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(54) **Title:** METHOD AND APPARATUS FOR COOLING ELECTRONICS WITH A COOLANT AT A SUBAMBIENT PRESSURE

(57) **Abstract:** According to one embodiment of the invention, a method is provided for cooling heat-generating structure disposed in an environment having an ambient pressure. The heat-generating structure includes electronics. The method includes providing a coolant, reducing a pressure of the coolant to a subambient pressure at which the coolant has a boiling temperature less than a temperature of the heat-generating structure, and bringing the heat-generating structure and the coolant at the subambient pressure into contact with one another, so that the coolant boils and vaporizes to thereby absorb heat from the heat- generating structure. In a more particular embodiment the coolant is either pure water or pure methanol with an electrical resistivity level of greater than one million Ohms-cm. Further, in another particular embodiment the method includes filtering the coolant to maintain its purity above a particular level.

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METHOD AND APPARATUS FOR COOLING ELECTRONICS WITH A COOLANT AT A SUBAMBIENT PRESSURE

TECHNICAL FIELD OF THE INVENTION

This invention relates in general to cooling techniques and, more particularly, to a method and apparatus for cooling electronics with a coolant at a subambient pressure.

BACKGROUND OF THE INVENTION

Some types of electronic circuits use relatively little power, and produce little heat. Circuits of this type can usually be cooled satisfactorily through a passive approach, such as convection cooling. In contrast, there are other circuits which consume large amounts of power, and produce large amounts of heat. One example is the circuitry used in a phased array antenna system. Others include other types of electronics, such as densely packed electronics used for current and future computational circuits, which can produce 1000-10,000 watts of heat per cubic centimeter, or more.

In the modern phased array antenna example, the system can easily produce 25 to 500 kilowatts of heat, or even more. Future computers are envisioned to produce equally large amounts of heat. One known approach for cooling this circuitry is to incorporate a refrigeration unit into the electronics cooling. However, suitable refrigeration units are large, heavy, and consume many kilowatts of power in order to provide adequate cooling. Although refrigeration units of this type have been generally adequate for their intended purposes, they have not been satisfactory in all respects. An equally important factor is the inability of existing methods to remove high flux heat loads from electronic components and modules. Existing approaches, which use a coolant flowing inside a coldplate or thermal plane to which electrical components and modules are mounted, have inadequate heat transfer performance to meet future needs. In addition, approaches using two-phase, sprayed fluorinerts are not satisfactory in all respects.

SUMMARY OF THE INVENTION

According to one embodiment of the invention, a method is provided for cooling heat-generating structure disposed in an environment having an ambient pressure. The heat-generating structure includes electronics. The method includes providing a coolant,

reducing a pressure of the coolant to a subambient pressure at which the coolant has a boiling temperature less than a temperature of the heat-generating structure, and bringing the heat-generating structure and the coolant at the subambient pressure into contact with one another, so that the coolant boils and vaporizes to thereby absorb heat from the heat-generating structure. In a more particular embodiment the coolant is either pure water or pure methanol with an electrical resistivity level of greater than one million Ohms-cm. Further, in another particular embodiment the method includes filtering the coolant to maintain its purity above a particular level.

Some embodiments of the invention may provide numerous technical advantages. Other embodiments may realize some, none, or all of these advantages. For example, according to one embodiment, large amounts of heat may be removed from a heat-generating structure, allowing, for example, more densely-packed electronics to be utilized.

Other advantages may be readily ascertainable by those skilled in the art.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of embodiments of the invention will be apparent from the detailed description taken in conjunction with the accompanying drawings in which:

FIGURE 1A is a block diagram of an apparatus which includes a heat-generating structure and an associated cooling arrangement that embodies aspects of the present invention;

FIGURE 1B is a side view of one example of the chamber and heat producing structure of the system of FIGURE 1A;

FIGURE 2 is a schematic diagram of one embodiment of the heat-generating structure of FIGURE 1;

FIGURE 3A is a schematic diagram of a flow-through module that includes an array of the circuit substrates of FIGURES 3B through 3D that may be cooled according to the method of FIGURE 1A;

FIGURES 3B through 3C are schematic diagrams showing various views of a circuit substrate that may be cooled according to the method of FIGURE 1A;

FIGURE 4A is a schematic diagram of a frame for holding an array of modules of FIGURE 3D; and

FIGURE 4B is an assembly combining the frame of FIGURE 4A and an array of modules of FIGURE 3D that may be cooled according to the method of FIGURE 1A.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS OF THE INVENTION

Example embodiments of the present invention and their advantages are best understood by referring to FIGURES 1A-4B of the drawings, like numerals being used for like and corresponding parts of the various drawings.

FIGURE 1A is a block diagram of an apparatus 10 that includes a heat-generating structure 12. The heat-generating structure 12 may be, in a particular embodiment, one or more microelectronic assemblies, which may produce an enormous amount of heat that is difficult to cool using conventional techniques. Alternatively, heat-generating structures may include no electronics and/or may not produce excessive amounts of heat. In general, although the teachings of the invention may provide greater benefit to cooling microelectronics that produce excessive amounts of heat, these teachings are applicable to cooling any type of device at high or lower levels of heat-generation. According to the teachings of one embodiment of the invention, heat-generating structure 12 is submerged within a bath of coolant 16 within a chamber 14 and/or subject to a flow of coolant 16 with coolant 16 being at a subambient pressure. One example is illustrated in FIGURE 1B. The bath may be a generally stationary bath or, alternatively, the bath may further utilize flowing coolant 16 to further enhance heat transfer from heat-generating structure 12 to coolant 16. Alternatively, the bath may be replaced with simply a flow of coolant over heat-generating structure 12.

Coolant 16 may be any liquid with suitable resistivity and latent heat of vaporization properties. In the environment in which microelectronics is used within heat-generating structure 12, the resistivity of coolant 16 should be high enough such that coolant 16 does not form a short in the microelectronics. Further, where large heat loads need to be disposed of, liquids with relatively high latent heats of vaporization are more desirable. Both pure water and methanol meet these criteria when high heat load microelectronics are used as part of heat-generating structure 12.

Pure water has a very high electrical resistivity of approximately 18.2 million Ohms-cm and pure methanol has a high electrical resistivity of approximately 40 million Ohms-cm. Consequently, such pure water or pure methanol would not cause electrical shorts in heat-generating structure 12 in the associated electrical signals or power leads. Use of pure water as coolant 16 is particularly desirable because of its relatively high latent heat of vaporization, which is about 24 times that of fluroinerts. Methanol also has a fairly high latent heat vaporization, about half of that of water. However, although pure water and methanol are particularly desirable coolants, other coolants may also be used.

System 10 is designed such that coolant 16 boils when it comes into contact with heat-generating structure 12. In particular, system 10 involves reducing the pressure of coolant 16 to subambient levels such that it boils at a desired temperature lower than the temperature at which the coolant 16 would otherwise boil. Thus system 10 may be referred to as a subambient cooling system. Subambient cooling systems suitable for use with the present disclosure include those described in the following patent applications assigned to the same assignee as the present invention: Method and Apparatus for Cooling with Coolant at a Subambient Pressure, filed July 11, 2002, having a serial number of 10/192,891, and an attorney docket number of 004578.1262; and Method and Apparatus for Controlling Cooling with Coolant at a Subambient Pressure, filed May 25, 2004, having a serial number of 10/853,038, and an attorney docket number of 004578.1402, which are both incorporated herein by reference for all purposes.

Providing coolant 16 at subambient levels permits the use of pure water and methanol as coolants, which are typically not useful in certain applications because of their relatively high boiling temperatures. Thus, the teachings of the invention recognize the desirability of combining boiling heat transfer at a subambient pressure, which is generally the best heat removal mechanism to extract heat from a surface, with direct application of the coolant to the heat-generating structure, such as by submerging or flowing the coolant over the structure. When used with electronic components as part of heat-generating structure 12, submersion of heat-generating structure 12, or sufficient flow of coolant 16 over heat-generating structure 12, allows heat to be removed from active and passive component surfaces and features, as well as removing heat from component leads. Additional details of system 10 are described below with reference to FIGURES 1A-4B.

Heat-generating structure 12 is configured so that the heat it generates is transferred to coolant 16 coming into contact with heat-generating structure 16. Coolant 16 flows through a tube 22. As discussed later, this fluid coolant is a two-phase coolant 16, which comes into contact with heat-generating structure 12 in liquid form. Absorption of heat from heat-generating structure 12 causes part or all of the liquid coolant 16 to boil and vaporize, such that some or all of the coolant 16 flowing through a tube 24 is in its vapor phase. This departing coolant 16 then flows successively through a separator 26, a heat exchanger 28, a pump 30, a metering pump 31, and a filtration bed 34 in order to again reach the inlet end of tube 22. As illustrated, only a portion of coolant 16 flows through metering pump 31 and filtration bed 34.

Pump 30 causes coolant 16 to circulate around the endless loop shown in FIGURE 1. In the embodiment of FIGURE 1, the pump 30 consumes only about 0.1 kilowatts to 2.0 kilowatts of power.

Separator 26 separates the vaporized portion of the liquid coolant 16 flowing through tube 24 from the unvaporized liquid portion. The vaporized portion is provided to heat exchanger 28, and the liquid portion is provided at separator pump 36. Separator pump 36 receives the liquid portion of the coolant that has not vaporized in tube 24 and circulates this fluid back through tube 22. Orifice 32 creates a pressure drop between throughput of pump 30 and the output of 32, where coolant 16 vaporizes.

As described above, the teachings of the invention recognize that in some instances it will be desirable to purify coolant 16 while it flows in the above-described loop to maintain its resistivity above a desired level. This is particularly true when coolant 16 is pure water and heat-generating structure 16 comprises electronic components. The particular desired level of resistivity will vary based on the structure and content of heat-generating structure 16, but in one example, maintaining the resistivity of coolant 16 above one million Ohms-cm is particularly desirable for avoiding electrical shorts. Filtration bed 34 is used to remove contaminants from coolant 16 such as salts, metallic constituents, or other contaminants that are generated or that enter the loop during operation, to ensure it has a resistivity sufficiently high enough during operation that it does not cause electrical shorts in heat-generating structure 12. Filtration bed 34 may remove carbon dioxide, free oxygen and metallics, and may utilize a distillation, reverse osmosis, or other suitable process. Only about 5-10% of the coolant flow would need to

be processed, in one embodiment, which is provided by metering pump 31. Other purification methods may also be used.

Ambient air or liquid 38 is caused to flow through heat exchanger 28, for example, by a not-illustrated fan of a known type. Alternatively, if the apparatus 10 was on a ship, the flow 38 could be ambient seawater or a distilled water secondary loop that transfers heat to seawater. The heat exchanger 28 transfers heat from the coolant to the air flow 38. The heat exchanger 28 thus cools the coolant, thereby causing any portion of the coolant which is in the vapor phase to condense back into its liquid phase.

Liquid coolant 16 exiting heat exchanger 28 is supplied to expansion reservoir 40. Since fluids typically take up more volume in their vapor phase than in their liquid phase, expansion reservoir 40 is provided in order to take up the volume of liquid coolant that is displaced when some or all of the coolant in the system changes from its liquid phase to its vapor phase. The amount of coolant 16 that is in its vapor phase can vary over time, due in part to the fact that the amount of heat being produced by heat-generating structure 16 will vary over time, as the heat-generating structure 16 may operate in various operational modes over time, in some embodiments.

In some embodiments, a controller may be utilized to control the amount of heat transfer from heat-generating structure 16, one example of which is desired in Method and Apparatus for Controlling Cooling with Coolant at a Subambient Pressure, filed May 25, 2004, having a serial number of 10/853,038, and an attorney docket number of 004578.1402, which is incorporated herein by reference. However, other control approaches may be used. In one particular embodiment, a pressure controller 42 maintains coolant 16 at a desired subambient pressure in portions of the cooling loop downstream of filtration bed 34 and upstream of pump 30. Typically, the ambient air pressure will be that of atmospheric air, which at sea level is 14.7 pounds per square inch absolute (psia). When heat-generating structure 12 undergoes transient heat loads, this subambient pressure may need to be adjusted to allow greater or lesser amounts of heat transfer from heat-generating structure 12 at a desired temperature. Heat-generating structure 12 is maintained at a desired temperature by feeding back the pressure of the coolant as it exits tube 22. This pressure is indicative of the temperature of the boiling coolant. In response, pressure controller 42 may respond by raising or lowering the pressure of coolant 16, which affects the boiling temperature of the coolant. By feeding back the coolant

pressure, as opposed to the temperature of heat-generating structure 12, associated thermal delay is eliminated from the control loop, permitting direct control of pressure without taking into account the thermal delay.

In one example, the coolant used is pure water. Pure water has a very high latent heat of vaporization thus it absorbs a substantial amount of heat as it vaporizes. However, water boils at a temperature of 100°C at atmospheric pressure of 14.7 psia. In order to provide suitable cooling for an electronic apparatus, coolant 16 needs to boil at a temperature in the range of approximately 50-65°C. When water is subjected to a subambient pressure of about 3 psia, its boiling temperature decreases to approximately 60°C. Thus, in the embodiment of FIGURE 1A, the orifice 32 permits the coolant pressure downstream from it to be less than the coolant pressure between the pump 30 and the orifice 32.

In one example, pure water flowing from the pump 30 to the orifice 32 and 34 has a temperature of approximately 60°C to 65°C, and a pressure in the range of approximately 15 psia to 100 psia. After passing through the orifice 32 and 34, the water will still have a temperature of approximately 60°C to 65°C, but will have a much lower pressure, in the range about 2 psia to 4 psia. Due to this reduced pressure, some or all of the water will boil as it passes through and absorbs heat from the heat-generating structure 12, and some or all of the water will thus vaporize. After exiting through tube 24, the water vapor (and any remaining liquid water) will still have the reduced pressure of about 2 psia to 4 psia.

When this subambient water vapor reaches the heat exchanger 28, heat will be transferred from the vapor to the forced air flow 38. The air flow 38 has a temperature less than a specified maximum of 55°C, and typically has an ambient temperature below 40°C. As heat is removed from the vapor, any portion of the water which is in its vapor phase will condense, such that all of the coolant water will be in liquid form when it exits the heat exchanger 28. This liquid will have a temperature of approximately 60°C to 65°C, and will still be at the subambient pressure of approximately 2 psia to 4 psia. This liquid coolant will then flow to the pump 30 with a tee connection prior to the expansion reservoir 40. The pump 30 will have the effect of increasing the pressure of the coolant water, to a value in the range of approximately 15 psia to 100 psia, as mentioned earlier.

It will be noted that the embodiment of FIGURE 1A may operate without any refrigeration system. In the context of high-power electronic circuitry, the absence of a

refrigeration system can result in a very significant reduction in the size, weight, and power consumption of the structure provided to cool the electronics system.

FIGURE 2 is a schematic diagram illustrating one example of heat-generating structure 12 that is particularly suited to cooling according to the method described in FIGURE 1A. It is emphasized, however, that this is merely one example. Heat-generating structure 52 includes, in this example, a plurality of electronic modules 54 thermally coupled to a mesh 60. Mesh 60 helps transfer heat from electronic modules 54 to coolant 16 and, in some embodiments, may also provide structural support for electronic modules 54. Mesh 60 is porous such that coolant 16 may flow through mesh 16, whether heat-generating structure 52 is submerged in coolant 16 or coolant 16 flows over and through heat-generating structure 52 through mesh 60.

In this example, electronic modules 54 include electronic device 62, having associated electronic components and an interconnect component 64. Interconnect component 64 provides for electrical connection to other devices. Interconnect component 64 may include a plurality of bumps 66, which not only provide for electrical connections but also may act as pin fins, providing increased heat transfer due to the associated increased surface area contact with coolant 16. Heat-generating structure 52 may also be formed with a plurality of interconnect lines 68 electrically connecting electronic modules 54 to each other or to other devices.

In operation, heat-generating structure 52 is either submerged in coolant 16, as illustrated in FIGURE 1B, or coolant 16 may be flowed over heat-generating structure 52. In either case, coolant 16 comes into contact with electronic modules 54 and mesh 60, and in response, receives heat and begins to boil, transferring heat from heat-generating structure 52 to coolant 16. Mesh 60 assists with this heat transfer, in this example, by increasing contact area with coolant 16 and conducting heat away from electronic modules 54 to coolant 16. Yet, because mesh 60 is porous, coolant 16 may flow through the mesh and allow heat-generating structure 52 to be submerged in coolant 16. It is noted that even if submerged, coolant 16 may nevertheless flow over and through heat-generating structure 52 to further increase heat transfer.

FIGURE 3A illustrates a flow through module 100 that may form a part of an alternative embodiment of heat-generating structure 12. Module 100 includes a plurality of components best illustrated in FIGURE 3B through 3D. FIGURE 3B is a side view,

FIGURE 3C is a top view, and FIGURE 3D is a bottom view of a circuit substrate 102 according to the teachings of the invention. FIGURE 3A is taken along the direction of lines 3A-3A of FIGURE 3C, but for an array of circuit substrates 102. Circuit substrate 102 includes a plurality of electronic devices 104 formed on a substrate 106. Coupled to substrate 106 are a plurality of micro pin fins 108, best illustrated in FIGURE 3D. Interconnects 107 are disposed on top of substrate 106 for providing electrical connection to electronic devices 104. In one embodiment, substrate 106 is highly thermally conductive to enhance heat transfer.

Each one of circuit substrates 102 is shown positioned in an array configuration to form module 100, illustrated in FIGURE 3A. Disposed between adjacent circuit substrates 102 are void spaces 110. Void spaces 110 provide a space for coolant 16 to flow or to otherwise come into contact with circuit substrates 102. A plurality of interconnect stringers 112 may separate adjacent circuit and associated substrates 102. Interconnect stringers 112 may provide suitable electrical connections, as well as structured support for circuit substrates 102, as well as thermal coupling to coolant 16 within void regions 110. Further, blank or dummy substrates may be utilized to route signals or power from one interconnect stringer 112 to another, in addition to that routed on the edges of the module 100.

In operation, coolant may flow through, or be maintained within, void regions 110, within the context of system 10, or other suitable cooling system, allowing heat transfer from circuit and associated substrate 102 to the coolant. In the illustrated embodiment, flow is into or out of the page of FIGURE 3A. Micro pin fins 108 further enhance heat transfer by increasing surface area contact with the coolant. Other forms of enhancements such as fins, dimples, or microchannels can be used. Such a system may allow direct contact between the coolant and any heat generating electronics, resulting in efficient boiling heat transfer. In some embodiments, circuit substrate 102 may be encapsulated, or alternatively, electronic components within may be directly exposed to the coolant, allowing for even greater heat transfer.

FIGURE 4A is a schematic diagram of a frame 120 having a frame structure 122 formed with a plurality of frame voids 124. In one embodiment, a single module 100 may be disposed in each frame void 124. Frame structure 122 may be formed with a plurality of interconnects 126, allowing electrical connection of portions of module 100 to other

modules 100 or to other devices. A completed array of module 100 disposed within frame 120 is illustrated in FIGURE 4B as assembly 128.

As described above with module 100, the entire assembly 128 may be submerged in coolant 16, or coolant 16 may otherwise flow through the voids within assembly 128 to provide heat transfer. It is noted that modules 100 and/or assembly 128 may have a significant depth (into the page) in some embodiments, allowing for cooling of more components. Alternatively, modules 100 and/or assembly 128 may be substantially two-dimensional.

A heat-generating structure 12 may comprise a plurality of assemblies 128 that are interconnected through a signal and power bus or a motherboard, which may include fiber optics. In one embodiment, all assemblies 128 are mounted horizontally with a forced flow of coolant 16 upward through a stack of multiple assemblies. In this case, the individual substrates are vertical, which allows the upward flowing of coolant along their lengths. In another embodiment, a water injection manifold associated with each assembly may be used to force water through each flow through module 100 mounted on frame 120.

Although the present invention has been described in detail, it should be understood that various changes, alterations, substitutions, and modifications can be made to the teachings disclosed herein without departing from the spirit and scope of the present invention which is solely defined by the appended claims.

WHAT IS CLAIMED IS:

1. A method for cooling heat-generating structure disposed in an environment having an ambient pressure, the heat-generating structure comprising electronics, the method comprising:

providing a coolant;

reducing a pressure of the coolant to a subambient pressure at which the pure water has a boiling temperature less than a temperature of the heat-generating structure; and

bringing the heat-generating structure and the coolant into contact with each other at a subambient pressure, so that the pure water boils and vaporizes to thereby absorb heat from the heat-generating structure.

2. The method of Claim 1, wherein the coolant is pure water having an electrical resistivity greater than one million Ohms-cm.

3. The method of Claim 1, wherein the coolant is methanol.

4. A method of Claim 1, and further comprising filtering the coolant while at a subambient pressure to maintain a desired purity level.

5. The method of Claim 1, further comprising circulating the coolant through a flow loop while maintaining the pressure of the pure water within a range having an upper bound less than the ambient pressure.

6. The method of Claim 5, and further comprising configuring the loop to include a water purification system.

7. The method of Claim 5, further comprising the configuring the loop to include a heat exchanger for removing heat from the pure water so as to condense the pure water to a liquid.

8. The method of Claim 7, further comprising causing the heat exchanger to transfer heat from the coolant to a further medium having an ambient temperature that is less than the boiling temperature of the coolant at the subambient pressure.

9. The method of Claim 5, further comprising configuring the loop to include a pump for circulating the pure water through the loop.

10. The method of Claim 1, wherein bringing the heat-generating structure and the coolant into contact with each other comprises submerging the heat-generating structure into the coolant comprises submerging the heat-generating structure into a bath of the pure water while the pure water is flowing.

11. The method of Claim 1, comprises flowing the coolant over the heat-generating structure.

12. The method of Claim 11, wherein bringing the heat-generating structure and the coolant into contact with each other comprises submerging the heat-generating structure into the coolant comprises submerging the heat-generating structure into a bath of the pure water while the pure water is flowing.

13. The method of Claim 11, wherein submerging the heat-generating structure into the coolant further comprises submerging the heat-generating structure into a bath of the pure water having an electrical resistivity greater than one million Ohms-cm.

14. The method of Claim 1, and further comprising configuring the heat-generating structure to include a plurality of electronic modules and a porous mesh coupled to each electronic module.

15. The method of Claim 14, wherein each electronic module is electrically connected to at least one other of the plurality of electronic modules.

16. The method of Claim 1, and further comprising configuring the heat-generating structure to include:

a frame having a plurality of frame voids;

a plurality of modules each disposed in respective ones of the frame voids, each module comprising an array of circuit substrates separated by void regions through which coolant may flow, each circuit substrate comprising:

a substrate; and

at least one electrical circuit disposed on the substrate.

17. The method of Claim 16, wherein configuring the heat-generating structure further includes providing a plurality of pin fins extending from the substrate.

18. An apparatus for cooling

a heat-generating structure disposed in an environment having an ambient pressure, the apparatus comprising:

a coolant;

a pressure reduction system operable to reduce a pressure of the coolant to a subambient pressure at which the coolant has a boiling temperature less than a temperature of the heat-generating structure; and

a submerged assembly operable to submerge the heat-generating structure in the coolant such that heat from the heat-generating structure causes the coolant to boil and vaporize, so that the coolant absorbs heat from the heat-generating structure as the coolant changes state.

19. The apparatus of Claim 18, wherein the coolant is selected from the group consisting of pure water and pure methanol having an electrical resistivity greater than one million Ohms-cm.

20. The apparatus of Claim 18, wherein the cooling system further includes a purification system operable to maintain the purity of the coolant at a level so the coolant has an electrical resistivity greater than one million Ohms-cm.

21. The apparatus of Claim 18, and further comprising a water purification system for purifying the coolant.

22. The apparatus of Claim 18, further comprising a heat exchanger for removing heat from the coolant so as to condense the coolant to a liquid.

23. The apparatus of Claim 21, and further comprising a pump for circulating the coolant.

24. The apparatus of Claim 18, and further comprising the heat-generating structure, the heat-generating structure comprising a plurality of electronic modules and a porous mesh coupled to each electronic module.

25. The apparatus of Claim 24, wherein each electronic module is electrically connected to at least one other of the plurality of electronic modules.

26. The apparatus of Claim 18, wherein the heat-generating structure comprises:

a frame having a plurality of frame voids;

a plurality of modules each disposed in respective ones of the frame voids, each module comprising an array of circuit substrates separated by void regions through which coolant may flow, each circuit substrate comprising:

a substrate; and

at least one electrical circuit disposed on the substrate.

27. The apparatus of Claim 26, and further comprising a plurality of pin fins extending from each substrate.

28. An apparatus comprising:

a porous mesh; and

a plurality of electronic modules connected to the porous mesh.

29. The apparatus of Claim 28, and further comprising at least one interconnect electronically coupling one of the plurality of electronic modules to at least one other of the plurality of electronic modules.

30. The apparatus of claim 29, wherein at least one of the electronic modules comprises a plurality of thermally conductive bumps electrically connected to the at least one interconnect.

31. The apparatus of Claim 28, and further comprising pure water having an electrical resistivity greater than one million Ohms-cm, the porous mesh and the plurality of electronic modules submerged in the pure water.

32. The apparatus of Claim 31, wherein the pure water comprises pure water flowing relative to the porous mesh and the plurality of porous modules.

33. The apparatus of Claim 24, and further comprising:

a coolant;

a pressure reduction system operable to reduce a pressure of the coolant to a pressure at which the coolant has a boiling temperature less than a temperature of the heat-generating structure; and

a submerged assembly in which the porous mesh and the plurality of electronic modules connected to the mesh are submerged within the coolant.

34. An apparatus comprising:

a frame having a plurality of frame voids;

a plurality of modules each disposed in respective ones of the frame voids, each module comprising an array of circuit substrates separated by void regions through which coolant may flow, each circuit substrate comprising:

a substrate; and

at least one electrical circuit disposed on the substrate.

35. The apparatus of Claim 34, and further comprising pure water, the frame and plurality of modules submerged within the pure water.

36. The apparatus of Claim 34, and further comprising methanol, the frame and plurality of modules submerged within the methanol.

37. The apparatus of Claim 34, and further comprising a coolant, the frame and plurality of modules submerged within the coolant.

38. The apparatus of Claim 37, wherein the coolant is at a pressure less than 14.7 psia.

FIG. 1A

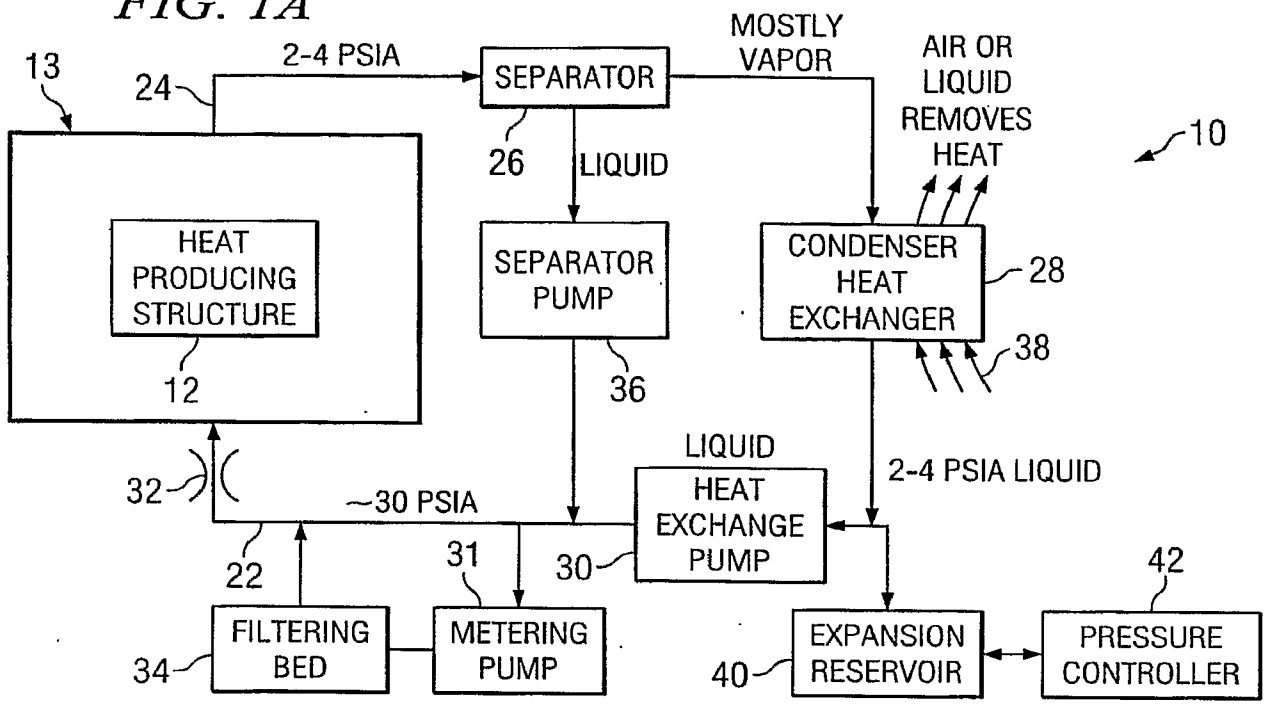


FIG. 1B

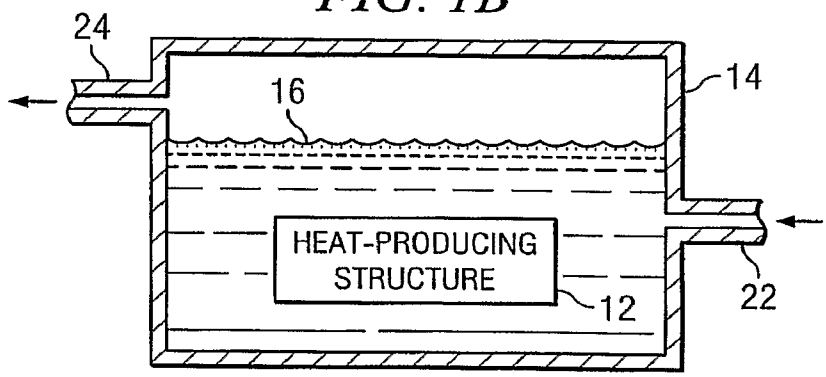


FIG. 2

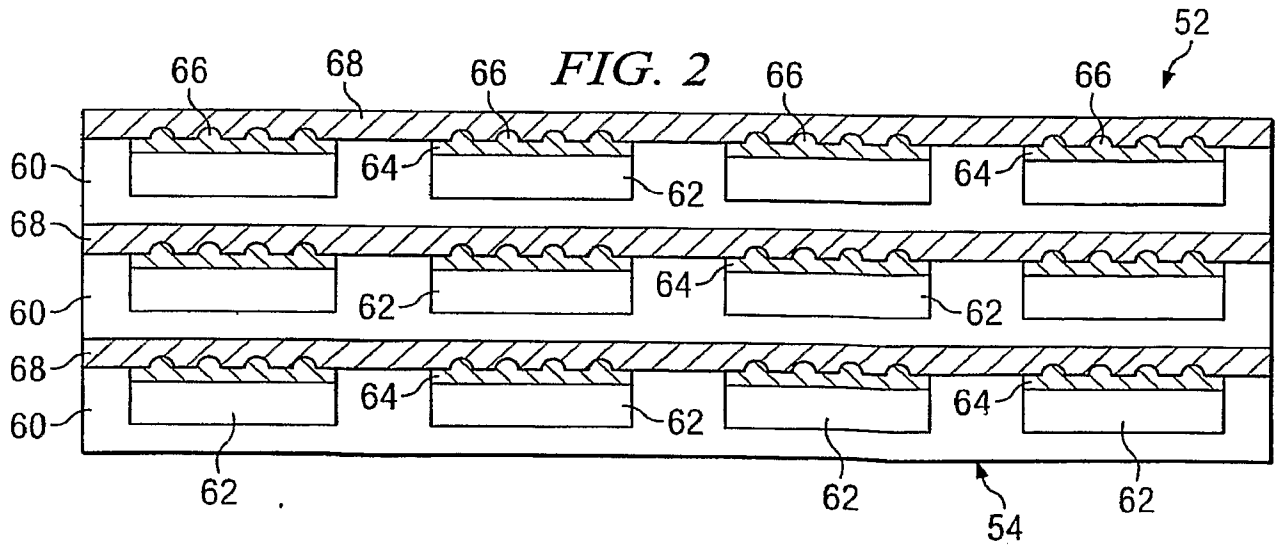


FIG. 3A

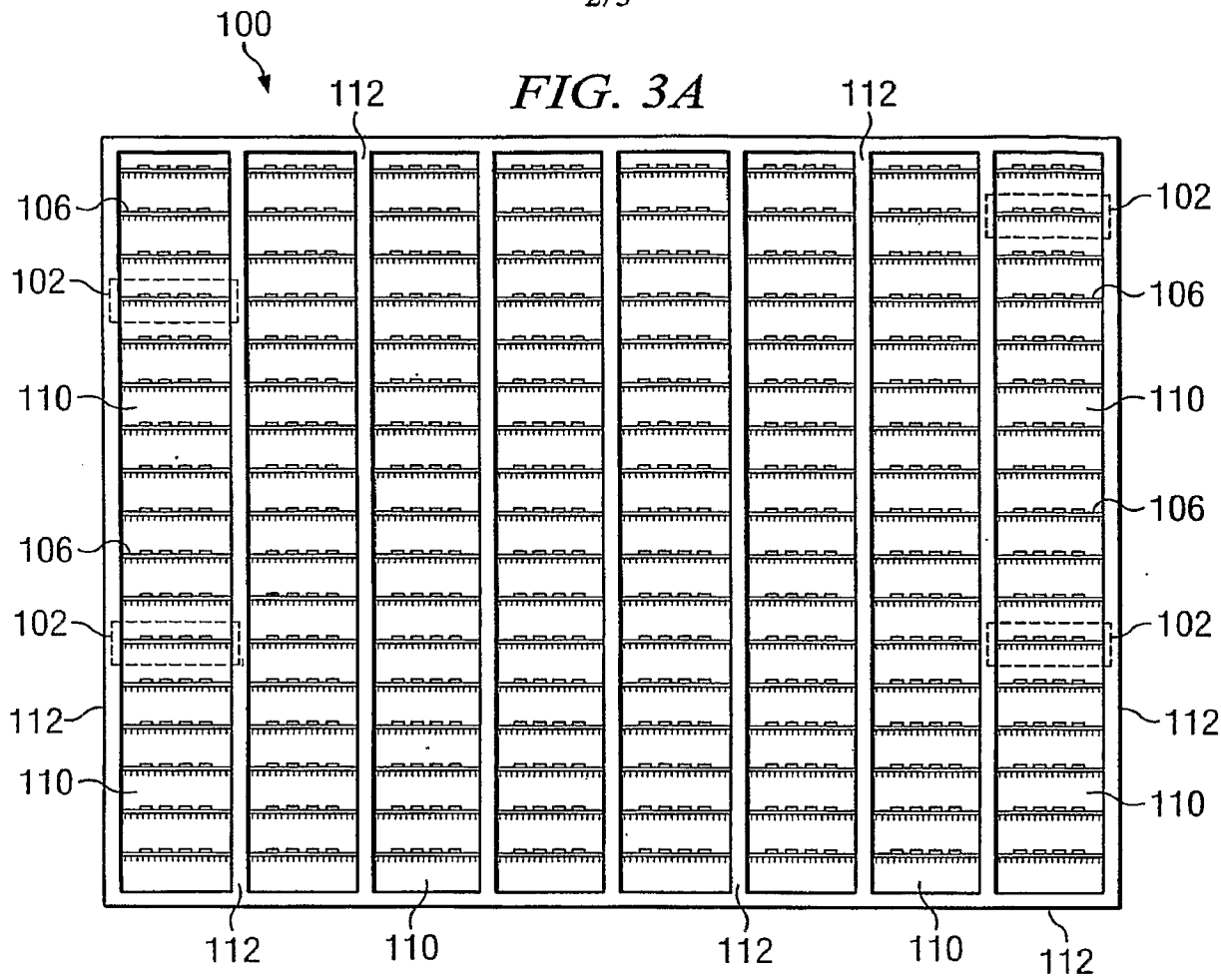


FIG. 3B

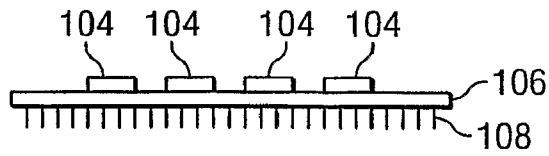


FIG. 3C

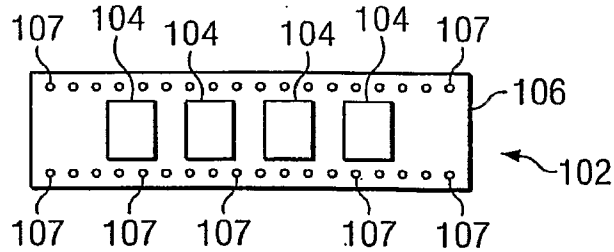
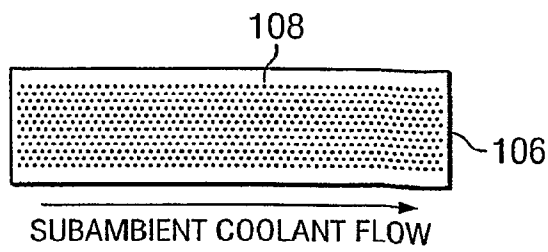


FIG. 3D



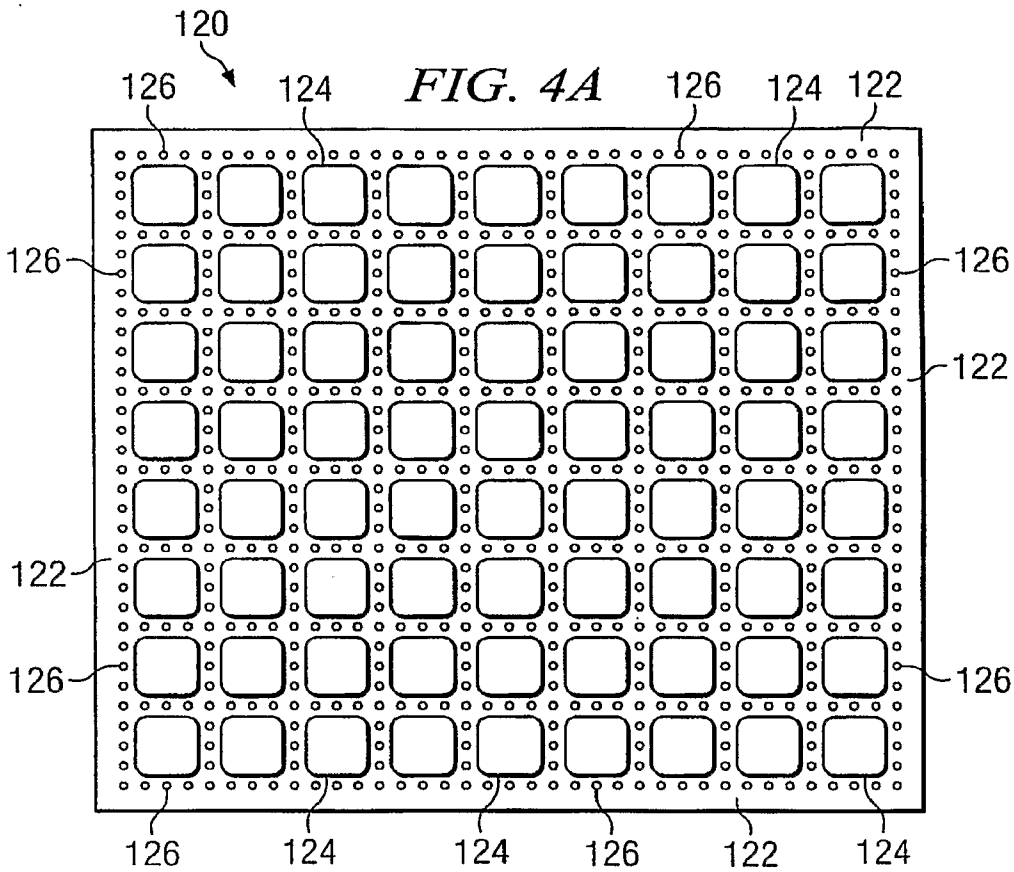

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FIG. 4A

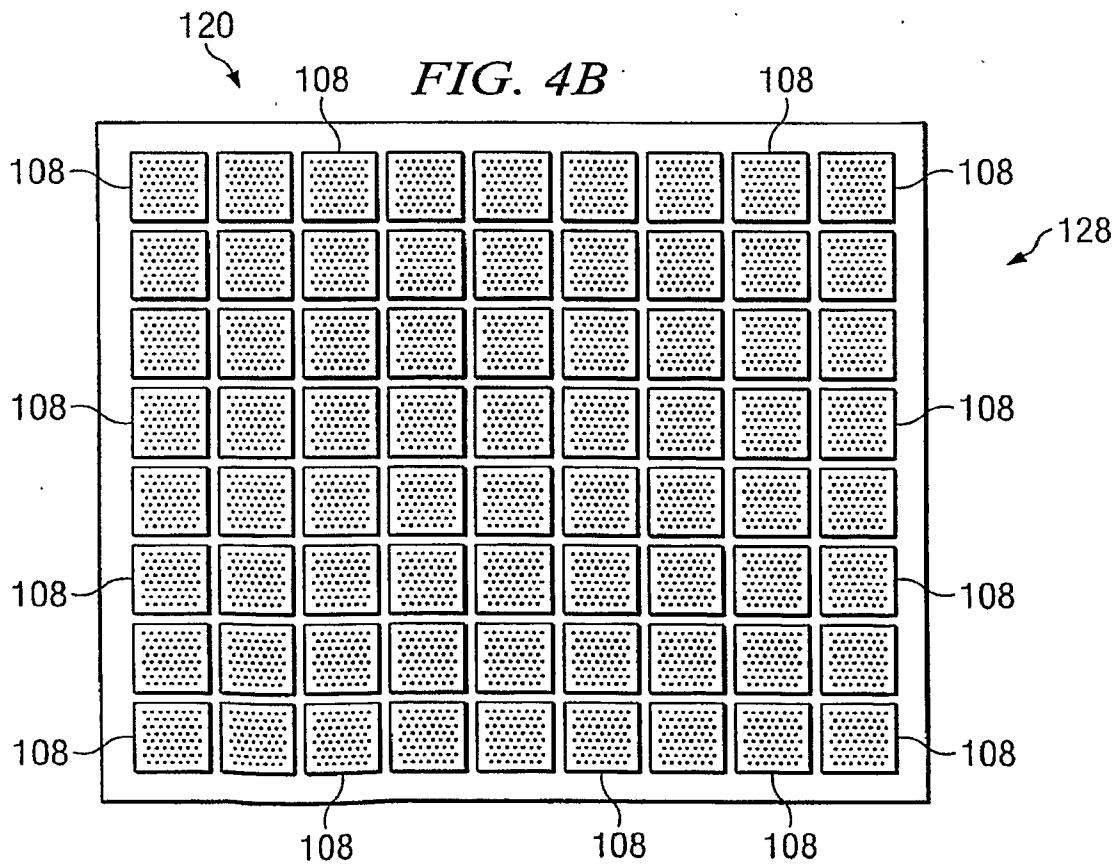

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FIG. 4B