



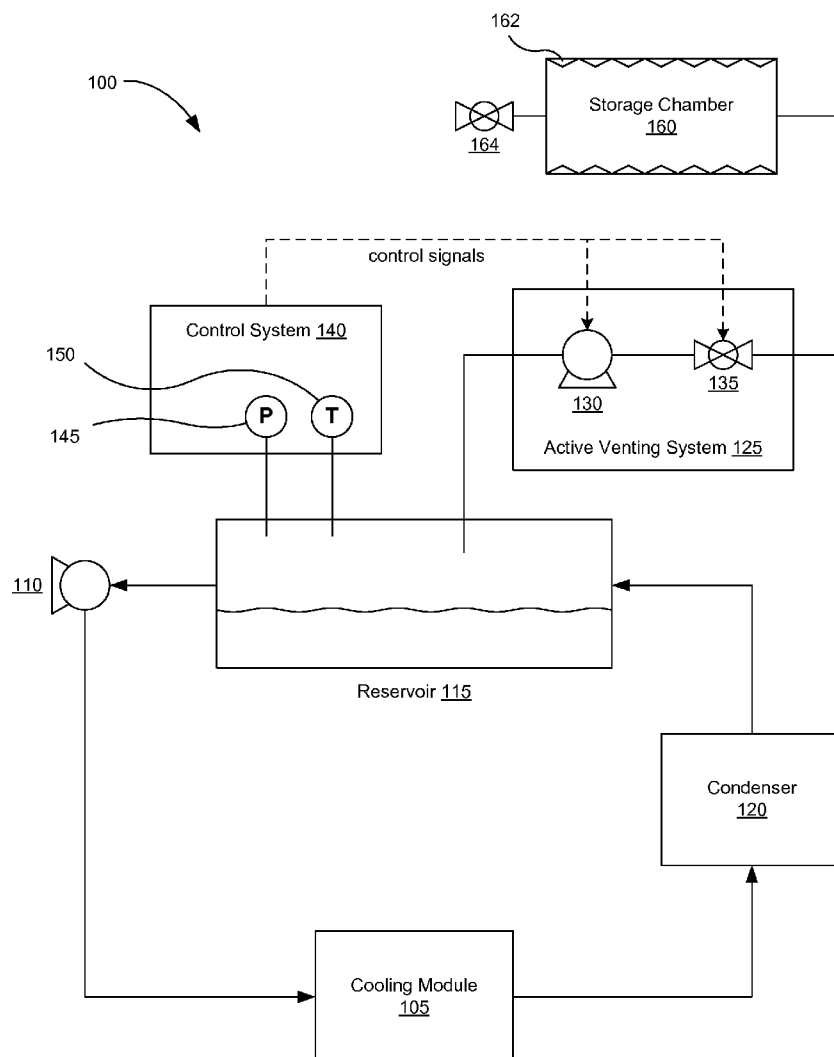
US 20070193285A1

(19) **United States**(12) **Patent Application Publication**
Knight et al.(10) **Pub. No.: US 2007/0193285 A1**(43) **Pub. Date: Aug. 23, 2007**(54) **TESTING FOR LEAKS IN A TWO-PHASE
LIQUID COOLING SYSTEM**(76) Inventors: **Paul A. Knight**, Spokane, WA
(US); **John R. Mason**, Coeur
d'Alene, ID (US)

Correspondence Address:

FENWICK & WEST LLP
SILICON VALLEY CENTER, 801 CALIFORNIA
STREET
MOUNTAIN VIEW, CA 94041(21) Appl. No.: **11/677,202**(22) Filed: **Feb. 21, 2007****Related U.S. Application Data**(60) Provisional application No. 60/775,496, filed on Feb.
21, 2006.**Publication Classification**(51) **Int. Cl.****F25B 49/00** (2006.01)**F25B 45/00** (2006.01)**F25B 43/04** (2006.01)(52) **U.S. Cl. 62/126; 62/149; 62/475**(57) **ABSTRACT**

A two-phase liquid cooling system includes an active venting system for regulating an amount of non-condensable gas within the cooling system. Various venting structures may be used to remove gases from the cooling system, some of which are designed to remove the non-condensable gases and avoid removing the vapor-phase coolant. A control system activates the venting system to achieve a desired pressure, which may be based on measured process conditions within the cooling system. A venting and refilling arrangement may serve multiple cooling systems in a parallel arrangement. A return path of the cooling system can be tested for coolant leaks by increasing the pressure in the return path and placing a coolant detector near the path.



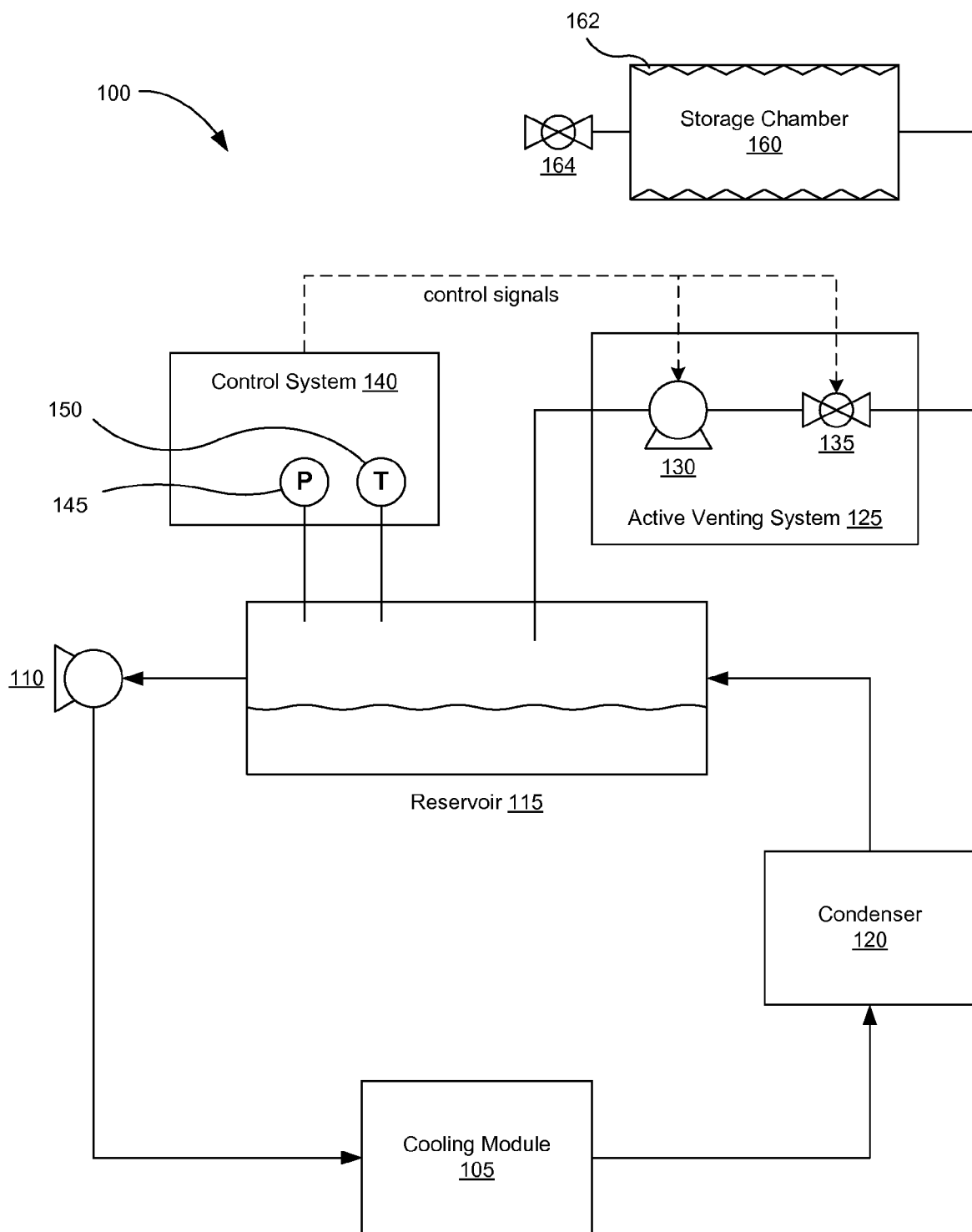


FIG. 1

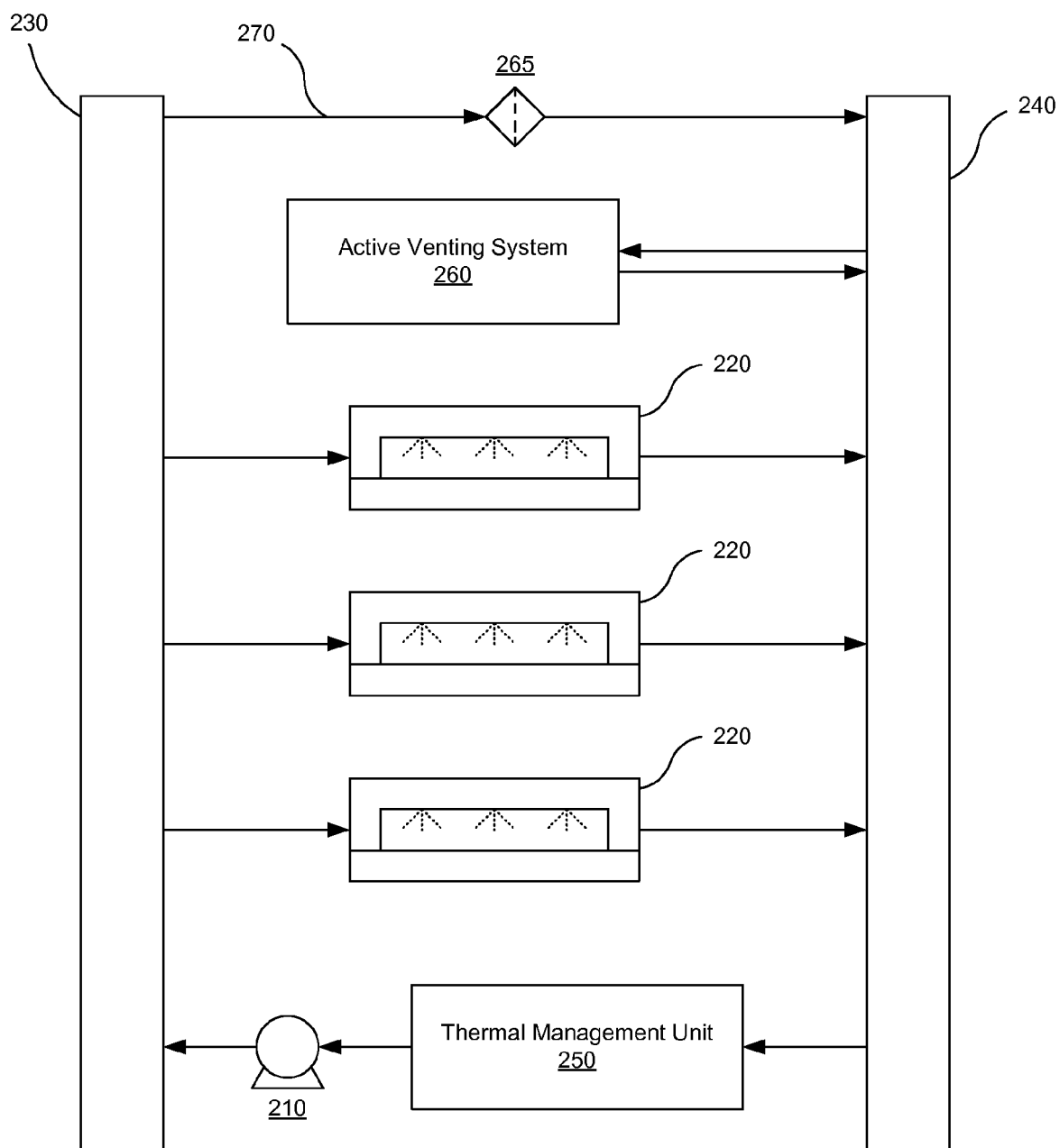


FIG. 2

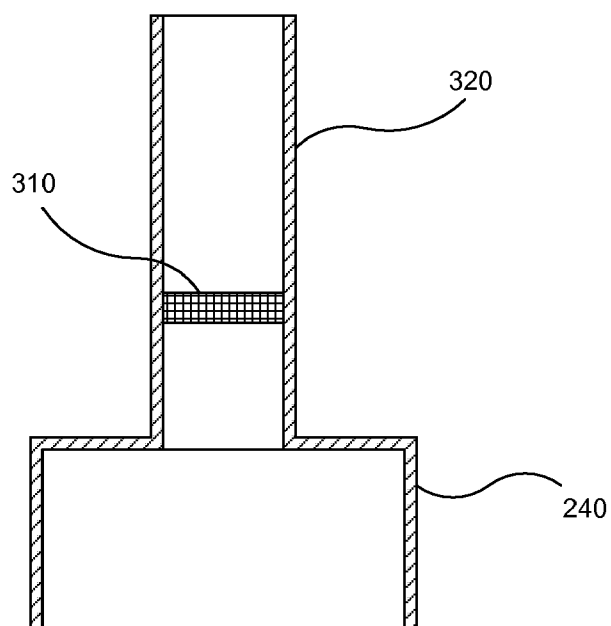


FIG. 3

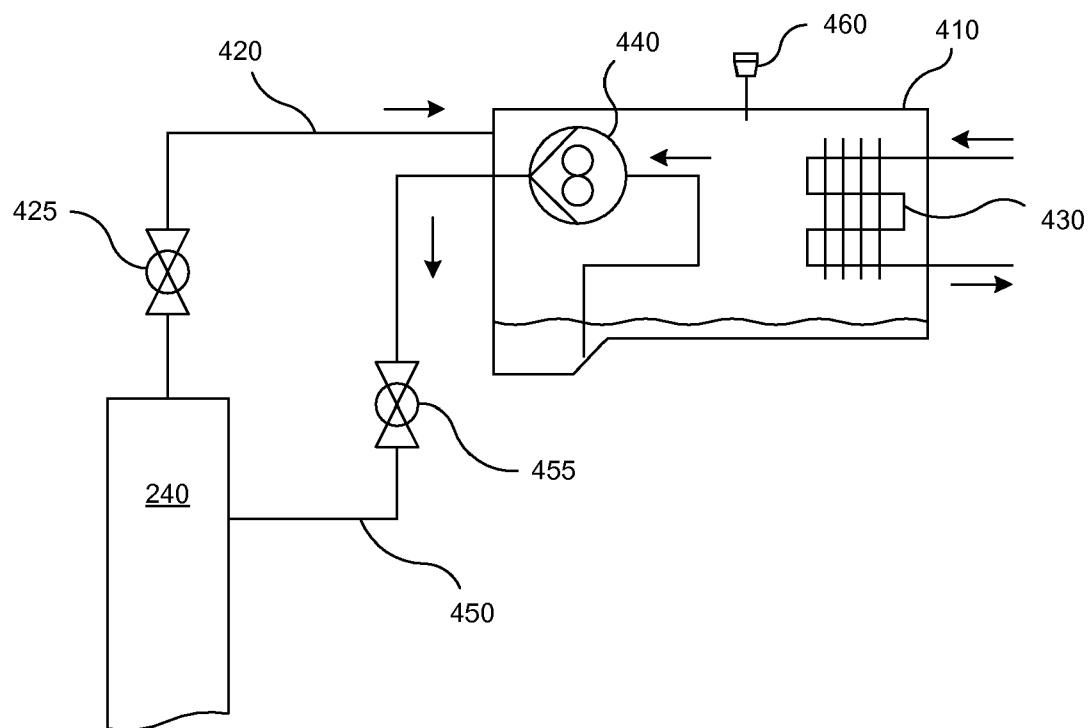


FIG. 4

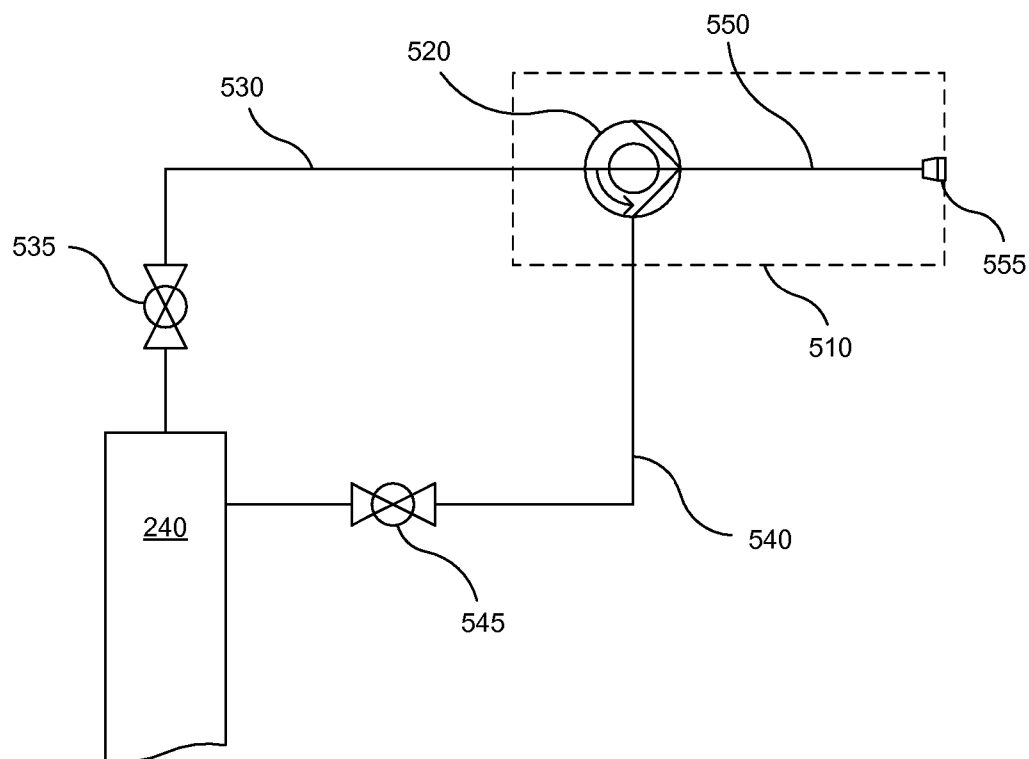


FIG. 5

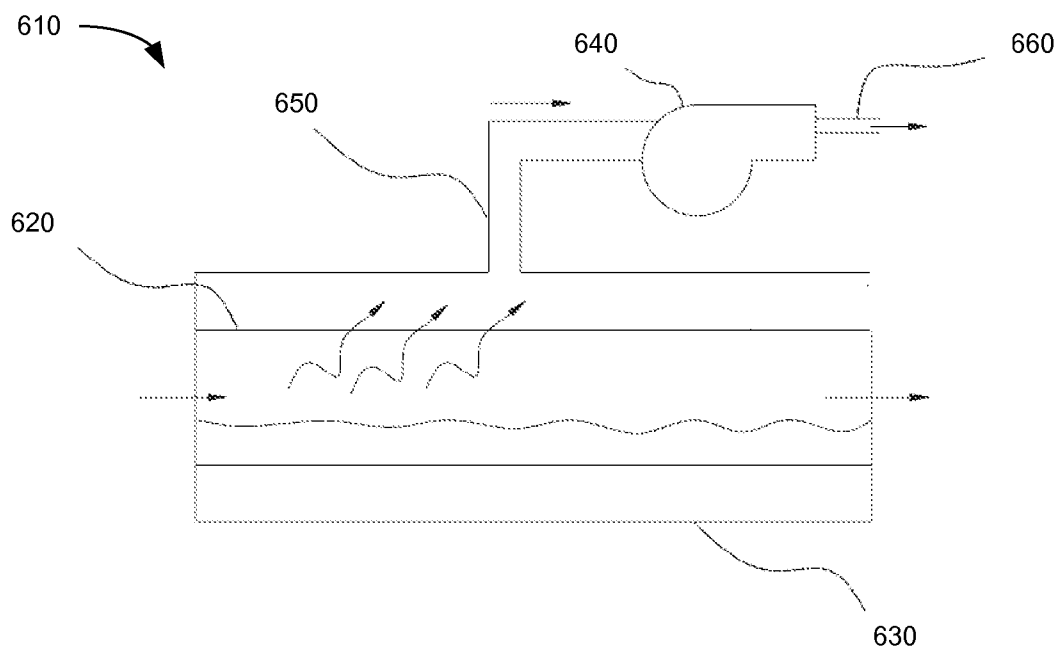


FIG. 6

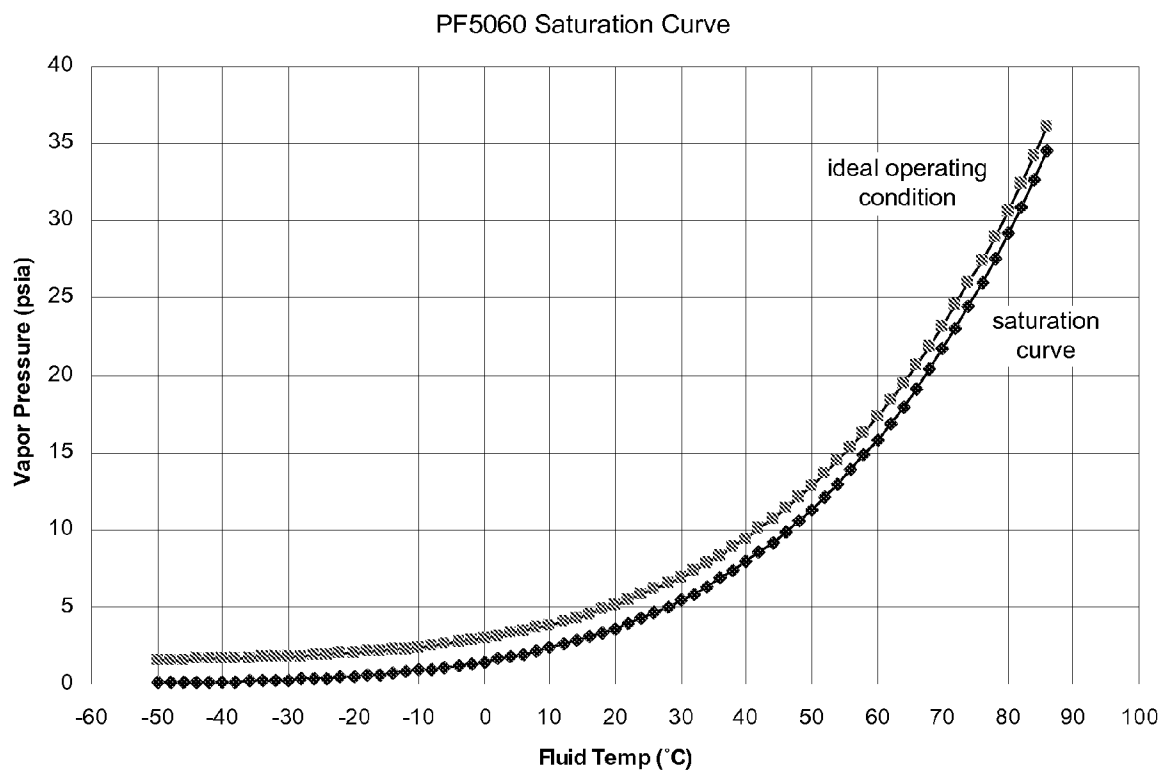


FIG. 7

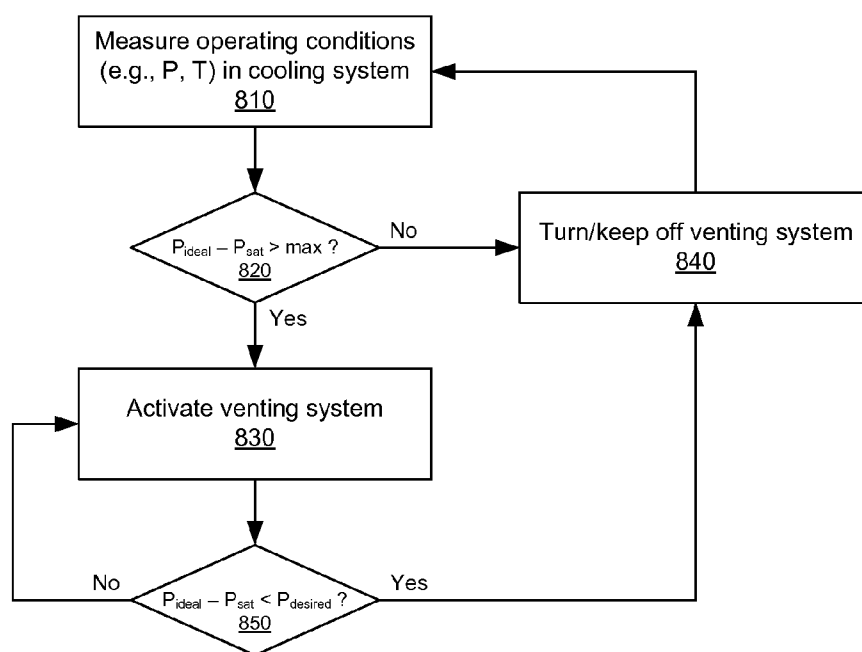


FIG. 8

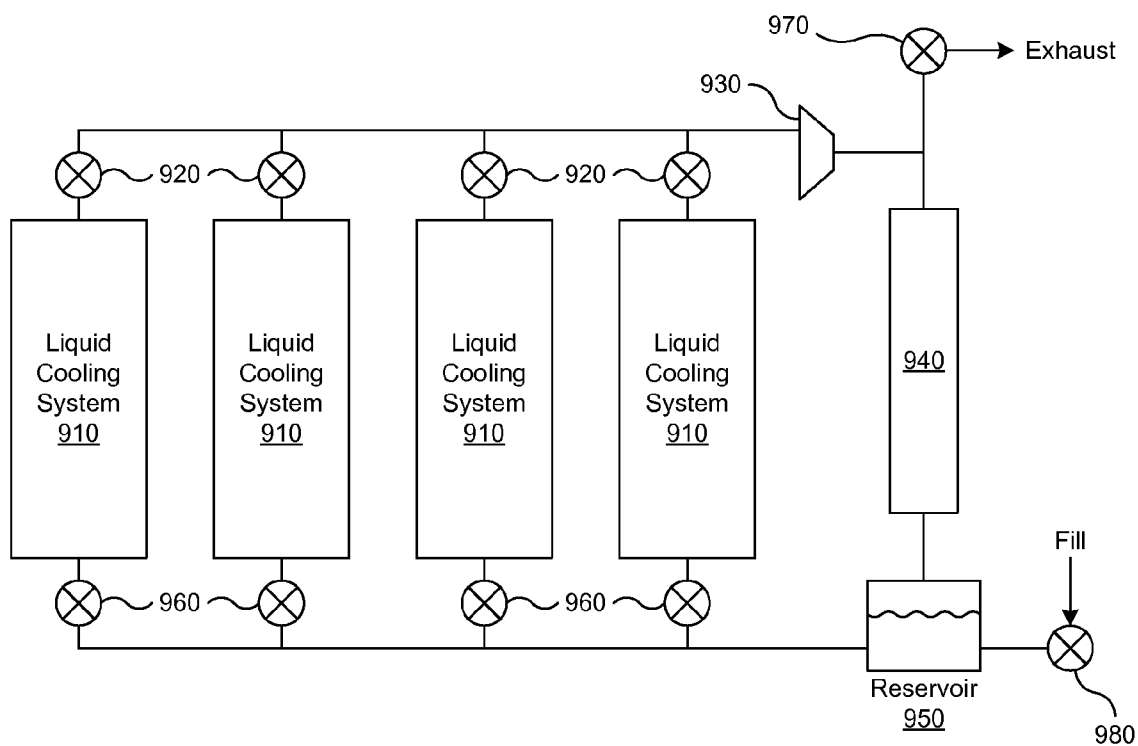


FIG. 9

PF-5060 Saturation Curve

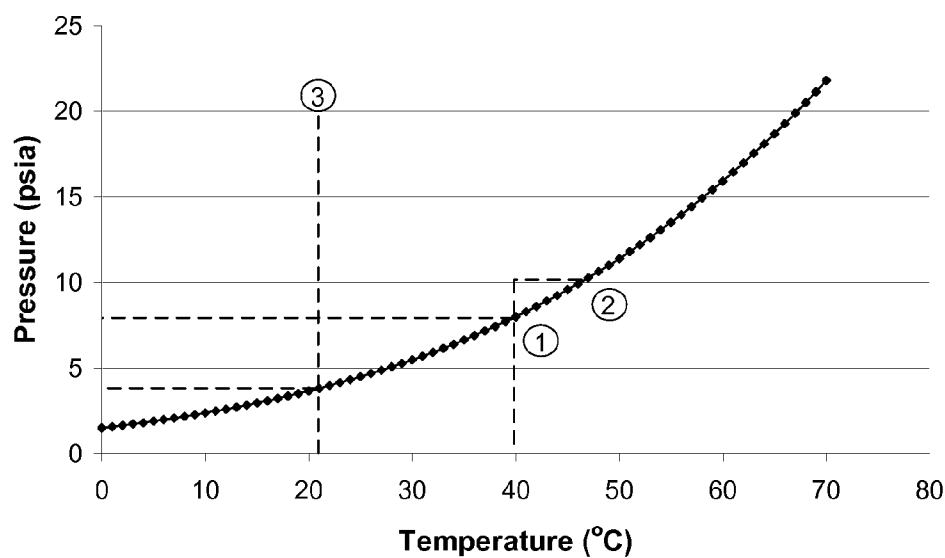


FIG. 10

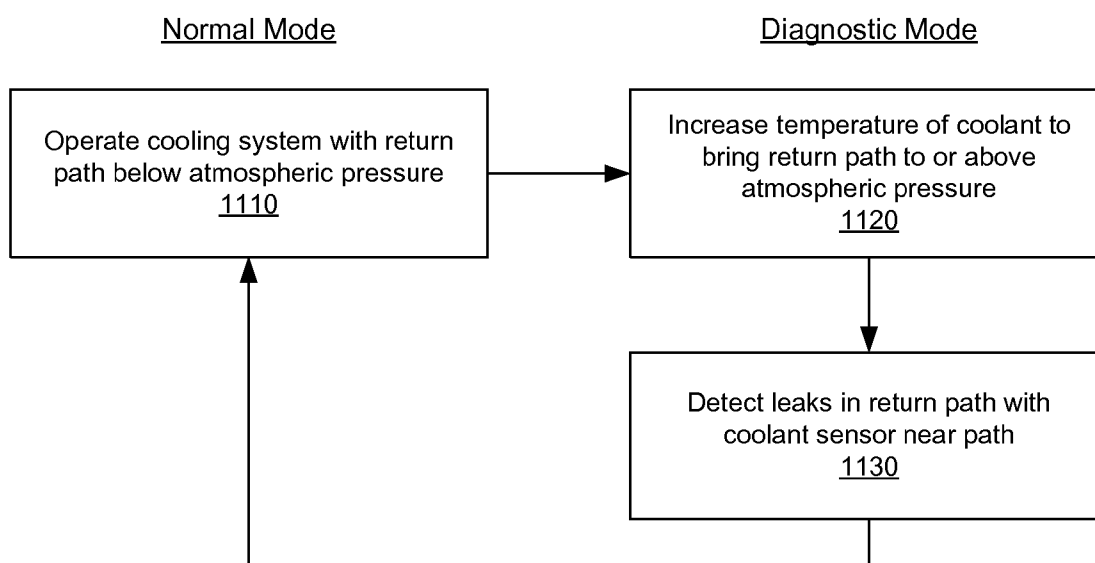


FIG. 11

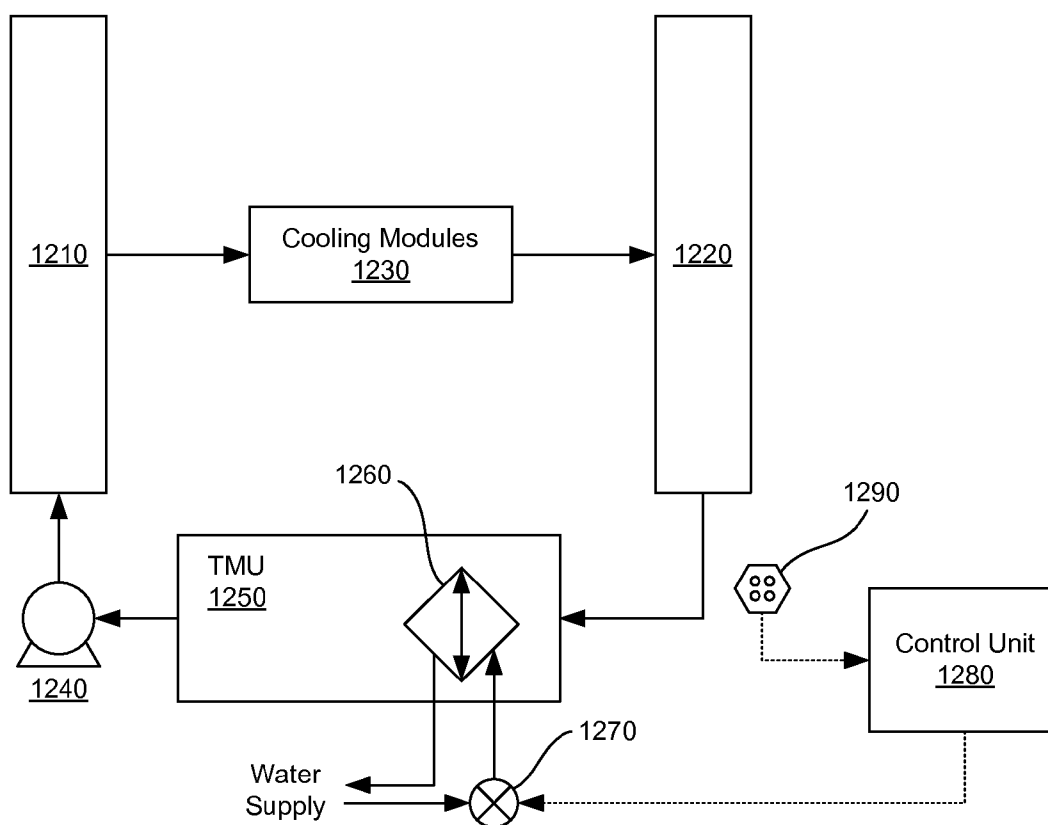


FIG. 12

TESTING FOR LEAKS IN A TWO-PHASE LIQUID COOLING SYSTEM

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 60/775,496, filed Feb. 21, 2006, which is incorporated by reference in its entirety. This application is also related to U.S. application Ser. No. 11/384,195, filed Mar. 17, 2006, and to U.S. application Ser. No. 11/466,076, filed Aug. 21, 2006, each of which is incorporated by reference in its entirety.

BACKGROUND

[0002] This invention relates generally to two-phase liquid cooling systems, such as those configured to cool rack-mounted electronics, and more particularly to detecting coolant leaks in two-phase liquid cooling systems.

[0003] Liquid cooling is well known in the art of cooling electronics. As air cooling heat sinks continue to be pushed to new performance levels, so has their cost, complexity, and weight. Because computer power consumptions will continue to increase, liquid cooling systems will provide significant advantages to computer manufacturers and electronic system providers.

[0004] Liquid cooling technologies use a cooling fluid for removing heat from an electronic component. Liquids can hold more heat and transfer heat at a rate many times that of air. Single-phase liquid cooling systems place a liquid in thermal contact with the component to be cooled. With these systems, the cooling fluid absorbs heat as sensible energy. Other liquid cooling systems, such as spray cooling, are two-phase processes. In the two-phase cooling systems, heat is absorbed by the cooling fluid primarily through latent energy gains. Two-phase cooling, commonly referred to as evaporative cooling, allows for more efficient, more compact, and higher performing liquid cooling systems than systems based on single-phase cooling.

[0005] An example two-phase cooling method is spray cooling. Spray cooling uses a pump to supply fluid to one or more nozzles, which transform the coolant supply into droplets. These droplets impinge the surface of the component to be cooled and can create a thin coolant film. Energy is transferred from the surface of the component to the thin-film of coolant. Because the fluid is dispensed at or near its saturation point, the absorbed heat causes the thin-film to turn to vapor. This vapor is then removed from the component, condensed (often by means of a heat exchanger or condenser), and returned to the pump.

[0006] Significant efforts have been expended in the development and optimization of spray cooling. A doctoral dissertation by Tilton entitled "Spray Cooling" (1989), available through the University of Kentucky library system, describes how optimization of spray cooling system parameters, such as droplet size, distribution, and momentum can create a thin coolant film capable of absorbing high heat fluxes. In addition to the system parameters described by the Tilton dissertation, U.S. Pat. No. 5,220,804 provides a method of increasing a spray cooling system's ability to remove heat. The '804 patent describes a method of managing system vapor that further thins the coolant film, which increases evaporation, improves convective heat transfer, and improves liquid and vapor reclaim.

[0007] Dielectric fluids such as FLUORINERT® (a trademark of 3M Company) are well-suited for use in electronic cooling systems, as they are safe for electronic components and systems. The fluids have boiling points close to atmospheric conditions and have latent heat of vaporization values that provide efficient two-phase cooling.

[0008] The operating parameters, such as temperature and pressure, are important for achieving efficient and optimal cooling in a two-phase cooling system. Leaks in the system can throw these parameters off balance, as leaks can result in non-condensable air added to the system or coolant loss from the system. The result of leaks is often to degrade the thermal performance of the system. Some leaks may be detected using a refrigerant detector moved along a flow path of the cooling system. If the detector is located near the vicinity of a leak in which coolant is leaking from the system, the detector will indicate the presence of the coolant and, therefore, a leak in the system. With many refrigerants used in two-phase cooling systems, however, the coolant vapor in the return side of the system is lower than atmospheric pressure. For this reason, any leaks in the return path generally result in air leaking into the system rather than coolant leaking out of the system. The refrigerant detector—or any kind of external sensor—is not helpful in such a case.

SUMMARY OF THE INVENTION

[0009] A technique is thus provided for detecting leaks in a return path in a two-phase liquid cooling system or any other path in the system in which, during normal operation of the system, the path is at a pressure below atmospheric pressure. To test for leaks in such a path, the pressure in the path is temporarily raised, causing coolant to be expelled through any leaks in the path. A coolant sensor can then be used to detect any leaks. Once the testing is completed, the path is returned to normal operation for more efficient cooling.

[0010] In one embodiment, a two-phase cooling system directs a coolant via a supply path to one or more cooling modules and collects the coolant via a return path in a thermal management unit, which cools and redeploys the coolant to the cooling modules. During normal operation of the cooling system, the return path is at a pressure below atmospheric pressure. A control unit is coupled to the cooling system and, when leak testing is desired, the control unit increases the pressure of the return path to a pressure at or above atmospheric pressure. In this diagnostic mode, a sensor can be used to detect any coolant leaking from the return path of the cooling system. Once the testing is completed, the control unit can return the cooling system to its normal operation.

[0011] These and other features, aspects, and advantages of various embodiments of the invention will become better understood with regard to the following description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] In the course of the detailed description to follow, reference will be made to the attached drawings. These drawings show different aspects of embodiments of the present invention and, where appropriate, reference numerals illustrating like structures, components, and/or elements in different figures are labeled similarly. It is understood that various combinations of the structures, components, and/or

elements other than those specifically shown are contemplated and within the scope of the present invention:

[0013] FIG. 1 is a schematic diagram of a two-phase liquid cooling system with active venting, in accordance with an embodiment of the invention.

[0014] FIG. 2 is a schematic diagram of a rack-mounted spray cooling system, in accordance with an embodiment of the invention.

[0015] FIG. 3 is a schematic diagram of a semi-permeable membrane separator, in accordance with an embodiment of the invention.

[0016] FIG. 4 is a schematic diagram of a condensing separator, in accordance with an embodiment of the invention.

[0017] FIG. 5 is a schematic diagram of a centrifugal separator, in accordance with an embodiment of the invention.

[0018] FIG. 6 is a schematic diagram of a permeable tube vacuum mechanism, in accordance with an embodiment of the invention.

[0019] FIG. 7 is a chart showing a typical saturation curve for an example cooling liquid.

[0020] FIG. 8 is a flow diagram of a control process for activating the active venting system to remove non-condensable gases from the cooling system, in accordance with an embodiment of the invention.

[0021] FIG. 9 is a schematic of a venting and refilling system for servicing multiple liquid cooling systems, in accordance with an embodiment of the invention.

[0022] FIG. 10 is a chart showing the process conditions during operation of a liquid cooling system, in accordance with an embodiment of the invention.

[0023] FIG. 11 is a flow chart of a process for detecting leaks in the return path of a cooling system, in accordance with an embodiment of the invention.

[0024] FIG. 12 is a system for detecting leaks in the return path of a cooling system, in accordance with an embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Two-Phase Cooling System with Active Venting

[0025] FIG. 1 illustrates one embodiment of a two-phase liquid cooling system **100** with active venting capabilities. The liquid cooling system **100** includes at least one cooling module **105**, a pump **110**, a reservoir **115**, and a condenser **120**. The pump **110** pressurizes a supply of liquid coolant from the reservoir **115** and delivers the liquid coolant to the cooling module **105**. The cooling module **105** places the liquid coolant in thermal contact with a heat-producing device (not shown), such as but not limited to computer processors, blade servers, circuit boards, memory, video cards, power devices, and the like. In the cooling module **105**, heat from the heat-producing device transforms at least a portion of the liquid coolant into a vapor phase fluid. The cooling fluid is transferred to a condenser **120**, which removes heat and condenses the vapor phase fluid back into the liquid phase and delivers it to a reservoir **115**. The liquid coolant can then be recycled in the system by the pump **110**.

[0026] Although the two-phase liquid cooling system **100** is shown with only the main components, the system **100** may include other well known components, such as filters, heaters, manifolds, coolers, and other components of fluid

systems. In addition, the system **100** is described as just one example of a system in which the active venting techniques described herein can be applied. The system **100** may be a modular cold plate type system or a global cooling system where the cooling fluid comes directly in contact with the electronics to be cooled. Moreover, the cooling system **100** is not limited to any particular type of two-phase liquid cooling system. Rather, the techniques described herein can be applied to any type of two-phase liquid cooling system, such as, but not limited to, spray cooling, micro-channels, mini-channels, pool boiling, immersion cooling, or jet impingement. Examples of liquid cooling systems and their components that can be used with embodiments of the invention are described in the following, each of which is incorporated by reference in its entirety: U.S. Pat. No. 6,889,515, which describes a spray cooling system; U.S. Pat. No. 6,955,062, which describes a spray cooling system for transverse thin-film evaporative spray cooling; and U.S. Pat. No. 5,220,804, which describes a high heat flux evaporative spray cooling; and U.S. Pat. No. 5,880,931 which describes a spray cooled circuit card cage.

[0027] Coupled to the cooling system **100** is an active venting system **125** for removing gases and/or adding gases to the liquid cooling system **100**. As shown in FIG. 1, the active venting system **125** may be coupled to a volume in the system **100** where gases are present, such as the volume above liquid coolant in the reservoir **115**. In other embodiments, the venting system **125** may be coupled to other places in the flow path of the cooling system **100**, such as in a return manifold in the path from the cooling module **105** to the pump **110** (such as return manifold **240** shown in FIG. 2, for example). In the embodiment shown in FIG. 1, the venting system **125** comprises an auxiliary pump **130** coupled to the volume in the reservoir **115**. The auxiliary pump **130** is further coupled to a check valve **135**, which prevents air from entering the venting system **125**.

[0028] A control system **140** is coupled to the venting system **125** to provide for selective activation of the venting of gases by the venting system **125**. Using control signals (illustrated as dotted lines in FIG. 1), the control system **140** may control the auxiliary pump **130**, thereby causing the venting system **125** to remove and/or add gases into or out of the cooling system **100**. For other embodiments of the venting system **125**, the control system **140** is configured to provide appropriate control signals.

[0029] In one embodiment, the non-condensable gases removed by the active venting system **125** are released into the surrounding environment. In some applications, however, it is undesirable to allow the non-condensable gases to be released. To address this need, in another embodiment, the active venting system **125** vents, pumps, or otherwise directs the non-condensable gases removed from the cooling system **100** into a sealed chamber **160** for storage therein. The sealed chamber allows the cooling system **100** to be used in very sensitive areas where the non-condensable gases cannot be introduced.

[0030] In another embodiment, the gas storage chamber **160** houses a condenser unit **162**, which may comprise condensing fins that aid in condensing any vapor in the chamber **160**. The chamber is further coupled to a relief valve **164**. The relief valve **164** is designed to relieve the stored or collected non-condensable gases once a certain pressure inside the storage chamber **160** is reached. In one embodiment, the pressure relief valve **164** comprises a

spring-loaded valve that automatically opens at a 10 psi differential between the inside of the chamber and the atmosphere. With the chamber 160 at room temperature, the added pressure helps to ensure that only air escapes from the system.

[0031] The control system 140 activates the venting system 125 based on process conditions within the cooling system. In this way, the control system 140 can achieve certain desired operating conditions in the cooling system 100. Although a variety of process conditions can be used to describe the cooling system, in one embodiment the process conditions include the pressure and temperature of the gases above the liquid coolant in the reservoir 115. Accordingly, a pressure transducer 145 and temperature sensor 150 (which may comprise a thermocouple, thermistor, resistance temperature detector (RTD), thermopile, infrared sensor, or any other suitable temperature sensor) coupled to the reservoir 115 provide readings of these process conditions. The control system 140 uses these pressure and temperature readings to determine whether and when to activate the venting system 125. Various embodiments of algorithms that the control system 140 can be used to activate the venting system 125 are described in more detail below; however, it can be appreciated that the control system 140 can receive additional types of inputs and can be programmed to perform any number of algorithms to achieve a desired effect in the cooling system 100. Moreover, the pressure transducer 145 and temperature sensor 150 may be located at other parts of the system, such as in a return manifold path 240.

[0032] In one embodiment, the pressure transducer 145 is located at or near the top of the supply manifold 230, which is fluidly coupled to one or more cooling modules 220 in the system. This may be beneficial in certain embodiments because pressure drop within the supply manifold 230 is considerable in a larger manifold, so the greatest pressure drop may occur at that point. Locating the pressure transducer 145 in this location, therefore, may ensure that the correct operating pressure is maintained for proper atomization of the coolant at the uppermost connected cooling module 220.

[0033] Although the control system 140 is illustrated as a separate system in FIG. 1, it can be integrated into the active venting system 125 or any other part of the cooling system 100. Moreover, the control system may be implemented, in whole or in part, by hardware, software, firmware, or a combination thereof.

[0034] The active venting techniques described herein can be implemented in various types of two-phase liquid cooling systems. For example, FIG. 2 schematically illustrates a rack-mounted spray cooling system in which an embodiment of the active venting technique is employed. As shown in FIG. 2, a pump 210 directs a coolant through a plurality of spray cooling modules 220. Each spray cooling module 220 is located in a rack-mounted device and is configured to cool one or more heat-producing electronic devices by spraying the coolant liquid on the devices or on a surface thermally coupled thereto. The resulting two-phase coolant is then returned to a thermal management unit 250 by way of a return manifold 240. The two-phase coolant is condensed in the return manifold 240 and/or in the thermal management unit 250, where the liquid coolant is stored until being recycled through the system by the pump 210.

[0035] An active venting system 260 is coupled to the return manifold 240, where it has access to gases in the flow

path of the cooling system. As described above, the active venting system 260 may remove gases from and/or add gases to the flow path of the cooling system to adjust the pressure therein and thus affect the operation of the cooling system. Rather than being coupled to the return manifold 240, the active venting system 260 may alternatively be fluidly coupled to a volume of gas in the thermal management unit 250 for exchanging gases therewith. In a rack-mounted cooling system, the active venting system 260 and the thermal management unit 250 may also be rack-mounted devices.

[0036] One problem with the startup of a rack-mounted spray cooling system, where the supply manifold 230 and the return manifold 240 are mounted in the rack vertically, is that air can become trapped in the supply manifold 230 above the uppermost connection that leads to the uppermost cooling module 220. The trapped air undesirably increases system pressure, and because there is no fluid flow above the uppermost connection, the non-condensable gases must dissolve back into the coolant to be removed. It has been shown to take several days for the non-condensable gases to be removed fully with this configuration. After a system is shut down, moreover, a substantial amount of non-condensable gas may collect in the supply manifold 230, which again takes significant time to remove.

[0037] To address this problem, in one embodiment, a bypass flow path 270 is placed between the supply manifold 230 and the return manifold 240 near the tops thereof. The flow path 270 allows a small flow (e.g., around 1% of the full flow) of gas to pass from the top of the supply manifold 230 to the return manifold 240. The flow path 270 may comprise a tube, and a chemical filter 265 may be installed in the flow path 270, since this provides an ideal service location. The bypass flow path 270 with chemical filter 265 could replace a bypass filtration line that is often used within the thermal management unit 250. In an alternative embodiment, the bypass path 270 can be separate from the filter 265, although it is typically desired to reduce the number of fluid joints in the system.

Active Venting System Embodiments

[0038] As described above, many coolants used in two-phase fluid cooling applications may absorb a significant amount of air or other non-condensable gases. Because the non-condensable gases remain in gas form throughout the cooling system, they impart a partial pressure that adds to the pressure within the cooling system. Although a slightly increased pressure may be useful to avoid cavitation in the pumps, it can also have detrimental effects on the cooling performance of the system by increasing the boiling point of the coolant. Accordingly, it is often preferable to control the amount of non-condensable gases that are present in the cooling system. When removing gases from the system, therefore, it is generally preferable to remove the non-condensable gases while leaving the coolant vapor in the system. Various embodiments of the active venting system designed to achieve this purpose are described below.

[0039] FIG. 3 depicts a semi-permeable membrane separator embodiment for facilitating removal of non-condensable gases by a venting system. This embodiment is described in the context of the cooling system of FIG. 2, but it could be employed in any other type of cooling system. As illustrated, a semi-permeable membrane 310 may be located in a parallel configuration with the flow path between the

return manifold **240** and a return line **320** leading to a thermal management unit **250**, or with some other portion of the flow path. The membrane **310** is designed to be permeable to the coolant but not to the non-condensable gases that are expected to be in the system.

[0040] During operation of the venting system, the side of the membrane **310** that includes the coolant and non-condensable gas mixture is increased in pressure (e.g., by a pump, not shown). In this way, the coolant is allowed to pass through the membrane **310** and return to the thermal management unit **250**, while the non-condensable gas remains in the manifold **240** (or another volume from which the venting system can extract gas). This increases the concentration of the non-condensable gas versus the coolant vapor in the manifold **240**. If the venting system takes gases from the manifold **240**, the gas mixture taken by the venting system will thus have a relatively higher concentration of non-condensable gas versus coolant vapor than in the rest of the system. In another embodiment, the membrane **310** can be configured in the reverse manner (such as in the embodiment described below in connection with FIG. 6).

[0041] FIG. 4 shows a condensing separator embodiment of an active venting system **410**. This embodiment of the venting system **410** is designed to receive coolant vapor air mixture from the cooling modules, e.g., by tapping into the return manifold **240** of a cooling system such as that shown in FIG. 2. The venting system **410** could tap into the flow path of the cooling system downstream of a condenser or in a reservoir of a heat exchanger, but there would be less need for the condensing function of this embodiment since the coolant would be expected to be primarily in the liquid phase in those areas of the cooling system.

[0042] In operation, the venting system **410** receives a mixture of the coolant vapor and non-condensable gases from the return manifold **240**. A valve **425** may be provided on the gas input line **420** to control when the venting system can take in the gases. The input gases are received in a chamber of the venting system **410**, where a condenser **430** reduces the temperature of the gases until the coolant vapor condenses and collects as a liquid in the venting system. When a control system determines that the venting system should be activated to expel non-condensable gas from the system, the control system activates an auxiliary pump (as shown in FIG. 1) or other mechanism for removing some amount of the non-condensable gas in the venting system **410** through an exit port **460**. The control system may cause the input valve **425** to close for a period of time before activating the auxiliary pump, thereby giving the condenser **430** sufficient time to condense the coolant vapor to ensure that most of the gas expelled is the non-condensable gas.

[0043] At various times, such as when the venting system has a predetermined amount of liquid coolant collected (e.g., as measured by a level sensor, not shown), a liquid return pump **440** is activated. The liquid return pump **440** passes the condensed liquid coolant from the venting system **410** back to the return manifold **240** by way of a liquid return line **450**. A liquid return valve **455** may be provided in the liquid return line **450** to prevent liquid coolant from backing up into the venting system **410**. In this way, the coolant vapor from the cooling modules is condensed so that it can be recycled through the system, rather than being vented from it. The pump **440** may be optional, e.g., the coolant may be gravity drained from the reservoir and reintroduced into the cooling system as well.

[0044] FIG. 5 illustrates a centrifugal separator embodiment of an active venting system **510**, which separates the coolant vapor from the non-condensable gases. As illustrated, the venting system **510** may tap into the return manifold **240** of a cooling system such as that shown in FIG. 2; however, as with the condensing separator embodiment **410**, the venting system **510** could tap into other points in the flow path of the cooling system. The active venting system **510** thus receives a mixture of coolant vapor and non-condensable gases in a gas input line **530**, which may be opened or closed using an input valve **535**. The received mixture of gases is provided to a centrifugal vapor pump **520**, which is designed to separate the coolant vapor and non-condensable gas based on the difference in their densities.

[0045] The centrifugal vapor pump **520** is activated by the control system when it is determined that the venting system **510** should remove gas from the cooling system. The centrifugal vapor pump **520** removes dissolved non-condensable gas from the coolant vapor by passing the mixed gas stream through a series of rapidly spinning disks. As the rotational motion is imparted to the gas stream, the more dense gases (e.g., FLUORINERT®, in a mixture of FLUORINERT® and air) are forced to the perimeter, while the less dense gases continue down the center of the device and exit the centrifugal pump. The centrifugal vapor pump **520** can be controlled by manipulating the rotation speed of the spinning disks by an ordinary brushless DC controller, and by the flow rate of the vacuum pump that pulls the mixed vapor through the device and vents to the atmosphere. Alternatively, where the coolant vapor is less dense than the non-condensable gases, the configuration may be changed to allow the denser gases to be removed.

[0046] In the embodiment shown in FIG. 5, the venting system **510** is designed for a cooling system in which the non-condensable gases are less dense than the coolant vapor. The non-condensable gases are expelled from the venting system **510** via a line **550** and through an exhaust port **555**, which preferably does not allow air to pass into the venting system **510**. The denser coolant vapor returns to the return manifold **240** in a coolant return line **540**. The coolant return line **540** may include a valve **545** to prevent coolant from entering the venting system **510** through the return line **540**.

[0047] FIG. 6 shows another embodiment of a venting system **610** for removing non-condensable gases from a closed-loop cooling system. In this embodiment, at least a portion of the return path of the cooling system is passed through a coil or bundle of semi-permeable tubing **620**, which is permeable to non-condensable gases but not permeable to the coolant. (Although FIG. 6 shows a short length of tubing **620** in the housing **630**, having a coil or bundle of tubing **620** with a long length relative to the diameter of the tubing **620** increases the ratio of surface area to volume, thereby facilitating removal of non-condensable gases from the system.) In one embodiment, the coolant is FLUORINERT® and tube **620** is impermeable to FLUORINERT® but does exhibit marked permeability to air. The tubing **620** is located in a sealed housing **630**, which is coupled to a vacuum pump **640** by tubing **650** that is not permeable. When the vacuum pump **640** is activated, a vacuum is applied to the inside of the housing **630**, and thus, to the outside of the semi-permeable tubing **620**. This causes the non-condensable gas to migrate through the tubing **620**, while the coolant is left inside the tubing **620**. The non-

condensable gas is expelled from the housing 630 by the vacuum pump 640 through an exhaust line 660. The coolant, on the other hand, continues through the tubing 620 and is returned to the cooling system to be recycled.

[0048] In one embodiment, the tubing 620 comprises a co-extrusion having two or more layers, although the tubing 620 need not necessarily have more than one layer. In a multilayer embodiment, an exterior layer of the co-extruded tubing 620 may comprise ether or ester-based polyurethane, which is appropriate due to its high air and low PFC permeation properties. An interior layer of the co-extruded tubing 620 may comprise polyethylene, which has excellent fluid compatibility properties. The tubing 620 is preferably a semi-permeable membrane. This is in contrast to the tubing used in other parts of embodiments of the cooling system, in which co-extruded tubing that prevents permeation and provides good fluid compatibility while remaining flexible is used.

[0049] On one embodiment, the tubing used for some or all flexible connections within the system is a co-extruded tubing that comprises:

[0050] an outer layer composed of an Engage 8440 with Ampshield 1199: Ethylene Octene Co-polymer, where Ampshield is a 52% flame retardant in a low-density polyethylene carrier (0.032" thick);

[0051] a binding layer comprised of Bynel 4157: Linear low density polyethylene (LLDPE) (0.003" thick);

[0052] a next layer EVALCA F101: ethyl vinyl alcohol (EVOH) (0.005" thick);

[0053] a next binding layer of Bynel 4157: Linear low density polyethylene (LLDPE) (0.003" thick); and

[0054] an inner layer of Engage 8440: Ethylene Octene Co-polymer (0.02" thick).

The two Bynel layers in the above construction are binding or "tie" layers. The innermost layer is not adversely affected by fluids common to liquid cooling of electronics. The innermost layer also remains highly flexible at structural thicknesses and environmental conditions typically found for rack-mounted products. The EVOH layer is impermeable to FC-72, PF-5060, and other fluids commonly used in the electronics cooling industry, as well as to air or non-condensable gases. But because the EVOH layer tends to be too stiff if implemented in greater thicknesses, it is impractical as a flexible tubing by itself. Its presence in the co-extrusion is to prevent cooling fluid and/or air permeation, while its minimal thickness does little to affect flexibility. The outermost layer adds structural integrity without adversely affecting flexibility. In various embodiments of the system, a commercially available version containing a flame retardant may be chosen due to its enhanced commercial viability in the marketplace. Other co-extrusions that implement a different layer order may be used, as well as fewer layers or different thicknesses of the layers, although stiffness or permeability may be sacrificed with variations. To increase the flexibility of the tubing temporarily (e.g., to remove stresses in an installed system), the tubing can be heated.

[0055] Alternatively, the venting system could be designed using a tubing that is permeable to the coolant but not to the non-condensable gas. In such a case, the tubing could comprise polyvinylidene fluoride (PVDF), or KYNAR®, which is permeable to FLUORINERT® but not to air. The coolant would be collected outside of the tubing

and returned to the system, while the non-condensable gas left in the tubing would be exhausted from the system.

[0056] Embodiments of the co-extruded tubing described herein may be used for all fluid connections in the system where rigid tubing is impractical, such as to connect pumps to the supply manifold, the supply manifold to the spray modules, the spray modules to the return manifold, and the return manifold to the condenser. The co-extruded tubing may also connect the active venting system to the return manifold. The selection of materials for this and any other tubing may depend, in part, on the type of coolant used.

Operation

[0057] Controlling the pressure inside of the cooling system may be vitally important for many applications, as demonstrated by the saturation curve plotted in FIG. 7. The saturation curve provides the boiling point for a particular coolant for a range of pressures. It is often desirable to operate above the coolant's saturation curve, since the pumps can cavitate if the pressure is too low for a given temperature of operation. Adding air or other non-condensable gases is one way to move above the saturation curve to allow the pumps to operate. But with too much air the coolant evaporates at a relatively high temperature, which causes the two-phase cooling modules to operate at a higher temperature. Accordingly, in one embodiment, the cooling system includes an amount of air or other non-condensable gas in the system to balance these competing concerns. This is illustrated by the "ideal operating condition" curve in FIG. 7, although what is considered ideal operating conditions may change from application to application, so the curve in FIG. 7 is presented for illustration purposes only.

[0058] In one embodiment, the cooling system can regulate the amount of non-condensable gases in the cooling system using a control algorithm implemented by the control module described above. FIG. 8 provides one embodiment of a control algorithm for maintaining the cooling system at or near an ideal operating curve. In this control process, the pressure transducer 145 and temperature sensor 150 measure 810 the pressure and temperature in a location in the cooling system (such as a volume over a reservoir or a point in the return path). Based on this measured pressure and temperature, the control system calculates the ideal operating pressure of the system for the measured temperature. If 820 the difference between this ideal pressure and the saturation curve at the measured temperature is above a predetermined maximum differential (e.g., 3 psi), the control system activates 830 the venting system to reduce the pressure in the cooling system. Otherwise, the control system turns or keeps 850 off the venting system, after which the pressure and temperature are measured 810 again in a subsequent interval.

[0059] In one embodiment, the control system activates 830 the venting system according to a predetermined profile, which specifies an amount of time on and off for the venting system. The on period of the profile allows the system to exhaust a non-condensable gas for a period of time, while the off period allows the venting system to separate the coolant vapor from the non-condensable gas. The off period also allows the system as a whole to come into equilibrium, while other entrained non-condensable gases are moved to the venting system so they can be extracted. Although the particular profile used may depend on the system parameters, in one embodiment the profile is 10 seconds of venting followed by 3 minutes off. The venting system runs (e.g.,

according to the profile) until the control system determines **840** that the system pressure is within a predetermined differential (e.g., 2.5 psi) of the saturation curve at the system temperature. Once this condition is met, the control system turns **850** the venting system off, and the control cycle repeats.

[0060] In one embodiment, the control system may check the pressure difference between the system and the saturation curve so that it can maintain the system above a minimum differential (e.g., a 1.8 psi). This checking may occur, for example, continually during the running of a profile for the venting system. If the cooling system does come within the predetermined minimum differential of the saturation curve, the control system automatically shuts the venting system off. This helps to prevent the pumps from cavitating due to too low of a pressure in the cooling system.

[0061] During startup of the cooling system there may be different venting needs than during normal operation. For example, there is typically more need for venting since there is more air that has seeped into the cooling system. Moreover, the system can tolerate faster venting because the system is stagnant at startup; therefore, the vapor and air are more separated from one another. Once fluid is pumped through the system, the air and vapor tend to mix and extraction has to be done more slowly. Accordingly, a startup profile may be run until the cooling system reaches a desired point from the saturation curve, where the startup profile has more aggressive venting than the regular profile. In one embodiment, the startup profile runs the venting system for 55 seconds on and 5 seconds off, for up to 5 minutes or until the cooling system reaches 5 psi above the saturation curve. As with the regular venting profile, various other startup profiles may be defined based on other system parameters and needs.

[0062] Rather than trying to maintain the cooling system at an ideal operating curve, the control system can also be used to maintain the cooling system at a given temperature. This may be useful, for example, as a tool for the testing or burn-in of semiconductors. Because non-condensable gases within the working fluid of the system affect the component temperatures, adding the gases to the system or allowing the gases to remain in the system can raise the temperature of the components being cooled by the system. The control system may therefore receive additional inputs, such as the temperature of a particular component attached to the cooling system. By adjusting the gases within the cooling system, the control system can maintain these inputs at desired values.

Venting and Refilling of Multiple Cooling Systems

[0063] In other embodiments, the automated venting of two-phase liquid cooling systems can be applied by a central system coupled to a plurality of cooling systems in a parallel arrangement. The cooling systems may be rack-mounted cooling systems, where the overall system extends the automated venting techniques described herein to the multi-rack level. In addition to automated venting of multiple cooling systems, embodiments of the invention can also provide for the automated refill of multiple cooling systems from a central reservoir.

[0064] FIG. 9 illustrates one embodiment of a centralized system for providing venting and refilling for multiple two-phase liquid cooling systems **910**. Each cooling system **910** may comprise a plurality of two-phase liquid cooling modules, such as those described above. The plurality of

cooling modules may further be configured within electronic devices arranged in a rack-mounted system, as found in computer server environments, or they may be any other type of two-phase liquid cooling systems for which venting and/or refilling are desired. The components of the centralized venting and refilling system are coupled to the cooling systems **910** in a parallel arrangement. This arrangement allows the various liquid cooling systems **910** to be vented and/or refilled concurrently, and it also allows a subset of the cooling systems **910** to be serviced at any one time by closing the corresponding fluid path, as described below.

[0065] In the embodiment shown, the centralized venting and refilling system comprises a compressor **930**, a separation column **940**, a reservoir **950**, an exhaust valve **970**, and a fill valve **980**. The compressor **930** of the centralized system is coupled to an exhaust path from each of the liquid cooling systems **910**. The exhaust path for a particular cooling system **910** may be coupled from a simple vent from a condenser in the cooling system **910**, or it may be coupled to any other vent or port designed to exhaust gases from the cooling system **910**. A vent valve **920** in each exhaust path separates the compressor **930** from the corresponding cooling system **910**. Each vent valve **920** can be opened and closed to control when gases are allowed to vent from the corresponding cooling system **910**.

[0066] The centralized venting and refilling system may also include return paths that couple the system to an input port of each liquid cooling system **910**. These return paths allow selective refilling of each of the cooling systems **910** with the coolant liquid from the reservoir **950**. A refill valve **960** couples the input port of each cooling system **910** to the reservoir **950**, thereby allowing control of when and how much each cooling system **910** is refilled. In one embodiment, the reservoir **950** is held at a higher pressure than each cooling system **910**, so the coolant liquid in the reservoir **950** naturally flows into each cooling system **910** when the corresponding refill valves **960** are opened. Alternatively, a pump or other means may be used to cause the coolant liquid to flow from the reservoir **950** into the cooling systems **910** when desired. In one embodiment, the vent valves **920** and/or refill valves **960** may be automatically controllable valves, such as solenoid valves, which facilitate control of the valves' state from the centralized, automated venting and refill system.

[0067] FIG. 10 illustrates the temperature and pressure conditions in the venting and refilling systems during operation of the system in accordance with one embodiment. As with certain embodiments described above, the operation of this system is described using the coolant liquid PF-5060; however, it can be appreciated that embodiments of the invention can be practiced with a variety of other coolant fluids, also as described above. In the example shown, the desired operating point of an individual cooling system **910** (e.g., one rack in a multi-rack system) is identified on the PF 5060 saturation curve as point **1**. It is often desirable to operate the cooling system **910** at a sub-atmospheric pressure to provide lower possible CPU temperatures. Operating at sub-atmospheric pressures also tends to cause any leakage that occurs in the system to be air ingress only, thereby avoiding coolant vapor escape into the atmosphere.

[0068] During normal operation of the cooling systems **910**, air will typically leak into the system. This may occur due to any servicing operation (e.g., when the servers containing the individual cooling modules are attached to

the cooling system's manifold), during servicing of the thermal management units of each cooling system 910, or from permeation or minor leaks through seals and joints in the gas lines. As air leaks into each cooling system 910, the pressure climbs towards point 2 on the PF-5060 saturation curve. As the saturation pressure in the cooling module increases with the overall system pressure, the temperature of the cooling module—and hence, of a CPU or other device being cooled—likewise increases.

[0069] When the automated venting system determines that the pressure or temperature has reached a predetermined maximum (e.g., at point 2 on the chart of FIG. 10), the vent valves 920 for the cooling systems 910 are opened. The system may open all of the vent valves 920 at this time, or it may open only a subset of the vent valves 920 corresponding to the cooling systems 910 that are determined to need venting. This latter embodiment may be useful when the cooling systems 910 are monitored individually, and the system may determine that some, but not all, of the cooling systems 910 need venting to reduce the pressures therein.

[0070] Once the desired vent valves 920 are opened, the compressor 930 is turned on while the exhaust valve 970 is kept shut. This causes air—which may accumulate in the top of a vent manifold or condenser of the cooling system—along with a small amount of coolant vapor to be pumped into the separation column 940 from the cooling systems 910. The compressor 930 may continue to pump until the separation column 940 exceeds a predetermined amount, such as 20 psi. The vent valves 920 are then closed and the compressor 930 is turned off, trapping an amount of air and coolant vapor at the increased pressure.

[0071] The gases and fluid in the separation column 940 are then allowed to cool, e.g., to room temperature (or about 20° C.). At this point, the system is at point 3 on the chart of FIG. 10, where the saturation pressure of the PF-5060 coolant vapor is around 4 psi, and the remaining pressure in the column 940 is due to air and any other gasses in the system. The coolant vapor in the separation column 940 will tend to stratify, as PF-5060 vapor is more than ten times denser than the air in the column 940. The exhaust valve 970 near the top of the separation column 940 is then opened, which causes gases to vent from the column 940 due to the increased pressure in the column 940. Because the air is mostly at the top of the column 940, the majority of the gases being vented will tend to be air, thus limiting the amount of coolant vapor lost from the system. Alternatively, any one or any combination of the separation methods described herein may be used in lieu of or in combination with the separation column 940.

[0072] Over time, and from venting multiple cooling systems 910, coolant liquid will tend to accumulate in the system. In one embodiment, the separation column is coupled to the reservoir, which receives condensed coolant liquid from the column 940. This coolant liquid can be used to refill any individual cooling system 910 that is running low by simply opening the refill valve 960 for the corresponding cooling system 910. An increased pressure in the reservoir 950, or an optional pump, may be used to cause the coolant liquid to flow from the reservoir 950 into the desired cooling system 910. As needed, coolant fluid can be added to the system centrally by adding coolant fluid to the reservoir 950 via the fill valve 980.

[0073] As described herein, the entire system may be automated to vent individual or multiple cooling systems

910 based on the pressure in the corresponding cooling systems 910. The system may also be automated to fill the cooling systems 910 as needed based on the cooling liquid level in each cooling system 910. Embodiments of the system may be applied to rack-mounted systems, in which each rack containing multiple servers or other computer systems is treated as a single cooling system. The racks are then vented and refilled using the central system, thus allowing for scaling of the cooling systems without a proportional scaling of the associated maintenance. The centralized system also allows for automation, further reducing the maintenance of a multi-rack or otherwise plural cooling systems configuration. This system may thus greatly improve the ease of servicing in large data centers.

Testing for Leaks in the Cooling System

[0074] FIG. 11 illustrates a technique for testing for leaks in a two-phase liquid cooling system. FIG. 12 is a schematic diagram of a cooling system that can be used to test for leaks in accordance with the process shown in FIG. 11, although the leak detection technique described herein can be used with other types of cooling systems. In the cooling system shown, a coolant is cycled from a thermal management unit 1250 via a pump 1240 and supply manifold 1210. The coolant is then provided to one or more cooling modules 1230, in which heat energy from cool components being cooled by the system cause at least some of the coolant to evaporate. The coolant is then collected in a return manifold and received by the thermal management unit 1250 to be recycled through the system. To cool and/or condense the coolant before reusing it in the cooling modules 1230, the thermal management unit 1250 includes a heat exchanger 1260, which cools the coolant by passing a cooler liquid (such as water) through a path in the heat exchanger that is thermally coupled to the coolant path.

[0075] As illustrated in FIG. 11, the cooling system has a normal operation mode and a diagnostic mode. In the normal mode, the cooling system is operated 1110 such that a portion of the path through which the coolant is directed is under negative pressure (i.e., lower than atmospheric pressure). Typically, this low-pressure portion is the return path of the cooling system, where the coolant is returning to the thermal management unit 1250 after being evaporated within the cooling modules 1230. In this normal operation mode, any leaks in this path will result in air entering the system, due to the negative pressure of the return path.

[0076] When an operator wants to test the system for leaks, the operator puts the system in a diagnostic mode. In the diagnostic mode, the pressure in the return path is brought 1120 to or above atmospheric pressure. In one embodiment, the pressure in the return path is increased by increasing the temperature of the coolant provided by the thermal management unit 1250. Preferably, the temperature of the coolant from the thermal management unit 1250 is increased so that the cooling modules 1230 still operate to cool components (albeit less efficiently). With the pressure in the return path at or exceeding atmospheric pressure, leaks in the return path can be detected 1130 by placing a coolant sensor along the return path. For example, a leak can be inferred upon an indication by the sensor of the presence of coolant outside the return path. The operator can then more closely examine the portion of the return path near the detected leak so that the path can be repaired or replaced. Once any leak problems are resolved, the operator may return the cooling system to normal operation 1110.

[0077] In one embodiment, the cooling system includes a control unit 1280, which an operator may use to put the cooling system into the normal and diagnostic modes. In one embodiment, the control unit 1280 is coupled to control a valve 1270 in the water supply path of the heat exchanger 1260. To put the cooling system into diagnostic mode for leak detection, the control unit restricts the flow of water to the heat exchanger 1260 by controlling the valve 1270. This restriction can cause the coolant temperature throughout the cooling system—and thus the pressure of the coolant vapor in the return path—to rise to a level where the return path of the cooling system is at or above atmospheric pressure. A refrigerant detector 1290 can then be used to locate any leaks in the return path. The detector 1290 can be coupled to the control unit 1280 for data acquisition purposes, or it can be used independently thereof.

Thermal Management Unit Design

[0078] In one embodiment of the system, the reservoir and heat exchanger are preferably constructed as follows. Heated coolant, which may comprise fluid as saturated vapor or some mixture of liquid and vapor, enters the heat exchanger, is condensed and/or cooled, and then falls into the reservoir. From the reservoir, the fluid then enters a pump inlet and is pumped into the rest of the system. For such a fluid flow to occur, the reservoir is preferably positioned gravitationally below the exit of the heat exchanger and is formed to create a sump from which the pump draws fluid. In one embodiment, the reservoir is constructed to have an air/vapor space above the sump during operation of the cooling system. This construction facilitates a location from which non-condensable gasses can be extracted from the system. The heat exchanger may be of a commonly known bar and plate heat type that uses water as the heat exchange medium.

[0079] In one embodiment, the system uses a heat exchanger that occupies a greater area than the sump area and is slopped to facilitate drainage into the sump area. With this construction and relative sizing, the sump area can be made to contain only enough fluid to keep the pumps flooded, with some reserve for adding dry spray units and fluid losses such as permeation.

[0080] In another embodiment, a fluid return port of a pump connected to the reservoir is disconnectably matable to a self sealing connector mounted in a through port of the reservoir. The return port of the pump can be inserted into the connector, thereby biasing a seal in the connector. The pump can then be hard-mounted to the outer surface of the reservoir using a fastening means such as one or more threaded fasteners. The pump supply port is then fluidly connected to a flexible line that couples it to the rack supply manifold. Beneficially, the flexible supply line permits the pump to be engaged to the self sealing connector without adversely affecting alignment of the seals, where a dual o-ring seal on an outer circular structure of the pump return may be implemented. The flexible supply line and the rigid return connection structures may be reversed, and other non-o-ring sealing members (such as but not limited to face seals or gaskets) may be implemented.

[0081] In another embodiment, the thermal management unit has a modular design and includes variable flow valves controllably connected to a control unit that monitors temperature, pressure, and water leaks. The control unit is capable of increasing a flow rate of cooling water through the thermal management unit if a temperature or pressure

measured by the control unit is too high, or decreasing the flow rate through the thermal management unit if a measured temperature or pressure is too low. Finally, the control unit is capable of reducing or shutting off water flow if a water leak is detected within the modular system. In many instances, the facility water loop heat exchanger systems are designed to have a constant water temperature rise (e.g., 35° C. inlet and 30° C. outlet). By varying the water flow to the heat exchanger, flow can be reduced to maintain optimal water temperature.

[0082] In another embodiment, in the liquid to liquid heat exchanger the cooling water loop is connected directly to a facility cooling tower. The desired water temperature entering the facility cooling tower is maintained using a variable flow valve, controllably connected to a system controller that reads a temperature in the exit water flow of the thermal management unit. The valve may control flow into or out of the thermal management unit. Typically, the water entering a facility cooling tower needs to be maintained at a temperature of approximately 38° C. The thermal management unit exit water temperature can be maintained by regulating the flow of cooling water circulating through the thermal management unit. One benefit that may be realized by this implementation is that water towers generally provide a good heat rejection system because they operate within a narrow range (typically and ideally, a 10° F. rise). The change in temperature is measured and controlled to the desired change in temperature of the water. This functionality can be put into water safety valves for when there is a water leak.

[0083] In another embodiment, during operation of the cooling system, adequate vapor space above the fluid level may be desirable for easily separating non-condensable gasses from the working fluid. If too little vapor space exists, a significant amount of liquid may be pulled out with the vented gasses. This is highly undesirable. This condition may occur when an entire rack is populated with servers, and therefore with cooling modules. The condition might also occur when a cooling module is connected to the uppermost fluid port in a vertically mounted supply and return manifold, since the fluid levels in the manifolds rise according to the height of the connected units. To avoid this scenario, the height of the manifold may be increased. However, such a solution may be impractical because the manifold would typically be required to retrofit a standard size rack. In another embodiment, the scenario can be avoided by positioning the non-condensable gas extraction pump at the top of the rack (as would normally be done) and fluidly connect it to a vapor space in the reservoir at the bottom of the rack. This connecting fluid line then becomes a vertical separation tube, since due to buoyancy the air or other non-condensable gasses will naturally rise to the top of the tube. Even in a configuration in which non-condensable gases are pulled out of the heat exchanger, it may still be desirable to locate the active vent pump at the top of the rack so that the space between can be used for gravitational separation of the non-condensable gasses and coolant vapor.

SUMMARY

[0084] The foregoing description of the embodiments of the invention has been presented for the purpose of illustration; it is not intended to be exhaustive or to limit the invention to the precise forms disclosed. For example, many of the fastening, connection, manufacturing, and other

means and components that are described in various embodiments are widely known in the relevant field, and their exact nature or type is not necessary for a person of ordinary skill in the art or science to understand the invention. Persons skilled in the relevant art can appreciate that many modifications and variations are possible in light of the above teachings. It is therefore intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto.

What is claimed is:

1. A method for detecting leaks in a two-phase liquid cooling system, the method comprising:

operating a two-phase cooling system in a normal mode, wherein a coolant is directed via a supply path to one or more cooling modules and collected via a return path in a thermal management unit for cooling and redeployment to the cooling modules, the return path having a pressure below atmospheric pressure;

changing to a diagnostic mode, wherein the pressure of the return path is raised to a pressure at or above atmospheric pressure;

in the diagnostic mode, using a coolant sensor to locate any leaks in the return path; and

returning the cooling system to the normal mode, wherein the pressure of the return path is below atmospheric pressure.

2. The method of claim 1, wherein the pressure of the return path is increased by increasing the temperature of the coolant from the thermal management unit to the supply path.

3. The method of claim 2, wherein the temperature of the coolant from the thermal management unit to the supply path is increased by restricting fluid supplied to a heat exchanger in the thermal management unit that is configured to cool the coolant therein.

4. A method for detecting leaks in a two-phase liquid cooling system, the method comprising:

circulating a coolant through a two-phase cooling system, wherein at least a portion of the cooling system has a

low-pressure path through which coolant is directed at a pressure below atmospheric pressure;

a step for temporarily increasing the pressure of the low-pressure path of the cooling system above atmospheric pressure; and

testing for leaks in the low-pressure path by checking for coolant leaving the low-pressure path.

5. The method of claim 4, further comprising:

returning the low-pressure path to a pressure below atmospheric pressure.

6. A system for detecting leaks in a two-phase liquid cooling system, the system comprising:

a two-phase cooling system configured to direct a coolant via a supply path to one or more cooling modules and collect the coolant via a return path in a thermal management unit configured to cool and redeploy the coolant to the cooling modules, the return path having a pressure below atmospheric pressure during normal operation of the cooling system;

a control unit coupled to the cooling system, the control unit configured to increase the pressure of the return path to a pressure at or above atmospheric pressure for a diagnostic mode, the control unit further configured to return the cooling system to normal operation; and

a sensor configured to detect any coolant leaking from the return path of the cooling system during the diagnostic mode.

7. The system of claim 6, wherein the control unit is configured to increase the pressure of the return path by increasing the temperature of the coolant from the thermal management unit to the supply path.

8. The system of claim 7, wherein the thermal management unit comprises a heat exchanger configured to cool coolant received from the return path, and wherein the control unit is configured to increase the temperature of the coolant from the thermal management unit to the supply path by restricting fluid supplied to a heat exchanger to decrease the cooling of the coolant by the heat exchanger.

* * * * *