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(54) System and method for heat transfer

System und Verfahren zur Wärmeübertragung

Système et procédé de transfert de chaleur

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(56) References cited:
WO-A-03/054469 WO-A-2004/031675
WO-A-2004/040218 DE-A1- 19 941 398
US-A- 4 470 450 US-A- 4 890 668
US-A1- 2002 007 937 US-A1- 2003 051 857
US-B1- 7 004 240

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Description

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Application No. 60/486,467, filed July 14, 2003, and is a continuation-in-part of U.S. Application 10/602,022, filed June 24, 2003, which claims priority to U.S. Application 60/391,006, filed June 24, 2002, and is a continuation-in-part of U.S. Application No. 09/896,561, filed June 29, 2001, which itself claims priority to U.S. Application No. 60/215,588, filed June 30, 2000.

TECHNICAL FIELD

[0002] This description relates to a system and method for heat transfer.

BACKGROUND

[0003] Heat transport systems are used to transport heat from one location (the heat source) to another location (the heat sink). Heat transport systems can be used in terrestrial or extraterrestrial applications. For example, heat transport systems may be integrated by satellite equipment that operates within zero or low-gravity environments. As another example, heat transport systems can be used in electronic equipment, which often requires cooling during operation.

[0004] Loop Heat Pipes (LHPs) and Capillary Pumped Loops (CPLs) are passive two-phase heat transport systems. Each includes an evaporator thermally coupled to the heat source, a condenser thermally coupled to the heat sink, fluid that flows between the evaporator and the condenser, and a fluid reservoir for expansion of the fluid. The fluid within the heat transport system can be referred to as the working fluid. The evaporator includes a primary wick and a core that includes a fluid flow passage. Heat acquired by the evaporator is transported to and discharged by the condenser. These systems utilize capillary pressure developed in a fine-pored wick within the evaporator to promote circulation of working fluid from the evaporator to the condenser and back to the evaporator. The primary distinguishing characteristic between an LIT and a CPL is the location of the loop's reservoir, which is used to store excess fluid displaced from the loop during operation. In general, the reservoir of a CPL is located remotely from the evaporator, while the reservoir of an LHP is co-located with the evaporator.

[0005] Prior art document US2002/0007937 A1 discloses a LHP having a plural capillary evaporator structures wherein phase of the working fluid is controlled to maintain system stability. Prior art document US 4,470,450 discloses a heat transfer system wherein a closed loop heat transfer system comprises a heat pip and an external liquid phase pump that augments capillary pumping in the heat pipe. Prior art document US 4,890,668 discloses a closed loop heat transfer system

for achieving precise phase control over a working fluid circulating through a two-phase closed-loop heat transfer system.

SUMMARY

[0006] The present invention provides a system as defined in claim 1 and a method as defined in claim 30. According to one general aspect, a system includes a primary evaporator operable to facilitate heat transfer by evaporating received liquid to obtain vapor, the primary evaporator including a first port for receiving the liquid from a liquid line, a second port for outputting the vapor to a vapor line, and a third port for outputting excess liquid received from the liquid line to an excess fluid line. A condensing system is operable to receive the vapor from the vapor line, to condense at least some of the vapor, and to output the liquid to the liquid line.

[0007] A reservoir is in fluid communication with the condensing system, and the liquid is obtained at least partially from the reservoir. In the system, a primary loop includes the condensing system, the primary evaporator, the liquid line, and the vapor line, the primary loop being operable to provide a heat transfer path, and a secondary loop includes the condensing system, the primary evaporator, the liquid line, the vapor line, and the excess fluid line. The secondary loop is operable to provide a venting path for removing other vapor that is present within the liquid from the primary evaporator.

[0008] Implementations include the following features. The liquid in the primary evaporator and received from the liquid line includes the excess liquid in excess of a liquid amount necessary to maintain saturation of a primary wick within a core of the primary evaporator. In this case, the primary evaporator may include a secondary wick that is operable to perform phase separation of the other vapor from the liquid for output through the excess fluid line. Further, the primary wick and the secondary wick of the primary evaporator maintain capillary pumping of the liquid, the excess liquid, and the vapor, so as to maintain flow control to and through the primary evaporator.

[0009] A mechanical pump may be included that is operable to facilitate the heat transfer by actively pumping the liquid for evaporation by the primary evaporator, and for output as the excess liquid through the third port to the excess fluid line. In this case, the reservoir may be positioned between an output of the condensing system and an input of the mechanical pump, or the mechanical pump may be positioned between an input of the condensing system and an output of the primary evaporator.

[0010] A bypass valve may be included in parallel with the mechanical pump, and may be operable to bypass the mechanical pump during a passive pumping operation of liquid for evaporation by the primary evaporator. The mechanical pump may include a liquid pump that is oriented in series with the liquid line and positioned between the condensing system and the primary evapora-

tor, or a vapor compressor that is oriented in series with the vapor line and positioned between the primary evaporator and the condensing system.

[0011] A sensor may be included that is operable to communicate a saturation level of a wick of the primary evaporator to the mechanical pump, wherein a pumping pressure delivered by the mechanical pump is adjusted, based on the saturation level, so as to maintain saturation of the wick with the liquid. A liquid bypass valve may be connected between the liquid line and the vapor line and may be operable to maintain constant pump speed operations of the mechanical pump. The primary evaporator may include a primary wick and a secondary wick, compositions of which may comprise metal.

[0012] A priming system may be included within the secondary loop, and the priming system may include a secondary evaporator coupled to the vapor line, and a secondary reservoir may be in fluid communication with the secondary evaporator and coupled to the primary evaporator by the excess fluid line, wherein the priming system may be operable to provide the liquid to the primary evaporator at least partially from the secondary reservoir. The condensing system may include a first condenser within the primary loop and coupled to the liquid line and to the vapor line, and a second condenser within the secondary loop and coupled to the excess fluid line and to the secondary reservoir.

[0013] The third port of the primary evaporator may be primarily used to output the excess liquid to the excess fluid line, and the third port may include a subport for outputting the other vapor to a vapor line, such that the vapor line is included within the secondary loop.

[0014] The liquid line may be coaxial to and contained within the excess fluid line. A second primary evaporator may be connected in parallel with the primary evaporator within the primary loop. A back pressure regulator may be oriented in series with the vapor line and positioned between the primary evaporator and the condensing system, and may be operable to substantially equalize heat load between the primary evaporator and the secondary primary evaporator. In this case, the back pressure regulator may restrict vapor from reaching the condensing system until a vapor space of the primary evaporator and of the second primary evaporator is substantially devoid of liquid.

[0015] A second primary evaporator may be oriented in series with the primary evaporator within the primary loop. The condensing system may include a plurality of condensers connected in parallel to one another. In this case, liquid outputs may be associated with each of the plurality of condensers and may be operable to output the liquid to the primary evaporator, and condenser regulators may be coupled to the liquid outputs and operable to regulate liquid flow therefrom.

[0016] A second primary evaporator may be connected with the primary evaporator within the primary loop, and a thermal storage unit may be coupled to the second primary evaporator. A second primary evaporator may

be connected with the primary evaporator within the primary loop, and first and second flow controllers may be connected to the primary evaporator and the second primary evaporator, respectively, and may be operable to regulate liquid flow to the primary evaporator and the second primary evaporator, respectively, so as to ensure a substantially equal heat load distribution between the evaporators.

[0017] A second primary evaporator may be connected with the primary evaporator within the primary loop, and a condensing heat exchanger may be coupled to the second primary evaporator. A spray-cooled evaporator may be coupled to the condensing heat exchanger by way of a mechanical pump. The condensing system may include a body-mounted radiator, or may include a deployable or steerable radiator.

[0018] According to another general aspect, liquid is evaporated from a primary wick of a primary evaporator to thereby obtain vapor, the vapor is output through a vapor line coupled to the primary evaporator, and the vapor from the vapor line is condensed within a condensing system. The liquid is returned to the primary evaporator through a liquid line coupled to the primary evaporator, where a saturation amount of the liquid is provided so as to maintain a saturation of the primary wick during the evaporating. Excess liquid beyond the saturation amount is provided to the primary evaporator at least partially from a reservoir, through the liquid line, and the excess liquid and other vapor within the primary evaporator is swept to the condensing system.

[0019] Implementations may include one or more of the following features. For example, in evaporating liquid from the primary wick of the primary evaporator capillary pumping of the liquid, the excess liquid, and the vapor may be maintained, so as to maintain flow control to and through the primary evaporator.

[0020] Also, in outputting the vapor, the vapor may be output through a first port of the primary evaporator. In returning the liquid and providing excess liquid, the liquid and excess liquid may be returned through a second port of the primary evaporator. In sweeping the excess liquid and undesired vapor, the excess liquid and undesired vapor may be swept from a third port of the primary evaporator.

[0021] Outputting the vapor may include outputting the vapor through a first port of the primary evaporator. Returning the liquid and providing excess liquid may include returning the liquid and excess liquid through a second port of the primary evaporator, and sweeping the excess liquid and other vapor may include sweeping the excess liquid from a third port of the primary evaporator, and sweeping the other vapor from a fourth port of the primary evaporator.

[0022] Sweeping the excess liquid and other vapor may include separating the liquid and excess liquid from the other vapor with a secondary wick of the primary evaporator. Providing excess liquid may include pumping the excess liquid from the reservoir using a mechanical

pump. In this case, the mechanical pump may be bypassed using a bypass valve in parallel with the mechanical pump, during a passive pumping operation of the liquid for evaporation by the primary evaporator.

[0023] Pumping the excess liquid may include pumping the liquid and the excess liquid using a liquid pump that is oriented in series with the liquid line and positioned between the condensing system and the primary evaporator, or may include pumping the vapor to the condensing system using a vapor compressor that is oriented in series with the vapor line and positioned between the primary evaporator and the condensing system.

[0024] Providing excess liquid may include providing the excess liquid from a priming system in which the reservoir is in fluid communication with a secondary evaporator, where the reservoir may be coupled to the primary evaporator. In this case, condensing the vapor may include condensing the vapor within a first condenser of the condensing system, the first condenser being coupled to the liquid line and to the vapor line, and sweeping the excess liquid and undesired vapor may include condensing undesired vapor within a second condenser of the condensing system, where the second condenser may be coupled to a mixed fluid line and to the reservoir.

[0025] According to another general aspect, a system includes a heat transfer system including a main evaporator having a core, a primary wick, a secondary wick, a first port, a second port, and a third port, as well as a condenser coupled to the main evaporator by a liquid line and a vapor line. A heat transfer system loop is defined by the condenser, the liquid line, the vapor line, the first port, and the second port. A venting system is configured to remove vapor bubbles from the core of the main evaporator. The venting system includes a pumping system operable to provide excess liquid to the main evaporator beyond a saturation amount of liquid needed for saturating the primary wick, and a reservoir in fluid communication with the pumping system and providing the excess liquid. The vapor bubbles are vented from the core of the main evaporator through the third port, and a venting loop is defined by the condenser, the liquid line, the vapor line, the first port of the main evaporator, and the third port of the main evaporator.

[0026] Implementations may include one or more of the following features. For example, the pumping system may include a mechanical pump.

[0027] The primary wick and the secondary wick of the main evaporator may maintain capillary pumping of the liquid, the excess liquid, and the vapor, so as to maintain flow control to and through the primary evaporator. In this case, the pumping system may include a secondary evaporator in fluid communication with the reservoir and coupled to the vapor line. Further, The reservoir may be in fluid communication with the secondary wick of the main evaporator through a mixed fluid line coupled to the third port of the main evaporator. The excess liquid may be substantially removed from the core of the main evaporator through a fourth port of the main evaporator.

[0028] Other features will be apparent from the description, the drawings, and the claims.

DESCRIPTION OF DRAWINGS

[0029]

FIG. 1 is a schematic diagram of a heat transport system not in accordance with the present invention. FIG. 2 is a diagram of an implementation of the heat transport system schematically shown by FIG. 1.

FIG. 3 is a flow chart of a procedure for transporting heat using a heat transport system.

FIG. 4 is a graph showing temperature profiles of various components of the heat transport system during the process flow of FIG. 3.

FIG. 5A is a diagram of a three-port main evaporator shown within the heat transport system of FIG. 1.

FIG. 5B is a cross-sectional view of the main evaporator taken along 5B-5B of FIG. 5A.

FIG. 6 is a diagram of a four-port main evaporator that can be integrated into a heat transport system illustrated by FIG. 1.

FIG. 7 is a schematic diagram of an implementation of a heat transport system not in accordance with the present invention.

FIGS. 8A, 8B, 9A, and 9B are perspective views of applications using a heat transport system.

FIG. 8C is a cross-sectional view of a fluid line taken along 8C-8C of FIG. 8A.

FIGS. 8D and 9C are schematic diagrams of the implementations of the heat transport systems of FIGS. 8A and 9A, respectively.

FIG. 10 is a schematic diagram of another implementation of a heat transport system not in accordance with the present invention.

FIG. 11 is a schematic diagram of an implementation of an actively-pumped heat transport system in line with the claimed invention.

FIGS. 12-16 are schematics of implementations of the system of FIG. 11 that demonstrate various examples of thermal management components and features.

FIGS. 17A-17E are examples of mechanical pumps that may be used in the systems of FIGS. 11-16.

FIGS. 18A-18C illustrate examples of different evaporator and condenser architectures for use with the systems of FIGS. 11-16

FIG. 19 is a diagram of an example of a condenser flow regulator.

FIG. 20 is a diagram of an example of a back pressure regulator.

FIGS. 21 and 22 are diagrams of evaporator failure isolators.

FIGS. 23 and 24 illustrate examples of capillary pressure sensors.

FIG. 25 is a pressure drop diagram 2500 for a thermal management system.

Like reference symbols in the various drawings generally indicate like elements.

DETAILED DESCRIPTION

[0030] As discussed above, in a loop heat pipe (LHP), the reservoir is co-located with the evaporator, the reservoir is thermally and hydraulically connected with the evaporator through a heat-pipe-like conduit. In this way, liquid from the reservoir can be pumped to the evaporator, thus ensuring that the primary wick of the evaporator is sufficiently wetted or "primed" during start-up. Additionally, the design of the LHP reduces depletion of liquid from the primary wick of the evaporator during steady-state or transient operation of the evaporator within a heat transport system. Moreover, vapor and/or bubbles of non-condensable gas (NCG bubbles) vent from a core of the evaporator through the heat-pipe-like conduit into the reservoir.

[0031] Conventional LHPs require liquid to be present in the reservoir prior to start-up, that is, application of power to the evaporator of the LHP. However, liquid will not be present in the reservoir prior to start-up if, prior to start-up of the LHP, the working fluid in the LHP is in a supercritical state in which a temperature of the LHP is above the critical temperature of the working fluid. The critical temperature of a fluid is the highest temperature at which the fluid can exhibit a liquid-vapor equilibrium. For example, the LHP may be in a supercritical state if the working fluid is a cryogenic fluid, that is, a fluid having a boiling point below -150°C , or if the working fluid is a sub-ambient fluid, that is, a fluid having a boiling point below the temperature of the environment in which the LHP is operating.

[0032] Conventional LHPs also require liquid returning to the evaporator to be subcooled, that is, cooled to a temperature that is lower than the boiling point of the working fluid. Such a constraint makes it impractical to operate LHPs at a sub-ambient temperature. For example, if the working fluid is a cryogenic fluid, the LHP is likely operating in an environment having a temperature greater than the boiling point of the fluid.

[0033] Referring to Fig. 1, a heat transport system 100 is designed to overcome limitations of conventional LHPs, which may include those noted above. The heat transport system 100 includes a heat transfer system 105 and a priming system 110. The priming system 110 is configured to convert fluid within the heat transfer system 105 into a liquid, thus priming the heat transfer system 105. As used in this description, the term "fluid" is a generic term that refers to a substance that may be both a liquid and a vapor in saturated equilibrium.

[0034] The heat transfer system 105 includes a main evaporator 115, and a condenser 120 coupled to the main evaporator 115 by a liquid line 125 and a vapor line 130. The condenser 120 is in thermal communication with a heat sink 165, and the main evaporator 115 is in thermal communication with a heat source Q_{in} 116. The system

105 also may include a hot reservoir 147 coupled to the vapor line 130 for additional pressure containment, as needed. In particular, the hot reservoir 147 increases the volume of the system 100. If the working fluid is at a temperature above its critical temperature, that is, the highest temperature at which the working fluid can exhibit liquid-vapor equilibrium, its pressure is proportional to the mass in the system 100 (the charge) and inversely proportional to the volume of the system. Increasing the volume with the hot reservoir 147 lowers the fill pressure.

[0035] The main evaporator 115 includes a container 117 that houses a primary wick 140 within which a core 135 is defined. The main evaporator 115 includes a bayonet tube 142 and a secondary wick 145 within the core 135. The bayonet tube 142, the primary wick 140, and the secondary wick 145 define a liquid passage 143, a first vapor passage 144, and a second vapor passage 146. The secondary wick 145 provides phase control, that is, liquid/vapor separation in the core 135, as discussed in U.S. Application No. 09/896,561, filed June 29, 2001, which is incorporated herein by reference in its entirety. As shown, the main evaporator 115 has three ports, a liquid inlet 137 into the liquid passage 143, a vapor outlet 132 into the vapor line 130 from the second vapor passage 146, and a fluid outlet 139 from the liquid passage 143 (and possibly the first vapor passage 144, as discussed below). Further details on the structure of a three-port evaporator are discussed below with respect to Figs. 5A and 5B.

[0036] The priming system 110 includes a secondary or priming evaporator 150 coupled to the vapor line 130 and a reservoir 155 co-located with the secondary evaporator 150. The reservoir 155 is coupled to the core 135 of the main evaporator 115 by a secondary fluid line 160 and a secondary condenser 122. The secondary fluid line 160 couples to the fluid outlet 139 of the main evaporator 115. The priming system 110 also includes a controlled heat source Q_{sp} 151 in thermal communication with the secondary evaporator 150.

[0037] The secondary evaporator 150 includes a container 152 that houses a primary wick 190 within which a core 185 is defined. The secondary evaporator 150 includes a bayonet tube 153 and a secondary wick 180 that extend from the core 185, through a conduit 175, and into the reservoir 155. The secondary wick 180 provides a capillary link between the reservoir 155 and the secondary evaporator 150. The bayonet tube 153, the primary wick 190, and the secondary wick 180 define a liquid passage 182 coupled to the fluid line 160, a first vapor passage 181 coupled to the reservoir 155, and a second vapor passage 183 coupled to the vapor line 130. The reservoir 155 is thermally and hydraulically coupled to the core 185 of the secondary evaporator 150 through the liquid passage 182, the secondary wick 180, and the first vapor passage 181. Vapor and/or NCG bubbles from the core 185 of the secondary evaporator 150 are swept through the first vapor passage 181 to the reservoir 155 and condensable liquid is returned to the secondary

evaporator 150 through the secondary wick 180 from the reservoir 155. The primary wick 190 hydraulically links liquid within the core 185 to the heat source Q_{sp} 151, permitting liquid at an outer surface of the primary wick 190 to evaporate and form vapor within the second vapor passage 183 when heat is applied to the secondary evaporator 150.

[0038] The reservoir 155 is cold-biased, and thus, it is cooled by a cooling source that will allow it to operate, if unheated, at a temperature that is lower than the temperature at which the heat transfer system 105 operates. In one implementation, the reservoir 155 and the secondary condenser 122 are in thermal communication with the heat sink 165 that is thermally coupled to the condenser 120. For example, the reservoir 155 can be mounted to the heat sink 165 using a shunt 170, which may be made of a heat conductive material, such as aluminum, for example. In this way, the temperature of the reservoir 155 tracks the temperature of the condenser 120.

[0039] Fig. 2 shows an example of an implementation of the heat transport system 100. In this implementation, the condensers 120 and 122 are mounted to a cryocooler 200, which acts as a refrigerator, transferring heat from the condensers 120, 122 to the heat sink 165. Additionally, in the implementation of Fig. 2, the lines 125, 130, 160 are wound to reduce space requirements for the heat transport system 100.

[0040] Though not shown in Figs. 1 and 2, elements such as, for example, the reservoir 155 and the main evaporator 115, may be equipped with temperature sensors that can be used for diagnostic or testing purposes.

[0041] Referring also to Fig. 3, the system 100 performs a procedure 300 for transporting heat from the heat source Q_{in} 116 and for ensuring that the main evaporator 115 is wetted with liquid prior to startup. The procedure 300 is particularly useful when the heat transfer system 105 is at a supercritical state. Prior to initiation of the procedure 300, the system 100 is filled with a working fluid at a particular pressure, referred to as a "fill pressure."

[0042] Initially, the reservoir 155 is cold-biased by, for example, mounting the reservoir 155 to the heat sink 165 (step 305). The reservoir 155 may be cold-biased to a temperature below the critical temperature of the working fluid, which, as discussed, is the highest temperature at which the working fluid can exhibit liquid-vapor equilibrium. For example, if the fluid is ethane, which has a critical temperature of 33°C, the reservoir 155 is cooled to below 33°C. As the temperature of the reservoir 155 drops below the critical temperature of the working fluid, the reservoir 155 partially fills with a liquid condensate formed by the working fluid. The formation of liquid within the reservoir 155 wets the secondary wick 180 and the primary wick 190 of the secondary evaporator 150 (step 310).

[0043] Meanwhile, power is applied to the priming system 110 by applying heat from the heat source Q_{sp} 151

to the secondary evaporator 150 (step 315) to enhance or initiate circulation of fluid within the heat transfer system 105. Vapor output by the secondary evaporator 150 is pumped through the vapor line 130 and through the condenser 120 (step 320) due to capillary pressure at the interface between the primary wick 190 and the second vapor passage 183. As vapor passes through the condenser 120, it is converted to liquid (step 325). The liquid formed in the condenser 120 is pumped to the main evaporator 115 of the heat transfer system 105 (step 330). When the main evaporator 115 is at a higher temperature than the critical temperature of the fluid, the liquid entering the main evaporator 115 evaporates and cools the main evaporator 115. This process (steps 315-330) continues, causing the main evaporator 115 to reach a set point temperature (step 335), at which point the main evaporator is able to retain liquid and be wetted and to operate as a capillary pump. In one implementation, the set point temperature is the temperature to which the reservoir 155 has been cooled. In another implementation, the set point temperature is a temperature below the critical temperature of the working fluid. In a further implementation, the set point temperature is a temperature above the temperature to which the reservoir 155 has been cooled.

[0044] Once the set point temperature has been reached (step 335), the system 100 operates in a main mode (step 340) in which heat from the heat source Q_{in} 116 that is applied to the main evaporator 115 is transferred by the heat transfer system 105. Specifically, in the main mode, the main evaporator 115 develops capillary pumping to promote circulation of the working fluid through the heat transfer system 105. Also, in the main mode, the temperature of the reservoir 155 may be reduced below the set point temperature of the main evaporator 115. The rate at which the heat transfer system 105 cools down during the main mode depends, in part, on the cold biasing of the reservoir 155 because the temperature of the main evaporator 115 closely follows the temperature of the reservoir 155. Additionally, though not necessarily, a heater can be used to further control or regulate the temperature of the reservoir 155 during the main mode. Furthermore, in main mode, the power applied to the secondary evaporator 150 by the heat source Q_{sp} 151 is reduced, thus bringing the heat transfer system 105 down to a normal operating temperature for the fluid. For example, in the main mode, the heat load from the heat source Q_{sp} 151 to the secondary evaporator 150 is kept at a value equal to or in excess of heat conditions, as defined below. In one implementation, the heat load from the heat source Q_{sp} is kept to about 5 to 10% of the heat load applied to the main evaporator 115 from the heat source Q_{in} 116.

[0045] Thus, in the FIG. 3 implementation, the main mode is triggered by the determination that the set point temperature has been reached at the main evaporator 115 (step 335). In other implementations, the main mode may begin at other times or due to other triggers. For

example, the main mode may begin after the priming system is wet (step 310) or after the reservoir has been cold biased (step 305).

[0046] At any time during operation, the heat transfer system 105 can experience heat conditions that cause formation of vapor on the liquid side of the evaporator, such as those resulting from heat conduction across the primary wick 140 and parasitic heat applied to the liquid line 125. Specifically, heat conduction across the primary wick 140 can cause liquid in the core 135 to form vapor bubbles, which, if left within the core 135, would grow and block off liquid otherwise supplied to the primary wick 140, thus causing the main evaporator 115 to fail. One such heat condition is caused by parasitic heat input into the liquid line 125 (referred to as "parasitic heat gains"), which cause liquid within the liquid line 125 to form vapor.

[0047] To reduce the adverse impact of heat conditions such as those discussed above, the priming system 110 operates at a power level Q_{sp} 151 that is greater than or equal to the sum of the head conduction and the parasitic heat gains. As mentioned above, for example, the priming system 110 can operate at 5-10% of the power to the heat transfer system 105. In particular, fluid that includes a combination of vapor bubbles and liquid is swept out of the core 135 for discharge into the secondary fluid line 160 leading to the secondary condenser 122. In particular, vapor that forms within the core 135 travels along the bayonet tube 143 and directly into the fluid outlet port 139. Furthermore, vapor that forms within the first vapor passage 144 travels into the fluid outlet port 139 by either traveling through the secondary wick 145 (if the pore size of the secondary wick 145 is large enough to accommodate vapor bubbles) or through an opening (not shown) at an end of the secondary wick 145 near the outlet port 139 that provides a clear passage from the first vapor passages 144 to the outlet port 139. The secondary condenser 122 condenses the bubbles in the fluid and pushes the fluid to the reservoir 155 for reintroduction into the heat transfer system 105.

[0048] Similarly, to reduce parasitic heat input to the liquid line 125, the secondary fluid line 160 and the liquid line 125 can form a coaxial configuration such that the secondary fluid line 160 surrounds and insulates the liquid line 125 from surrounding heat. This implementation is discussed further below with reference to Figs. 8A and 8B. As a consequence of this configuration, it is possible for the surrounding heat to cause vapor bubbles to form in the secondary fluid line 160, instead of in the liquid line 125. As discussed, by virtue of capillary action affected at the secondary wick 145, fluid flows from the main evaporator 115 to the secondary condenser 122. This fluid flow, and the relatively low temperature of the secondary condenser 122, causes a sweeping of the vapor bubbles within the secondary fluid line 160 through the condenser 122, where they are condensed into liquid and pumped into the reservoir 155.

[0049] As shown in Fig. 4, data from a test run is shown. In this implementation, prior to startup of the main evap-

orator 115 at temperature 410, a temperature 400 of the main evaporator 115 is significantly higher than a temperature 405 of the reservoir 155, which has been cold-biased to the set point temperature (step 305). As the priming system 110 is wetted (step 310), power Q_{sp} 450 is applied to the secondary evaporator 150 (step 315) at a time 452, causing liquid to be pumped to the main evaporator 115 (step 330), the temperature 400 of the main evaporator 115 drops until it reaches the temperature 405 of the reservoir 155 at time 410. Power Q_{in} 460 is applied to the main evaporator 115 at a time 462, when the system 100 is operating in LHP mode (step 340). As shown, power input Q_{in} 460 to the main evaporator 115 is held relatively low while the main evaporator 115 is cooling down. Also shown are the temperatures 470 and 475, respectively, of the secondary fluid line 160 and the liquid line 125. After time 410, temperatures 470 and 475 track the temperature 400 of the main evaporator 115. Moreover, a temperature 415 of the secondary evaporator 150 follows closely with the temperature 405 of the reservoir 155 because of the thermal communication between the secondary evaporator 150 and the reservoir 155.

[0050] As mentioned, in one implementation, ethane may be used as the fluid in the heat transfer system 105. Although the critical temperature of ethane is 33°C, for the reasons generally described above, the system 100 can start up from a supercritical state in which the system 100 is at a temperature of 70°C. As power Q_{sp} is applied to the secondary evaporator 150, the temperatures of the condenser 120 and the reservoir 155 drop rapidly (between times 452 and 410). A trim heater can be used to control the temperature of the reservoir 155 and thus the condenser 120 to -10°C. To startup the main evaporator 115 from the supercritical temperature of 70°C, a heat load or power input Q_{sp} of 10W is applied to the secondary evaporator 150. Once the main evaporator 115 is primed, the power input from the heat source Q_{sp} 151 to the secondary evaporator 150 and the power applied to and through the trim heater both may be reduced to bring the temperature of the system 100 down to a nominal operating temperature of about -50°C. For instance, during the main mode, if a power input Q_{in} of 40W is applied to the main evaporator 115, the power input Q_{sp} to the secondary evaporator 150 can be reduced to approximately 3W while operating at -45°C to mitigate the 3W lost through heat conditions (as discussed above). As another example, the main evaporator 115 can operate with power input Q_{in} from about 10W to about 40W with 5W applied to the secondary evaporator 150 and with the temperature 405 of the reservoir 155 at approximately -45°C.

[0051] Referring to Figs. 5A and 5B, in one implementation, the main evaporator 115 is designed as a three-port evaporator 500 (which is the design shown in Fig. 1). Generally, in the three-port evaporator 500, liquid flows into a liquid inlet 505 into a core 510, defined by a primary wick 540, and fluid from the core 510 flows from

a fluid outlet 512 to a cold-biased reservoir (such as reservoir 155). The fluid and the core 510 are housed within a container 515 made of, for example, aluminum. In particular, fluid flowing from the liquid inlet 505 into the core 510 flows through a bayonet tube 520, into a liquid passage 521 that flows through and around the bayonet tube 520. Fluid can flow through a secondary wick 525 (such as secondary wick 145 of evaporator 115) made of a wick material 530 and an annular artery 535. The wick material 530 separates the annular artery 535 from a first vapor passage 560. As power from the heat source Q_{in} 116 is applied to the evaporator 500, liquid from the core 510 enters a primary wick 540 and evaporates, forming vapor that is free to flow along a second vapor passage 565 that includes one or more vapor grooves 545 and out a vapor outlet 550 into the vapor line 130. Vapor bubbles that form within first vapor passage 560 of the core 510 are swept out of the core 510 through the first vapor passage 560 and into the fluid outlet 512. As discussed above, vapor bubbles within the first vapor passage 560 may pass through the secondary wick 525 if the pore size of the secondary wick 525 is large enough to accommodate the vapor bubbles. Alternatively, or additionally, vapor bubbles within the first vapor passage 560 may pass through an opening of the secondary wick 525 formed at any suitable location along the secondary wick 525 to enter the liquid passage 521 or the fluid outlet 512.

[0052] Referring to Fig. 6, in another implementation, the main evaporator 115 is designed as a four-port evaporator 600, which is a design described in U.S. Application No. 09/896,561, filed June 29, 2001. Briefly, and with emphasis on aspects that differ from the three-port evaporator configuration, liquid flows into the evaporator 600 through a fluid inlet 605, through a bayonet 610, and into a core 615. The liquid within the core 615 enters a primary wick 620 and evaporates, forming vapor that is free to flow along vapor grooves 625 and out a vapor outlet 630 into the vapor line 130. A secondary wick 633 within the core 615 separates liquid within the core from vapor or bubbles in the core (that are produced when liquid in the core 615 heats). The liquid carrying bubbles formed within a first fluid passage 635 inside the secondary wick 633 flows out of a fluid outlet 640 and the vapor or bubbles formed within a vapor passage 642 positioned between the secondary wick 633 and the primary wick 620 flow out of a vapor outlet 645.

[0053] Referring to Fig. 7, a heat transport system 700 is shown in which the main evaporator is a four-port evaporator, such as that illustrated at references 600 of FIG. 6. The system 700 includes one or more heat transfer systems 705 and a priming system 710 configured to convert fluid within the heat transfer systems 705 into a liquid to prime the heat transfer systems 705. The four-port evaporators 600 are coupled to one or more condensers 715 by a vapor line 720 and a fluid line 725. The priming system 710 includes a cold-biased reservoir 730 hydraulically and thermally connected to a priming evaporator 735.

[0054] Whether using a three-port or four-port evaporator design, design considerations of heat transport systems such as the systems 100 and 700 may include various advantageous features. For example, with specific reference to elements of the system 100 (although similar comments may generally apply to the heat transport system 700 of FIG. 7, with reference to the corresponding elements as shown therein), such advantages may include startup of the main evaporator 115 from a supercritical state, management of parasitic heat leaks, heat conduction across the primary wick 140, cold biasing of the cold reservoir 155, and pressure containment at ambient temperatures that are greater than the critical temperature of the working fluid within the heat transfer system 105. To accommodate these design considerations, the body or container (such as container 515) of the evaporator 115 or 150 can be made of extruded 6063 aluminum and the primary wicks 140 and/or 190 can be made of a fine-pored wick. In one implementation, the outer diameter of the evaporator 115 or 150 is approximately 1.58 cm (0.625 inches) and the length of the container is approximately 15.24 cm (6 inches). The reservoir 155 may be cold-biased to an end panel of the radiator 165 using the aluminum shunt 170. Furthermore, a heater (such as a kapton heater) can be attached at a side of the reservoir 155.

[0055] In one implementation, the vapor line 130 is made with smooth walled stainless steel tubing having an outer diameter (OD) of 0.47 cm (3/16") and the liquid line 125 and the secondary fluid line 160 are made of smooth walled stainless steel tubing having an OD of 0.32 cm (1/8"). The lines 125, 130, 160 may be bent in a serpentine route and plated with gold to minimize parasitic heat gains. Additionally, the lines 125, 130, 160 may be enclosed in a stainless steel box with heaters to simulate a particular environment during testing. The stainless steel box can be insulated with multi-layer insulation (MLI) to minimize heat leaks through panels of the heat sink 165.

[0056] In one implementation, the condenser 122 and the secondary fluid line 160 are made of tubing having an OD of 0.64 cm (0.25 inches). The tubing is bonded to the panels of the heat sink 165 using, for example, epoxy. Each panel of the heat sink 165 is a 20.32 x 48.26 cm (8 x 19 inch) direct condensation, aluminum radiator that uses a 0.19 cm (1/16-inch) thick face sheet. Kapton heaters can be attached to the panels of the heat sink 165, near the condenser 120 to prevent inadvertent freezing of the working fluid. During operation, temperature sensors such as thermocouples can be used to monitor temperatures throughout the system 100.

[0057] The heat transport system 100 may be implemented in any circumstances where the critical temperature of the working fluid of the heat transfer system 105 is below the ambient temperature at which the system 100 is operating. The heat transport system 100 can be used to cool down components that require cryogenic cooling. Referring to Figs. 8A-8D, the heat transport sys-

tem 100 may be implemented in a miniaturized cryogenic system 800. In the miniaturized system 800, the lines 125, 130, 160 are made of flexible material to permit coil configurations 805, which save space. The miniaturized system 800 can operate at -238°C using neon fluid. Power input Qm 116 is approximately 0.3 to 2.5 W. The miniaturized system 800 thermally couples a cryogenic component (or heat source that requires cryogenic cooling) 816 to a cryogenic cooling source such as a cryocooler 810 coupled to cool the condensers 120, 122.

[0058] The miniaturized system 800 reduces mass, increases flexibility, and provides thermal switching capability when compared with traditional thermally-switchable, vibration-isolated systems. Traditional thermally-switchable, vibration-isolated systems require two flexible conductive links (FCLs), a cryogenic thermal switch (CTSW), and a conduction bar (CB) that form a loop to transfer heat from the cryogenic component to the cryogenic cooling source. In the miniaturized system 800, thermal performance is enhanced because the number of mechanical interfaces is reduced. Heat conditions at mechanical interfaces account for a large percentage of heat gains within traditional thermally-switchable, vibration-isolated systems. The CB and two FCLs are replaced with the low-mass, flexible, thin-walled tubing used for the coil configurations 805 of the miniaturized system 800.

[0059] Moreover, the miniaturized system 800 can function of a wide range of heat transport distances, which permits a configuration in which the cooling source (such as the cryocooler 810) is located remotely from the cryogenic component 816. The coil configurations 805 have a low mass and low surface area, thus reducing parasitic heat gains through the lines 125 and 160. The configuration of the cooling source 810 within miniaturized system 800 facilitates integration and packaging of the system 800 and reduces vibrations on the cooling source 810, which becomes particularly important in infrared sensor applications. In one implementation, the miniaturized system 800 was tested using neon, operating at 25-40K.

[0060] Referring to Figs. 9A-9C, the heat transport system 100 may be implemented in an adjustable mounted or Gimbaled system 1005 in which the main evaporator 115 and a portion of the lines 125, 160, and 130 are mounted to rotate about an elevation axis 1020 within a range of $\pm 45^\circ$ and a portion of the lines 125, 160, and 130 are mounted to rotate about an azimuth axis 1025 within a range of $\pm 220^\circ$. The lines 125, 160, 130 are formed from thin-walled tubing and are coiled around each axis of rotation. The system 1005 thermally couples a cryogenic component (or heat source that requires cryogenic cooling) 1016 such as a sensor of a cryogenic telescope to a cryogenic cooling source such as a cryocooler 1010 coupled to cool the condensers 120, 122. The cooling source 1010 is located at a stationary spacecraft 1060, thus reducing mass at the cryogenic telescope. Motor torque for controlling rotation of the lines

125, 160, 130, power requirements of the system 1005, control requirements for the spacecraft 1060, and pointing accuracy for the sensor 1016 are improved. The cryocooler 1010 and the radiator or heat sink 165 can be moved from the sensor 1016, reducing vibration within the sensor 1016. In one implementation, the system 1005 was tested to operate within the range of 70-115K when the working fluid is nitrogen.

[0061] The heat transfer system 105 may be used in medical applications, or in applications where equipment must be cooled to below-ambient temperatures. As another example, the heat transfer system 105 may be used to cool an infrared (IR) sensor, which operates at cryogenic temperatures to reduce ambient noise. The heat transfer system 105 may be used to cool a vending machine, which often houses items that preferably are chilled to sub-ambient temperatures. The heat transfer system 105 may be used to cool components such as a display or a hard drive of a computer, such as a laptop computer, handheld computer, or a desktop computer. The heat transfer system 105 can be used to cool one or more components in a transportation device such as an automobile or an airplane.

[0062] Other implementations are within the scope of the following claims. For example, the condenser 120 and heat sink 165 can be designed as an integral system, such as, for example, a radiator. Similarly, the secondary condenser 122 and heat sink 165 can be formed from a radiator. The heat sink 165 can be a passive heat sink (such as a radiator) or a cryocooler that actively cools the condensers 120, 122.

[0063] In another implementation, the temperature of the reservoir 155 is controlled using a heater. In a further implementation, the reservoir 155 is heated using parasitic heat. In another implementation, a coaxial ring of insulation is formed and placed between the liquid line 125 and the secondary fluid line 160, which surrounds the insulation ring.

[0064] FIG. 10 is a schematic diagram of an implementation of a heat transport system 1000. In FIG. 10, four-port evaporators 600 are arranged in a serial orientation. More particularly, the system 1000 includes multiple heat transfer systems 1005 and a priming system 1010 configured to convert fluid from within the heat transfer systems 1005 into a liquid capable of priming the heat transfer systems 1005. The heat transfer systems 1005 each include four-port evaporators 600 that are coupled to one or more condensers 1015 by a vapor line 1020 and a fluid line 1025. The priming system 1010 includes a cold-biased reservoir 1030 hydraulically and thermally connected to a priming evaporator 1035.

[0065] Similarly to the four-port, parallel arrangement shown in FIG. 7, and in accordance with the general principles associated with an operation of the heat transport system 100 described above with respect to FIG. 1, the heat transport system 1000 is capable of starting the main evaporators 600 from a supercritical state, managing parasitic heat leaks, sweeping excess vapor and Non-Con-

densable Gas bubbles (NCG) from the cores of the main evaporators 600, and various other features and advantages described herein.

[0066] Moreover, as illustrated by FIGS. 7 and 10, various implementations of heat transport systems may be used in many different operating environments, providing flexibility and a wide scope of use to designers of heat transport systems. For example, arrangements may be optimized to account for, for example, locations and types of heat sources, heat load sharing between the evaporators 600, a type of fluid used in the system(s), and various other operating parameters. Of course, it should be understood that the parallel and serial evaporator configurations of FIGS. 7 and 10 also may be implemented using three-port evaporators, such as, for example, the three-port evaporator 500 of FIGS. 5A and 5B.

[0067] FIG. 11 is a schematic diagram of an implementation of an actively-pumped heat transport system 1100 in line with the claimed invention. In FIG. 11, active loop pumping is enabled for the purpose of, for example, supporting improved waste heat rejection and heat transport capability when compared to heat transport systems that rely solely on passive (e.g., capillary) pumping.

[0068] More particularly, the system 1100 includes multiple heat transfer systems 1105, having evaporators 600, and a mechanical pump 1110 that is arranged in series between a condenser 1115 (and a vapor line 1120 feeding the condenser 1115) and the evaporators 600, along a liquid line 1125. A reservoir 1130 is disposed between the mechanical pump 1110 and the condenser 1115, where the reservoir 1130 may be used for, for example, managing excess fluid flow, fine temperature control through cold-biasing, and other features and uses as described herein and as are known.

[0069] The actively-pumped heat transport system 1100 including the mechanical pump 1110 shares certain features and advantages with the passive heat transport systems described above with respect to FIGS. 1-10. For example, the system 1100 includes a primary loop including the vapor line 1120 and the liquid line 1125, as well as secondary loop(s) defined by the secondary liquid flow channel 640 and the secondary vapor channel 645 (where it should be understood that the channels 640 and 645 may be replaced with the fluid channel 160 of FIG. 1 in a system using the three-port evaporator 500).

[0070] The mechanical pump 1110 thus provides a source of pumping power for moving fluid through the primary loop and/or the secondary loop of the heat transport system 1100. This pumping power may be used during various operations of the heat transport system 1100, and may be in addition to, or in the alternative to, other sources of pumping power.

[0071] For example, the pumping power provided by the pump 1110 may be used to provide liquid to the evaporators 600 during a start-up operation of the evaporators 600, perhaps in conjunction with a separate priming system. Such a priming system may include, for example, the priming system 110 of FIG. 1, or some other, con-

ventional priming system (not shown).

[0072] The pump 1110 also may be used during steady state operation of the system 1100, either continuously or intermittently, as needed to maintain a desired operational state of the system 1100. For example, the pump 1110 may be activated during start-up of the system 1100, and then may be bypassed or otherwise de-activated during steady-state operation of the system 1100, unless and until a secondary pumping source (e.g., passive pumping supplied by capillary pressure) is insufficient to provide adequate heat transfer. In this sense, the system 1100 may be considered a dual-pumping system, in which mechanical pumping, capillary pumping, or some combination of both, is available on an as-needed basis to an operator or designer of the system 1100. In particular, for instance, when the system 1100 is used to provide heat transfer over relatively large distances (e.g., 10 meters or more), the mechanical pump 1110 may be required to be used continuously to ensure adequate pumping power.

[0073] As a final example, and as discussed in more detail below, pumping power of the mechanical pump 1110 also may be used to ensure sweeping or venting of vapor bubbles from the cores of the evaporators 600. As such, a use or extent of the pumping power of the mechanical pump 1110 may be dependent on the extent to which such vapor bubbles exist (or are thought to exist) within the evaporator cores, or, similarly, may be dependent on the extent to which conditions for creating such vapor bubbles within the evaporator cores exists within and around the heat transport system 1100.

[0074] As just referenced and as described above in detail, the construction of three and/or four-port evaporators permit control and management of liquid and vapor phases within the evaporator core(s). Specifically, for example, fluid within the cores 615 of evaporators 600 that includes a combination of liquid and vapor bubbles may be swept out of the cores 615 for discharge into the secondary liquid channels 640 and vapor channels 645 (or into the mixed fluid line 160 in a three-port evaporator configuration).

[0075] As also described above, such mixed-phase fluid within the core 615 may result from various causes. For example, the mixed-phase fluid may result from heat conduction across the primary wick 620 and/or parasitic heat gains through the liquid line 1125 (e.g., when routing the liquid line through a "hot" environment). Whatever the cause of the mixed-phase flow, the system 1100 (using the mechanical pump 1110), and the systems described above (using the priming or secondary evaporators 150/710/1010 and associated reservoirs), are operable to provide excess liquid to the evaporators 600, above and beyond the minimum needed to maintain operation of the heat transport system (e.g., an amount needed to maintain saturation of the wicks and associated capillary pumping).

[0076] As a result, the system 1100, and the systems described above, are able to use this excess liquid to

vent or sweep the gaseous portion of the mixed-phase flow from the evaporators 600, using the secondary flow loops that include the secondary liquid/vapor channels 640/645 or the mixed fluid channel 160. In this way, excess vapor enters the secondary loop either through the secondary wick 635 (if feasible for a given pore size of the secondary wick 635), or through an opening at an end of the secondary wick near an outlet port for the secondary loop(s), and is returned to the condenser 1115 for condensation and subsequent return through the liquid line 1125 and/or to the reservoir 1130.

[0077] In one implementation, an amount of excess liquid provided to the cores of the evaporators 600 is optimized. In this implementation, the amount of excess liquid is sufficient to sweep all of the evaporator cores present in the system, but not substantially more than this amount, since excess fluid in the system 1100 may affect a performance and reliability of the system 1100. However, sweeping all of the evaporators 600 may be problematic, particularly, for example, when the evaporators 600 are not powered equally, or, in the limiting case, where one of the evaporators 600 receives no heat (or actually acts as a condenser).

[0078] One technique for optimizing an amount of excess fluid flow to the evaporators 600 includes an appropriate selection of line diameters of the evaporator wicks, and/or for the liquid line 1125 or the vapor line 1120. By selecting these line diameters appropriately, an amount of excess fluid beyond that required for operation of the evaporators 600 may be reduced or minimized, while still ensuring that the amount of excess fluid is sufficient to completely sweep or vent all of the evaporators 600.

[0079] More particularly, in an implementation such as the one just described, such line sizing may be a factor in determining an efficiency of the sweeping of the evaporators 600. In the case of FIG. 11, this sweeping efficiency may determine how much more liquid must be supplied to the evaporators 600 through the liquid line 1125 than what is required to satisfy the heat load(s) of the evaporators 600. Similarly, in the case of FIG. 1 or FIG. 7, the sweeping efficiency may determine how much power must be applied to the secondary evaporator in excess of what is required to satisfy the heat load of the main evaporators 115 or 600, respectively.

[0080] One parameter for describing the appropriate sizing criteria includes a ratio of the flow resistance of the sweepage line(s) 640/645 (or, in FIG. 1, the mixed fluid line 160) to a sum of the resistances of the liquid line 1125 (125 in FIG. 1) outside of the evaporator and the liquid flow passage in the evaporator core 615 (135 in FIG. 1). In general, a relatively large value of this ratio is preferred, and serves to decrease a sweepage power required to completely sweep all evaporator cores.

[0081] With such complete sweepage being provided, the system 1100 may use a narrow-diameter, small-pore, metal wick (e.g., 1 micron pore metal wick), which provides high thermal conductivity and increased pumping capability, relative to the polyethylene wicks that often

are used in conventional heat transport systems. Such polyethylene wicks may be used despite their reduced pumping capacity, in part due to their relatively wide diameter and large pore size which tend to reduce their thermal conductivity and therefore tend to reduce a presence of vapor within the liquid line 1125 and liquid core 615.

[0082] In other words, since the structure and function of the system 1100 enable venting or sweeping such undesirable vapor from the core 615, the system 1100 may not be required to resort to disadvantageous measures to avoid the presence of this vapor in the first place. As a result, the system 1100 may enjoy the advantages of narrow-diameter, small-pore, metal wicks, and, in particular, increased pumping against gravity by a factor of ten, relative to polyethylene wicks, for example. Similarly, the system 1100 may not require subcooled liquid to be returned to the core 615, such that the liquid line 1125 may be routed through hotter environments than are feasible with conventional systems that do not offer vapor sweepage, as it is described herein.

[0083] Accordingly, the system 1100 may provide many advantageous features for the transport and disposal of heat. For example, in addition or as an alternative to one or more of the features just described, the mechanical pump 1110 of the system 1100 may provide increased flow, increased flow controllability, and increased waste heat transportation and rejection, relative to passive systems (for example, heat transport may occur on the order of 50 kW or more, over a distance of 10 meters or more). As another example, the mechanically-pumped system 1100 may greatly reduce temperature gradients across phased array antennas that may include thousands of elements arranged in complex arrays, thereby reducing an overall size of such arrays and reducing or eliminating the need for separate heat pipes to maintain acceptable element temperatures within the arrays.

[0084] The system 1100 offers one or more of the following or other advantages over conventional actively-pumped systems, as well, including those that have been deployed, for example, in geosynchronous communication satellites. For instance, the two-phase nature of the system 1100 is beneficial to heat transfer at the thermal interfaces, and reduces required pumping power. Additionally, the sweepage of excess vapor and its complete condensation within the condenser 1115 may reduce an amount of mixed fluid (i.e., two-phase) flow experience by the mechanical pump 1110. As a result, a lifetime and reliability of the mechanical pump 1110 may be improved, since vapor within a liquid mechanical pump such as the pump 1110 tends to provide excessive stress within the pump.

[0085] In addition to some or all of these and other advantages, the system 1100 is compatible with a wide variety of thermal management components and features. Accordingly, FIGS. 12-16 are schematics of implementations of the system 1100 of FIG. 11 that demon-

strate examples of such thermal management components and features.

[0086] In FIG. 12, a system 1200 operates essentially as described above with respect to the system 1100. The mechanical pump 1110 is illustrated as a liquid pump 1202 that is in series with a liquid line 1204 that is connected to evaporators 1206. The evaporators 1206 vent or sweep two-phase fluid flow from their respective liquid cores through a mixed fluid line 1208, as already described. The evaporators 1206 also output vapor through a vapor line 1210 to a condenser 1212, which, in FIG. 12, includes a body-mounted radiator (discussed in more detail below).

[0087] The mixed fluid line 1208 is shown as a dotted line in FIG. 12 to indicate the variety of forms it may take within the system 1200. For example, the mixed fluid line 1208 may be implemented in a coaxial fashion with respect to the liquid flow line 1204, as described above with respect to, for example, FIG. 8C. Such an implementation assists in protecting the liquid line 1204 from parasitic heat effects that may cause vapor and/or NCG bubbles within the liquid line 1204, and allows the liquid line 1204 to be routed through relatively hot environments without experiencing parasitic heat gain.

[0088] Further, the mixed fluid line 1208 may be used in conjunction with a secondary evaporator 1214, which, when used with a (cold-biased) reservoir 1216 in one of the various manners described above, provides for advantages such as, for example, operation of the system 1200 (or the system 1100) in a passive mode, in which the mechanical pump 1202 (or 1110) is bypassed, perhaps using a pump bypass valve 1218, and the system 1200 (or 1100) relies solely on capillary pumping for fluid flow.

[0089] To the extent that the system 1200 uses fine-pore metal wicks, as described above with respect to FIG. 11, its passive pumping capacity in this mode may be improved relative to other passive, capillary-pumped loops. Although the secondary evaporator is shown only conceptually in FIGS. 12-15, its use should be apparent based on the above descriptions of secondary evaporators 150, 710, and 1010. Moreover, a particular implementation for using such a secondary evaporator in the context of a mechanically-pumped heat transfer system is discussed in detail with respect to FIG. 16.

[0090] As referred to above with respect to FIG. 11, the secondary evaporator 1214 is not required for the system 1200 to operate in passive mode. For example, in such a passive mode, a conventional priming system may be used for starting the system 1200 (e.g., for wetting the primary wicks of the evaporators 1206). Alternatively, the liquid pump 1202 may be used to prime the evaporator(s) 1206 initially for starting, and/or may be used to maintain saturation of the primary wicks of the evaporators 1206 intermittently thereafter. The choice of which start-up method(s) to use, or whether or when to use the system 1200 in a passive mode at all, is, of course, dependent on various operational and environmental fac-

tors of the system 1200, such as, for example one or more of the type of working fluid, a critical temperature of the working fluid, an ambient operating temperature of the system 1200, the amount of heat to be dissipated, and various other factors.

[0091] The above discussion of a general operation of the system 1200 included reference to the evaporators 1206, similar in structure and function to one or more of the various evaporators discussed herein, and using a cold plate as a heat transfer surface. However, it is a strength of the system 1200 that multiple types and arrangements of evaporators and heat transfer surfaces may be used.

[0092] For example, in FIG. 12 the system 1200 includes an evaporator 1220 that is interfaced with a thermal storage unit 1222. In one implementation, the thermal storage unit 1222 may be used as a heat load transformer for pulsed power applications, such as, for example, space-based laser applications. The thermal storage unit may include, for example, 250 W-hr graphite hardware and a paraffin-based, lightweight composite design.

[0093] Further in FIG. 12, the system 1200 may include an evaporator 1224 that is interfaced with a condensing heat exchanger 1226, which is used to couple a spray-cooled evaporator 1228 into the system 1200. The heat exchanger 1226 may be, for example, a high efficiency, two-phase/two-phase heat exchanger. A liquid pump 1230 is used to pump liquid from the condensing heat exchanger 1226 through the spray-cooled evaporator 1228, to thereby form a separate loop coupled to the loop(s) of the primary thermal bus of the system 1200.

[0094] In particular, such a separate loop may be used to connect the spray-cooled evaporator 1228 to the system 1200, due to the fact that a nozzle pressure drop (e.g., 0.7 bar) of the spray-cooled evaporator 1228 relative to a capillary pressure rise (e.g., 0.4 bar) in the system 1200 may make parallel of the spray-cooled evaporator difficult in some use environments. In other implementations, however, the spray-cooled evaporator 1228 may be integral to the system 1200, instead of being coupled through the condensing heat exchanger 1226.

[0095] The spray-cooled evaporator 1228 may be used for efficient thermal control of high heat flux sources. For example, 500 W/cm^2 has been demonstrated with a heat transport system using ammonia as the working fluid. A loop using the spray-cooled evaporator 1228 may be operated near saturation in order to maximize heat transfer.

[0096] Such a spray-cooled evaporator 1228 may be particularly useful, for example, in spacecraft thermal management. For instance, in spacecraft electronics, heat fluxes at transistor gates are approaching 0.155 MW/cm^2 (1 MW/in^2). As component size continues to shrink and heat fluxes rise further, state-of-the-art systems may be used to offset the associated increases in local temperature drops. The significantly higher heat transfer coefficient afforded by spray cooling, using the spray-cooled evaporator 1228, may be advantageous in

this respect.

[0097] Factors to consider in using the spray-cooled evaporator 1228 include, for example, nozzle optimization and scalability of the spray-cooled evaporator 1228 to extended surface areas. In one implementation, the spray-cooled evaporator 1228 may be used for cooling laser diode applications.

[0098] In FIGS. 11 and 12, and in light of the above discussion, it should be understood that the capillary pumping developed by the evaporator wicks, as described above, may generally maintain phase separation at each heat source interface of the evaporators, and thereby assure excellent heat transfer characteristics and automatic flow control among the evaporators, even when no flow controllers are used. A pressure diagram illustrating this phenomenon is described in more detail below with respect to FIG. 25.

[0099] Also, it should be apparent from FIG. 12 and the above discussion that many variations exist with respect to a number, type, and arrangement of evaporators that may be used in the system 1200. Further examples of evaporator configurations are discussed below with respect to FIGS. 18A-18C.

[0100] Similarly, many types of condenser configurations may be used. For example, the condenser 1212 referred to above may include a body-mounted radiator, while a condenser 1232 may include a multi-fold, deployable or steerable radiator. Particularly in high-power spacecraft, these radiators may be direct condensation or may use discrete heat pipes, depending on, for example, system reliability factors and/or a mass of micro-meteoroid shielding. As just mentioned, the radiator 1232 also may be made steerable for non-geostationary applications, in order, for example, to minimize radiator backloading. Gimbaled heat transport systems used in conventional telecom satellite systems may be used to enable such steerable radiators. Further, passive two-phase loops (e.g., LHPs) also may be incorporated into two-axis gimbaled systems. Other examples of condenser configurations are discussed below with respect to FIGS. 18A-18C.

[0101] Finally with respect to FIG. 12, a liquid bypass valve 1218 is illustrated that may be used, for example, to maintain constant pump speed operations with the liquid pump 1202, and which may improve a pump lifetime of the pump 1202. Further, flexible elements 1236 are illustrated in order to indicate that the various elements of the system 1200 may be routed over and through a wide variety of use environments.

[0102] FIG. 13 is a schematic illustrating a heat transport system 1300 that shares many elements with the system 1200 of FIG. 12 (indicated in FIG. 13 by like-numbered elements). In FIG. 13, however, the mechanical pump 1102 of FIG. 11 is represented by a vapor compressor 1302, which may be a variable-speed vapor compressor. A liquid/vapor separator 1304 (or a vapor superheater, not shown) may be used to prevent liquid from entering the compressor, and, similarly to the by-

pass valve 1218 of FIG. 12, a compressor bypass valve 1306 may be used to operate the system 1300 in a passive (capillary) pumping mode.

[0103] The choice of whether to use the liquid pump 1202 or the vapor compressor 1302 is typically a design consideration. Generally, the liquid pump 1202 offers lighter weight and increased pumping power relative to the vapor compressor 1302 (due to, for example, the lower volumetric flow rate of the former). On the other hand, the vapor compressor 1302 offers heat pumping (i.e., an increased condensation temperature), which may reduce radiator heat and overall system mass, and, additionally, may offer a longer operational lifetime.

[0104] The liquid pump 1202 may include, for example, a hermetically sealed, magnetically driven, centrifugal design. Other liquid pumps for space station applications, e.g., waste water and carbon dioxide, also may be used.

[0105] The vapor compressor 1302 may be a variable-speed compressor, and may include, for example, a hermetically-sealed, oil-less centrifugal compressor with gas or magnetic bearings. A low-lift heat pump, which includes a similar compressor, also may be used. Further examples of specific types of pumps are provided below, and, in particular, with respect to FIGS. 17A-17E.

[0106] As also illustrated in FIG. 13, a vapor compressor 1308 may be used in the loop formed by the spray-cooled evaporator 1228 and the condensing heat exchanger 1226, instead of the liquid pump 1230. The choice between the liquid pump 1230 and the vapor compressor 1308 may be driven by, for example, design choices similar to those just described.

[0107] Further in FIG. 13, flow controllers 1310 may be used to ensure a desired heat load distribution between the evaporators 1206, 1220, and 1224. For example, the flow controllers 1310 may be used to route more or less liquid to a particular evaporator, depending on, for example, an amount of heat present at that evaporator, or, in the case of the evaporator 1220, an amount of heat to be stored in the thermal storage unit 1222. In order to provide equal heat load distribution, for example, feedback may be provided from an output of each of the evaporators 1206, 1220, and 1224 to the flow controllers 1310. An example of this implementation is illustrated in more detail below, with respect to FIG. 15. The flow controllers 1310 are shown in FIG. 13 as liquid flow controllers, but also may include other types of flow controllers, such as, for example, vapor flow controllers.

[0108] Referring to FIG. 14, an implementation of a system 1400 is shown that includes condenser capillary flow regulators 1402. The regulators 1402 are included to increase or maximize condenser efficiency, reduce or minimize condenser size, and ensure subcooled liquid return to the liquid pump 1202. The flow regulators 1402 are discussed in more detail below with respect to FIG. 19.

[0109] Also in FIG. 14, a vapor bypass line 1404 is shown in conjunction with a low temperature heat source 1406 (and/or the spray-cooled evaporator 1228). Specif-

ically, the vapor bypass 1404 bypasses the vapor compressor 1308 and facilitates operation of the condensing heat exchanger 1226.

[0110] Referring to FIG. 15, an implementation 1500 is shown that includes superheat feedback flow controllers 1502 for regulating evaporator flow control. A regenerator 1504 is connected to the vapor compressor 1302, and generally is operable to reuse the latent heat in the steam that leaves the compressor 1302 to assist in operation of the compressor 1302. An expansion valve 1506 is included to meter the liquid flow that enters the evaporators from the liquid line 1204, such that the liquid flow enters the evaporators at a desired rate, e.g., a rate that matches the amount of liquid being evaporated in the evaporators.

[0111] Referring to FIG. 16, an implementation of a system 1600 is shown that includes a secondary evaporator 1602, which is used similarly to the secondary evaporator 150 of FIG. 1, the secondary evaporator 710 of FIG. 7, and the secondary evaporator 1010 of FIG. 10. That is, the secondary evaporator 1602 is used as a priming evaporator for ensuring successful start-up of the system 1600, and for ensuring sufficient excess flow through the primary evaporator cores to enable venting of excess vapor and NCG bubbles therefrom, particularly during a passive (capillary) operation of the system 1600.

[0112] More specifically, as should be apparent from the above discussion, the secondary evaporator 1602 is thermally and hydraulically connected to a cold-biased reservoir 1604. As described with respect to FIG. 3, application of power (heat) to the secondary evaporator 1604 causes evaporation therefrom, which travels through a back pressure regulator (BPR) 1606 (discussed in more detail below) and is condensed within one or more condensers 1608. Flow regulators 1610 (similar to the regulators 1402 discussed above, and co-located with one another or with their respective condensers) regulate the condensed liquid flow from the condensers 1608 through a mechanical pump 1612. From there, the condensed liquid flows through an inner liquid flow line of a coaxial flow line 1614. In this way, the liquid reaches cold plate evaporator(s) 1616, as well as a thermal mass (storage unit) 1618 and a remote evaporator 1620.

[0113] Further, an isothermalized plate or structure 1622 may be included. Such a structure may be useful, for example, in settings where a constant temperature surface is desired or required, such as, for example, some laser systems. To the extent that such systems require a constant temperature surface it may be efficient to use the (waste) heat being transported by the system 1600 to keep the structure 1622 at a constant temperature. When the structure 1622 is used, a flow regulator 1624 (perhaps similar to the regulators 1402 of FIG. 14) may be used to ensure that a proper amount of vapor from a vapor return line 1626 is provided to the structure 1622.

[0114] A liquid line heat exchanger 1628 is used to

provide subcooling of the liquid before it is routed to the evaporators. Also, as just referred to, the vapor return line 1626 returns vapor to the secondary evaporator 1602 and to the BPR 1606. The BPR 1606, generally speaking, ensures that no vapor reaches the condensers unless a vapor space for all evaporators in the system is devoid of liquid. As such, heat load sharing among the many parallel (or series) evaporators may be increased. An example of the BPR 1606 is discussed in detail below with respect to FIG. 20.

[0115] FIGS. 11-16 illustrate various implementations of actively-pumped thermal management systems, which include different combinations and arrangements of thermal management components. In order to further illustrate the flexibility of design and use of such thermal management systems, additional examples of such thermal components and their uses are provided below with respect to FIGS. 17-25. It should be understood that such thermal components, and others, may be used in conjunction with some or all of the implementations of FIGS. 11-16, or in other implementations.

[0116] FIGS. 17A-17E are examples of mechanical pumps that may be used in the systems of FIGS. 11-16. Specifically, FIG. 17A illustrates a bellows pump, while FIG. 17B illustrates a centrifugal pump. FIG. 17C illustrates a diaphragm pump, and FIG. 17D illustrates a gear pump. Finally, FIG. 17E illustrates a peristaltic pump. It should be understood that the illustrated pumps are merely examples of known pumps that may be used in an actively-pumped thermal management system, and other types of pumps also may be used.

[0117] FIGS. 18A-18C illustrate examples of different evaporator and condenser architectures for use with the systems of FIGS. 11-16. As already discussed, such architectures may be characterized by virtually any parallel or series arrangement of evaporators and condensers. In FIG. 18A, a heat flow arrangement involving a centralized thermal bus 1802 is used for defense space applications requiring on-orbit servicing. In this concept, multiple parallel evaporators 1804 are used to cool internal electronics 1806, thermal storage units 1808, on-gimbal components 1810 on a gimbaled payload 1812 that is connected to the bus 1802 by a coil 1814, and on-orbit replaceable electronics modules 1816. Spot coolers 1818 may be used as needed, and the bus 1802 is connected to a deployable or steerable direct condensation radiator 1820 by a coil 1822. The deployable radiator 1820 may include a secondary loop heat pipe evaporator/reservoir mounted on the radiator 1820 to insure that the radiator 1820 is cold-biased.

[0118] In FIG. 18B, an evaporator section 1824 includes multiple cold plates 1826 connected in parallel to a starter pump 1828 and thermal storage units (TSUs) 1830. A two-axis gimbaled cold plate 1832 is also connected to the evaporator section 1824, by way of a coil 1834. The cold plate 1826 may feature equipment mounting locations 1836 having an advanced interface design, as well as additional spot cooler loops 1838. In this ex-

ample, a two-axis gimbaled condenser 1840 is connected to the evaporator section 1824 by a coil 1842, and is connected to a pump 1844 and reservoir 1846. Additional cooling may be supplied by a chiller 1848 that is connected to the condenser 1840.

[0119] In FIG. 18C, a possible design for use in a space shuttle bay is illustrated, in which an evaporator section 1850 includes a deployable evaporator section 1852 with a coil or hinge 1854, modular electronic boxes 1856, and thermal storage units 1858. A deployable radiator 1860 includes a pump 1862 and reservoir 1864, as well as a coil or hinge 1866.

[0120] FIG. 19 is a diagram of an example of the condenser flow regulator 1402 of FIGS. 14-16. In FIG. 19, a capillary structure 1902 receives a combined liquid/vapor flow 1904 and from an associated condenser, and ensures liquid return to an associated liquid line. As discussed above, the regulator 1402 may thus increase a performance, and reduce a size of, associated parallel condensers.

[0121] FIG. 20 is a diagram of an example of the back pressure regulator (BPR) 1606 of FIG. 16. As discussed above, the BPR 1606 typically is added to a condenser inlet in order to enable heat load sharing in either an active or passive (capillary) pumping mode of a thermal management system, such as the systems of FIGS. 11-16.

[0122] In FIG. 20, the BPR 1606 is attached at a vapor transport line 2002 on one end at a radiator header 2004 at the other end. The BPR 1606 includes a tubular shell external structure 2006 that has an internal annular wick 2008. The wick 2008 has a first, sealed end 2010 and a second, unsealed (open) end 2012. The sealed end 2010 of the wick 2008 is surrounded by an annular gap 2014 filled with vapor. The unsealed end 2012 of the wick 2008 is surrounded by an annular gap 2016 filled with liquid. As shown, the annular gaps 2014/2016 extend only a portion of the length of the BPR 1606. In a central (low conductance) portion 2018 of the BPR 1606, the tubular shell 2006 makes contact with the wick outer surface, and thereby seals the annular gap 2014 from the annular gap 2012.

[0123] Thus, the BPR 1606 typically is positioned at the inlet to the condenser, where the vapor line 2002 meets the condenser inlet header 2004. As such, the unsealed end 2012 of the internal wick 2008 is thermally linked to a cooling source 2020 (e.g., radiator or other heat sink), and is connected to the condenser inlet header end 2004 of the BPR 1606. The other end 2010 (sealed end of the internal wick 2008) is connected in series to the vapor line 2002.

[0124] The BPR 1606 ensures that no vapor reaches the condenser unless the vapor space for all evaporators in the system is devoid of liquid. As such, heat load sharing among the many parallel or series evaporators in the system may be increased. The BPR 1606 typically uses pores 2022 selected such that the pore size is larger than the pore size(s) of any of the system evaporators. Thus,

as vapor is produced, it is contained within all the evaporator vapor side space, and is thereby given an opportunity to condense. The vapor clears all evaporator vapor side space of liquid, and, once that condition is achieved, pushes through the BPR wick 2008 and allows flow to reach the connected condenser.

[0125] FIGS. 21 and 22 are diagrams of evaporator failure isolators 2100 and 2200, respectively, which may be used in any multi-evaporator implementations of the systems of FIGS. 11-16. The isolators 2100 and 2200 generally are operable to prevent evaporator pump failures at any particular evaporator from propagating throughout an associated thermal management system.

[0126] In FIG. 21, the isolator 2100 includes a first port 2102 for receiving liquid flow from a liquid line 2104 supplying liquid to a plurality of evaporators. A liquid return port 2106 outputs liquid to other isolators, and a liquid outlet port 2108 outputs liquid to an associated capillary pump (evaporator).

[0127] A tube 2110 defines a body of the isolator 2100 that includes a wick 2112 and a flow annulus 2114. Along with a swage seal 2116, the wick 2112 and flow annulus 2114 enable isolation of the liquid flow to an associated evaporator, through the liquid outlet port 2108. If the associated evaporator experiences pump failure, it may be bypassed by the isolator 2100 until repair may be affected.

[0128] Similarly, in FIG. 22, an isolator 2200 includes a liquid flow annulus 2202 through which subcooled liquid flows from an associated reservoir to remaining pumps. Isolation seals 2204 ensure that liquid flow to associated pumps is maintained through ports 2206, such that only currently-functioning pumps receive liquid flow.

[0129] FIGS. 23 and 24 illustrate examples of capillary pressure sensors 2300 and 2400, respectively. Such capillary pressure sensors, generally speaking, provide feedback control for a mechanical pump (e.g., the mechanical pump 1102 of FIG. 11), and enable heat load sharing among multiple evaporators.

[0130] In FIGS. 23 and 24, a liquid line 2302 and vapor line 2304 are coupled hydraulically to the capillary pressure sensors 2300 and 2400. Particularly, in FIG. 23, the liquid and vapor lines are adjacent to one or more evaporators, and the capillary pressure sensor 2300 includes a hermetic envelope 2306, an internal wicking structure 2308, and multiple temperature sensors 2310.

[0131] The wicking structure 2308 includes a continuous wick element 2312 with the same capillary pumping radius 2314 (r_{pewap}) as an evaporator wick that hydraulically links the liquid line 2302 to one or more segments 2316, 2318, and 2320 with larger capillary pumping radii (r_{p1} , r_{p2} , and r_{p3}). The capillary sensor 2300 is thermally coupled to one or more heat sources 2322.

[0132] In operation, the temperature sensors 2310 measure envelope temperature above each wick segment 2316, 2318, 2320, and/or temperature differences between the envelopes above each wick segment 2316, 2318, 2320. Temperature increases on the envelope in-

dicates that the wick segment below the envelope may no longer be saturated with liquid, due to inability of the wick segment to support the pressure difference between the vapor line 2304 and the liquid line 2302. Thus, temperature feedback may be used to adjust a pumping pressure delivered by the mechanical pump 1102, by, for example, adjusting pump speed or adjusting a position of an associated pump bypass valve, in order to maintain saturation of the appropriate wick segment(s).

[0133] In FIG. 24, a heat sink 2402 provides cold bias between the wick segments 2316, 2318, and 2320, and sensors 2310 are used to measure temperature in the cold-biased zone(s). The wick segments 2316, 2318, and 2320 may be arranged in sequence, with the wick segment with the largest capillary radius nearest as associated vapor manifold.

[0134] In operation, temperature increases on the envelope indicate that the wick segment between the sensor and the vapor manifold may no longer be saturated with liquid, due to, for example, an inability of the wick segment to support a pressure difference between the vapor line 2304 and the liquid line 2302. Then, temperature feedback may be used to adjust the pumping pressure delivered by the mechanical pump, by either adjusting pump speed or the position of a pump bypass valve, to maintain saturation of the appropriate wick segment(s).

[0135] FIG. 25 is a pressure drop diagram 2500 for a thermal management system, such as the various implementations of thermal management systems discussed above. In FIG. 25, the pump 1110 provides a pressure difference ΔP_{pump} 2502 that is slightly higher than the low pressure point 2504 of the system at the reservoir. $\Delta P_{\text{Flow Reg}}$ 2506, the pressure differences provided by the flow regulators 1402, are lower than the pressure difference ΔP_{LHP} 2508 of the Loop Heat Pipe. Other than the pressure differences $\Delta P_{\text{visc } 5,6}$ 2510, 2512, where a viscous pressure drop may dominate in effect, pressure differentials $\Delta P_{\text{cap } 1,2,3}$ 2514, 2516, 2518 demonstrate the positive pressure differentials that enable capillary back pressure(s) the evaporators of the thermal management system, using the evaporator wicks, that allow excellent heat transfer and flow control, in conjunction with the mechanical pump 1110. Finally, a pressure difference $\Delta P_{\text{cap } 4}$ 2520 illustrates a pressure difference maintained for regulating flow through the condenser(s) 1115.

[0136] As shown in FIGS. 11-25, many different implementations exist for actively-pumped thermal management systems. Such systems include capillary and/or mechanically pumped two-phase thermal management systems that combine the low input power, passive system advantages (e.g., heat load sharing, no moving parts) of small pore wick (capillary) pumped two-phase loop systems with the operational flexibility advantages (e.g., fluid flow-heat flow decoupling and flow controllability) of mechanically pumped two-phase loop systems.

[0137] As described, such thermal management sys-

tems absorb waste heat from a wide range of sources, including, for example, waste heat of electronics and power conditioning equipment, high-power spacecraft, antennas, batteries, and laser systems. Military applications, such as space-based radar and lasers, offer a wide suite of potential heat sources, and the elements required for their thermal management. Accordingly, such military applications, such as those requiring counterspace detection and offensive force projection capabilities, may benefit from such thermal management systems, which provide high heat transport capability and high heat rejection, as well as high flux heat acquisition and efficient thermal storage, all the while minimizing system mass and maintaining operational reliability over the mission life. Commercial applications, such as, for example, soda-dispensing machines and notebook computers, also may benefit from the implementations of heat transport systems discussed herein, or variations thereof.

Claims

1. A system for heat transfer comprising:

a primary evaporator (115, 500, 600) configured to be operable to facilitate heat transfer by evaporating received liquid to obtain vapor, the primary evaporator (115, 500, 600) including a first port (137) for receiving the liquid from a liquid line (125), a second port (132) for outputting the vapor to a vapor line (130), and a third port (139) for outputting excess liquid received from the liquid line (125) to an excess fluid line, the primary evaporator (115, 500, 600) further including a core (135), a primary wick (140), and a secondary wick (145);

a condensing system configured to be operable to receive the vapor from the vapor line (130), to condense at least some of the vapor, and to output the liquid to the liquid line (125);

a primary loop including the condensing system, the primary evaporator (115, 500, 600), the liquid line (125), the vapor line (130), the first port (137), and the second port (132), the primary loop being configured to be operable to provide a heat transfer path;

a secondary loop including the condensing system, the primary evaporator (115, 500, 600), the liquid line (125), the vapor line (130), the first port (137), the third port (139) and the excess fluid line, the secondary loop being configured to be operable to provide a venting path for removing other vapor that is present within the liquid from the primary evaporator (115, 500, 600); and

a venting system being configured to remove vapor bubbles from the core (135) of the primary evaporator (115, 500, 600) to the condensing

system, the venting system including:

- an active pumping system (1100) being configured to be operable to provide excess liquid to the primary evaporator (115, 500, 600) beyond a saturation amount of liquid needed for saturating the primary wick (140); and
 a reservoir (1130) in fluid communication with the condensing system, the reservoir (1130) being in fluid communication with the pumping system (1100) and configured to provide the excess liquid, wherein the venting system is configured to vent vapor bubbles and excess liquid from the core (135) of the primary evaporator (115, 500, 600) through the third port (139) to the excess fluid line with the active pumping system (1100).
2. The system of claim 1 wherein the liquid in the primary evaporator (115, 500, 600) and received from the liquid line (125) includes the excess liquid in excess of a liquid amount necessary to maintain saturation of a primary wick (140) within a core (135) of the primary evaporator (115, 500, 600).
 3. The system of claim 2 wherein the primary evaporator (115, 500, 600) includes a secondary wick (145) that is operable to perform phase separation of the other vapor from the liquid for output through the excess fluid line.
 4. The system of claim 3 wherein the primary wick (140) and the secondary wick (145) of the primary evaporator (115, 500, 600) maintain capillary pumping of the liquid, the excess liquid, and the vapor, so as to maintain flow control to and through the primary evaporator (115, 500, 600).
 5. The system of claim 1, where the pumping system (1100) comprises a mechanical pump (1110) that is operable to facilitate the heat transfer by actively pumping the liquid for evaporation by the primary evaporator (115, 500, 600), and for output as the excess liquid through the third port (139) to the excess fluid line.
 6. The system of claim 5 wherein the reservoir (1130) is positioned between an output of the condensing system and an input of the mechanical pump (1110).
 7. The system of claim 5 wherein the mechanical pump (1110) is positioned between an input of the condensing system and an output of the primary evaporator (115, 500, 600).
 8. The system of claim 5 further comprising a bypass valve (1218, 1234) in parallel with the mechanical pump (1110) and operable to bypass the mechanical pump (1110) during a passive pumping operation of liquid for evaporation by the primary evaporator (115, 500, 600).
 9. The system of claim 5 wherein the mechanical pump (1110) includes a liquid pump (1202/1230) that is oriented in series with the liquid line (125) and positioned between the condensing system and the primary evaporator (115, 500, 600).
 10. The system of claim 5 wherein the mechanical pump (1110) includes a vapor compressor (1302) that is oriented in series with the vapor line (130) and positioned between the primary evaporator (115, 500, 600) and the condensing system.
 11. The system of claim 5 further comprising:
 a sensor (2300, 2400) that is operable to communicate a saturation level of a wick of the primary evaporator (115, 500, 600) to the mechanical pump (1110),
 wherein a pumping pressure delivered by the mechanical pump (1110) is adjusted, based on the saturation level, so as to maintain saturation of the wick with the liquid.
 12. The system of claim 5 further comprising a liquid bypass valve (1218, 1234) connected between the liquid line (125) and the vapor line (130) and operable to maintain constant pump speed operations of the mechanical pump (1110).
 13. The system of claim 5 wherein the primary evaporator (115, 500, 600) includes a primary wick (140) and a secondary wick (145), compositions of which comprise metal.
 14. The system of claim 1 further comprising a priming system within the secondary loop, the priming system comprising:
 a secondary evaporator (150, 710, 1010, 1602) coupled to the vapor line (130); and
 a secondary reservoir (155) in fluid communication with the secondary evaporator (150, 710, 1010, 1602) and coupled to the primary evaporator (115, 500, 600) by the excess fluid line, wherein the priming system is operable to provide the liquid to the primary evaporator (115, 500, 600) at least partially from the secondary reservoir (155).
 15. The system of claim 14 wherein the condensing system comprises:

- a first condenser within the primary loop and coupled to the liquid line (125) and to the vapor line (130); and
a second condenser (122) within the secondary loop and coupled to the excess fluid line and to the secondary reservoir (155).
16. The system of claim 1 wherein the third port (139) of the primary evaporator (115, 500, 600) is primarily used to output the excess liquid to the excess fluid line, and wherein the third port (139) comprises a subport for outputting the other vapor to a vapor line (130), such that the vapor line (130) is included within the secondary loop.
17. The system of claim 1 wherein the liquid line (125) is coaxial to and contained within the excess fluid line.
18. The system of claim 1 further comprising a second primary evaporator (150) that is connected in-parallel with the primary evaporator (115, 500, 600) within the primary loop.
19. The system of claim 18 further comprising a back pressure regulator (1606) that is oriented in series with the vapor line (130) and positioned between the primary evaporator (115, 500, 600) and the condensing system, and that is operable to substantially equalize heat load between the primary evaporator (115, 500, 600) and the secondary primary evaporator (150).
20. The system of claim 19 wherein the back pressure regulator restricts vapor from reaching the condensing system until a vapor space of the primary evaporator (115, 500, 600) and of the second primary evaporator (150) is substantially devoid of liquid.
21. The system of claim 1 further comprising a second primary evaporator (150) that is oriented in series with the primary evaporator (115, 500, 600) within the primary loop.
22. The system of claim 1 wherein the condensing system comprises a plurality of condensers connected in parallel to one another.
23. The system of claim 22 comprising:
liquid outputs associated with each of the plurality of condensers and operable to output the liquid to the primary evaporator (115, 500, 600); and
condenser regulators coupled to the liquid outputs and operable to regulate liquid flow therefrom.
24. The system of claim 1 further comprising:
a second primary evaporator (150) that is connected with the primary evaporator (115, 500, 600) within the primary loop; and
a thermal storage unit (1222, 1808, 1830, 1858) coupled to the second primary evaporator (150).
25. The system of claim 1 further comprising:
a second primary evaporator (150) that is connected with the primary evaporator (115, 500, 600) within the primary loop; and
first and second flow controllers connected to the primary evaporator (115, 500, 600) and the second primary evaporator (150), respectively, and operable to regulate liquid flow to the primary evaporator (115, 500, 600) and the second primary evaporator (150), respectively, so as to ensure a substantially equal heat load distribution between the evaporators.
26. The system of claim 1 further comprising:
a second primary evaporator (150) that is connected with the primary evaporator (115, 500, 600) within the primary loop; and
a condensing heat exchanger coupled to the second primary evaporator (150).
27. The system of claim 26 comprising a spray-cooled evaporator (1228) coupled to the condensing heat exchanger by way of a mechanical pump (1110).
28. The system of claim 1 wherein the condensing system comprises a body-mounted radiator (1232).
29. The system of claim 1 wherein the condensing system comprises a deployable or steerable radiator (1232).
30. A method for heat transfer comprising:
evaporating liquid from a primary wick (140) of a primary evaporator (115, 500, 600) to thereby obtain vapor;
outputting the vapor through a vapor line (130) coupled to the primary evaporator (115, 500, 600);
condensing the vapor from the vapor line (130) within a condensing system;
returning the liquid to the primary evaporator (115, 500, 600) through a liquid line (125) coupled to the primary evaporator (115, 500, 600), wherein a saturation amount of the liquid is provided so as to maintain a saturation of the primary wick (140) during the evaporating;
providing excess liquid beyond the saturation

- amount to the primary evaporator (115, 500, 600) at least partially from a reservoir (1130), through the liquid line (125) with a mechanical pump; and
sweeping the excess liquid and other vapor within the primary evaporator (115, 500, 600) to the condensing system with the mechanical pump through an excess fluid line.
- 31.** The method of claim 30 wherein evaporating liquid from the primary wick (140) of the primary evaporator (115, 500, 600) comprises maintaining capillary pumping of the liquid, the excess liquid, and the vapor, so as to maintain flow control to and through the primary evaporator (115, 500, 600).
- 32.** The method of claim 30 wherein:
- outputting the vapor comprises outputting the vapor through a first port (137) of the primary evaporator (115, 500, 600);
returning the liquid and providing excess liquid comprises returning the liquid and excess liquid through a second port (132) of the primary evaporator (115, 500, 600); and
sweeping the excess liquid and undesired vapor comprises sweeping the excess liquid and undesired vapor from a third port (139) of the primary evaporator (115, 500, 600).
- 33.** The method of claim 30 wherein:
- outputting the vapor comprises outputting the vapor through a first port (137) of the primary evaporator (115, 500, 600);
returning the liquid and providing excess liquid comprises returning the liquid and excess liquid through a second port (132) of the primary evaporator (115, 500, 600); and
sweeping the excess liquid and other vapor comprises sweeping the excess liquid from a third port (139) of the primary evaporator (115, 500, 600), and sweeping the other vapor from a fourth port of the primary evaporator (115, 500, 600).
- 34.** The method of claim 30 wherein sweeping the excess liquid and other vapor includes separating the liquid and excess liquid from the other vapor with a secondary wick (145) of the primary evaporator (115, 500, 600).
- 35.** The method of claim 34 comprising bypassing the mechanical pump using a bypass valve (1218, 1234) in parallel with the mechanical pump during a passive pumping operation of the liquid for evaporation by the primary evaporator (115, 500, 600).
- 36.** The method of claim 34 wherein pumping the excess liquid comprises pumping the liquid and the excess liquid using a liquid pump that is oriented in series with the liquid line (125) and positioned between the condensing system and the primary evaporator (115, 500, 600).
- 37.** The method of claim 34 wherein pumping the excess liquid comprises pumping the vapor to the condensing system using a vapor compressor (1302) that is oriented in series with the vapor line (130) and positioned between the primary evaporator (115, 500, 600) and the condensing system.
- 38.** The method of claim 30 wherein providing excess liquid comprises providing the excess liquid from a priming system in which the reservoir (1130) is in fluid communication with a secondary evaporator (150, 710, 1010, 1602), where the reservoir (1130) is coupled to the primary evaporator (115, 500, 600).
- 39.** The method of claim 38 wherein:
- condensing the vapor comprises condensing the vapor within a first condenser of the condensing system, the first condenser being coupled to the liquid line (125) and to the vapor line (130); and
sweeping the excess liquid and undesired vapor comprises condensing undesired vapor within a second condenser (122) of the condensing system, the second condenser (122) being coupled to a mixed fluid line and to the reservoir (1130).
- 40.** The system of claim 1, wherein the pumping system comprises a mechanical pump (1110).
- 41.** The system of claim 40 wherein the primary wick (140) and the secondary wick (145) of the primary evaporator (115, 500, 600) maintain capillary pumping of the liquid, the excess liquid, and the vapor, so as to maintain flow control to and through the primary evaporator (115, 500, 600).
- 42.** The system of claim 1, wherein the pumping system (1100) further comprises a secondary evaporator (150, 710, 1010, 1602) in fluid communication with the reservoir (1130) and coupled to the vapor line (130).
- 43.** The system of claim 42 wherein the reservoir (1130) is in fluid communication with the secondary wick (145) of the primary evaporator (115, 500, 600) through a mixed fluid line coupled to the third port (139) of the primary evaporator (115, 500, 600).
- 44.** The system of claim 1, wherein the excess liquid is substantially removed from the core (135) of the pri-

mary evaporator (115, 500, 600) through a fourth port of the primary evaporator (115, 500, 600).

Patentansprüche

1. System zur Wärmeübertragung, das Folgendes umfasst:

einen primären Verdampfer (115, 500, 600), der dafür konfiguriert ist, funktionsfähig zu sein, um eine Wärmeübertragung zu erleichtern durch Verdampfen von aufgenommener Flüssigkeit, um Dampf zu erhalten, wobei der primäre Verdampfer (115, 500, 600) einen ersten Anschluss (137) zum Aufnehmen der Flüssigkeit aus einer Flüssigkeitsleitung (125), einen zweiten Anschluss (132) zum Ausgeben des Dampfes an eine Dampfleitung (130) und einen dritten Anschluss (139) zum Ausgeben überschüssiger aus der Flüssigkeitsleitung aufgenommener Flüssigkeit an eine Überschussfluidleitung einschließt, wobei der primäre Verdampfer (115, 500, 600) ferner einen Kern (135), einen primären Docht (140) und einen sekundären Docht (145) einschließt,

ein Kondensationssystem, das dafür konfiguriert ist, funktionsfähig zu sein, um den Dampf aus der Dampfleitung (130) aufzunehmen, wenigstens etwas von dem Dampf zu kondensieren und die Flüssigkeit an die Flüssigkeitsleitung (125) auszugeben,

einen primären Kreislauf, der das Kondensationssystem, den primären Verdampfer (115, 500, 600), die Flüssigkeitsleitung (125), die Dampfleitung (130), den ersten Anschluss (137) und den zweiten Anschluss (132) einschließt, wobei der primäre Kreislauf dafür konfiguriert ist, funktionsfähig zu sein, um eine Wärmeübertragungsbahn bereitzustellen,

einen sekundären Kreislauf, der das Kondensationssystem, den primären Verdampfer (115, 500, 600), die Flüssigkeitsleitung (125), die Dampfleitung (130), den ersten Anschluss (137), den dritten Anschluss (139) und die Überschussfluidleitung einschließt, wobei der sekundäre Kreislauf dafür konfiguriert ist, funktionsfähig zu sein, um eine Lüftungsbahn zum Entfernen von anderem Dampf der innerhalb der Flüssigkeit aus dem primären Verdampfer (115, 500, 600) vorhanden ist, bereitzustellen,

ein Lüftungssystem, das dafür konfiguriert ist, Dampfblasen aus dem Kern (135) des primären Verdampfers (115, 500, 600) zu dem Kondensationssystem zu entfernen, wobei das Lüftungssystem Folgendes einschließt:

ein aktives Pumpsystem (1100), das dafür

konfiguriert ist, funktionsfähig zu sein, um dem primären Verdampfer (115, 500, 600) überschüssige Flüssigkeit über ein Sättigungsmaß an Flüssigkeit hinaus bereitzustellen, das zum Sättigen des primären Dochts (140) benötigt wird, und ein Reservoir (1130) in Fluidverbindung mit dem Kondensationssystem, wobei das Reservoir (1130) in Fluidverbindung mit dem Pumpsystem (1100) steht und dafür konfiguriert ist, die überschüssige Flüssigkeit bereitzustellen, wobei das Lüftungssystem dafür konfiguriert ist, Dampfblasen und überschüssige Flüssigkeit aus dem Kern (135) des primären Verdampfers (115, 500, 600) durch den dritten Anschluss (139) zu der Überschussfluidleitung mit dem aktiven Pumpsystem (1100) abzulassen.

2. System nach Anspruch 1, wobei die Flüssigkeit im primären Verdampfer (115, 500, 600) und die aus der Flüssigkeitsleitung (125) aufgenommen wird, die überschüssige Flüssigkeit über einer Flüssigkeitsmenge, die notwendig ist, um eine Sättigung des primären Dochts (140) innerhalb eines Kerns (135) des primären Verdampfers (115, 500, 600) aufrechtzuerhalten, einschließt.
3. System nach Anspruch 2, wobei der primäre Verdampfer (115, 500, 600) einen sekundären Docht (145) einschließt, der funktionsfähig ist, um eine Phasentrennung des anderen Dampfes von der Flüssigkeit für eine Ausgabe durch die Überschussfluidleitung durchzuführen.
4. System nach Anspruch 3, wobei der primäre Docht (140) und der sekundäre Docht (145) des primären Verdampfers (115, 500, 600) ein kapillares Pumpen der Flüssigkeit, der überschüssigen Flüssigkeit und des Dampfes aufrechterhalten, um so eine Durchflusskontrolle zu dem primären Verdampfer (115, 500, 600) und durch denselben aufrechtzuerhalten.
5. System nach Anspruch 1, wobei das Pumpsystem (1100) eine mechanische Pumpe (1110) umfasst, die funktionsfähig ist, um die Wärmeübertragung durch aktives Pumpen zur Verdampfung durch den primären Verdampfer (115, 500, 600) und zur Ausgabe als die überschüssige Flüssigkeit durch den dritten Anschluss (139) an die Überschussfluidleitung zu erleichtern.
6. System nach Anspruch 5, wobei das Reservoir (1300) zwischen einem Ausgang des Kondensationssystems und einem Eingang der mechanischen Pumpe (1110) angeordnet ist.
7. System nach Anspruch 5, wobei die mechanische

Pumpe (1110) zwischen einem Eingang des Kondensationssystems und einem Ausgang des primären Verdampfers (115, 500, 600) angeordnet ist.

8. System nach Anspruch 5, das ferner ein Umgehungsventil (1218, 1234) umfasst, parallel mit der mechanischen Pumpe (1110) und funktionsfähig, um die mechanische Pumpe (1110) während eines passiven Pumpvorgangs von Flüssigkeit zur Verdampfung durch den primären Verdampfer (115, 500, 600) zu umgehen. 5
9. System nach Anspruch 5, wobei die mechanische Pumpe (1110) eine Flüssigkeitspumpe (1202/1230) einschließt, die in Reihe mit der Flüssigkeitsleitung (125) und zwischen dem Kondensationssystem und dem primären Verdampfer (115, 500, 600) angeordnet ist. 10
10. System nach Anspruch 5, wobei die mechanische Pumpe (1110) einen Dampfverdichter (1302) einschließt, der in Reihe mit der Dampfleitung (130) ausgerichtet und zwischen dem primären Verdampfer (115, 500, 600) und dem Kondensationssystem angeordnet ist. 15
11. System nach Anspruch 5, das ferner Folgendes umfasst: 20

einen Sensor (2300, 2400), der funktionsfähig ist, um ein Sättigungsniveau eines Dochts des primären Verdampfers (115, 500, 600) der mechanischen Pumpe (1110) mitzuteilen, wobei ein durch die mechanische Pumpe (1110) gelieferter Pumpdruck auf Grundlage des Sättigungsniveaus eingestellt wird, um so eine Sättigung des Dochts mit der Flüssigkeit aufrechtzuerhalten. 25
12. System nach Anspruch 5, das ferner ein Flüssigkeitsumgehungsventil (1218, 1234) umfasst, das zwischen der Flüssigkeitsleitung (125) und der Dampfleitung (130) angeschlossen und funktionsfähig ist, um Operationen mit konstanter Pumpengeschwindigkeit der mechanischen Pumpe (1110) aufrechtzuerhalten. 30
13. System nach Anspruch 5, wobei der primäre Verdampfer (115, 500, 600) einen primären Docht (140) und einen sekundären Docht (145) einschließt, deren Zusammensetzungen Metall umfassen. 35
14. System nach Anspruch 1, das ferner ein Auffüllsystem innerhalb des sekundären Kreislafs umfasst, wobei das Auffüllsystem Folgendes umfasst: 40

einen sekundären Verdampfer (150, 710, 1010, 1602), der mit der Dampfleitung (130) verbun-

den ist, und

ein sekundäres Reservoir (155) in Fluidverbindung mit dem sekundären Verdampfer (150, 710, 1010, 1602) und durch die Überschussfluidleitung verbunden mit dem primären Verdampfer (115, 500, 600), wobei das Auffüllsystem funktionsfähig ist, um dem primären Verdampfer (115, 500, 600) die Flüssigkeit zumindest teilweise aus dem sekundären Reservoir (155) zuzuführen.

15. System nach Anspruch 14, wobei das Kondensationssystem Folgendes umfasst: 45

einen ersten Kondensator innerhalb des primären Kreislafs und verbunden mit der Flüssigkeitsleitung (125) und mit der Dampfleitung und einen zweiten Kondensator (122) innerhalb des sekundären Kreislafs und verbunden mit der Überschussfluidleitung und mit dem sekundären Reservoir (155).
16. System nach Anspruch 1, wobei der dritte Anschluss (139) des primären Verdampfers (115, 500, 600) hauptsächlich verwendet wird, um die überschüssige Flüssigkeit an die Überschussfluidleitung auszugeben, und wobei der dritte Anschluss (139) einen Unteranschluss zum Ausgeben des anderen Dampfes an eine Dampfleitung (130) umfasst, so dass die Dampfleitung (130) innerhalb des sekundären Kreislafs eingeschlossen ist. 50
17. System nach Anspruch 1, wobei die Flüssigkeitsleitung (125) coaxial zu der Überschussfluidleitung und innerhalb derselben enthalten ist. 55
18. System nach Anspruch 1, das ferner einen zweiten primären Verdampfer (150) umfasst, der parallel mit dem primären Verdampfer (115, 500, 600) innerhalb des primären Kreislafs verbunden ist.
19. System nach Anspruch 18, das ferner einen Gegendruckregler (1606) umfasst, der in Reihe mit der Dampfleitung (130) ausgerichtet und zwischen dem primären Verdampfer (115, 500, 600) und dem Kondensationssystem angeordnet ist und der funktionsfähig ist, um im Wesentlichen die Wärmebelastung zwischen dem primären Verdampfer (115, 500, 600) und dem zweiten primären Verdampfer (150) auszugleichen.
20. System nach Anspruch 19, wobei der Gegendruckregler den Dampf daran hindert, das Kondensationssystem zu erreichen, bis ein Dampfraum des primären Verdampfers (115, 500, 600) und des zweiten primären Verdampfers (150) im Wesentlichen frei von Flüssigkeit ist.

21. System nach Anspruch 1, das ferner einen zweiten primären Verdampfer (150) umfasst, der in Reihe mit dem primären Verdampfer (115, 500, 600) ausgerichtet ist.

22. System nach Anspruch 1, wobei das Kondensationssystem mehrere Kondensatoren umfasst, die parallel miteinander verbunden sind.

23. System nach Anspruch 22, das Folgendes umfasst:

Flüssigkeitsauslässe, die mit jedem der mehreren Kondensatoren verbunden und funktionsfähig sind, um die Flüssigkeit zu dem primären Verdampfer (115, 500, 600) auszugeben, und Kondensatorregler, die mit den Flüssigkeitsauslässen verbunden und funktionsfähig sind, um den Flüssigkeitsfluss aus denselben zu regulieren.

24. System nach Anspruch 1, das ferner Folgendes umfasst:

einen zweiten primären Verdampfer (150), der mit dem primären Verdampfer (115, 500, 600) innerhalb des primären Kreislafs verbunden ist, und

eine Wärmespeichereinheit (1222, 1808, 1830, 1858), die mit dem zweiten primären Verdampfer (150) verbunden ist.

25. System nach Anspruch 1, das ferner Folgendes umfasst:

einen zweiten primären Verdampfer (150), der mit dem primären Verdampfer (115, 500, 600) innerhalb des primären Kreislafs verbunden ist, und

einen ersten und einen zweiten Durchflussregler, die jeweils mit dem primären Verdampfer (115, 500, 600) beziehungsweise dem zweiten primären Verdampfer (150) verbunden und funktionsfähig sind, um den Flüssigkeitsfluss zu dem primären Verdampfer (115, 500, 600) beziehungsweise dem zweiten primären Verdampfer (150) zu regulieren, um so eine im Wesentlichen gleiche Wärmebelastungsverteilung zwischen den Verdampfern sicherzustellen.

26. System nach Anspruch 1, das ferner Folgendes umfasst:

einen zweiten primären Verdampfer (150), der mit dem primären Verdampfer (115, 500, 600) innerhalb des primären Kreislafs verbunden ist, und

einen Kondensationswärmetauscher, der mit dem zweiten primären Verdampfer (150) ver-

bunden ist.

27. System nach Anspruch 26, das einen sprühgeköhlten Verdampfer (1228) umfasst, der mit Hilfe einer mechanischen Pumpe (1110) mit dem Kondensationswärmetauscher verbunden ist.

28. System nach Anspruch 1, wobei das Kondensationssystem einen gehäusemontierten Radiator (1232) umfasst.

29. System nach Anspruch 1, wobei das Kondensationssystem einen entfaltbaren oder steuerbaren Radiator (1232) umfasst.

30. Verfahren zur Wärmeübertragung, das Folgendes umfasst:

Verdampfen von Flüssigkeit von einem primären Docht (140) eines primären Verdampfers (115, 500, 600), um dadurch Dampf zu erhalten, Ausgeben des Dampfes durch eine Dampfleitung (130), die mit dem primären Verdampfer (115, 500, 600) verbunden ist,

Kondensieren des Dampfes aus der Dampfleitung (130) innerhalb eines Kondensationssystems,

Zurückführen der Flüssigkeit zu dem primären Verdampfer (115, 500, 600) durch eine Flüssigkeitsleitung (125), die mit dem primären Verdampfer (115, 500, 600) verbunden ist, wobei ein Sättigungsmaß der Flüssigkeit gewährleistet wird, um so eine Sättigung des primären Dochtes (140) während des Verdampfens aufrechtzuerhalten,

Bereitstellen überschüssiger Flüssigkeit über das Sättigungsmaß hinaus für den primären Verdampfer (115, 500, 600) wenigstens teilweise aus einem Reservoir (1130), durch die Flüssigkeitsleitung (125) mit einer mechanischen Pumpe, und

Spülen der überschüssigen Flüssigkeit und anderen Dampfes innerhalb des primären Verdampfers (115, 500, 600) zu dem Kondensationssystem mit der mechanischen Pumpe durch eine Überschussfluidleitung.

31. Verfahren nach Anspruch 30, wobei das Verdampfen von Flüssigkeit von dem primären Docht (140) eines primären Verdampfers (115, 500, 600) das Aufrechterhalten eines kapillaren Pumpen der Flüssigkeit, der überschüssigen Flüssigkeit und des Dampfes umfasst, um so eine Durchflusskontrolle zu dem primären Verdampfer (115, 500, 600) und durch denselben aufrechtzuerhalten.

32. Verfahren nach Anspruch 30, wobei:

- das Ausgeben des Dampfes das Ausgeben des Dampfes durch einen ersten Anschluss (137) des primären Verdampfers (115, 500, 600) umfasst,
- das Zurückführen der Flüssigkeit und das Bereitstellen überschüssiger Flüssigkeit das Zurückführen der Flüssigkeit und der überschüssigen Flüssigkeit durch einen zweiten Anschluss (132) des primären Verdampfers (115, 500, 600) umfasst und
- das Spülen der überschüssigen Flüssigkeit und unerwünschten Dampfes das Spülen der überschüssigen Flüssigkeit und unerwünschten Dampfes aus einem dritten Anschluss (139) des primären Verdampfers (115, 500, 600) umfasst.
- 33.** Verfahren nach Anspruch 30, wobei:
- das Ausgeben des Dampfes das Ausgeben des Dampfes durch einen ersten Anschluss (137) des primären Verdampfers (115, 500, 600) umfasst,
- das Zurückführen der Flüssigkeit und das Bereitstellen überschüssiger Flüssigkeit das Zurückführen der Flüssigkeit und der überschüssigen Flüssigkeit durch einen zweiten Anschluss (132) des primären Verdampfers (115, 500, 600) umfasst und
- das Spülen der überschüssigen Flüssigkeit und anderen Dampfes das Spülen der überschüssigen Flüssigkeit aus einem dritten Anschluss (139) des primären Verdampfers (115, 500, 600) und das Spülen des anderen Dampfes aus einem vierten Anschluss des primären Verdampfers (115, 500, 600) umfasst.
- 34.** Verfahren nach Anspruch 34, wobei das Spülen der überschüssigen Flüssigkeit und anderen Dampfes das Trennen der Flüssigkeit und der überschüssigen Flüssigkeit von dem anderen Dampf mit einem sekundären Docht (145) des primären Verdampfers (115, 500, 600) umfasst.
- 35.** Verfahren nach Anspruch 34, welches das Umgehen der mechanischen Pumpe durch ein Umgehungsventil (1218, 1234), parallel mit der mechanischen Pumpe, während eines passiven Pumpvorgangs der Flüssigkeit zur Verdampfung durch den primären Verdampfer (115, 500, 600) umfasst.
- 36.** Verfahren nach Anspruch 34, wobei das Pumpen der überschüssigen Flüssigkeit das Pumpen der Flüssigkeit und der überschüssigen Flüssigkeit unter Verwendung einer Flüssigkeitspumpe umfasst, die in Reihe mit der Flüssigkeitsleitung (125) und zwischen dem Kondensationssystem und dem primären Verdampfer (115, 500, 600) angeordnet ist.
- 37.** Verfahren nach Anspruch 34, wobei das Pumpen der überschüssigen Flüssigkeit das Pumpen des Dampfes zu dem Kondensationssystem unter Verwendung eines Dampfverdichters (1302) umfasst, der in Reihe mit der Dampfleitung (130) ausgerichtet und zwischen dem primären Verdampfer (115, 500, 600) und dem Kondensationssystem angeordnet ist.
- 38.** Verfahren nach Anspruch 30, wobei das Bereitstellen überschüssiger Flüssigkeit das Bereitstellen der überschüssigen Flüssigkeit aus einem Auffüllsystem umfasst, in dem das Reservoir (1130) in Fluidverbindung mit einem sekundären Verdampfer (150, 710, 1010, 1602) steht, wobei das Reservoir (1130) mit dem primären Verdampfer (115, 500, 600) verbunden ist.
- 39.** Verfahren nach Anspruch 38, wobei:
- das Kondensieren des Dampfes das Kondensieren des Dampfes innerhalb eines ersten Kondensators des Kondensationssystems umfasst, wobei der erste Kondensator mit der Flüssigkeitsleitung (125) und mit der Dampfleitung (130) verbunden ist,
- das Spülen der überschüssigen Flüssigkeit und unerwünschten Dampfes das Kondensieren unerwünschten Dampfes innerhalb eines zweiten Kondensators (122) des Kondensationssystems umfasst, wobei der zweite Kondensator (122) mit einer Mischfluidleitung und mit dem Reservoir (1130) verbunden ist.
- 40.** System nach Anspruch 1, wobei das Pumpsystem eine mechanische Pumpe (1110) umfasst.
- 41.** System nach Anspruch 40, wobei der primäre Docht (140) und der sekundäre Docht (145) des primären Verdampfers (115, 500, 600) ein kapillares Pumpen der Flüssigkeit, der überschüssigen Flüssigkeit und des Dampfes aufrechterhalten, um so eine Durchflusskontrolle zu dem primären Verdampfer (115, 500, 600) und durch denselben aufrechtzuerhalten.
- 42.** System nach Anspruch 1, wobei das Pumpsystem (1100) ferner einen sekundären Verdampfer (150, 710, 1010, 1602) in Fluidverbindung mit dem Reservoir (1130) und verbunden mit der Dampfleitung (130) umfasst.
- 43.** System nach Anspruch 42, wobei das Reservoir (1130) durch eine Mischfluidleitung, die mit dem dritten Anschluss (139) des primären Verdampfers (115, 500, 600) verbunden ist, in Fluidverbindung mit dem sekundären Docht (145) des primären Verdampfers (115, 500, 600) steht.
- 44.** System nach Anspruch 1, wobei die überschüssige

Flüssigkeit durch einen vierten Anschluss des primären Verdampfers (115, 500, 600) im Wesentlichen aus dem Kern (135) des primären Verdampfers (115, 500, 600) entfernt wird.

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Revendications

1. Système de transfert de chaleur, comprenant :

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un évaporateur primaire (115, 500, 600) configuré pour servir à faciliter un transfert de chaleur grâce à une étape consistant à faire évaporer du liquide reçu afin d'obtenir de la vapeur, l'évaporateur primaire (115, 500, 600) comprenant un premier orifice (137) permettant de recevoir le liquide à partir d'une conduite de liquide (125), un deuxième orifice (132) permettant de produire la vapeur vers une conduite de vapeur (130), et un troisième orifice (139) permettant de produire du liquide excédentaire reçu à partir de la conduite de liquide (125) vers une conduite de fluide excédentaire, l'évaporateur primaire (115, 500, 600) comprenant en outre un bloc (135), une mèche primaire (140), et une mèche secondaire (145) ;

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un système de condensation configuré pour servir à recevoir la vapeur à partir de la conduite de vapeur (130), condenser au moins une partie de la vapeur, et produire le liquide vers la conduite de liquide (125) ;

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une boucle primaire comprenant le système de condensation, l'évaporateur primaire (115, 500, 600), la conduite de liquide (125), la conduite de vapeur (130), le premier orifice (137), et le deuxième orifice (132), la boucle primaire étant configurée pour servir à fournir un trajet de transfert de chaleur ;

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une boucle secondaire comprenant le système de condensation, l'évaporateur primaire (115, 500, 600), la conduite de liquide (125), la conduite de vapeur (130), le premier orifice (137), le troisième orifice (139) et la conduite de fluide excédentaire, la boucle secondaire étant configurée pour servir à fournir un trajet de mise à l'air afin de retirer une autre vapeur présente au sein du liquide à partir de l'évaporateur primaire (115, 500, 600) ; et

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un système de mise à l'air configuré pour retirer des bulles de vapeur à partir du bloc (135) de l'évaporateur primaire (115, 500, 600) vers le système de condensation, le système de mise à l'air comprenant :

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un système de pompage actif (1100) configuré pour servir à fournir du liquide excédentaire vers l'évaporateur primaire (115, 500, 600) au-delà d'une quantité de satura-

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tion de liquide nécessaire pour saturer la mèche primaire (140) ; et

un réservoir (1130) en communication fluide avec le système de condensation, le réservoir (1130) étant en communication fluide avec le système de pompage (1100) et étant configuré pour fournir le liquide excédentaire, dans lequel le système de mise à l'air est configuré pour mettre à l'air des bulles de vapeur et du liquide excédentaire à partir du bloc (135) de l'évaporateur primaire (115, 500, 600) à travers le troisième orifice (139) vers la conduite de fluide excédentaire grâce au système de pompage actif (1100).

2. Système selon la revendication 1, dans lequel le liquide présent dans l'évaporateur primaire (115, 500, 600) et reçu à partir de la conduite de liquide (125) comprend le liquide excédentaire en une quantité supérieure à une quantité de liquide nécessaire pour maintenir une saturation d'une mèche primaire (140) au sein d'un bloc (135) de l'évaporateur primaire (115, 500, 600).

3. Système selon la revendication 2, dans lequel l'évaporateur primaire (115, 500, 600) comprend une mèche secondaire (145) qui peut servir à mettre en oeuvre une séparation de phase de l'autre vapeur par rapport au liquide en vue d'une production à travers la conduite de fluide excédentaire.

4. Système selon la revendication 3, dans lequel la mèche primaire (140) et la mèche secondaire (145) de l'évaporateur primaire (115, 500, 600) maintiennent un pompage capillaire du liquide, du liquide excédentaire, et de la vapeur, de manière à maintenir une régulation du débit vers et à travers l'évaporateur primaire (115, 500, 600).

5. Système selon la revendication 1, dans lequel le système de pompage (1100) comprend une pompe mécanique (1110) qui peut servir à faciliter le transfert de chaleur grâce à une étape consistant à pomper de manière active le liquide en vue d'une évaporation par l'évaporateur primaire (115, 500, 600), et en vue d'une production en tant que liquide excédentaire à travers le troisième orifice (139) vers la conduite de fluide excédentaire.

6. Système selon la revendication 5, dans lequel le réservoir (1130) est positionné entre une sortie du système de condensation et une entrée de la pompe mécanique (1110).

7. Système selon la revendication 5, dans lequel la pompe mécanique (1110) est positionnée entre une entrée du système de condensation et une sortie de

l'évaporateur primaire (115, 500, 600).

8. Système selon la revendication 5, comprenant en outre une soupape de dérivation (1218, 1234) en parallèle avec la pompe mécanique (1110) et pouvant servir à dériver la pompe mécanique (1110) pendant une opération de pompage passif de liquide en vue d'une évaporation par l'évaporateur primaire (115, 500, 600). 5
9. Système selon la revendication 5, dans lequel la pompe mécanique (1110) comprend une pompe à liquide (1202/1230) qui est orientée en série avec la conduite de liquide (125) et est positionnée entre le système de condensation et l'évaporateur primaire (115, 500, 600). 10 15
10. Système selon la revendication 5, dans lequel la pompe mécanique (1110) comprend un compresseur de vapeur (1302) qui est orienté en série avec la conduite de vapeur (130) et est positionné entre l'évaporateur primaire (115, 500, 600) et le système de condensation. 20
11. Système selon la revendication 5, comprenant en outre : 25
 - un capteur (2300, 2400) qui peut servir à communiquer un niveau de saturation de la mèche de l'évaporateur primaire (115, 500, 600) à la pompe mécanique (1110), 30
 - dans lequel une pression de pompage fournie par la pompe mécanique (1110) est ajustée, en se basant sur le niveau de saturation, de manière à maintenir une saturation de la mèche par le liquide. 35
12. Système selon la revendication 5, comprenant en outre une soupape de dérivation de liquide (1218, 1234) raccordée entre la conduite de liquide (125) et la conduite de vapeur (130) et pouvant servir à maintenir des opérations de la pompe mécanique (1110) à vitesse de pompage constante. 40
13. Système selon la revendication 5, dans lequel l'évaporateur primaire (115, 500, 600) comprend une mèche primaire (140) et une mèche secondaire (145), dont les compositions incluent du métal. 45
14. Système selon la revendication 1, comprenant en outre un système d'amorçage au sein de la boucle secondaire, le système d'amorçage comprenant : 50
 - un évaporateur secondaire (150, 170, 1010, 1602) couplé à la conduite de vapeur (130) ; et 55
 - un réservoir secondaire (155) en communication fluïdique avec l'évaporateur secondaire (150, 710, 1010, 1602) et couplé à l'évaporateur

primaire (115, 500, 600) grâce à la conduite de fluide excédentaire, dans lequel le système d'amorçage peut servir à fournir le liquide vers l'évaporateur primaire (115, 500, 600) au moins partiellement à partir du réservoir secondaire (155).

15. Système selon la revendication 14, dans lequel le système de condensation comprend :
 - un premier condenseur présent au sein de la boucle primaire et couplé à la conduite de liquide (125) et à la conduite de vapeur (130) ; et
 - un deuxième condenseur (122) présent au sein de la boucle secondaire et couplé à la conduite de fluide excédentaire et au réservoir secondaire (155).
16. Système selon la revendication 1, dans lequel le troisième orifice (139) de l'évaporateur primaire (115, 500, 600) est utilisé de manière initiale pour produire le liquide excédentaire vers la conduite de fluide excédentaire, et dans lequel le troisième orifice (139) comprend un sous-orifice permettant de produire l'autre vapeur vers une conduite de vapeur (130), de sorte que la conduite de vapeur (130) est incluse dans la boucle secondaire.
17. Système selon la revendication 1, dans lequel la conduite de liquide (125) est coaxiale à, et contenue dans, la conduite de fluide excédentaire.
18. Système selon la revendication 1, comprenant en outre un deuxième évaporateur primaire (150) qui est raccordé en parallèle avec l'évaporateur primaire (115, 500, 600) au sein de la boucle primaire.
19. Système selon la revendication 18, comprenant en outre un régulateur de contre-pression (1606) qui est orienté en série avec la conduite de vapeur (130) et est positionné entre l'évaporateur primaire (115, 500, 600) et le système de condensation, et qui peut servir à équilibrer de manière substantielle la charge thermique entre l'évaporateur primaire (115, 500, 600) et le deuxième évaporateur primaire (150).
20. Système selon la revendication 19, dans lequel le régulateur de contre-pression empêche la vapeur d'atteindre le système de condensation jusqu'à ce qu'un espace de vapeur de l'évaporateur primaire (115, 500, 600) et du deuxième évaporateur primaire (150) soit essentiellement dépourvu de liquide.
21. Système selon la revendication 1, comprenant en outre un deuxième évaporateur primaire (150) qui est orienté en série avec l'évaporateur primaire (115, 500, 600) au sein de la boucle primaire.

22. Système selon la revendication 1, dans lequel le système de condensation comprend une pluralité de condenseurs raccordés en parallèle les uns aux autres.

23. Système selon la revendication 22, comprenant :

des sorties de liquide associées à chacun parmi la pluralité de condenseurs et pouvant servir à produire le liquide vers l'évaporateur primaire (115, 500, 600) ; et
des régulateurs de condenseur couplés aux sorties de liquide et pouvant servir à réguler l'écoulement de liquide à partir de celles-ci.

24. Système selon la revendication 1, comprenant en outre :

un deuxième évaporateur primaire (150) qui est raccordé à l'évaporateur primaire (115, 500, 600) au sein de la boucle primaire ; et
une unité de stockage thermique (1222, 1808, 1830, 1858) couplée au deuxième évaporateur primaire (150).

25. Système selon la revendication 1, comprenant en outre :

un deuxième évaporateur primaire (150) qui est raccordé à l'évaporateur primaire (115, 500, 600) au sein de la boucle primaire ; et
des premier et deuxième régulateurs de débit raccordés à l'évaporateur primaire (115, 500, 600) et au deuxième évaporateur primaire (150), respectivement, et pouvant servir à réguler un débit de liquide vers l'évaporateur primaire (115, 500, 600) et vers le deuxième évaporateur primaire (150), respectivement, de manière à garantir une répartition de charge thermique essentiellement égale entre les évaporateurs.

26. Système selon la revendication 1, comprenant en outre :

un deuxième évaporateur primaire (150) qui est raccordé à l'évaporateur primaire (115, 500, 600) au sein de la boucle primaire ; et
un échangeur de chaleur à condensation couplé au deuxième évaporateur primaire (150).

27. Système selon la revendication 26, comprenant un évaporateur refroidi par aspersion (1228) couplé à l'échangeur de chaleur à condensation au moyen d'une pompe mécanique (1110).

28. Système selon la revendication 1, dans lequel le système de condensation comprend un radiateur (1232) lié à la structure.

29. Système selon la revendication 1, dans lequel le système de condensation comprend un radiateur (1232) pouvant être déployé ou orienté.

30. Procédé de transfert de chaleur, comprenant les étapes consistant à :

faire évaporer du liquide à partir d'une mèche primaire (140) d'un évaporateur primaire (115, 500, 600) afin d'obtenir ainsi de la vapeur ;
produire la vapeur vers une conduite de vapeur (130) couplée à l'évaporateur primaire (115, 500, 600) ;
condenser la vapeur à partir de la conduite de vapeur (130) au sein d'un système de condensation ;
renvoyer le liquide vers l'évaporateur primaire (115, 500, 600) à travers une conduite de liquide (125) couplée à l'évaporateur primaire (115, 500, 600), dans lequel une quantité de saturation du liquide est fournie de manière à maintenir une saturation de la mèche primaire (140) pendant l'évaporation ;
fournir du liquide excédentaire au-delà de la quantité de saturation vers l'évaporateur primaire (115, 500, 600) au moins partiellement à partir d'un réservoir (1130), à travers la conduite de liquide (125), grâce à une pompe mécanique ; et
éliminer le liquide excédentaire et l'autre vapeur au sein de l'évaporateur primaire (115, 500, 600) vers le système de condensation grâce à la pompe mécanique à travers une conduite de fluide excédentaire.

31. Procédé selon la revendication 30, dans lequel l'étape consistant à faire évaporer le liquide à partir de la mèche primaire (140) de l'évaporateur primaire (115, 500, 600) comprend une étape consistant à maintenir un pompage capillaire du liquide, du liquide excédentaire, et de la vapeur, de manière à maintenir une régulation du débit vers et à travers l'évaporateur primaire (115, 500, 600).

32. Procédé selon la revendication 30, dans lequel :

l'étape de production de la vapeur comprend une étape consistant à produire la vapeur à travers un premier orifice (137) de l'évaporateur primaire (115, 500, 600) ;
les étapes de renvoi du liquide et de fourniture du liquide excédentaire comprennent une étape consistant à renvoyer le liquide et le liquide excédentaire à travers un deuxième orifice (132) de l'évaporateur primaire (115, 500, 600) ; et
l'étape d'élimination du liquide excédentaire et de la vapeur non souhaitée comprend une étape consistant à éliminer le liquide excédentaire et la vapeur non souhaitée à partir d'un troisième

orifice (139) de l'évaporateur primaire (115, 500, 600).

33. Procédé selon la revendication 30, dans lequel :

l'étape de production de la vapeur comprend une étape consistant à produire la vapeur à travers un premier orifice (137) de l'évaporateur primaire (115, 500, 600) ;
les étapes de renvoi du liquide et de fourniture du liquide excédentaire comprennent une étape consistant à renvoyer le liquide et le liquide excédentaire à travers un deuxième orifice (132) de l'évaporateur primaire (115, 500, 600) ; et
l'étape d'élimination du liquide excédentaire et de l'autre vapeur comprend les étapes consistant à éliminer le liquide excédentaire à partir d'un troisième orifice (139) de l'évaporateur primaire (115, 500, 600) et à éliminer l'autre vapeur à partir d'un quatrième orifice de l'évaporateur primaire (115, 500, 600).

34. Procédé selon la revendication 30, dans lequel l'étape d'élimination du liquide excédentaire et de l'autre vapeur comprend une étape consistant à séparer le liquide et le liquide excédentaire par rapport à l'autre vapeur grâce à une mèche secondaire (145) de l'évaporateur primaire (115, 500, 600).

35. Procédé selon la revendication 34, comprenant une étape consistant à dériver la pompe mécanique à l'aide d'une soupape de dérivation (1218, 1234) en parallèle avec la pompe mécanique pendant une opération de pompage passif du liquide en vue d'une évaporation par l'évaporateur primaire (115, 500, 600).

36. Procédé selon la revendication 34, dans lequel l'étape de pompage du liquide excédentaire comprend une étape consistant à pomper le liquide et le liquide excédentaire à l'aide d'une pompe à liquide qui est orientée en série avec la conduite de liquide (125) et est positionnée entre le système de condensation et l'évaporateur primaire (115, 500, 600).

37. Procédé selon la revendication 34, dans lequel l'étape de pompage du liquide excédentaire comprend une étape consistant à pomper la vapeur vers le système de condensation à l'aide d'un compresseur de vapeur (1302) qui est orienté en série avec la conduite de vapeur (130) et est positionné entre l'évaporateur primaire (115, 500, 600) et le système de condensation.

38. Procédé selon la revendication 30, dans lequel l'étape de fourniture du liquide excédentaire comprend une étape consistant à fournir le liquide excédentaire à partir d'un système d'amorçage au sein duquel le

réservoir (1130) est en communication fluidique avec un évaporateur secondaire (150, 710, 1010, 1602), le réservoir (1130) étant couplé à l'évaporateur primaire (115, 500, 600).

39. Procédé selon la revendication 38, dans lequel :

l'étape de condensation de la vapeur comprend une étape consistant à condenser la vapeur au sein d'un premier condenseur du système de condensation, le premier condenseur étant couplé à la conduite de liquide (125) et à la conduite de vapeur (130) ; et
l'étape d'élimination du liquide excédentaire et de la vapeur non souhaitée comprend une étape consistant à condenser la vapeur non souhaitée au sein d'un deuxième condenseur (122) du système de condensation, le deuxième condenseur (122) étant couplé à une conduite de fluide mixte et au réservoir (1130).

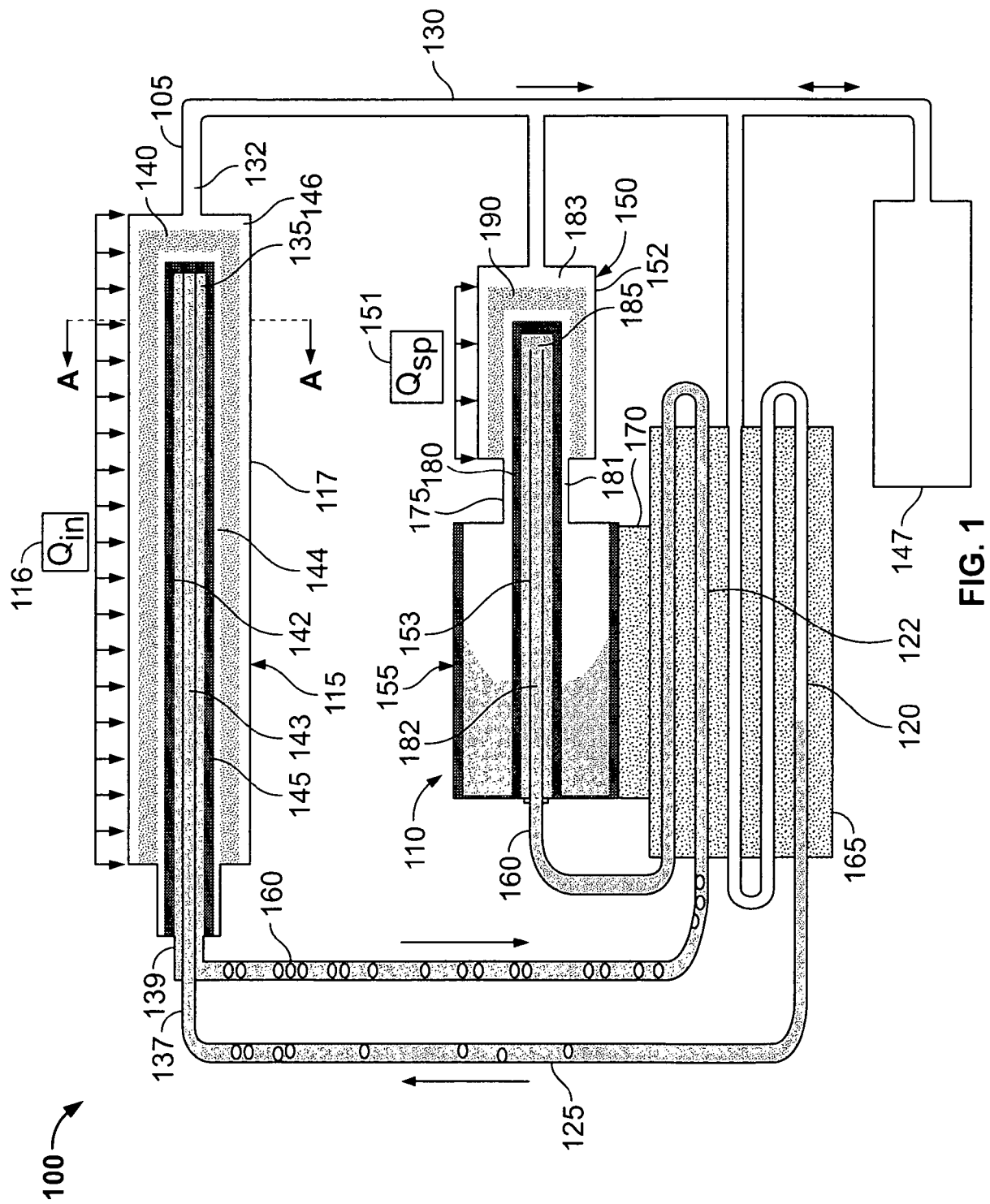
40. Système selon la revendication 1, dans lequel le système de pompage comprend une pompe mécanique (1110).

41. Système selon la revendication 40, dans lequel la mèche primaire (140) et la mèche secondaire (145) de l'évaporateur primaire (115, 500, 600) maintiennent un pompage capillaire du liquide, du liquide excédentaire, et de la vapeur, de manière à maintenir une régulation du débit vers et à travers l'évaporateur primaire (115, 500, 600).

42. Système selon la revendication 1, dans lequel le système de pompage (1100) comprend en outre un évaporateur secondaire (150, 710, 1010, 1602) en communication fluidique avec le réservoir (1130) et couplé à la conduite de vapeur (130).

43. Système selon la revendication 42, dans lequel le réservoir (1130) est en communication fluidique avec la mèche secondaire (145) de l'évaporateur primaire (115, 500, 600) à travers une conduite de fluide mixte couplée au troisième orifice (139) de l'évaporateur primaire (115, 500, 600).

44. Système selon la revendication 1, dans lequel le liquide excédentaire est essentiellement retiré du bloc (135) de l'évaporateur primaire (115, 500, 600) à travers un quatrième orifice de l'évaporateur primaire (115, 500, 600).



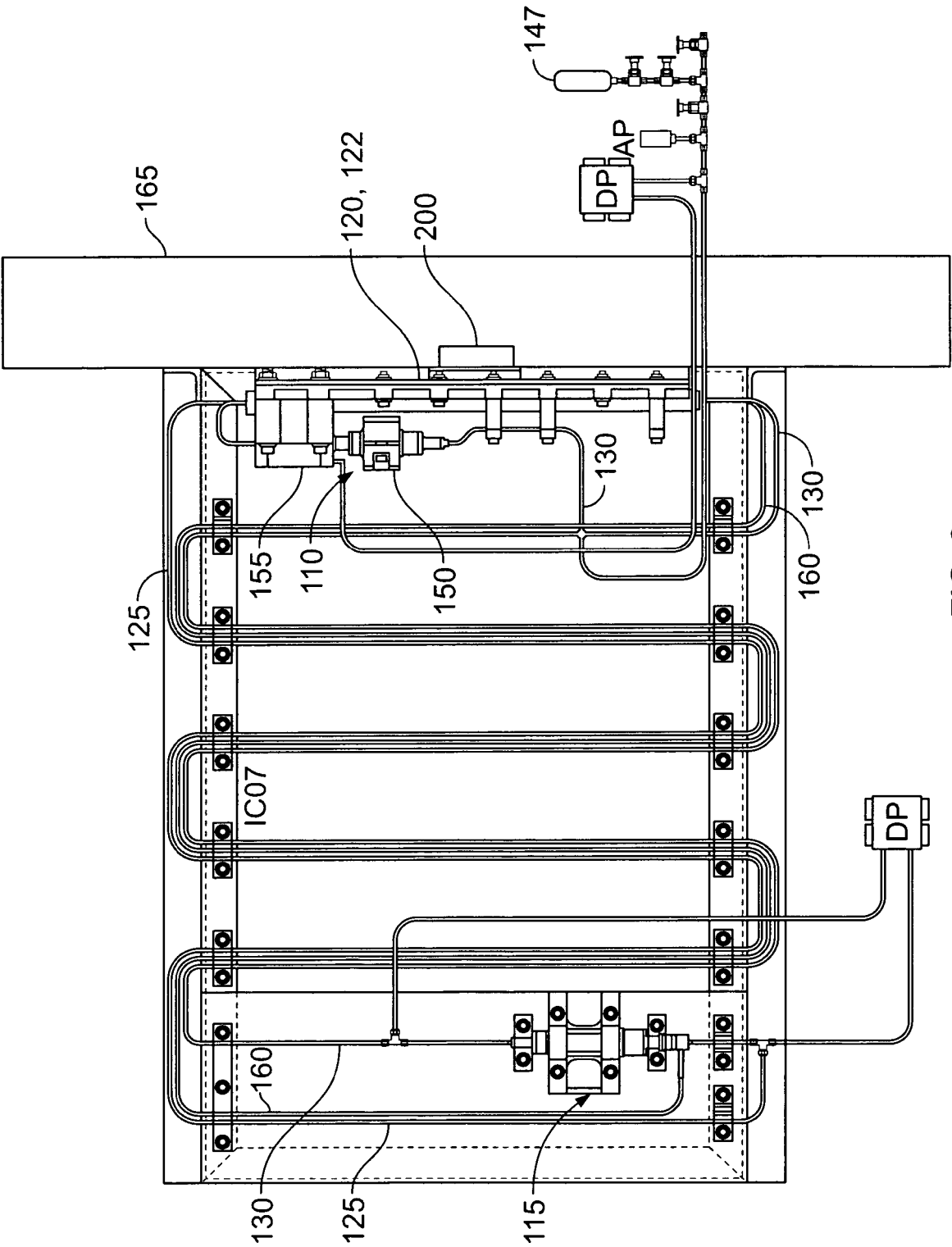


FIG. 2

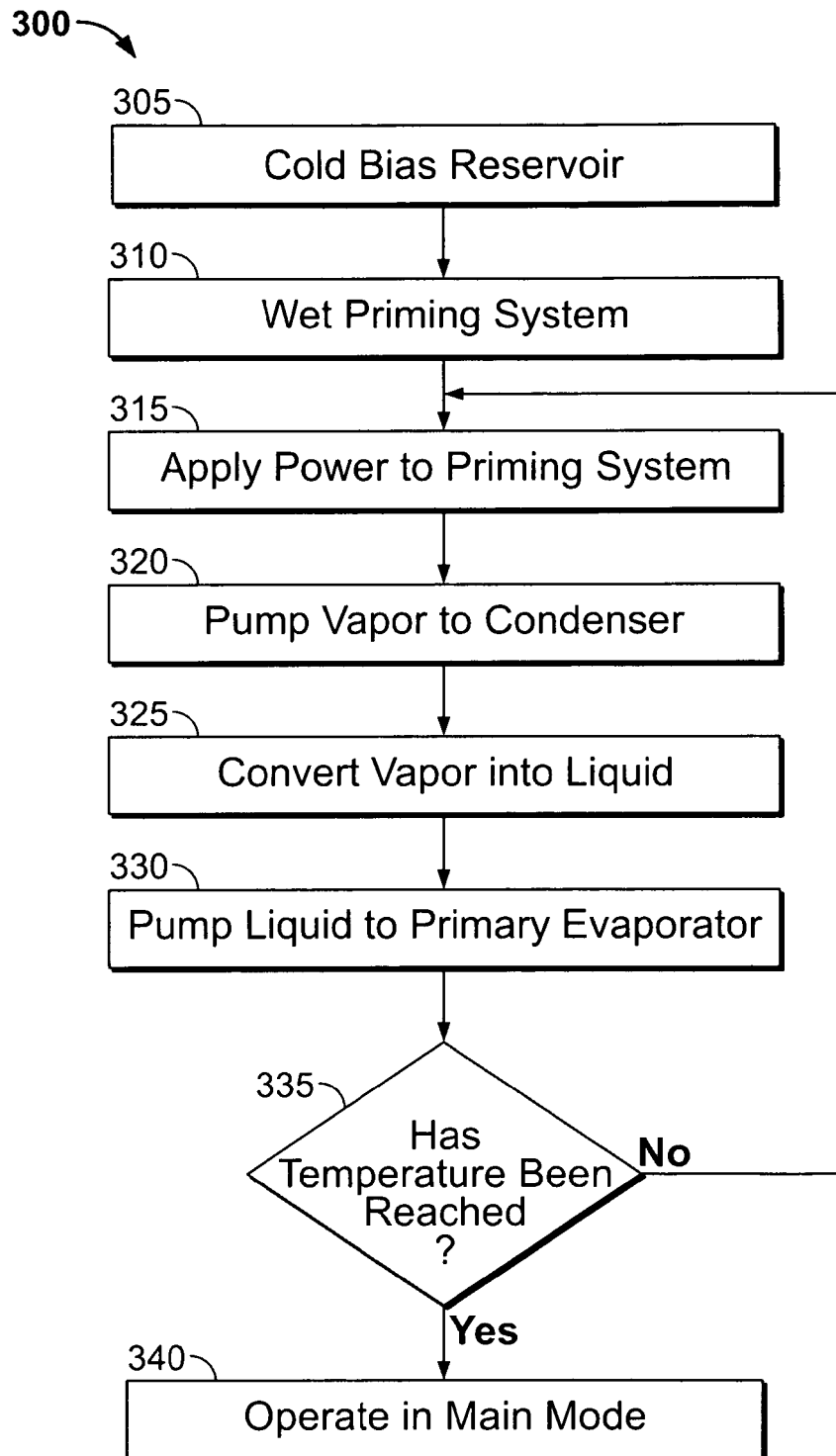


FIG. 3

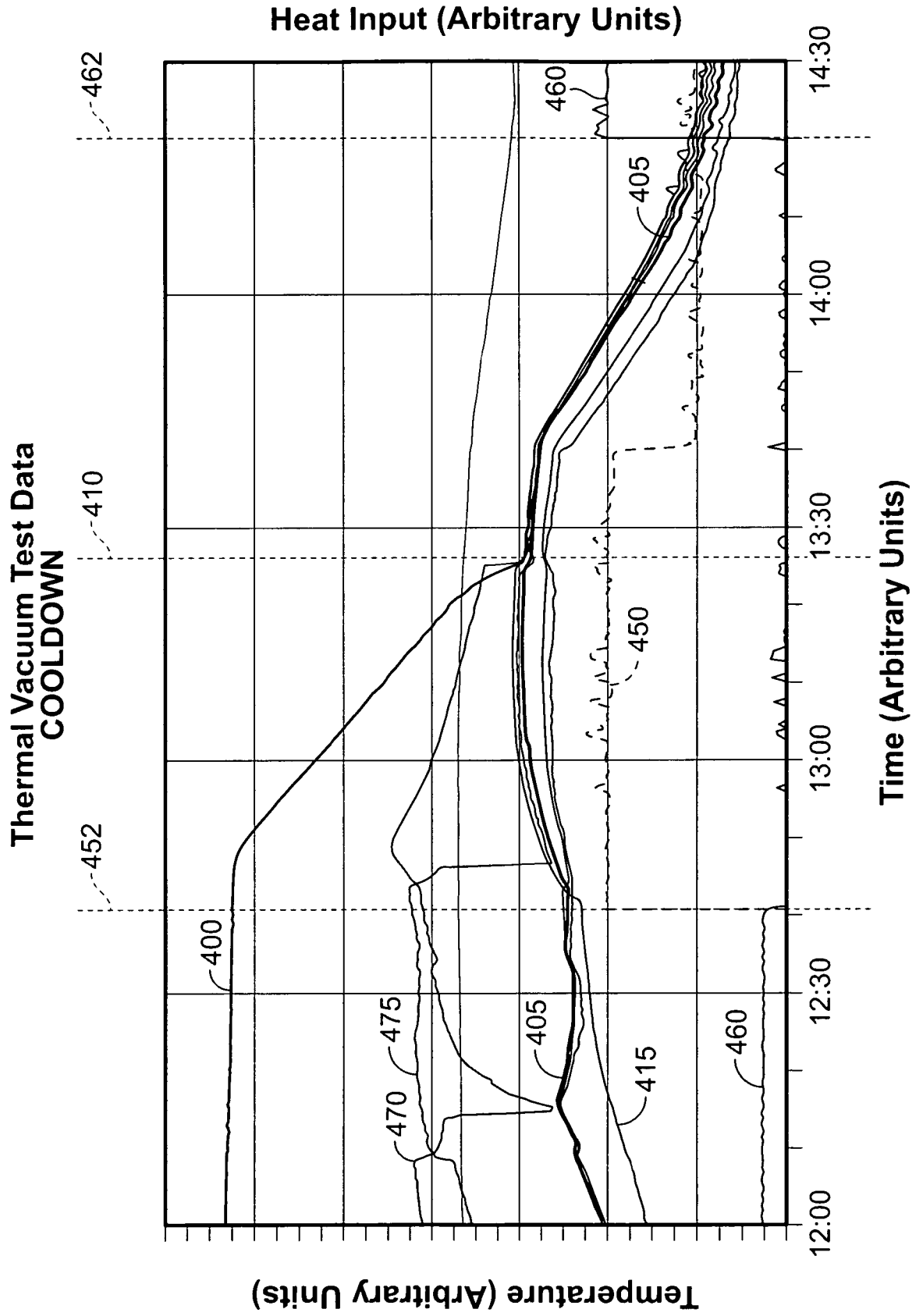


FIG. 4

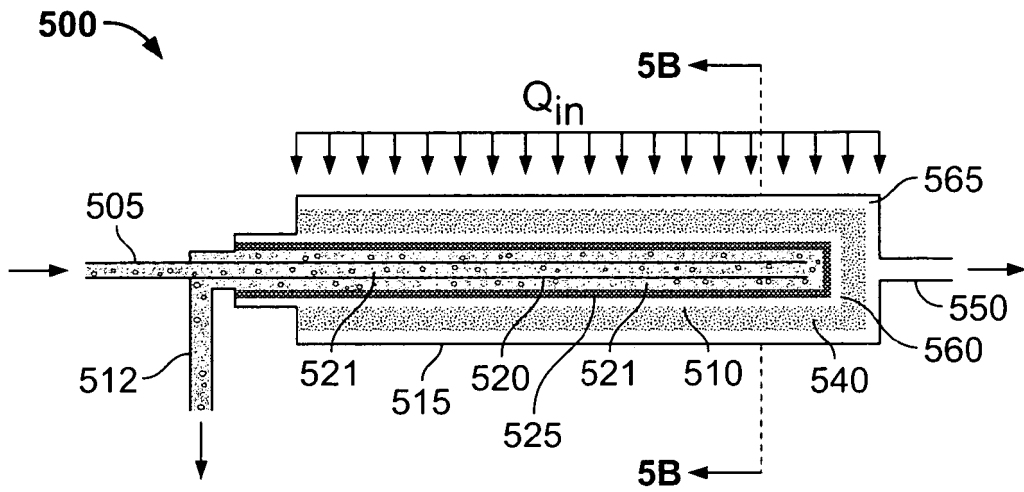


FIG. 5A

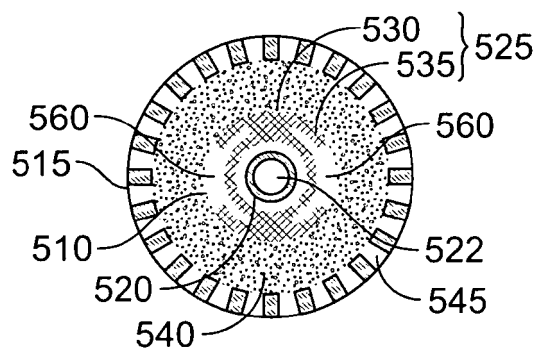


FIG. 5B

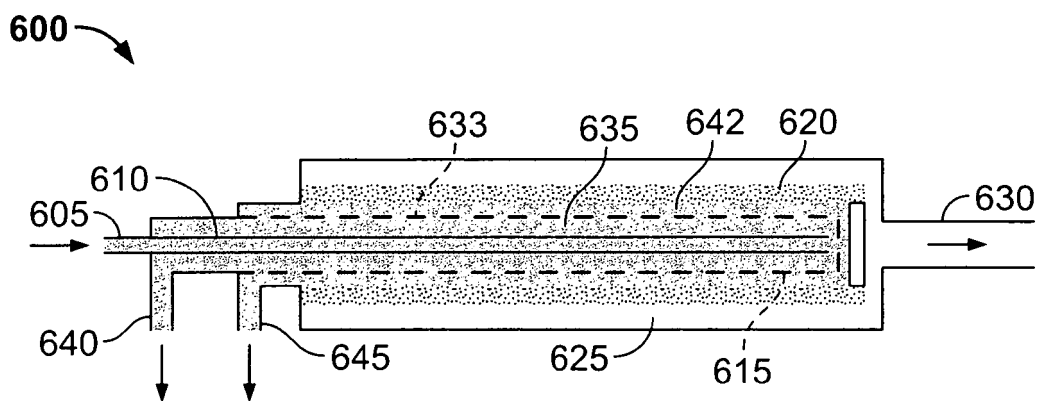


FIG. 6

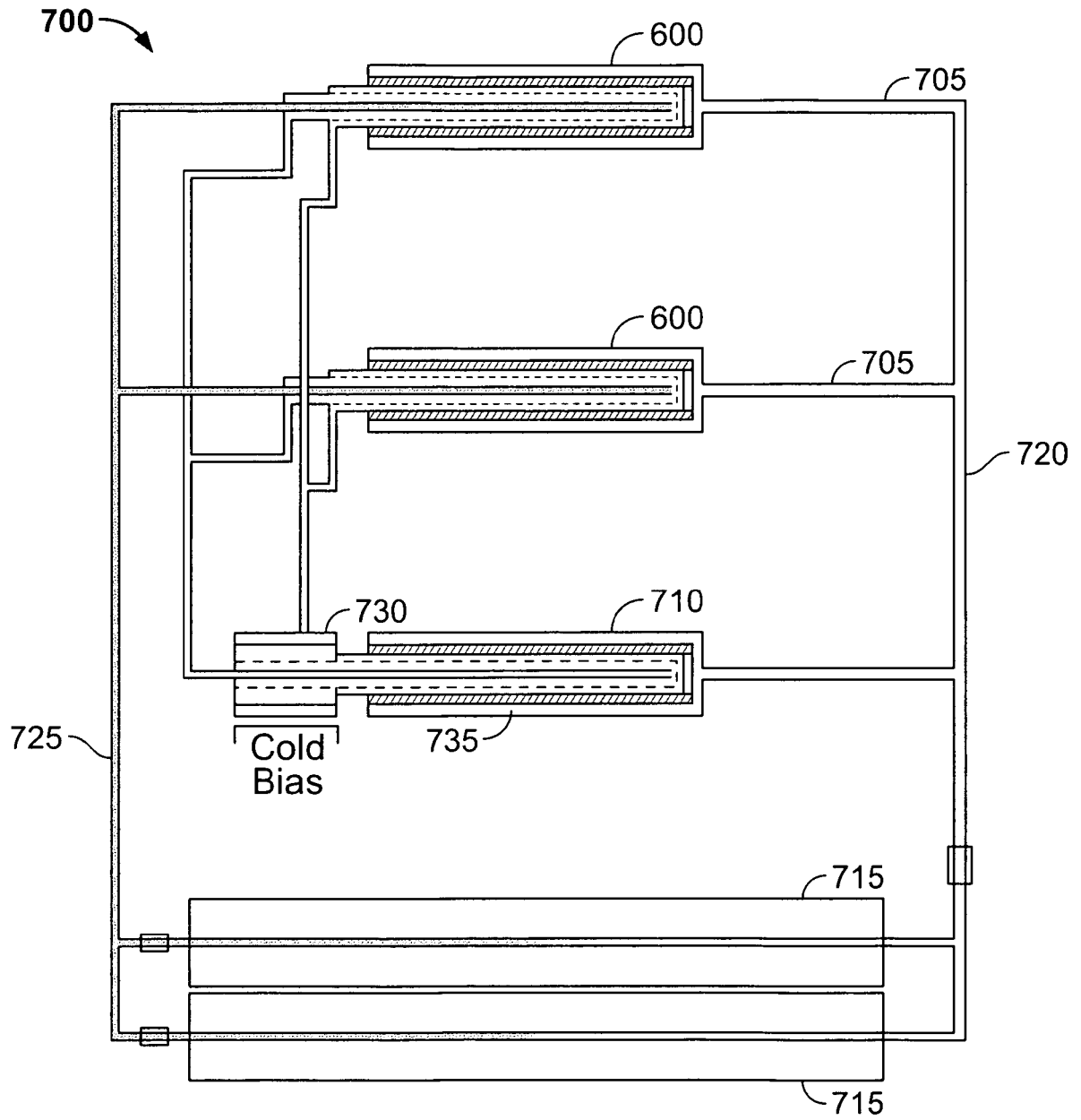


FIG. 7

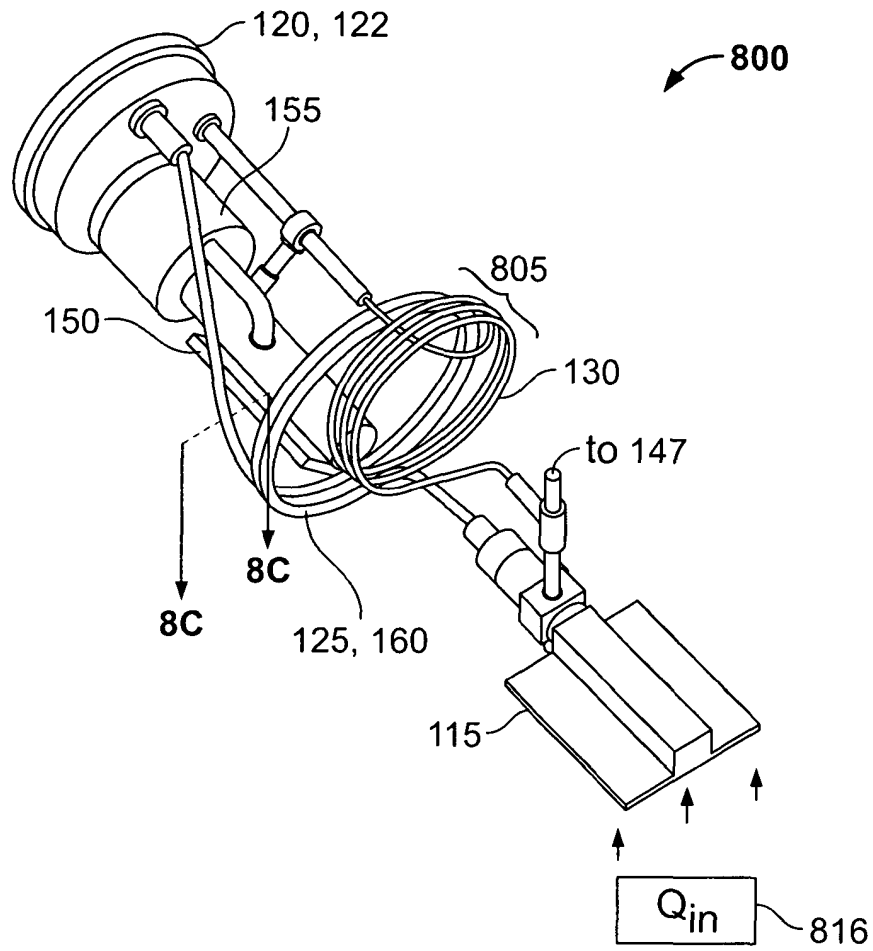


FIG. 8A

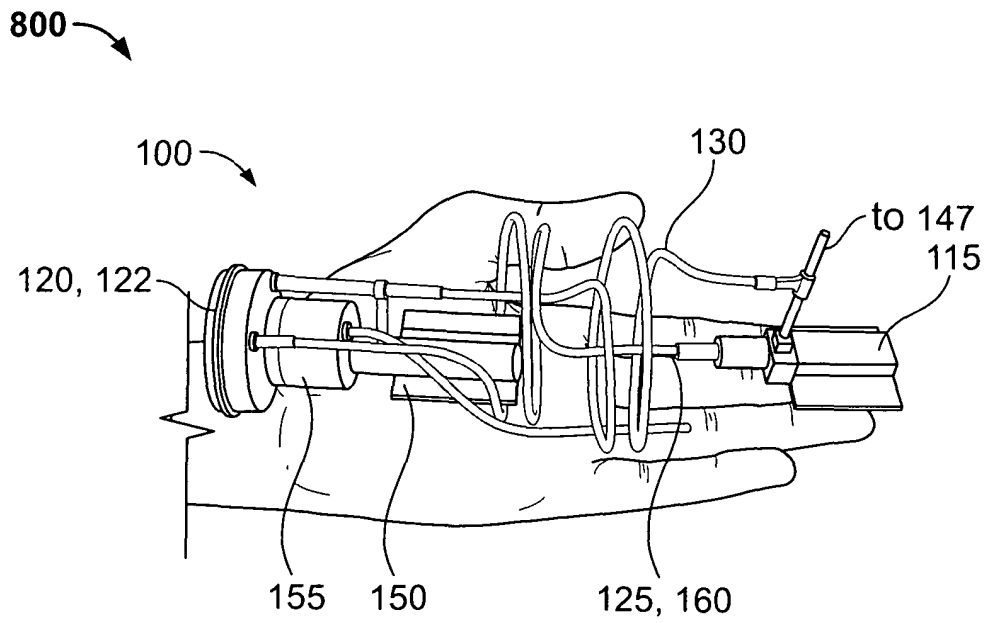


FIG. 8B

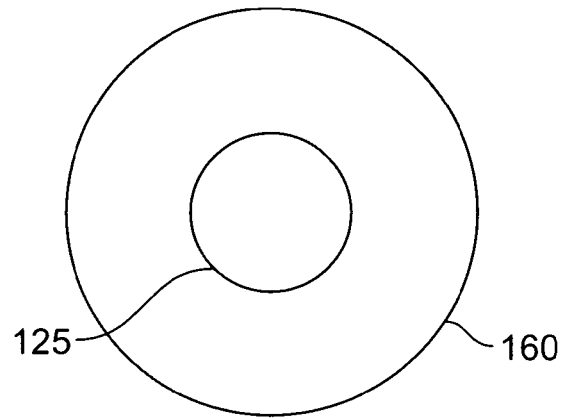


FIG. 8C

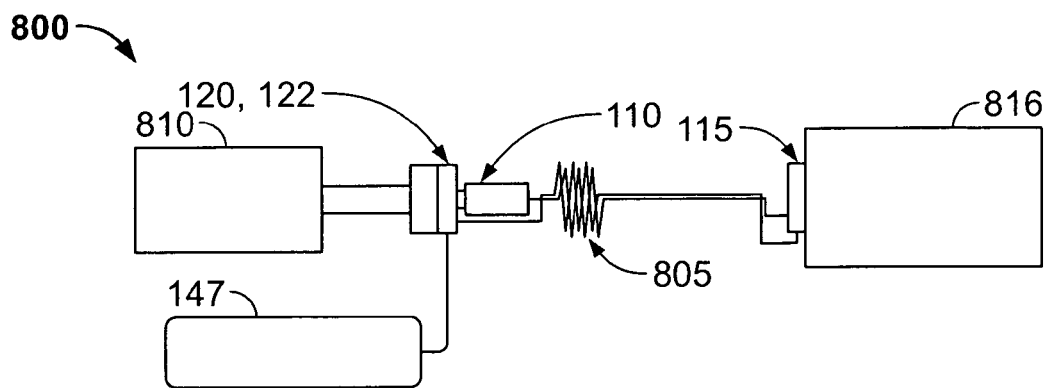


FIG. 8D

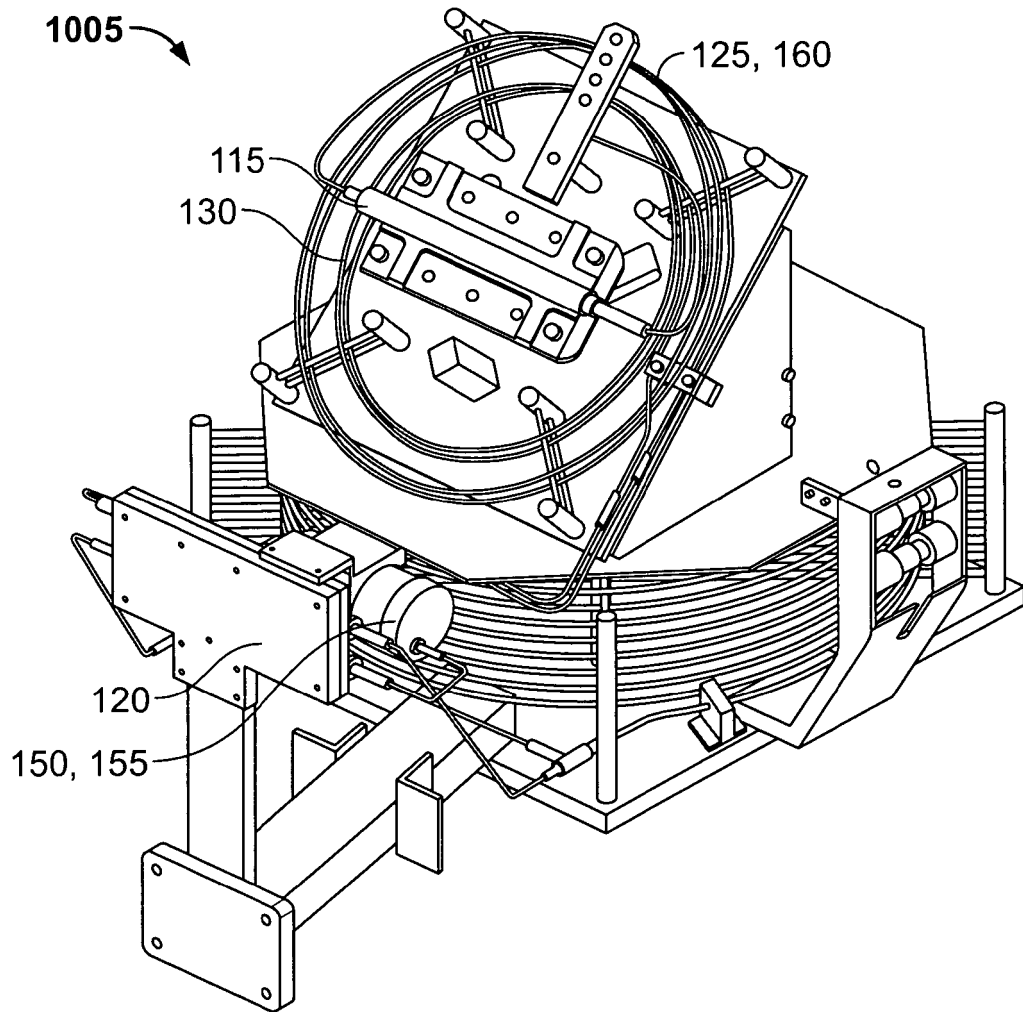


FIG. 9A

1005

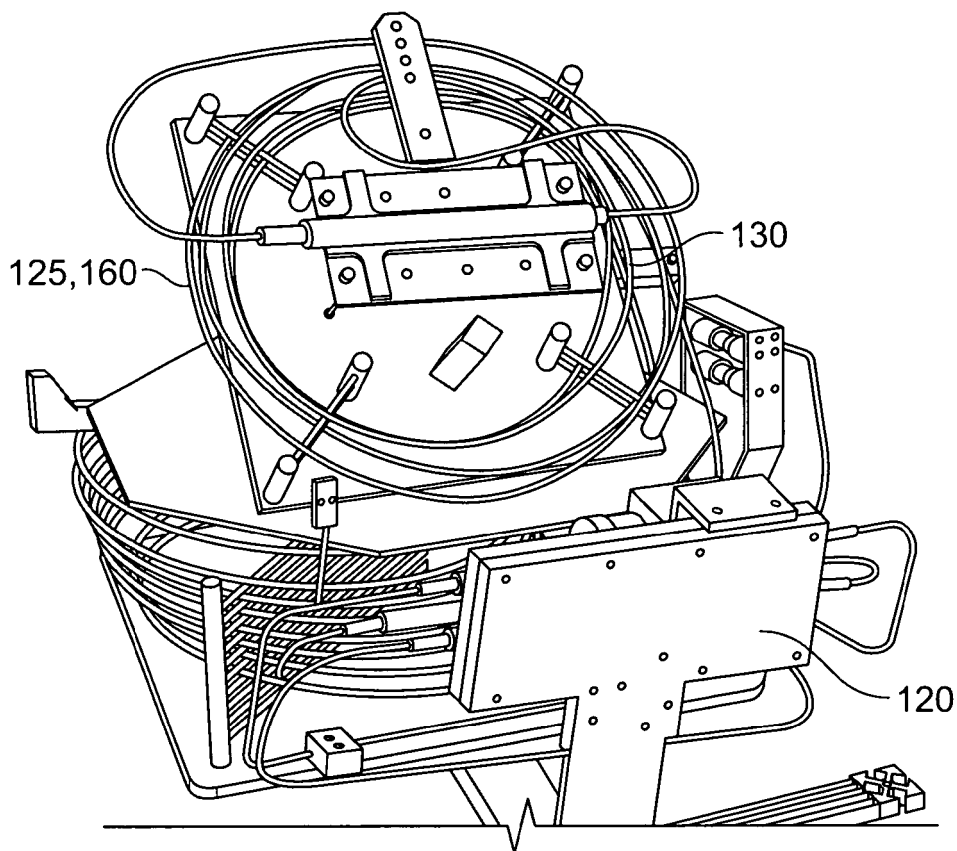


FIG. 9B

1005

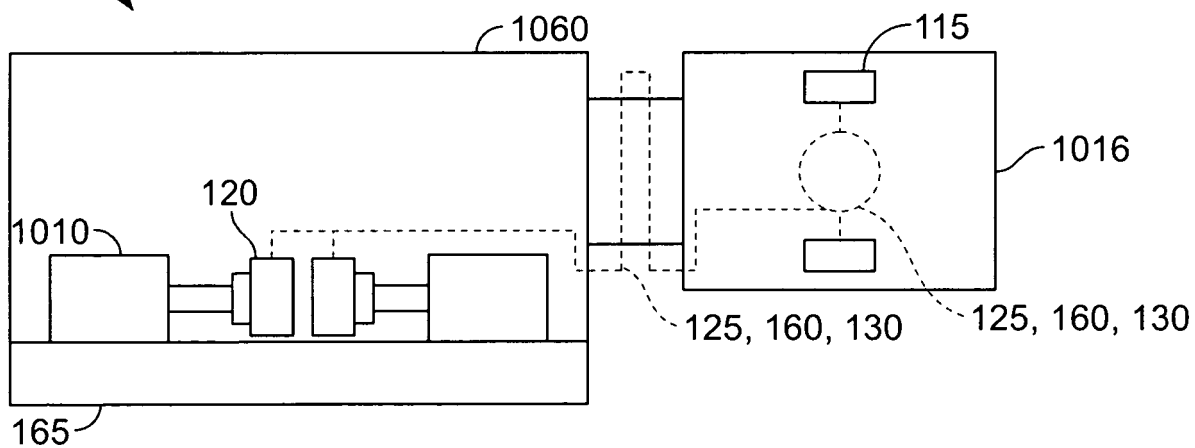


FIG. 9C

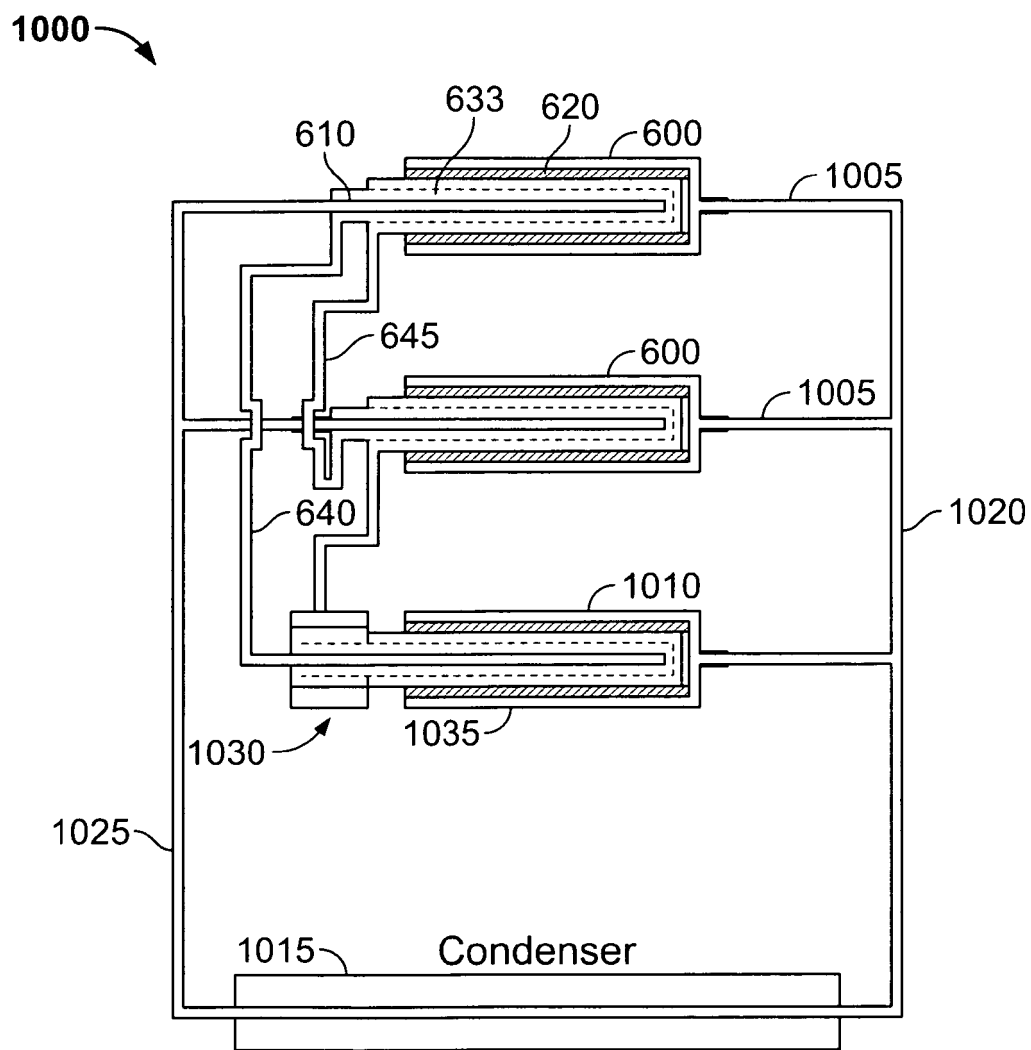


FIG. 10

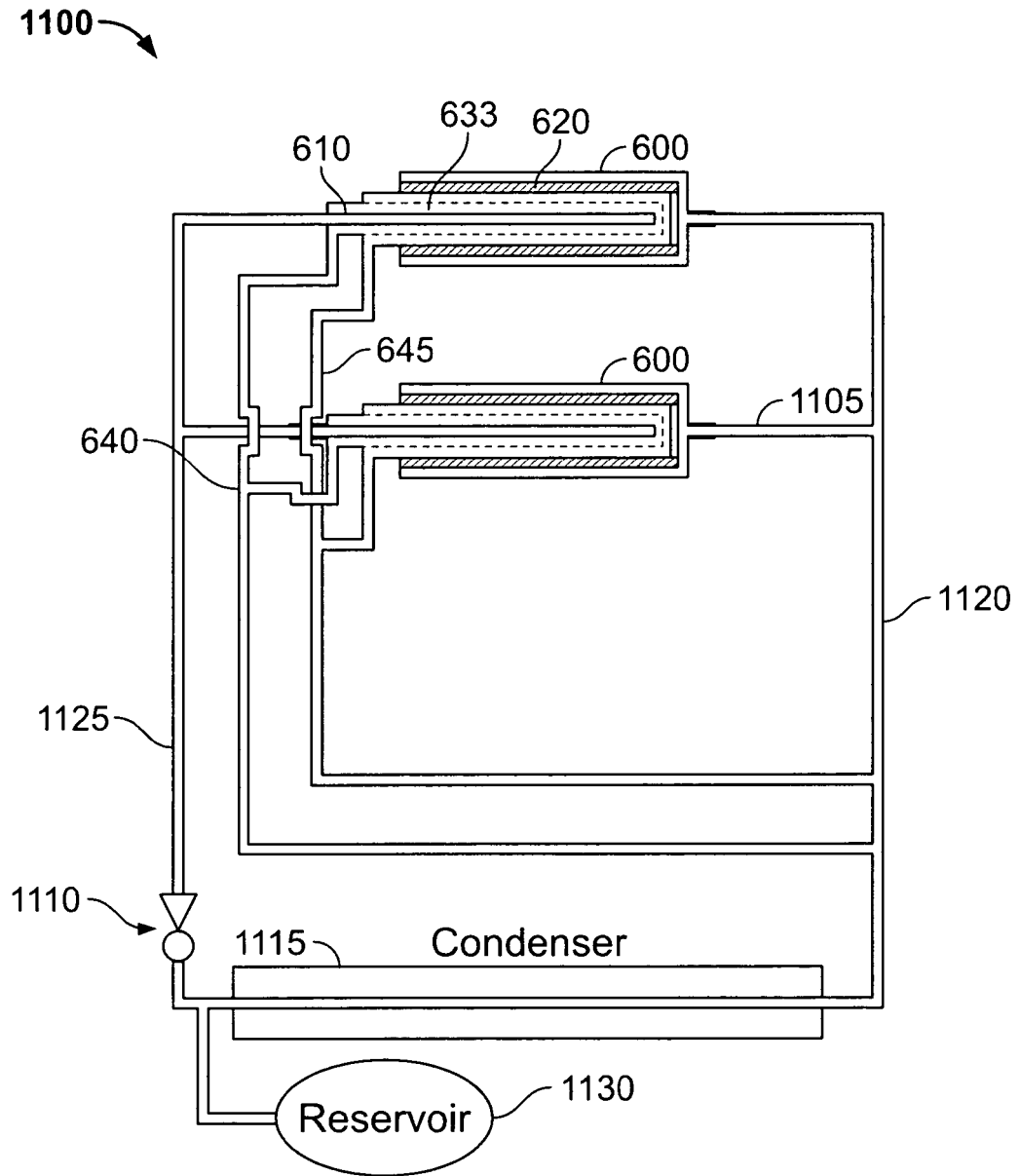


FIG. 11

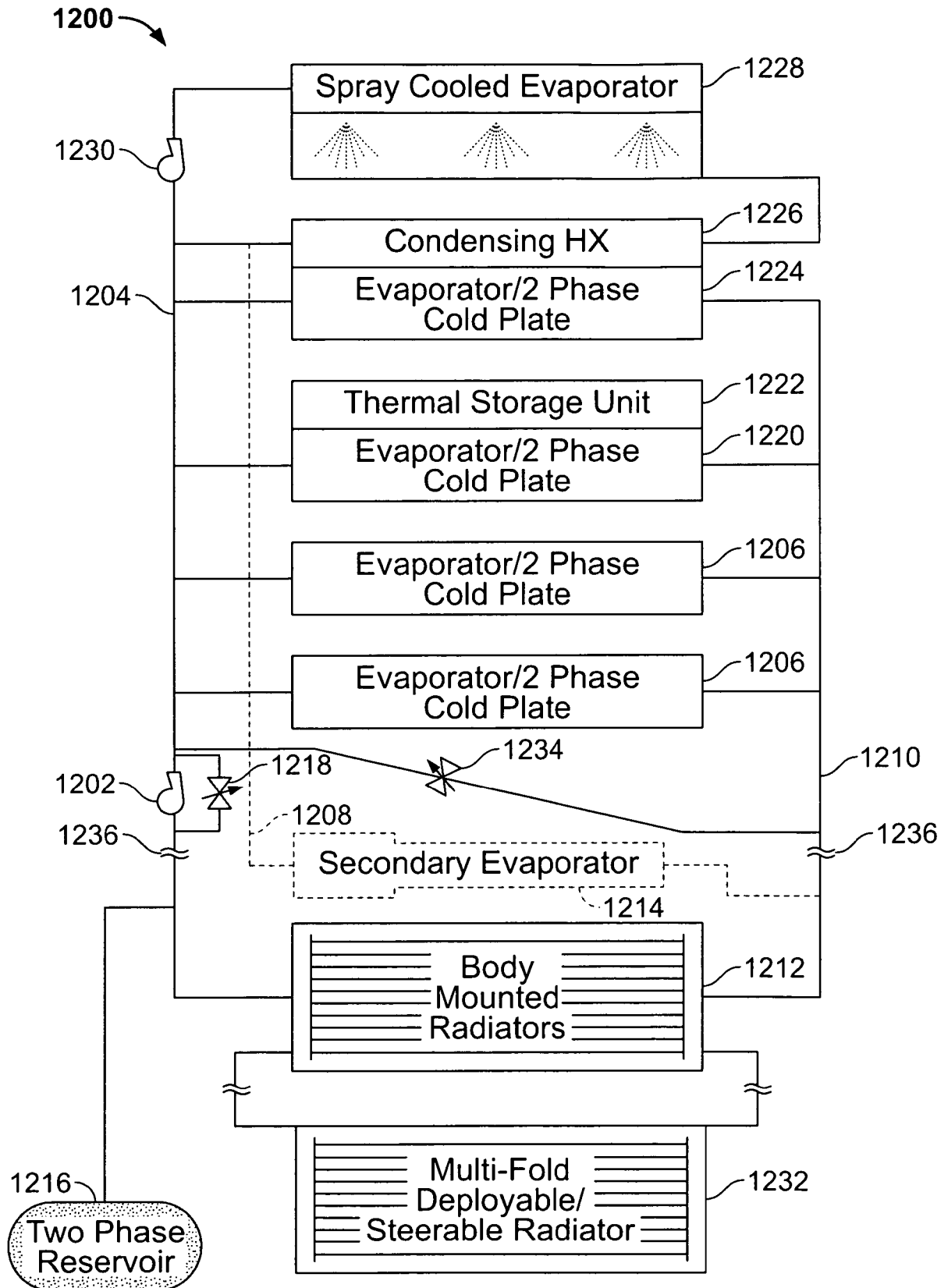


FIG. 12

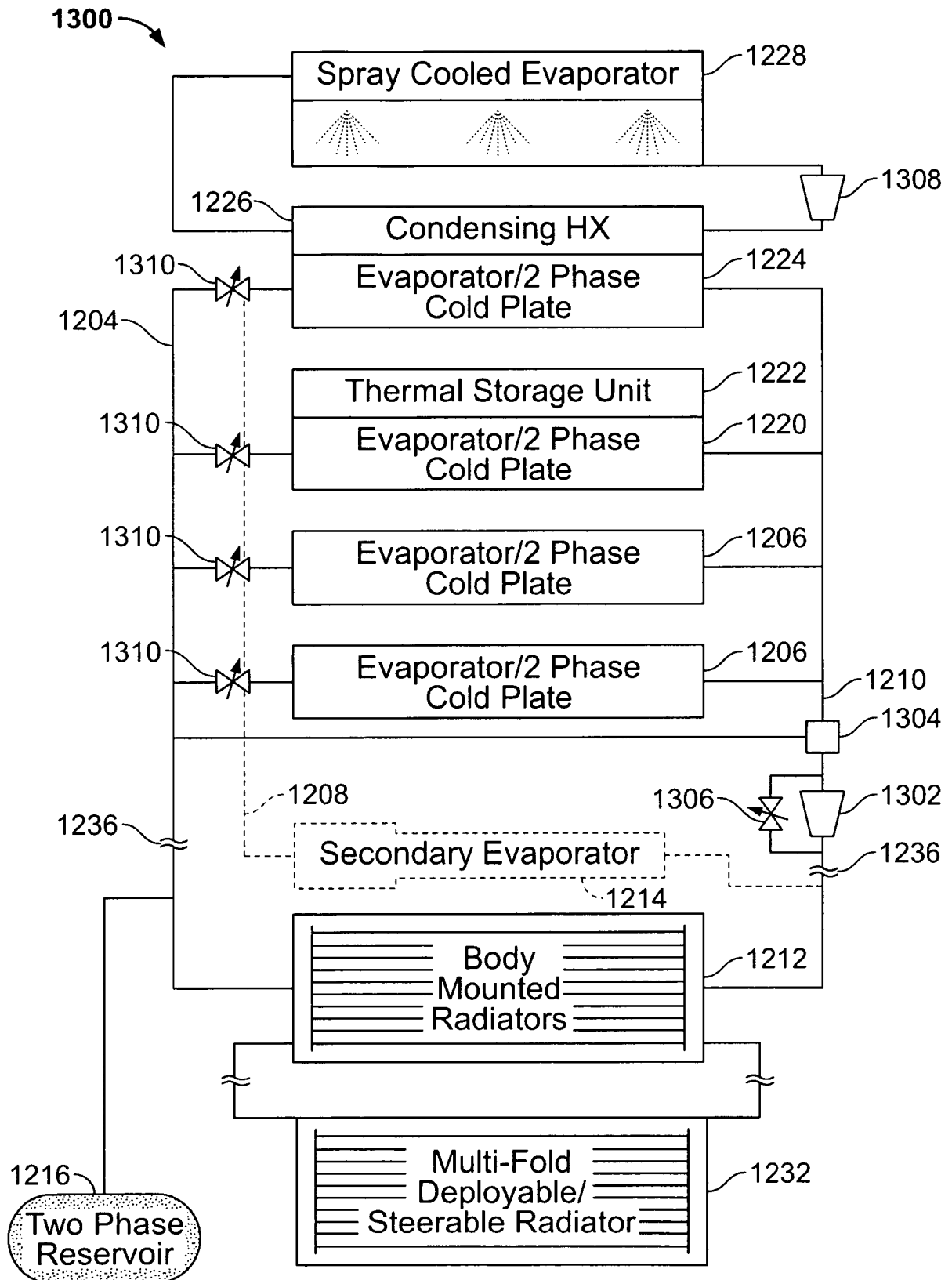


FIG. 13

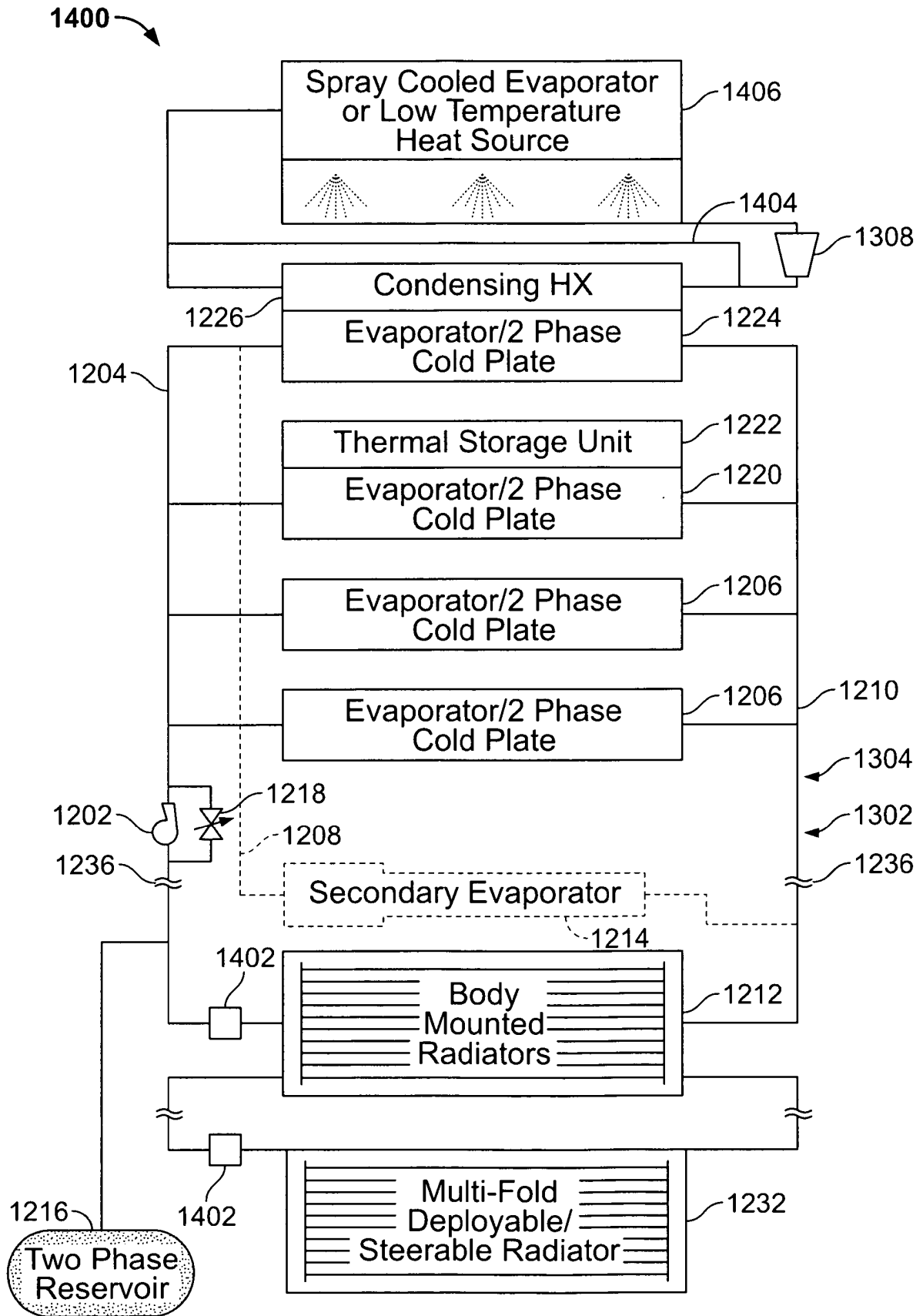


FIG. 14

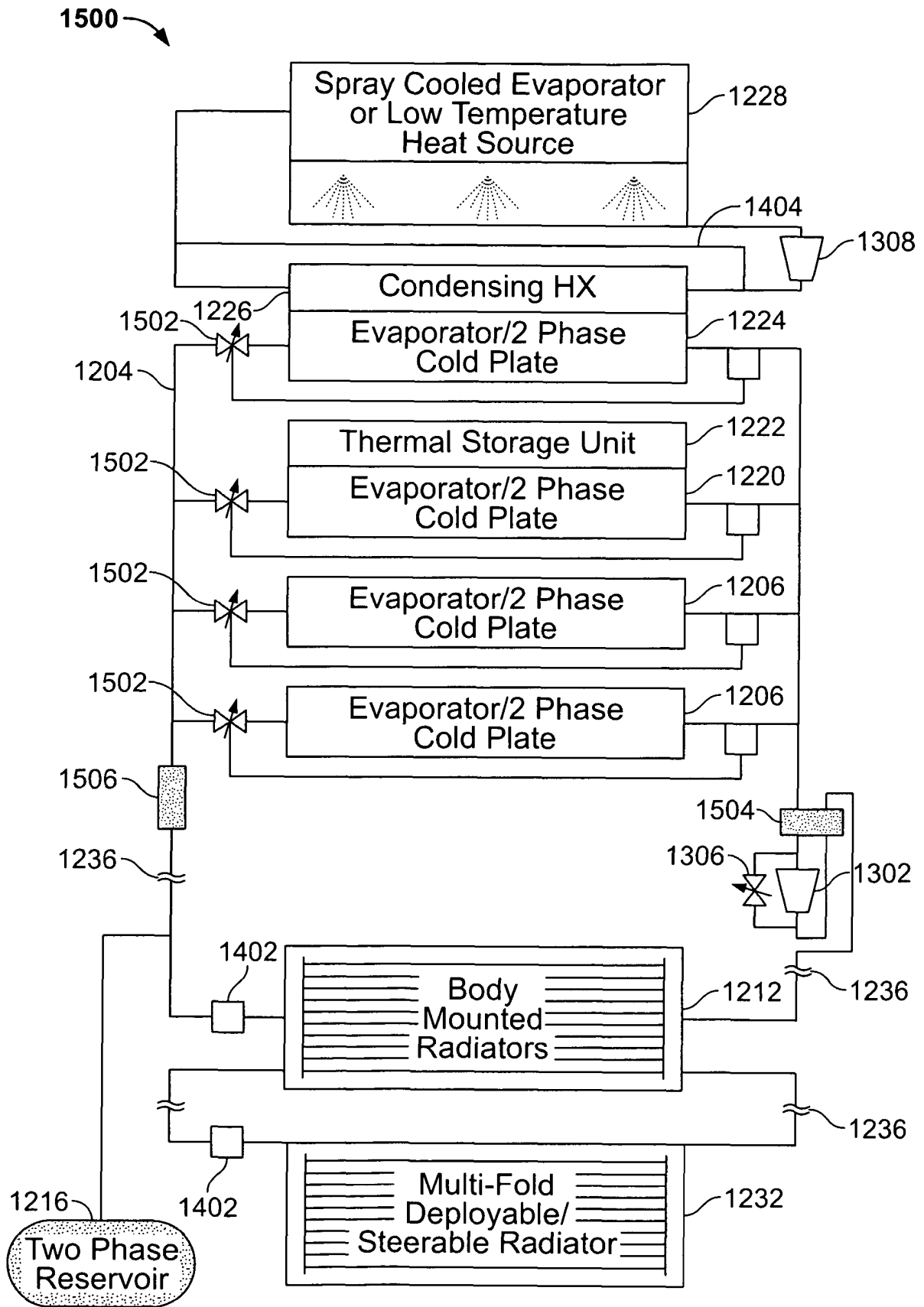


FIG. 15

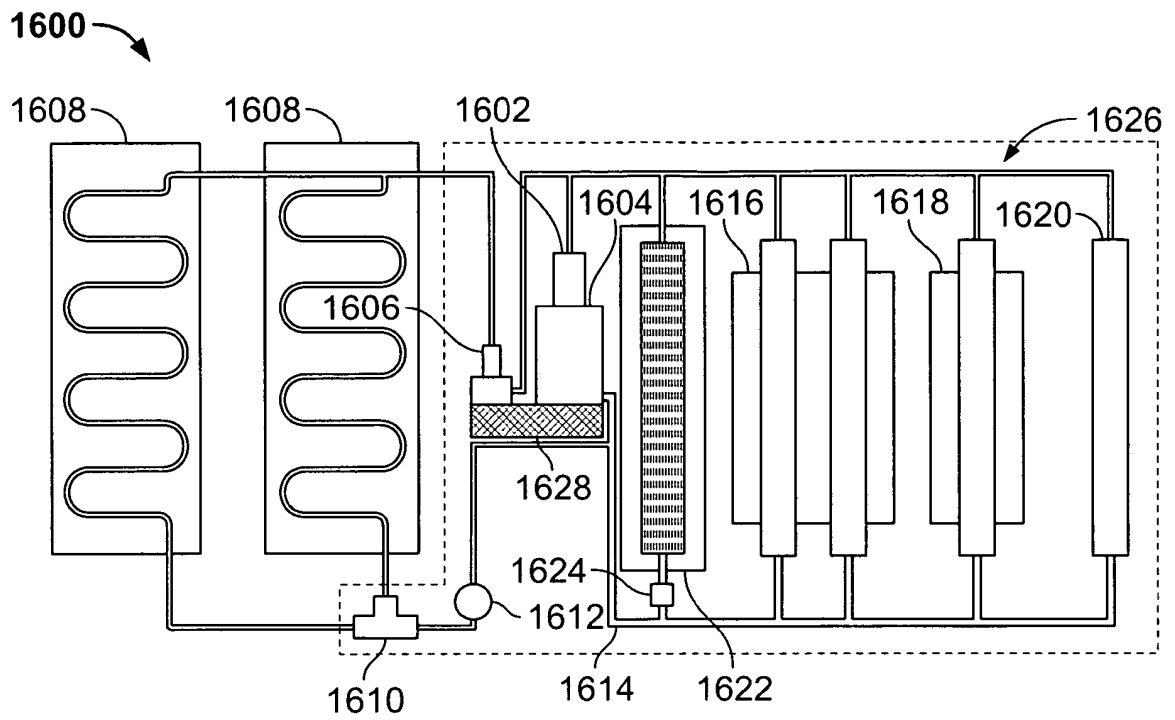


FIG. 16

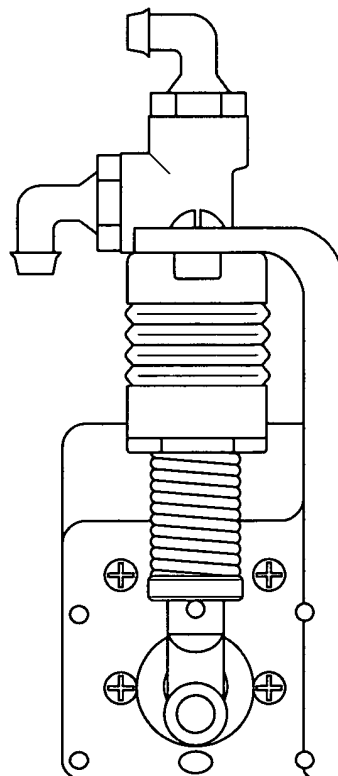


FIG. 17A

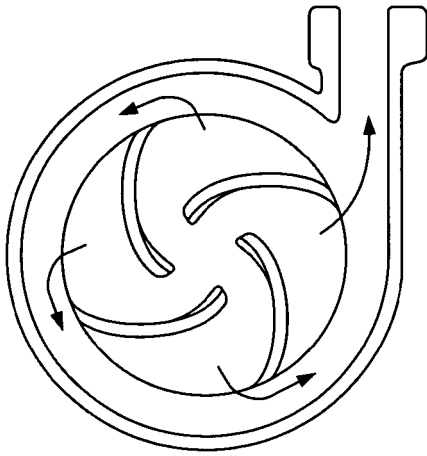


FIG. 17B

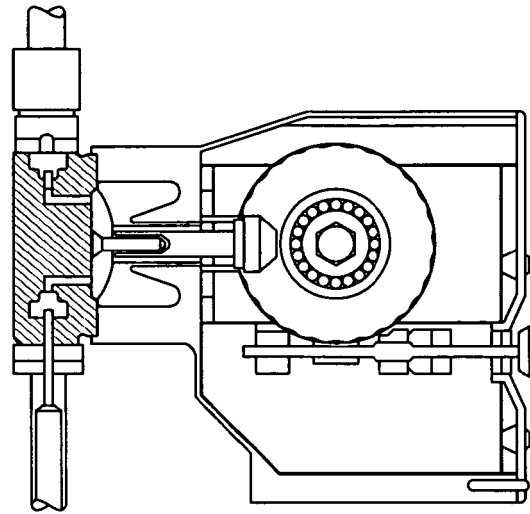


FIG. 17C

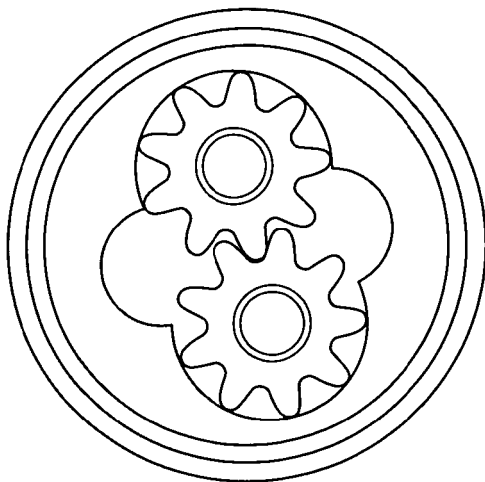


FIG. 17D

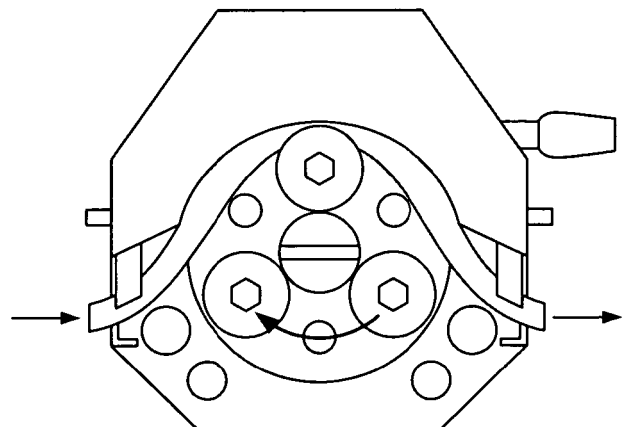


FIG. 17E

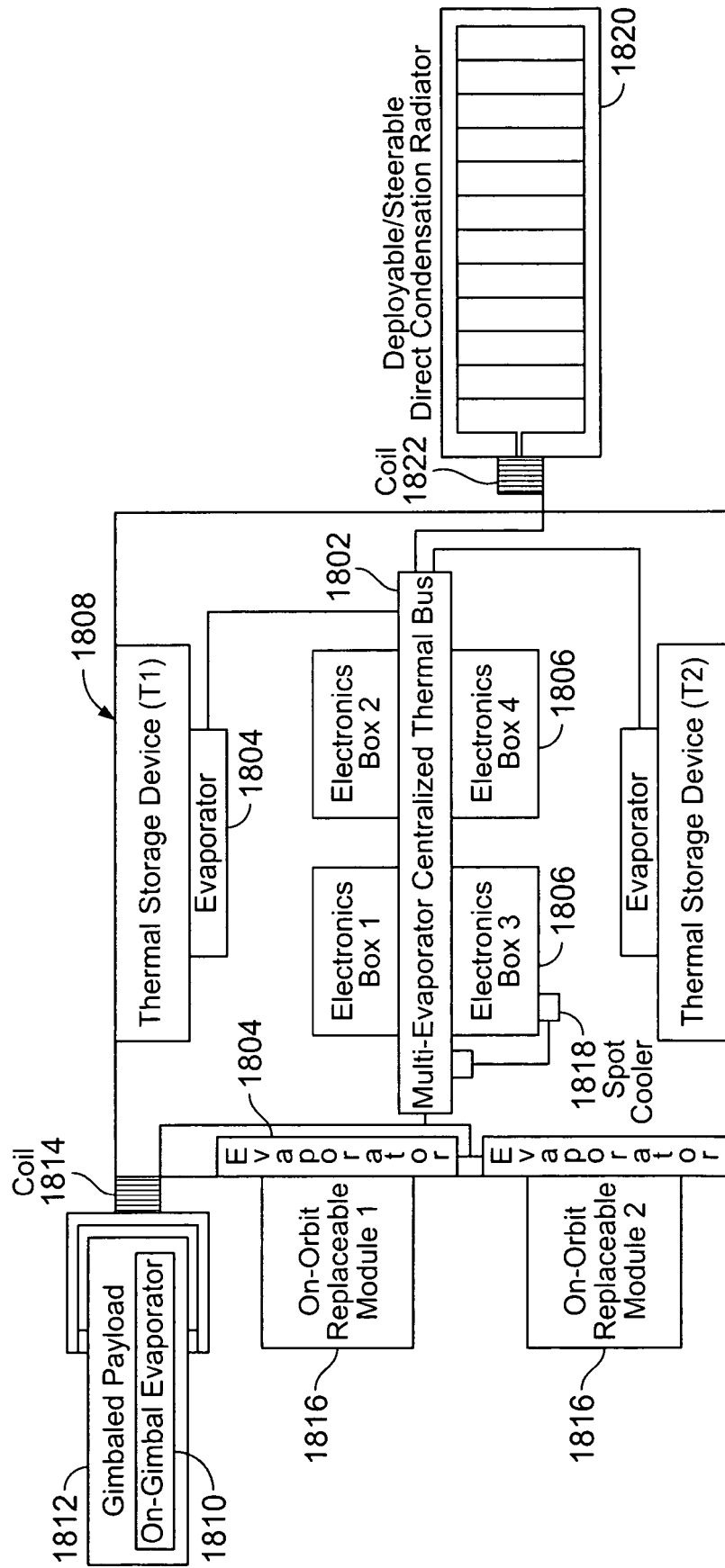


FIG. 18A

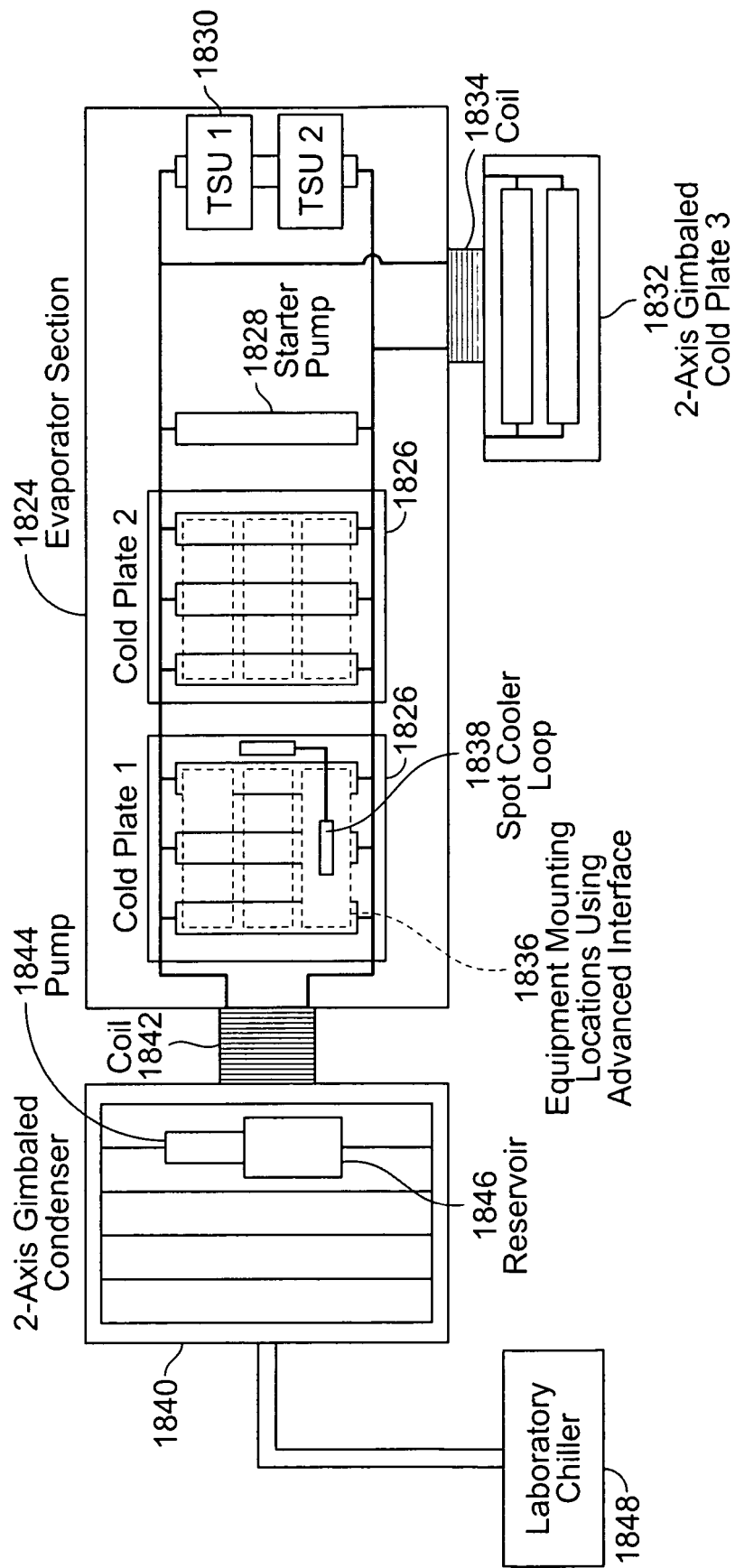


FIG. 18B

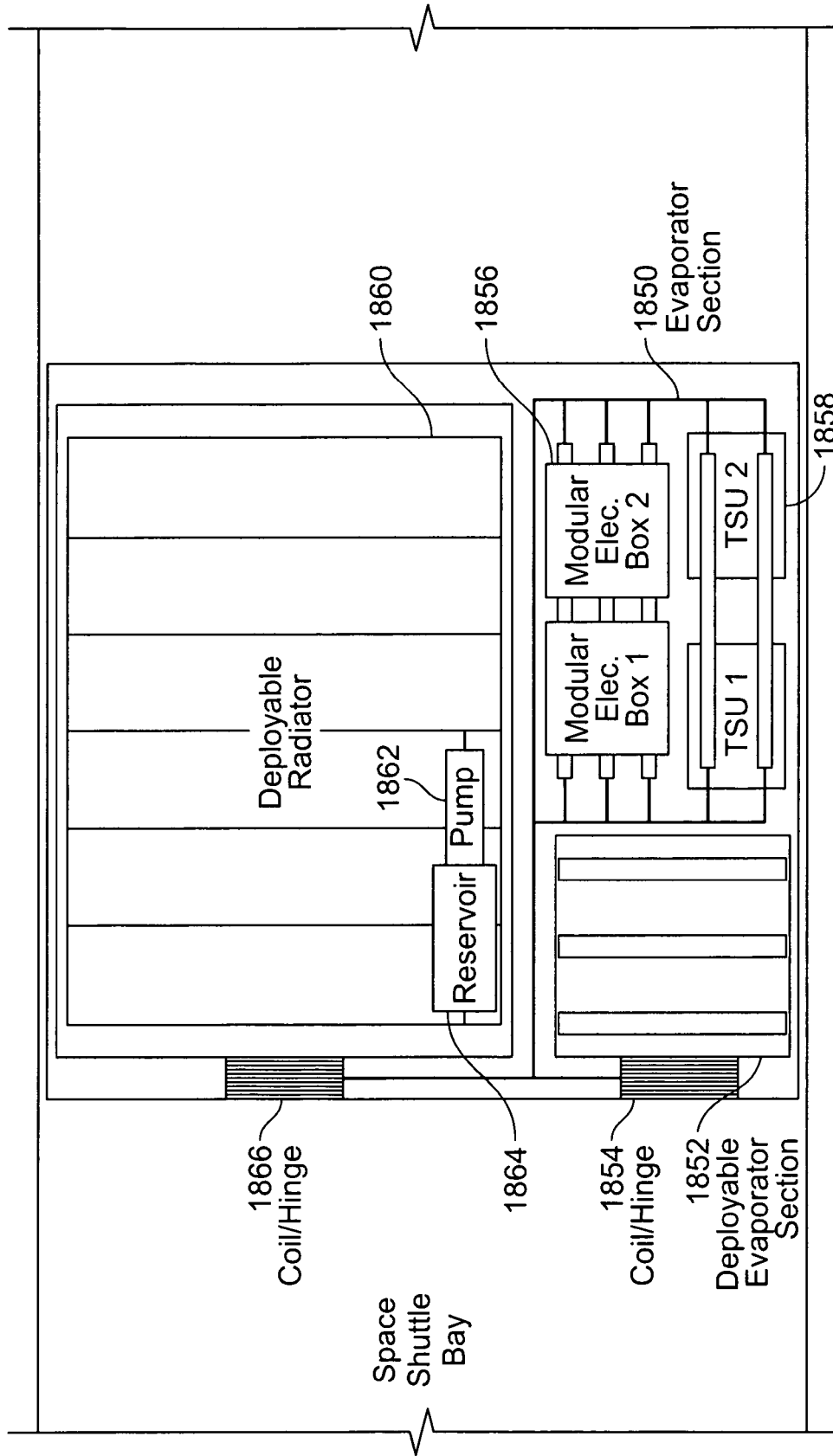


FIG. 18C

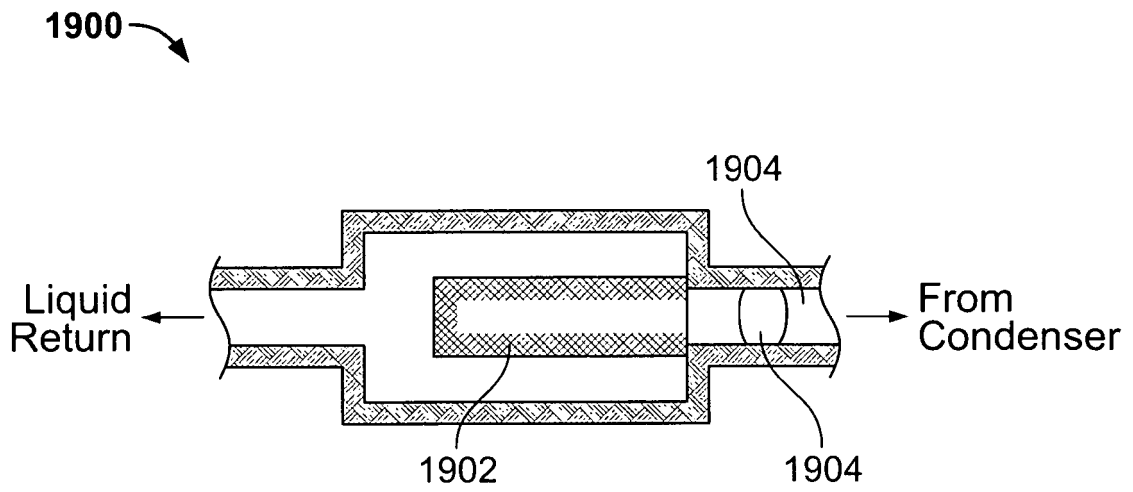


FIG. 19

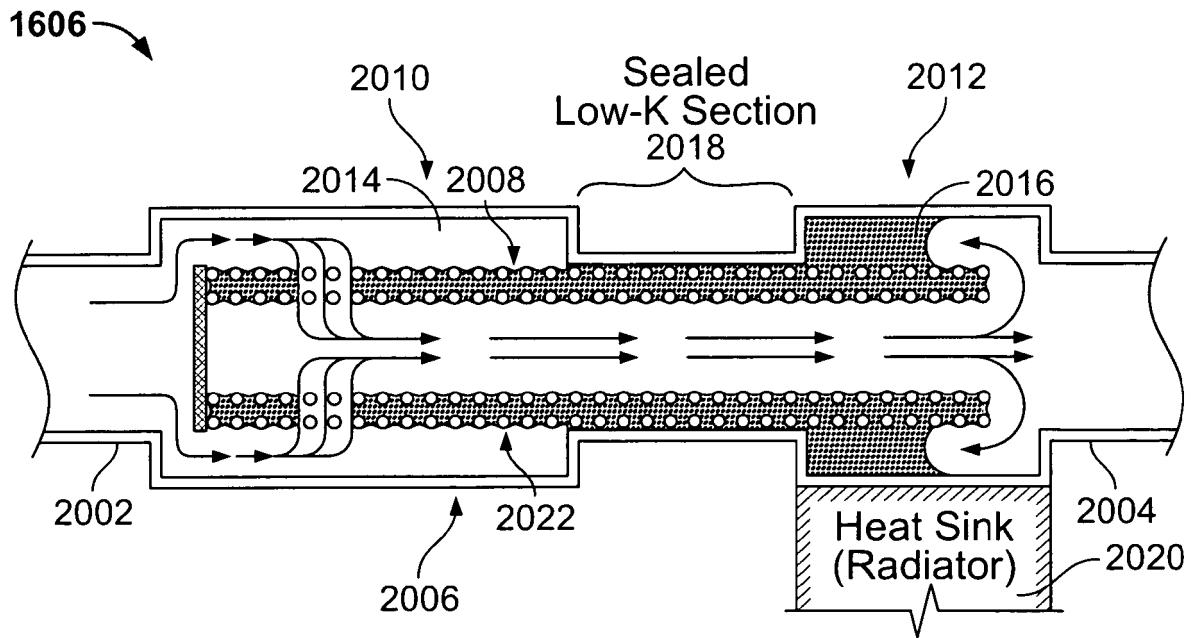


FIG. 20

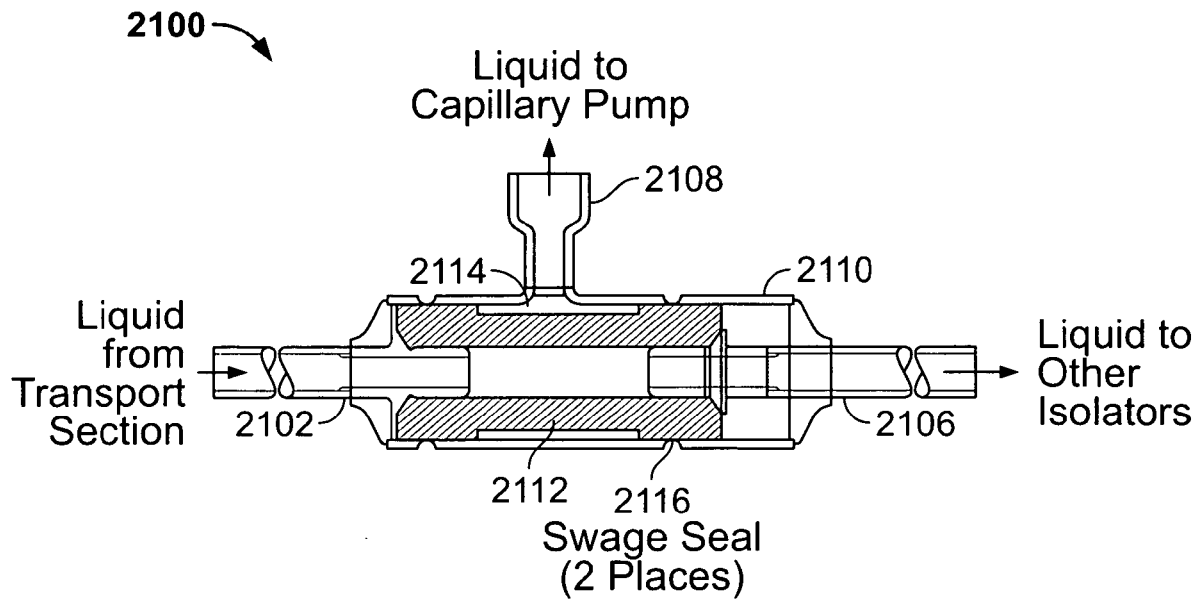


FIG. 21

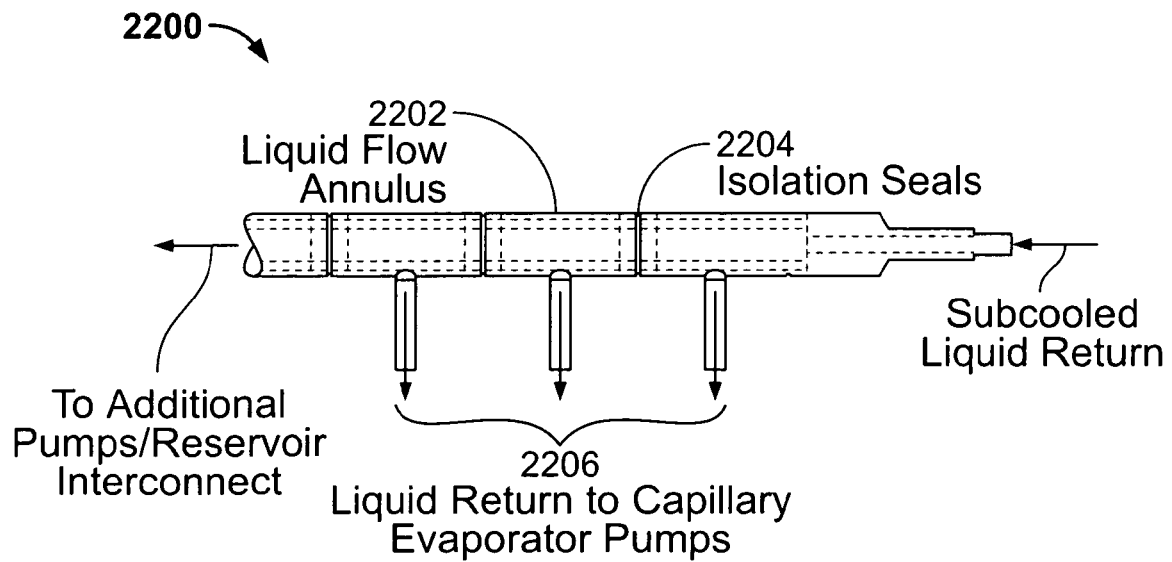


FIG. 22

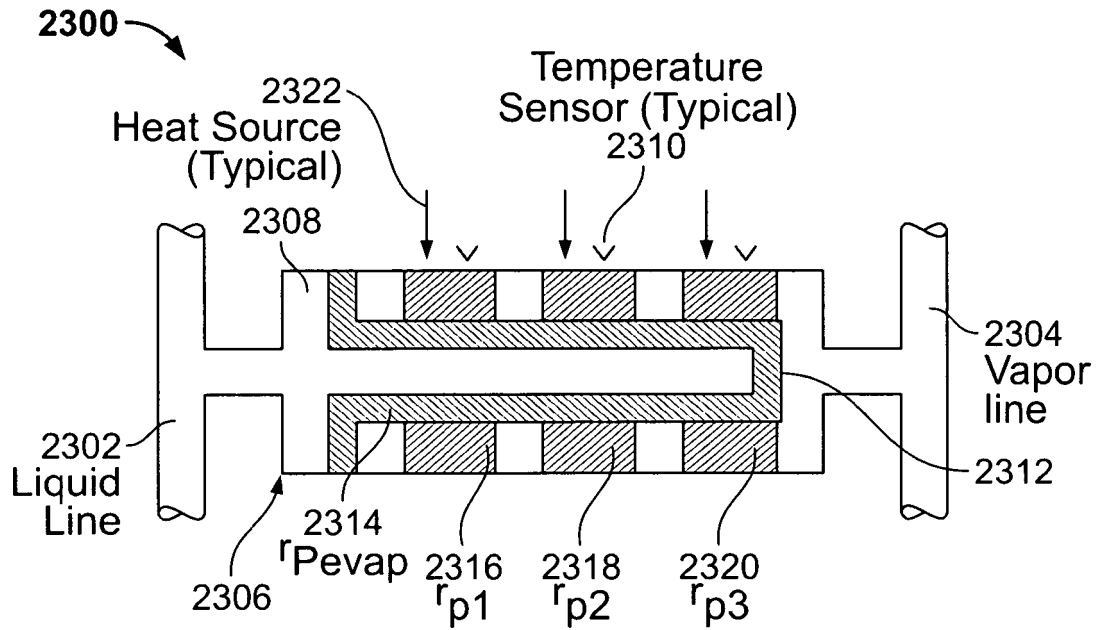


FIG. 23

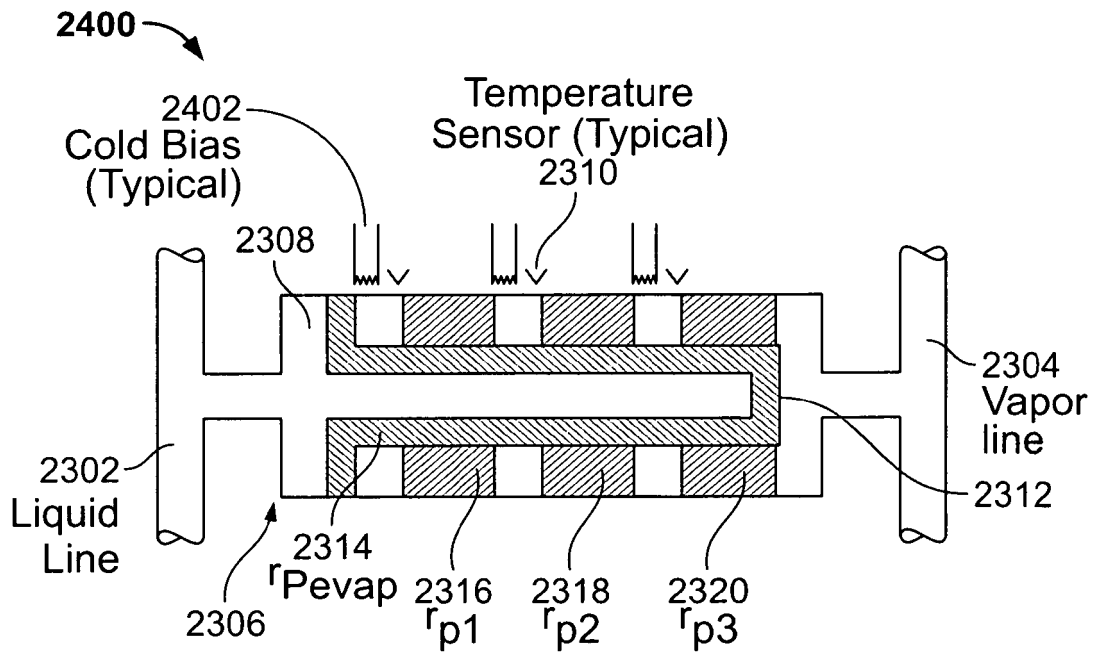


FIG. 24

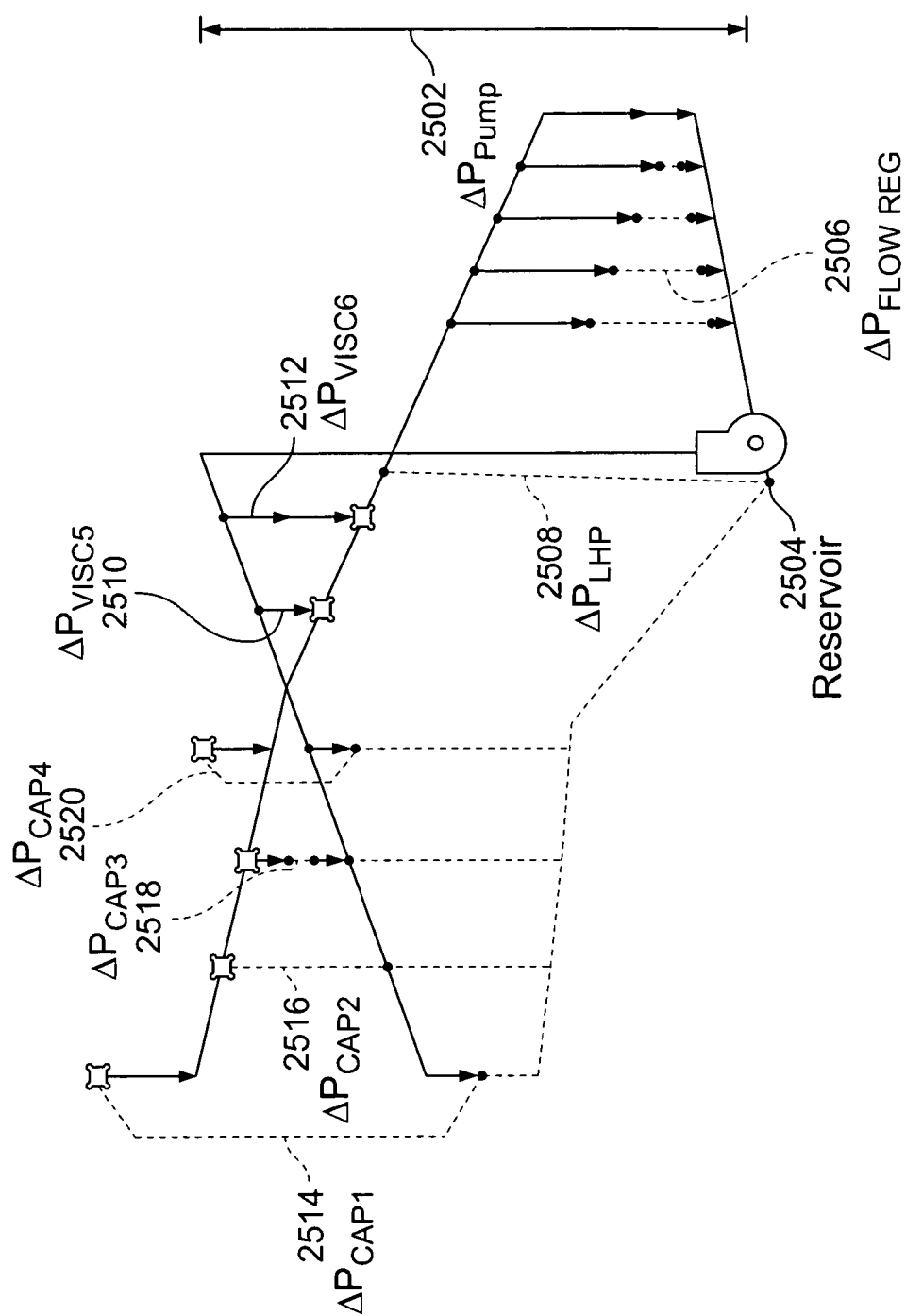


FIG. 25

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 48646703 P [0001]
- US 60202203 A [0001]
- US 39100602 P [0001]
- US 89656101 A [0001] [0035] [0052]
- US 21558800 P [0001]
- US 20020007937 A1 [0005]
- US 4470450 A [0005]
- US 4890668 A [0005]