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.
FIG. 1
FIG. 2
FIG. 5

FIG. 6
Measure operating conditions (e.g., P, T) in cooling system 810

\[
P_{\text{ext}} - P_{\text{at}} > \text{max?} \quad 820
\]

No

Turn/keep off venting system 840

Yes

Activate venting system 830

\[
P_{\text{ext}} - P_{\text{at}} < P_{\text{source}}? \quad 850
\]

No

Yes

FIG. 8
TWO-PHASE LIQUID COOLING SYSTEM WITH ACTIVE VENTING

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.

BACKGROUND

[0002] 1. Field of the Invention

[0003] This invention relates generally to two-phase liquid cooling systems, and more particularly to two-phase liquid cooling systems that have an active venting system for regulating the pressure within the system by removing gases such as non-condensable gases from the cooling system.

[0004] 2. Background of the Invention

[0005] 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.

[0006] 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.

[0007] 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 dispersed 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.

[0008] 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.

[0009] 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.

[0010] A significant challenge in the use of some two-phase cooling systems is presented by non-condensable gases. Dielectric fluids like FLUORINERT® can contain significant amounts of air and other non-condensable gases in solution. When the dielectric fluid is placed into a system at atmospheric conditions, the fluid may thus contain a significant amount of air dissolved in the fluid. During use within a thermal management system, according to Henry’s Law, as the fluid approaches its saturation temperature the amount of air in solution decreases. The air that was previously in solution occupies a volume within the system. According to the ideal gas law, the partial pressure of the air will raise the boiling point of the cooling fluid above the natural saturation curve. This, in turn, reduces the cooling efficiency of the system because it raises the boiling point of the fluid to a level that renders less than ideal cooling performance. But some amount of air is useful for some cooling systems, for example, to avoid pump cavitation. The actual amount of air in the system can vary as air seeps into the system during operation, so it can be difficult to maintain the amount of air within the system at an optimal level.

[0011] For the foregoing reasons, there is a need for a two-phase liquid cooling solution that can maintain an ideal amount of air or other non-condensable gas within the system. With changing conditions inside a cooling system, there is a need for a method of regulating the non-condensable gases in the cooling system. Such a cooling system would result in significant improvements in both the performance and reliability of the two-phase liquid cooling process.

SUMMARY OF THE INVENTION

[0012] To avoid at least some of the problems encountered with existing two-phase liquid cooling systems, as described above, a cooling system with active venting is provided. An active venting system actively regulates the pressure within the cooling system, for example, by regulating the amount of non-condensable gases in the cooling system. With appropriate control of the active venting system, the performance and reliability of the system can be increased and maintained over long and continuous periods of operation.

[0013] Embodiments of the invention include liquid cooling systems and methods that can provide thermal management for one or more electronic components. In one embodiment, a cooling system includes a cooling liquid, or coolant, that is circulated through a closed loop by one or more pumps. The cooling fluid enters one or more cooling modules as a liquid or saturated liquid, and changes phase in the cooling module by means of latent energy gains. The resulting liquid and vapor mixture is then removed from the cooling module and condensed so that it can be returned to the pump and circulated back through the system. An active venting system is coupled to a volume in the cooling system to regulate the pressure in the cooling system. A control...
system is coupled to the active venting system to activate the venting based on any of a number of criteria, such as process conditions within the cooling system.

[0014] The active cooling system can exhaust gases out of the system using various mechanisms. In one embodiment, a vent is located between the cooling module and the pump, and an auxiliary pump is coupled to the vent to pump a desired amount of gas out of the system. The control system is coupled to the auxiliary pump and vent to provide the ability to regulate the amount of gas removed from the system. The active venting system may also be capable of adding gases into the cooling system (e.g., by pumping air into the system) when a pressure increase is desired. In this way, the cooling system can regulate the pressure in the cooling system to achieve a desired overall cooling efficiency. Adding air to the cooling system may also help avoid cavitation in the pumps.

[0015] Within the cooling system there may be one or more non-condensable gases. Non-condensable gases may include any gases or mixtures thereof that do not condense into liquid form under conditions experienced during normal operation of the two-phase liquid-cooling system. Air is a common non-condensable gas in cooling systems, since they are typically run at pressures below atmospheric so that air tends to seep in slowly through points in the system that are not completely sealed or otherwise allow air permeation into the system. The non-condensable gases cause a partial pressure within the closed volume of the cooling system, which alters the boiling point of the cooling fluid and thus affects the operation of the cooling system. While removing the gases from the system, it is often desirable to remove the non-condensable gases while minimizing the removal of the coolant in vapor phase. Otherwise, over time the cooling system would lose coolant and would need to have the coolant replaced. By removing non-condensable gases rather than vapor-phase coolant from the cooling system, the need to replace coolant is reduced. Accordingly, the active venting system may be configured to remove an amount of the non-condensable gases from the system.

[0016] Various embodiments of the system include mechanisms in the venting system for separating the coolant vapor from the non-condensable gases to be removed. By separating the coolant vapor from the non-condensable gases, the active venting system can remove only the non-condensable gases and allow the coolant vapor to recycle through the cooling system. In one embodiment, the active cooling system includes using a semi-permeable membrane separator coupled between the cooling module and the return line, allowing only coolant vapor to recycle through the system. In other embodiments, the active venting system comprises a condensing separator, a centrifugal gas separator, or a semi-permeable membrane separator (such as a permeable tube vacuum system) to separate the vapor cooling fluid from the non-condensable gases to be removed.

[0017] In one embodiment, the control system measures process conditions such as the temperature and pressure within a volume of the cooling system. Based on the measured temperature and pressure, the control system determines whether the process conditions within the system are inside a desired range. In one embodiment, the control system determines that removal of non-condensable gases is needed based on the saturation curve of the coolant. For example, the control system may detect when the pressure and temperature inside the system deviate from the saturation curve of the coolant by a predetermined amount. When the control system determines that venting is needed, it activates the venting system, for example, causing the active venting system to open the vent and turn on the auxiliary pump to remove gases in the system.

[0018] 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

[0019] 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:

[0020] FIG. 1 is a schematic diagram of a two-phase liquid cooling system with active venting, in accordance with an embodiment of the invention.

[0021] FIG. 2 is a schematic diagram of a rack-mounted spray cooling system, in accordance with an embodiment of the invention.

[0022] FIG. 3 is a schematic diagram of a semi-permeable membrane separator, in accordance with an embodiment of the invention.

[0023] FIG. 4 is a schematic diagram of a condensing separator, in accordance with an embodiment of the invention.

[0024] FIG. 5 is a schematic diagram of a centrifugal separator, in accordance with an embodiment of the invention.

[0025] FIG. 6 is a schematic diagram of a permeable tube vacuum mechanism, in accordance with an embodiment of the invention.

[0026] FIG. 7 is a chart showing a typical saturation curve for an example cooling liquid.

[0027] 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 system.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Two-Phase Cooling System with Active Venting

[0028] 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.

[0029] 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.

[0030] 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 (as 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.

[0031] 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.

[0032] 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.

[0033] 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 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.

[0034] 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 use 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 a return manifold (see FIG. 2).

[0035] 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.

[0036] 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 supply manifold 130 to 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.

[0037] 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.

[0038] 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.

[0039] To address this problem, in one embodiment, a bypass flow path 260 is placed between the supply manifold 230 and the return manifold 240 near the top thereof. The flow path 260 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 260 may comprise a tube, and a chemical filter 265 may be installed in the flow path 260, since this provides an ideal service location. The bypass flow path 260 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 260 can be separate from the filter 265, although it is typically desired to reduce number of fluid joints in the system.

Active Venting System Embodiments

[0040] 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 efficiency 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.

[0041] 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.

[0042] 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).

[0043] 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.

[0044] 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.

[0045] 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 venting 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.

[0046] 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.

[0047] 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.

[0048] 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.

[0049] 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. 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.

[0050] In one embodiment, the tubing 620 comprises a co-extrusion having at least two layers. 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 a co-extruded tubing that prevents permeation and provides good fluid compatibility while remaining flexible is used. This co-extruded tubing 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.

[0051] On one embodiment, the tubing used for some or all flexible connections within the system is a co-extruded tubing that comprises:

[0052] 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);

[0053] a binding layer comprised of Bynel 4157: Linear low density polyethylene (LLDPE) (0.006" thick);

[0054] a next layer EVALCA F101: ethyl vinyl alcohol (EVOH) (0.005" thick);

[0055] a next binding layer of Bynel 4157: Linear low density polyethylene (LLDPE) (0.003" thick); and

[0056] 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.

[0057] 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.

Operation

[0058] 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.

[0059] 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.

[0060] 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.

[0061] 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., 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 a pressure in the cooling system.

[0062] 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.

[0063] 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.

Summary

[0064] 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 two-phase liquid cooling system with active venting, the system comprising:
   a closed-loop flow path for circulating a coolant;
   a two-phase liquid cooling module in the flow path for evaporative cooling of a device;
   a venting system for exhausting gas outside the cooling system from a volume fluidly coupled to the flow path; and
   a control system operatively coupled to the venting system, the control system configured to activate the venting system based on process conditions within the cooling system.

2. The system of claim 1, wherein the venting system is designed to remove non-condensable gases and substantially no coolant from the system.

3. The system of claim 1, wherein the venting system comprises a vacuum pump for removing gas from the volume fluidly coupled to the flow path.

4. The system of claim 1, wherein the venting system comprises a valve for disallowing air from outside the cooling system to enter the venting system.

5. The system of claim 1, wherein the volume to which the venting system is coupled is further coupled to a return line that has a membrane that is permeable to the coolant and not permeable to the non-condensable gases, thereby increasing the relative concentration of non-condensable gases in the volume for being removed from the cooling system.

6. The system of claim 1, wherein the venting system comprises a condenser to condense the coolant and thereby separate the coolant from the non-condensable gases.

7. The system of claim 1, wherein the venting system comprises a centrifugal separator to separate the coolant and the non-condensable gases based on density.

8. The system of claim 1, wherein the venting system comprises:
   a semi-permeable tubing coupled to the flow path, the semi-permeable tubing permeable to the non-condensable gases and not permeable to the coolant;
   a vacuum chamber housing the semi-permeable tubing; and
   a pump coupled to the housing to remove gases therefrom.

9. The system of claim 1, wherein the venting system is coupled to a sealed chamber for storing gases vented from the cooling system.

10. The system of claim 9, wherein the sealed chamber includes a condenser for condensing any coolant vapor therein and a valve for venting gas from the chamber when the pressure therein reaches a predetermined maximum.

11. The system of claim 1, wherein the process conditions within the cooling system include temperature and pressure.

12. The system of claim 1, wherein the control system is configured to activate the venting system to keep the coolant in the cooling system at a point near the coolant’s saturation curve.

13. The system of claim 1, wherein the control system is configured to activate the venting system to keep the coolant in the cooling system within a predetermined tolerance from the coolant’s saturation curve.

14. The system of claim 1, wherein the control system is configured to perform a step for regulating the pressure within the cooling system.

15. The system of claim 1, wherein the cooling system is a rack-mounting system.

16. The system of claim 1, wherein the cooling module is a sprayer cooling module.

17. The system of claim 1, wherein the volume from which the venting system exhausts gas is a reservoir in a heat exchanger of the cooling system.

18. The system of claim 1, wherein the volume from which the venting system exhausts gas is a return manifold in the flow path.

19. A cooling system comprising:
   a closed-loop fluid path having an internal volume, the internal volume for holding:
   a cooling fluid having a vapor portion occupying a partial amount of the internal volume and a liquid portion occupying a partial amount of the internal volume, and
   a non-condensable gas occupying a partial amount of the internal volume;
   one or more two-phase liquid cooling modules in the fluid path; and
   a means for regulating an amount of the non-condensable gas within the internal volume.

20. The system of claim 20, wherein the means for regulating is configured to remove substantially no coolant from the system.

21. The system of claim 20, wherein the means for regulating is coupled to a sealed chamber for storing gases vented from the cooling system.

22. The system of claim 20, wherein the means for regulating is configured to control an amount of the non-condensable gas within the internal volume based on any one of a temperature and a pressure at a location in the internal volume.

23. The system of claim 20, wherein the means for regulating is configured to keep the cooling fluid at a point near the cooling fluid’s saturation curve.

24. The system of claim 20, wherein the means for regulating is configured to keep the cooling fluid within a predetermined tolerance from the cooling fluid’s saturation curve.
27. The system of claim 20, wherein the means for regulating is configured to maintain a desired temperature at the cooling modules.

28. The system of claim 20, wherein the cooling system is a rack-mounting system.

29. The system of claim 20, wherein the cooling module is a spray cooling module.

30. A closed-loop liquid cooling system having an internal volume, the system comprising:
   a cooling fluid having a vapor portion occupying a partial amount of the internal volume and a liquid portion occupying a partial amount of the internal volume;
   a non-condensable gas occupying a partial amount of the internal volume; and
   a means for regulating the amount of the non-condensable gas within the internal volume.

31. The system of claim 30, wherein the means for regulating is configured to remove substantially no coolant from the system.

32. The system of claim 30, wherein the means for regulating is configured to control an amount of the non-condensable gas within the internal volume based on at least one of a temperature and a pressure at a location in the internal volume.

33. The system of claim 30, wherein the means for regulating is configured to keep the cooling fluid at a point near the cooling fluid’s saturation curve.

34. The system of claim 30, wherein the means for regulating is configured to keep the cooling fluid within a predetermined tolerance from the cooling fluid’s saturation curve.

35. The system of claim 30, wherein the cooling system is a rack-mounting system.

36. The system of claim 30, wherein the cooling system further comprises one or more spray cooling modules.

37. A method for venting a non-condensable gas from a two-phase liquid cooling system, the method comprising:
   passing a coolant through a closed-loop flow path, the flow path including one or more cooling modules;
   cooling a heat producing device using the cooling modules, the cooling resulting in the formation of coolant vapor;
   collecting the coolant vapor and a non-condensable gas in a volume fluidly coupled to the flow path; and
   venting an amount of the non-condensable gas from the volume to outside the cooling system, the venting based on measured process conditions within the cooling system.

38. The method of claim 37, wherein the venting removes non-condensable gases and substantially no coolant from the system.

39. The method of claim 37, wherein the volume from which the non-condensable gas is vented is coupled to a return line that has a membrane that is permeable to the coolant and not permeable to the non-condensable gas, thereby increasing the relative concentration of non-condensable gases in the volume for being removed from the cooling system.

40. The method of claim 37, further comprising:
   condensing coolant in the volume to separate the coolant from the non-condensable gas being vented.

41. The method of claim 37, further comprising:
   separating the coolant from the non-condensable gas being vented using a centrifugal separator.

42. The method of claim 37, wherein the venting system comprises:
   directing a flow of the coolant and non-condensable gas through a semi-permeable tubing in a vacuum chamber, the semi-permeable tubing permeable to the non-condensable gases and not permeable to the coolant;
   reducing the pressure in the vacuum chamber to collect non-condensable gas from the tubing to the vacuum chamber; and
   pumping the non-condensable gas from the vacuum chamber.

43. The method of claim 37, wherein the vented non-condensable gas is directed to a sealed chamber.

44. The method of claim 38, further comprising:
   condensing coolant vapor in the sealed chamber; and
   venting gas from the sealed chamber through a valve when the pressure in the sealed chamber reaches a predetermined maximum.

45. The method of claim 37, wherein the process conditions within the cooling system include temperature and pressure.

46. The method of claim 37, wherein the venting is controlled to keep the coolant in the cooling system at a point near the coolant’s saturation curve.

47. The method of claim 37, wherein the venting is controlled to keep the coolant in the cooling system within a predetermined tolerance from the coolant’s saturation curve.

48. The method of claim 37, wherein the venting is controlled to maintain a desired temperature at a cooling module.

49. The method of claim 37, wherein the cooling modules are spray cooling modules.

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