the effectiveness of the defrosting, operation of the fan 60 is stopped during the defrost mode. In order to expand the refrigerant downstream of the environmental heat exchanger 56 prior to returning to the compressor 40, the shut-off valve 90 is closed and at least one of the second and third expansion valves EXP2, EXP3 is open to meter the refrigerant and expand it to low pressure before it reaches the compressor return line 80, the accumulator 82, and the inlet of the compressor 40. In the illustrated schematic, the third expansion valve EXP3 leading to the battery chiller 72 remains closed while the second expansion valve EXP2 is opened to expand refrigerant into the cabin cooler 68. Depending on the circumstances and the request of the occupants in the cabin 32, operation of the electric heater 92 may begin or may be increased in order to maintain the desired cabin temperature. Assuming that the cabin heating mode of Fig. 4 is to resume upon completion of the defrosting of the environmental heat exchanger 56, the shut-off valve 90 and the expansion valves EXP1, EXP2, EXP3 return to the configurations of Fig. 4. Further, operation of the electric heater 92 may be decreased or stopped.

[0028] Fig. 6 schematically illustrates the thermal management system 20 in a sixth mode in which the thermal management system 20 operates primarily according to the second mode for cabin cooling, though modified to provide defogging of the cabin glass. Air to the cabin 32 is cooled and humidity removed by the cabin cooler 68, and then heated in the HVAC air handling unit. The air is heated by the hot gaseous refrigerant in the cabin heater 48. In some cases, the air may be heated by the electric heater 92. Unlike in the second mode for cabin cooling (without defogging) in which the air flap 94 is closed, the air flap 94 in the sixth mode of Fig. 6 is in the first or open position as shown in solid in Fig. 9 so that the cabin heater 48 and the electric heater 92 are in the HVAC airflow circuit between the fan 76 and the cabin 32. Heat is transferred from the cabin heater 48 to the cabin air resulting in condensation of the refrigerant from hot gas to hot liquid. The refrigerant flows toward and through the first expansion valve EXPl, which is in the fully open or bypass configuration. As the refrigerant already at least somewhat condensed before reaching the environmental heat exchanger 56, the environmental heat exchanger 56 may fill with refrigerant and become a sub-cooler. Refrigerant flows from the environmental heat exchanger 56 to the second expansion valve EXP2 where it is expanded for passage through the cabin cooler 68 before reaching the compressor return line 80. Although not explicitly shown, the third expansion valve EXP3 may be open to provide battery pack cooling in the sixth mode, or at least a subset of the sixth mode (e.g., depending upon a sensed battery pack temperature).

[0029] Fig. 7 schematically illustrates the thermal management system 20 in a seventh mode in which the thermal management system 20 operates similarly to the sixth mode of Fig. 6 in that both the cabin heater 48 and the cabin cooler 68 are active. However, unlike the sixth mode of Fig. 6, the seventh mode of Fig. 7 is designed to provide cabin heating with defogging. The first expansion valve EXPl downstream of the cabin heater 48 is not fully open, but only open with a restricted opening to expand the refrigerant to lower temperature and lower pressure. Thus, low pressure refrigerant is provided to the environmental heat exchanger 56, which acts as an evaporator coil and absorbs heat from the ambient air. From the environmental heat exchanger 56, refrigerant flows through the second expansion valve EXP2 to the cabin cooler 68 before passing through the compressor return line 80 to the accumulator 82 and the inlet of the compressor 80. The second expansion valve EXP2 may perform an additional throttling function to further reduce the temperature and pressure of the refrigerant or may be open to allow the refrigerant to pass through with a minimal change in temperature and pressure (e.g., less than 5 Kelvin temperature drop, along with the corresponding pressure drop from the known pressure-temperature relationship). Air to the cabin 32 is cooled and dried by the cold cabin cooler 68, and then further heated in the HVAC air handling unit to provide an overall heating effect to the cabin 32. The air is heated by the hot gaseous refrigerant in the cabin heater 48. In some constructions, the air may be heated by the electric heater 92. The air flap 94 in the seventh mode of Fig. 7 is in the first or open position as shown in solid in Fig. 9 so that the cabin heater 48 and the electric heater 92 are in the HVAC airflow circuit between the fan 76 and the cabin 32. Though not as likely as in the sixth mode, since ambient temperatures are presumably lower when operating in the seventh mode, the third expansion valve EXP3 may be open to provide battery pack cooling in the seventh mode, or at least a subset of the seventh mode (e.g., depending upon a sensed battery pack temperature).

[0030] Fig. 8 illustrates a front portion of the electric vehicle 24 in further detail, illustrating an exemplary arrangement of the components of the thermal management system 20 of Figs. 1-7. The elements of the system 20 that are positioned in the HVAC air handling unit (i.e., the cabin cooler 68, the cabin heater 48, and the electric heater 92) are positioned rearward of the other components, and closest to the cabin 32 to establish fluid communication therewith. Though not shown, the fan 76 is also positioned along the HVAC air handling unit as shown in Fig. 9. The remaining components of the thermal management system 20 not provided in the HVAC air handling unit are positioned under a front hood 26 of the electric vehicle 24 (i.e., the under-hood utility space conventionally known as the "engine bay" in a conventional front-engine combustion engine-powered vehicle). The forwardmost component is the environmental heat exchanger 56, located at the front end of the electric vehicle 24 to maximize the ability to exchange heat with ambient air. Two, three, or all four of the valves of the thermal management system 20 (i.e., the shut-off valve 90 and the three expansion valves EXP1, EXP2, EXP3) can be located in a single valve block 100, indicated by the dashed line box. The valve block 100 can physically integrate the plurality of valves while maintaining actuation of each valve function (e.g., by individual actuators or mechanisms responsive to a controller, not shown). Thus, installation into the vehicle 24 can be simplified without limiting system performance. The valve block 100 can be positioned between the HVAC air handling unit and the compressor 40 along the longitudinal direction of the vehicle 24.

[0031] Though not discussed in detail above, the thermal management system 20 requires a plurality of sensors to operate and facilitate switching amongst the various modes of performance. All of the sensors can be provided in communication with the controller, and the controller is also in communication with a plurality of cabin controls (selectors for the cabin occupants to activate the various modes). Cooling of the battery pack 28, however, is not managed by the cabin occupants but rather automatically in response to monitoring of a parameter indicative of the battery pack temperature (e.g., directly measuring battery pack temperature, or measuring the temperature of a fluid in communication with the battery pack 28). The plurality of system sensors can include a first sensor 108 operable to measure refrigerant pressure and optionally temperature at the compressor outlet (e.g., in the discharge line 44), and a second sensor 112 operable to measure refrigerant pressure and optionally temperature returning to the compressor inlet (e.g., at the compressor return line 80). The plurality of system sensors can further include a first temperature sensor 116 operable to measure refrigerant temperature T_{env} exiting the environmental heat exchanger 56, a second temperature sensor 120 operable to measure refrigerant temperature T_c exiting the battery chiller 72, and a third temperature sensor 124 operable to measure refrigerant temperature T_e exiting the cabin cooler 68. The temperature sensors 116, 120, 124 can be used for the controller to evaluate and ensure that the desired amount of evaporation of the refrigerant has occurred (according to and dependent upon the particular mode). Though the first, second, and third temperature sensors 116, 120, 124 necessarily measure refrigerant temperature in different locations, a single sensor block can be pre-manufactured to include some or all of the sensors 112, 116, 120, 124. Thus, installation into the vehicle 24 can be simplified.

[0032] CLAIMS

What is claimed is:

1. An electric vehicle thermal management system comprising:

a refrigeration system including

an electrically-driven compressor,

a cabin heater,

a cabin cooler,

first, second, and third expansion valves,

an environmental heat exchanger,

a battery chiller positioned between a downstream side of the third expansion valve and an inlet of the compressor,

a connector line provided between a downstream side of the environmental heat exchanger and the inlet of the compressor to selectively bypass the second and third expansion valves, wherein a valve is operable to selectively open and close the connector line, and

a circulating refrigerant;

an air handling unit having a fan operable to blow air across the cabin cooler to the cabin; and

a bypass device is operable in both a first configuration in which the cabin heater is active for transferring heat to the cabin and a bypass configuration in which the bypass device blocks the cabin heater from transferring heat to the cabin,

wherein the refrigeration system is configurable to selectively provide cabin cooling in a first mode operating as an air conditioning system to transfer thermal energy from the refrigerant to ambient at the environmental heat exchanger, and to provide cabin heating in a second mode operating as a heat pump to absorb thermal energy into the refrigerant from ambient at the environmental heat exchanger, and

wherein the first expansion valve is operable to independently control the expansion of the refrigerant to the environmental heat exchanger and is further operable to pass the refrigerant to the environmental heat exchanger without expansion, and wherein the second expansion valve is operable to independently control the expansion of the refrigerant to the cabin cooler and is further operable to block the refrigerant from flowing into the cabin cooler from the environmental heat exchanger.

2. The electric vehicle thermal management system of claim 1, further comprising an electric heater positioned in the air handling unit with the cabin heater and the cabin cooler.

3. The electric vehicle thermal management system of claim 2, wherein the electric heater is a positive temperature coefficient heater.

4. The electric vehicle thermal management system of claim 1, wherein the cabin cooler and the battery chiller, along with the respective second and third expansion valves are connected in parallel and share a common compressor return line to the inlet of the compressor.

5. The electric vehicle thermal management system of claim 1, wherein, along with cabin cooling, the refrigeration system is further operable to selectively provide battery cooling in the first mode by independent control of expansion of the refrigerant through the third expansion valve to the battery chiller.

6. The electric vehicle thermal management system of claim 1, wherein in the first mode of operation for cabin cooling, the refrigerant is routed from the compressor through the cabin heater, through the first expansion valve without expansion, and through the environmental heat exchanger before the refrigerant is expanded through the second expansion valve to the cabin cooler, and wherein the bypass device is in the bypass configuration in the first mode to deactivate the cabin heater.

7. The electric vehicle thermal management system of claim 6, wherein an additional mode of operation for cabin defogging with cabin cooling is provided when the bypass device is moved from the bypass configuration to the first configuration.

8. The electric vehicle thermal management system of claim 1, wherein in the second mode of operation for cabin heating, the second expansion valve is closed to block the refrigerant from being routed through the cabin cooler, and wherein in an additional mode of operation for cabin defogging with cabin heating, the refrigerant is sequentially passed through the first expansion valve into the environmental heat exchanger and then through the second expansion valve to the cabin cooler after exiting the cabin heater.

9. The electric vehicle thermal management system of claim 1, wherein, in a battery cooling mode, the refrigerant is routed from the compressor through the cabin heater, through the first expansion valve without expansion, and through the environmental heat exchanger, before the refrigerant is expanded through the third expansion valve to the battery chiller.

10. The electric vehicle thermal management system of claim 9, wherein, in the battery cooling mode, the bypass device is in the bypass configuration to deactivate the cabin heater.

11. The electric vehicle thermal management system of claim 1, wherein the valve and all three of the first, second, and third expansion valves are provided in an integrated valve component provided with refrigerant connections to each of the environmental heat exchanger, the compressor, the battery chiller, the cabin cooler, and the cabin heater.

12. An electric vehicle thermal management system comprising:

a refrigeration system including

an electrically-driven compressor,

a cabin heater,

a cabin cooler,

an environmental heat exchanger,

a battery chiller positioned between a downstream side of the third expansion valve and an inlet of the compressor,

a first expansion valve positioned between the cabin heater and the environmental heat exchanger, the first expansion valve having at least a first configuration operable to restrict a flow of refrigerant for expansion to the environmental heat exchanger and a second bypass configuration operable to pass a flow of refrigerant to the environmental heat exchanger without expansion,

a second expansion valve, positioned immediately upstream of the cabin cooler, the second expansion valve having at least a first configuration operable to restrict a flow of refrigerant for expansion to the cabin cooler and a second closed configuration operable to block a flow of refrigerant, and

a third expansion valve positioned immediately upstream of the battery chiller, the third expansion valve having at least a first configuration operable to restrict a flow of refrigerant for expansion to the battery chiller and a second closed configuration operable to block a flow of refrigerant,

a connector line provided between a downstream side of the environmental heat exchanger and the inlet of the compressor to selectively bypass the second and third expansion valves, wherein a valve is operable to selectively open and close the connector line, and

a circulating refrigerant;

an air handling unit having a fan operable to blow air across the cabin cooler to the cabin; and

a bypass device operable in both a first configuration in which the cabin heater is active for transferring heat to the cabin and a bypass configuration in which the bypass device blocks the cabin heater from transferring heat to the cabin, wherein the thermal management system is operable to selectively provide all of the following operating modes by switching the first expansion valve between the first and bypass configurations, switching the second expansion valve between the first and closed configurations, switching the third expansion valve between the first and closed configurations, switching the connector line between open and closed, and switching the bypass device between the first configuration and the bypass configuration:

a combined cabin and battery cooling mode, a cabin cooling mode, a battery cooling mode, a cabin heating mode, a cabin cooling with defogging mode, and a cabin heating with defogging mode.

13. The electric vehicle thermal management system of claim 12, wherein in both the combined cabin and battery cooling mode and the cabin cooling mode, the refrigeration system is operable to transfer thermal energy from the refrigerant to ambient at the environmental heat exchanger, and wherein the refrigeration system is configurable to operate as a heat pump in the cabin heating mode to absorb thermal energy into the refrigerant from ambient at the environmental heat exchanger.

14. The electric vehicle thermal management system of claim 12, wherein the connector line valve and all three of the first, second, and third expansion valves are provided in an integrated valve component provided with refrigerant connections to each of the environmental heat exchanger, the compressor, the battery chiller, the cabin cooler, and the cabin heater.

15. The electric vehicle thermal management system of claim 12, further comprising an electric heater positioned in the air handling unit with the cabin heater and the cabin cooler.

16. The electric vehicle thermal management system of claim 15, wherein the electric heater is a positive temperature coefficient heater.

17. The electric vehicle thermal management system of claim 12, wherein the cabin cooler and the battery chiller, along with the respective second and third expansion valves are connected in parallel and share a common compressor return line to the inlet of the compressor.

18. The electric vehicle thermal management system of claim 12, wherein in the cabin cooling mode, the refrigerant is routed from the compressor through the cabin heater, through the first expansion valve in the bypass configuration, and through the environmental heat exchanger before the refrigerant is expanded through the second expansion valve to the cabin cooler, and wherein the bypass device is in the bypass configuration in the first mode to deactivate the cabin heater.

19. The electric vehicle thermal management system of claim 18, wherein an additional mode of operation for cabin defogging and cabin cooling is provided when the bypass device is moved from the bypass configuration to the first configuration.

20. The electric vehicle thermal management system of claim 12, wherein in the cabin heating mode, the second expansion valve is in the closed configuration to block the refrigerant from being routed through the cabin cooler, and wherein in the cabin heating with defogging mode, the refrigerant is sequentially passed through the first expansion valve into the environmental heat exchanger and then through the second expansion valve to the cabin cooler after exiting the cabin heater.

21. The electric vehicle thermal management system of claim 12, wherein, in the battery cooling mode, the refrigerant is routed from the compressor through the cabin heater, through the first expansion valve in the bypass configuration, and through the environmental heat exchanger, before the refrigerant is expanded through the third expansion valve to the battery chiller.

22. The electric vehicle thermal management system of claim 21, wherein, in the battery cooling mode, the bypass device is in the bypass configuration to deactivate the cabin heater.

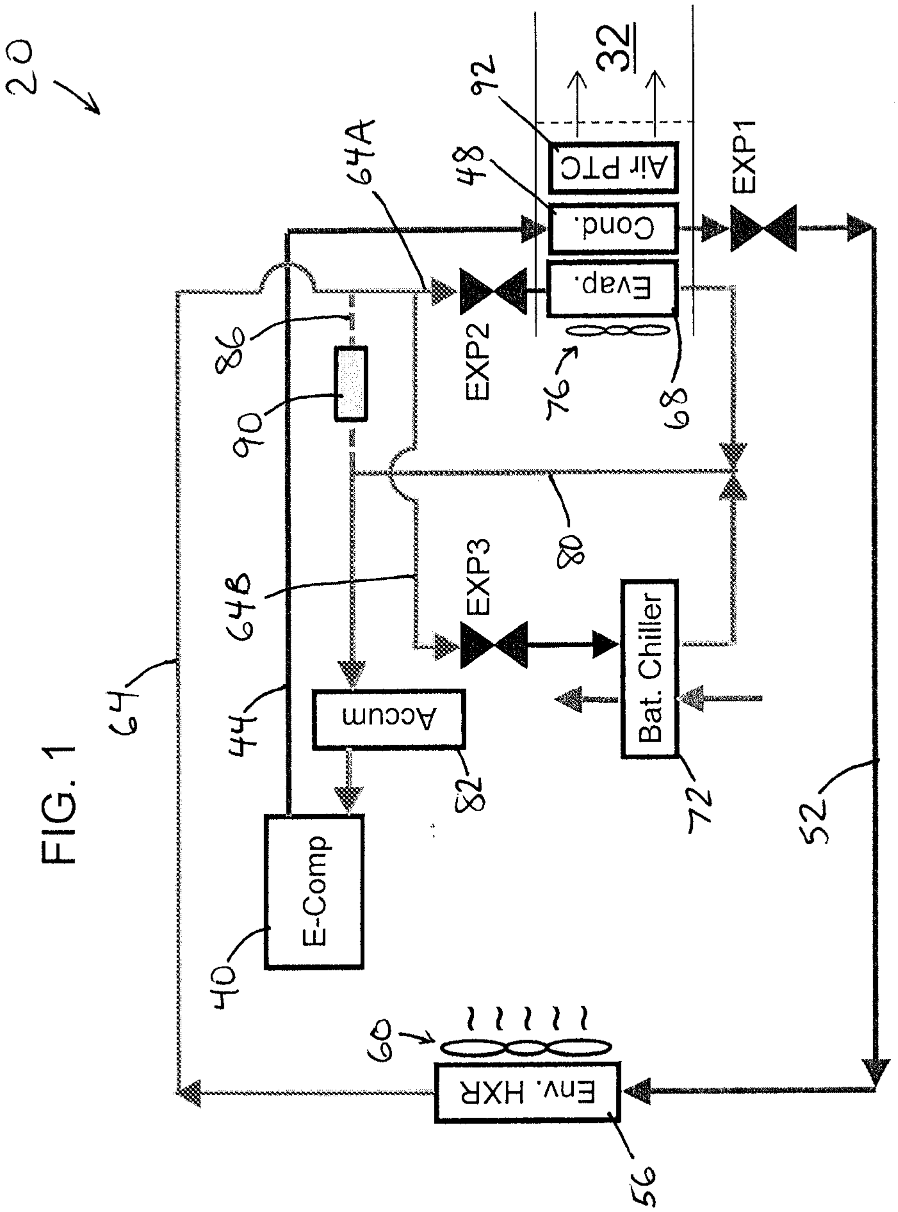


FIG. 1

Cabin & Battery Cooling

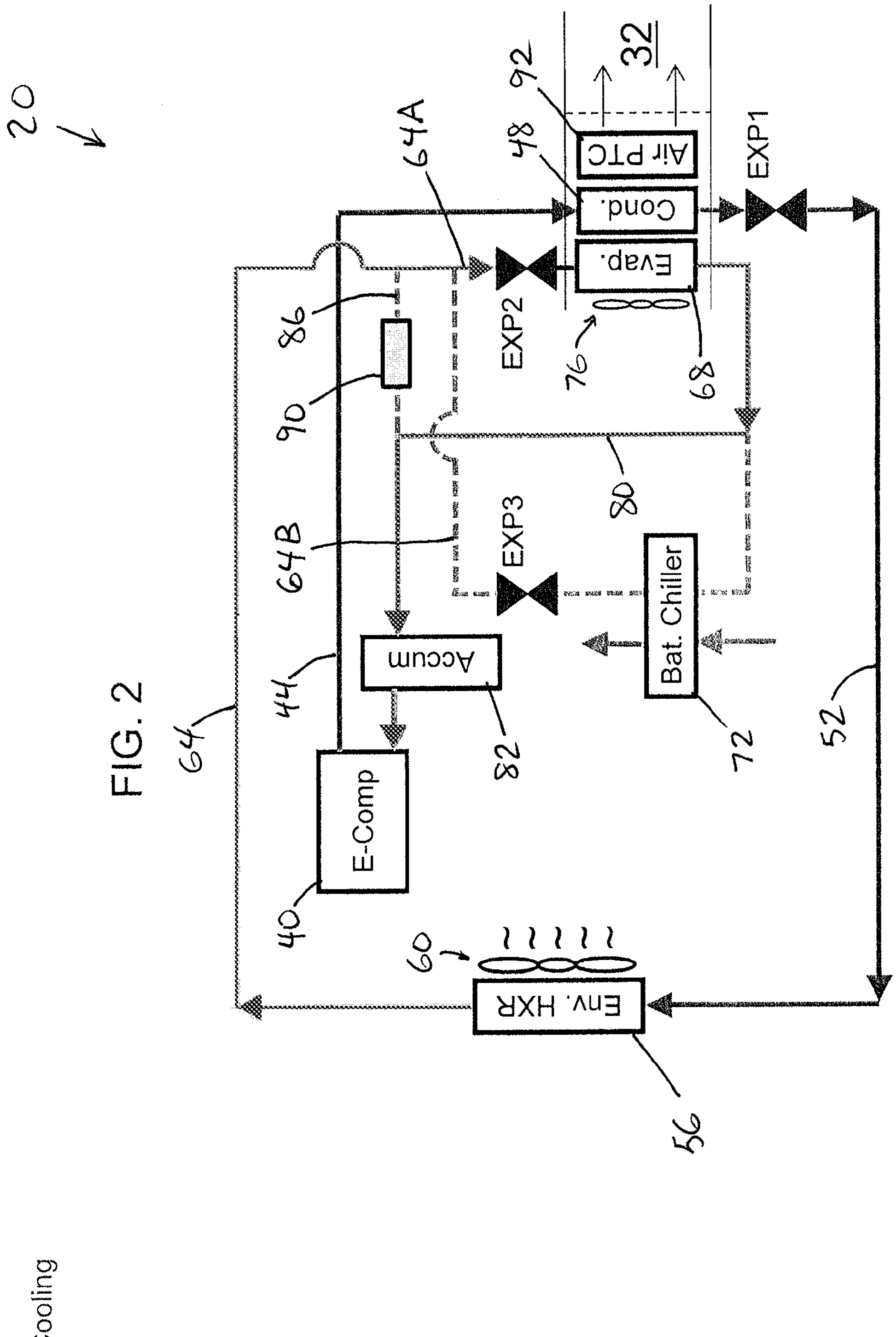


FIG. 2

Cabin Cooling

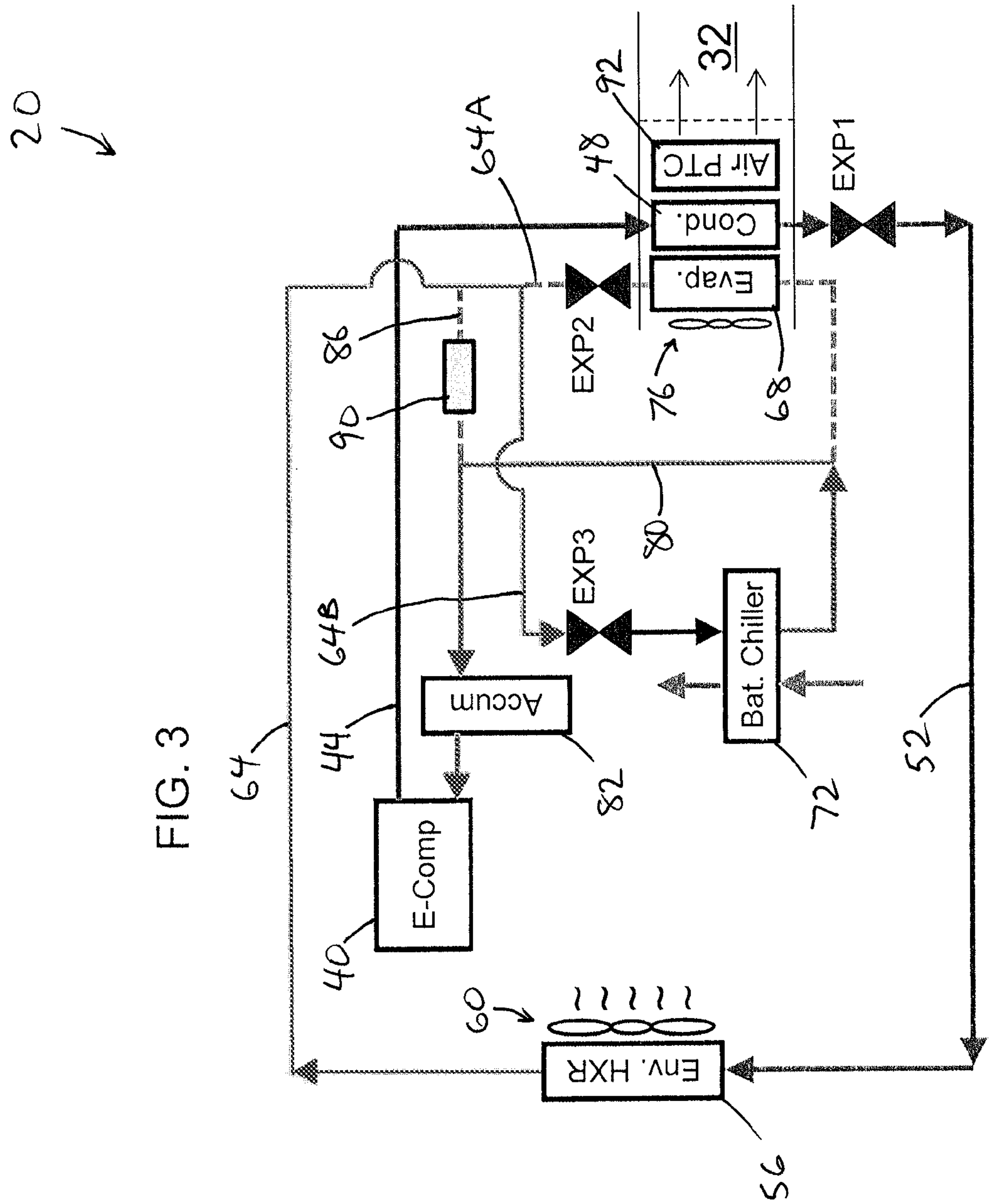


FIG. 3

Battery Cooling

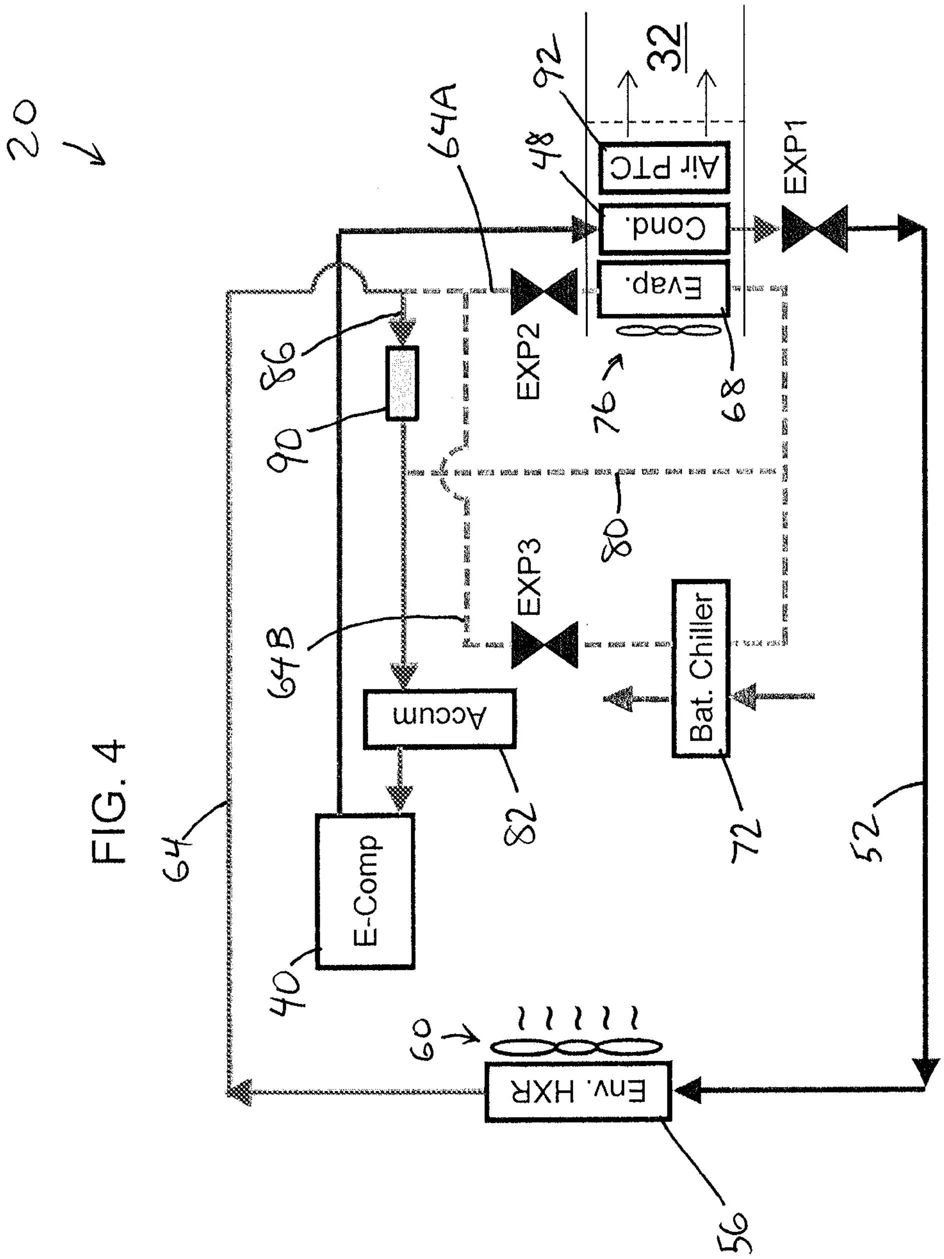
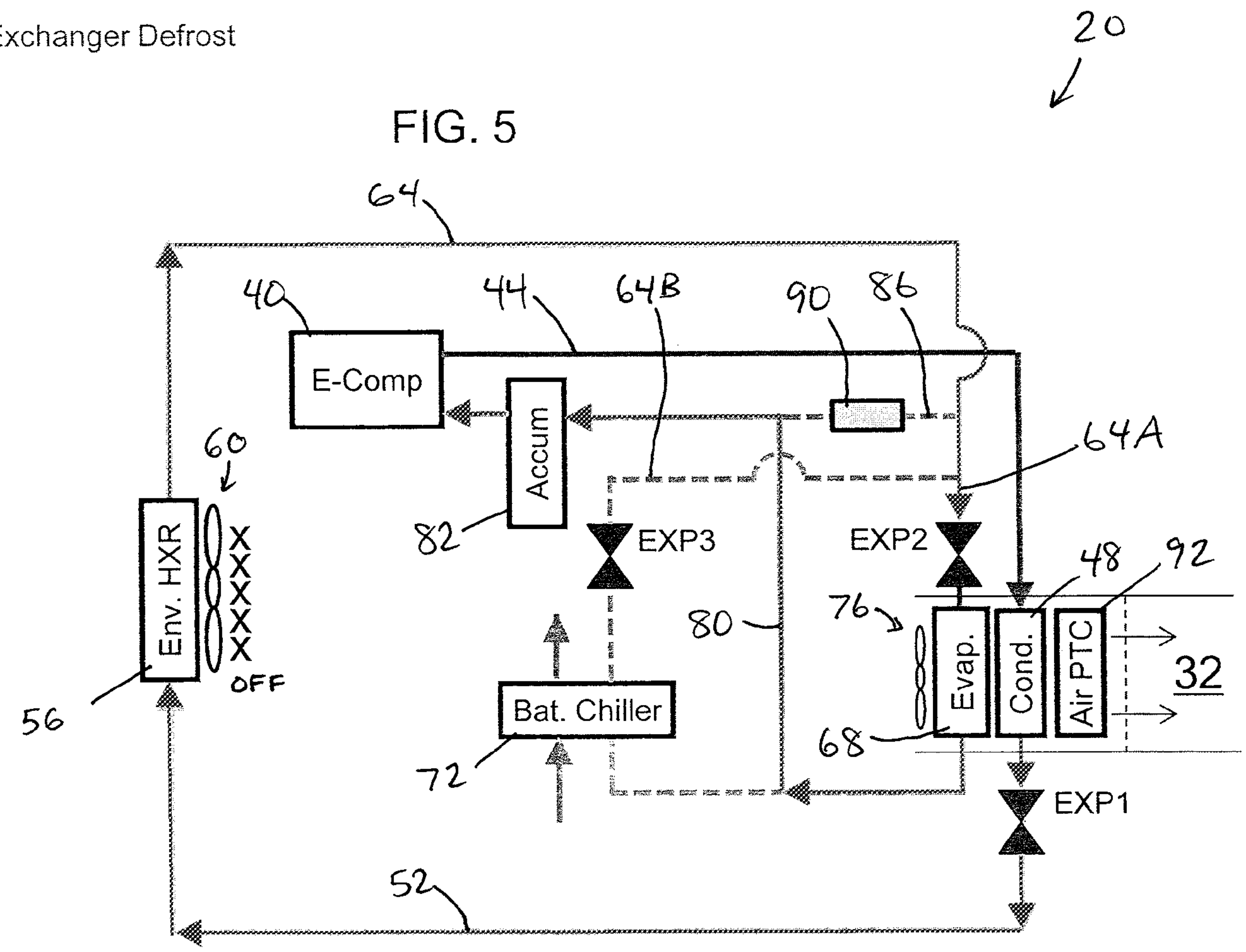


FIG. 4

Cabin Heating

Environmental Heat Exchanger Defrost

FIG. 5



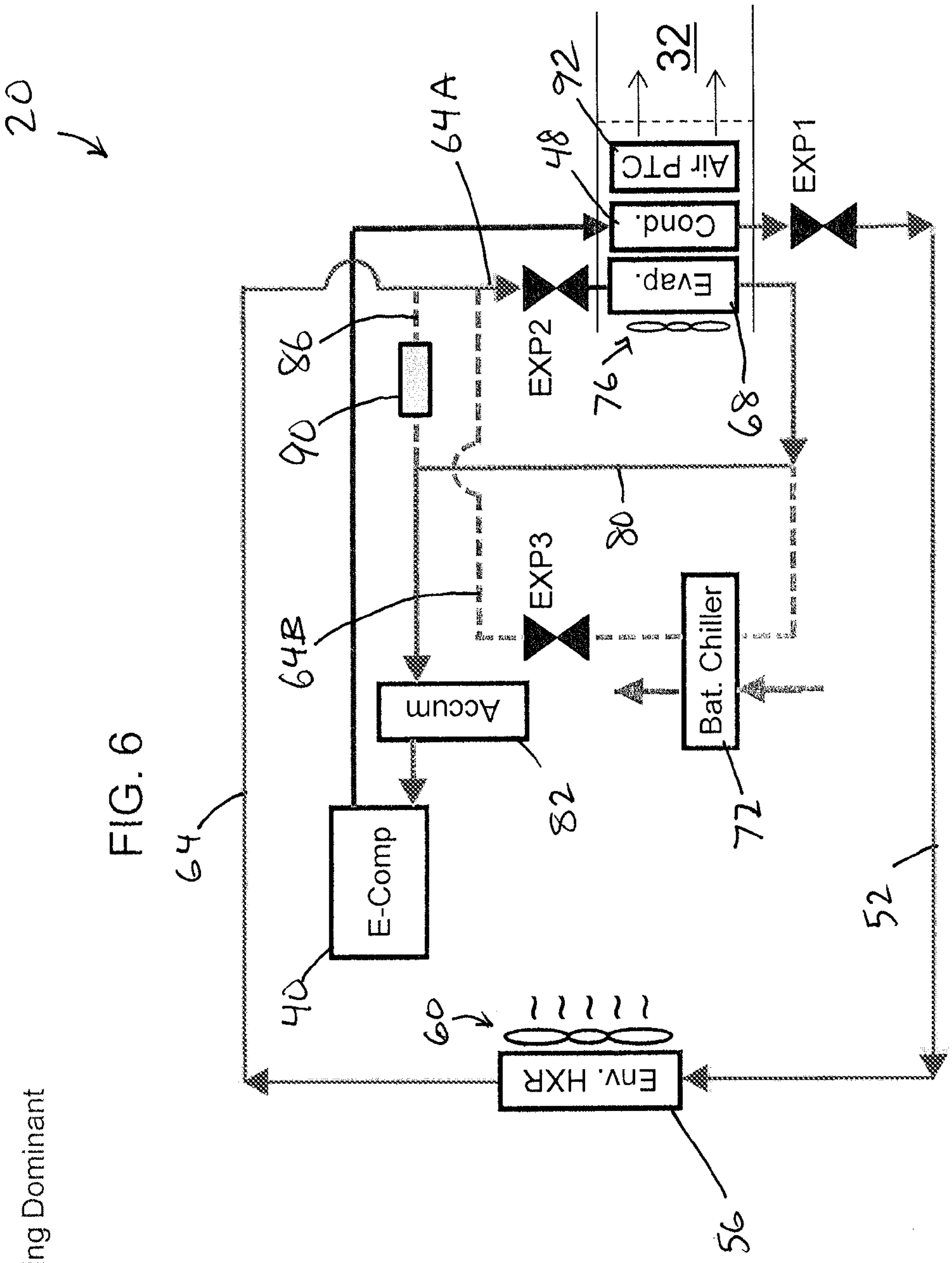
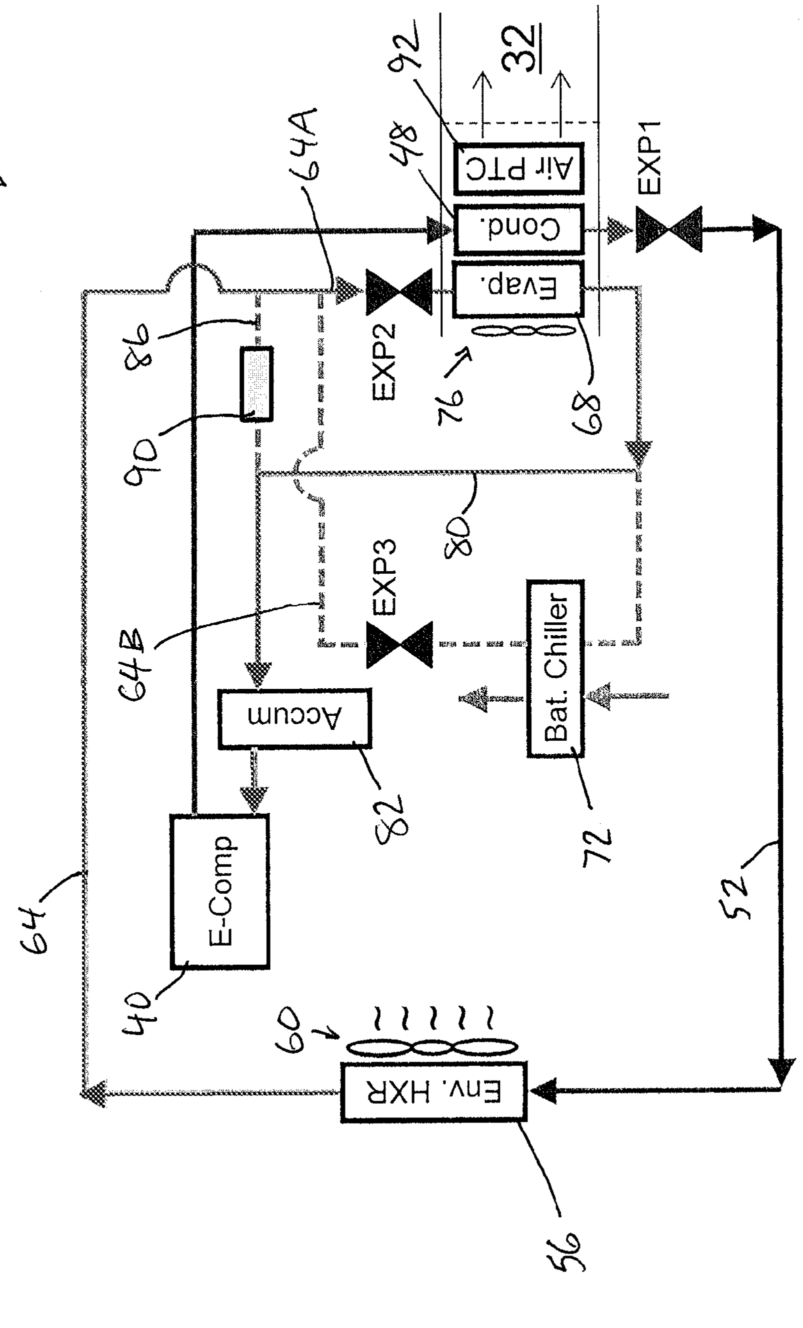


FIG. 6

Defog 1: Cabin Cooling Dominant

Defog 2: Cabin Heating Dominant

FIG. 7



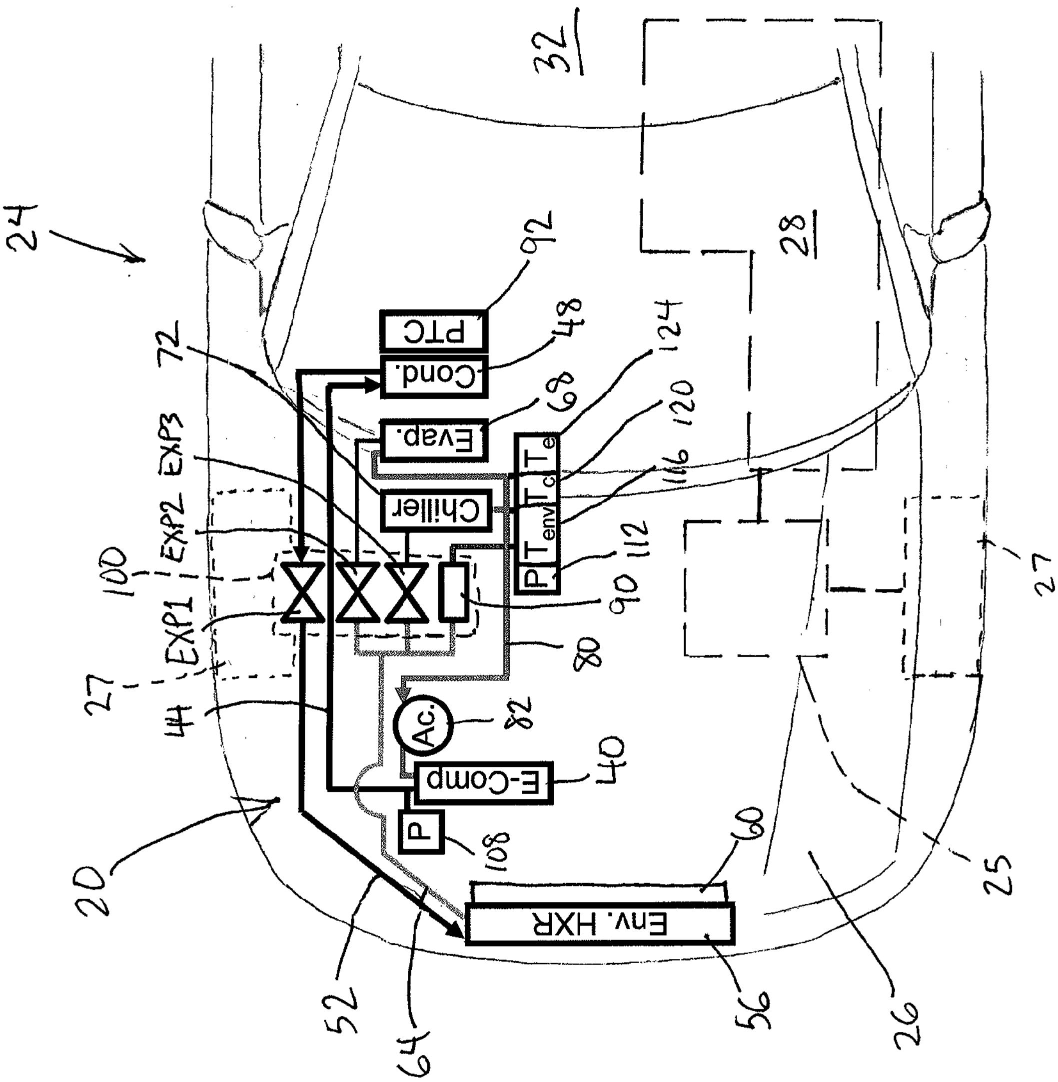

PTC
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FIG. 8

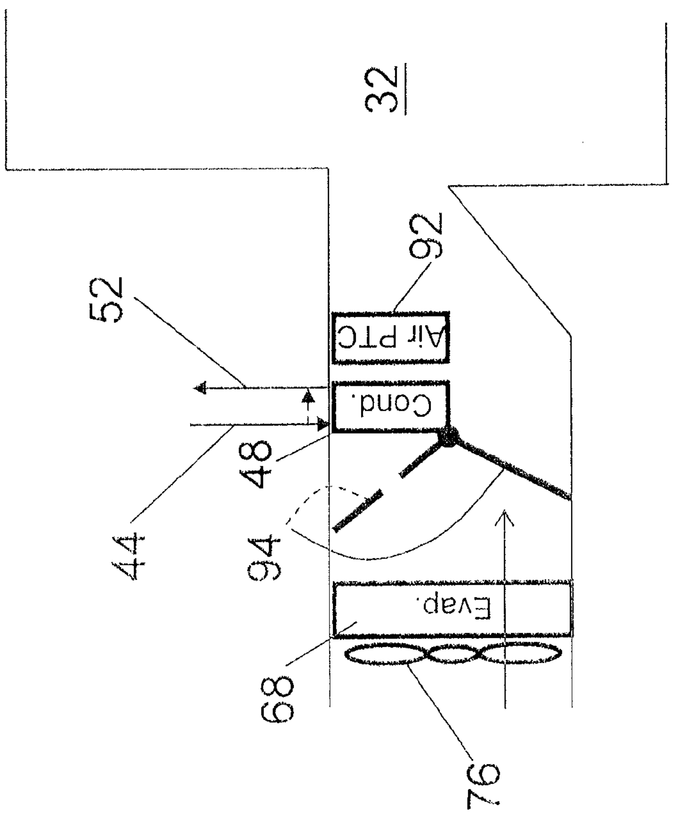

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2017/082376

A. CLASSIFICATION OF SUBJECT MATTER

B60H 1/00(2006.01)i

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)

B60H

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)

SIPOABS,CNABS,DWPI,CNKI:heater? , management, thermal, cooler? , compressor? , vehicle, battery, chiller

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 105835655 A (FORD GLOBAL TECHNOLOGIES LLC) 10 August 2016 (2016-08-10) description, paragraphs [0027]-[0038] and figures 2-3	1-22
A	CN 103968600 A (GM GLOBAL TECHNOLOGY OPERATIONS LLC) 06 August 2014 (2014-08-06) see the whole document	1-22
A	CN 103612570 A (CHERY AUTOMOBILE CO LTD) 05 March 2014 (2014-03-05) see the whole document	1-22
A	US 2016344075 A1 (FORD GLOBAL TECH LLC) 24 November 2016 (2016-11-24) see the whole document	1-22

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

* Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be of particular relevance
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- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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- "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
15 January 2018	**26 January 2018**

Name and mailing address of the ISA/CN	Authorized officer
STATE INTELLECTUAL PROPERTY OFFICE OF THE P.R.CHINA **6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing 100088** **China**	**WU,Fei**
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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2017/082376

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
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				CN	103968600	B	07 July 2017
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				DE	102016108571	A1	24 November 2016