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(54) METHOD AND APPARATUS FOR COOLING WITH COOLANT AT A SUBAMBIENT PRESSURE

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See application file for complete search history.

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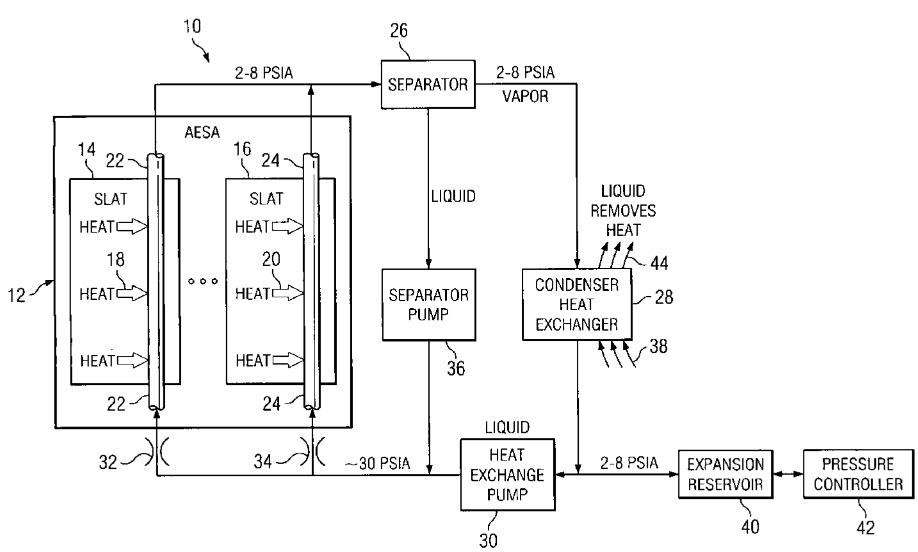
(57) **ABSTRACT**

According to one embodiment, an apparatus includes a fluid coolant and structure which reduces a pressure of the fluid coolant through a subambient pressure at which the coolant has a cooling temperature less than a temperature of the heat-generating structure. The apparatus also includes structure that directs a flow of the fluid coolant in the form of a liquid at a subambient pressure in a manner causing the liquid coolant to be brought into thermal communication with the heat-generating structure. The heat from the heat-generating structure causes the liquid coolant to boil and vaporize so that the coolant absorbs heat from the heat-generating structure as the coolant changes state. The structure is configured to circulate the fluid coolant through a flow loop while maintaining the pressure of the fluid coolant within a range having an upper bound less than ambient pressure. The apparatus also includes a first heat exchanger for exchanging heat between the fluid coolant flowing through the loop and a second coolant in an intermediary loop so as to condense the fluid coolant flowing through the loop to a liquid. The apparatus also includes a second heat exchanger for exchanging heat between the second coolant in the intermediary cooling loop and a body of water on which the ship is disposed.

19 Claims, 2 Drawing Sheets



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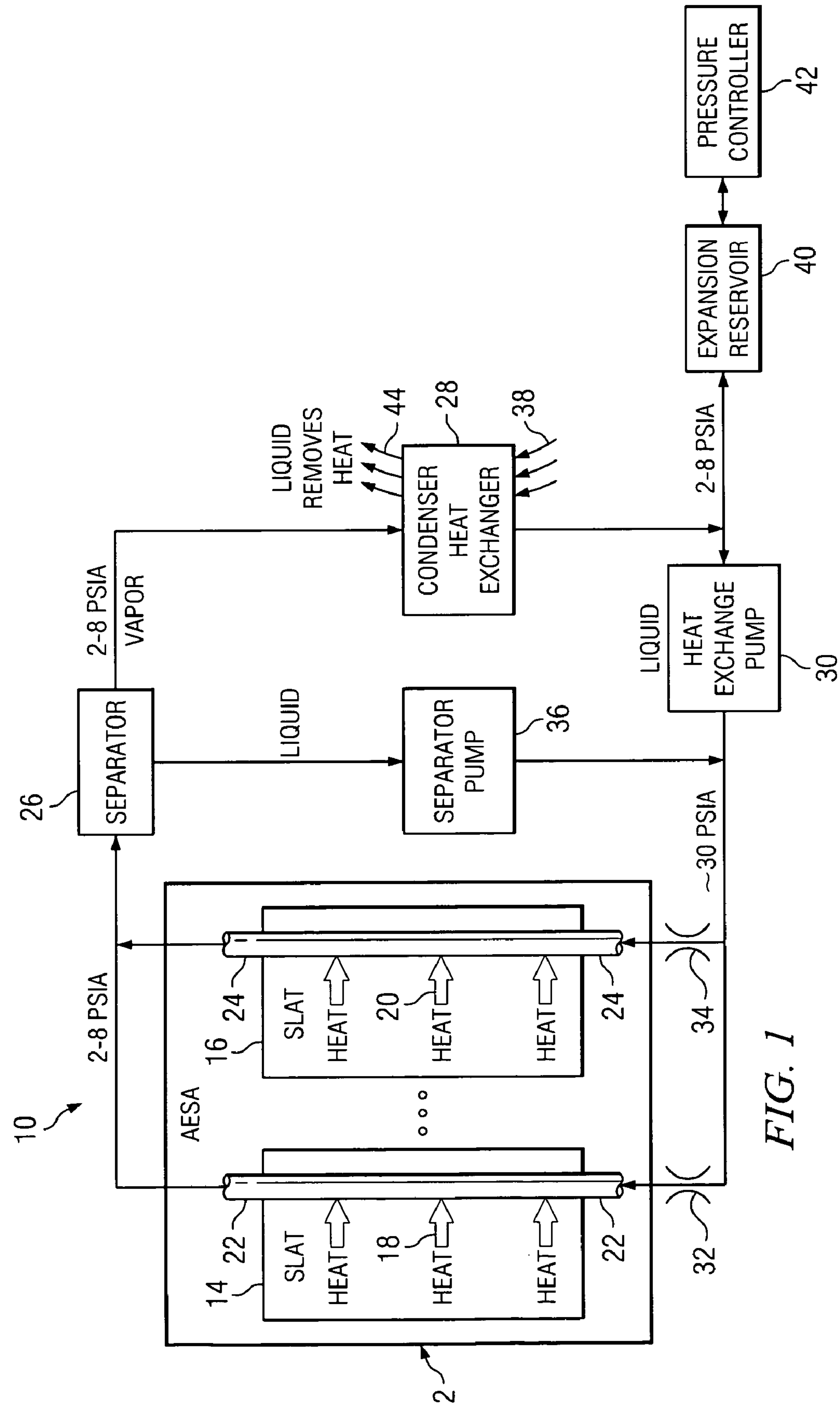
PRESSURE CONTROLLER
42
EXPANSION RESERVOIR
40
2-8 PSIA
LIQUID REMOVES HEAT
44
28
38
CONDENSER HEAT EXCHANGER
2-8 PSIA
VAPOR
LIQUID
HEAT EXCHANGE PUMP
30
SEPARATOR
26
LIQUID
SEPARATOR PUMP
36
~30 PSIA
2-8 PSIA
10
AESA
SLAT
HEAT
HEAT
HEAT
24
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16
24
34
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HEAT
HEAT
HEAT
22
18
14
22
32
12

FIG. 1

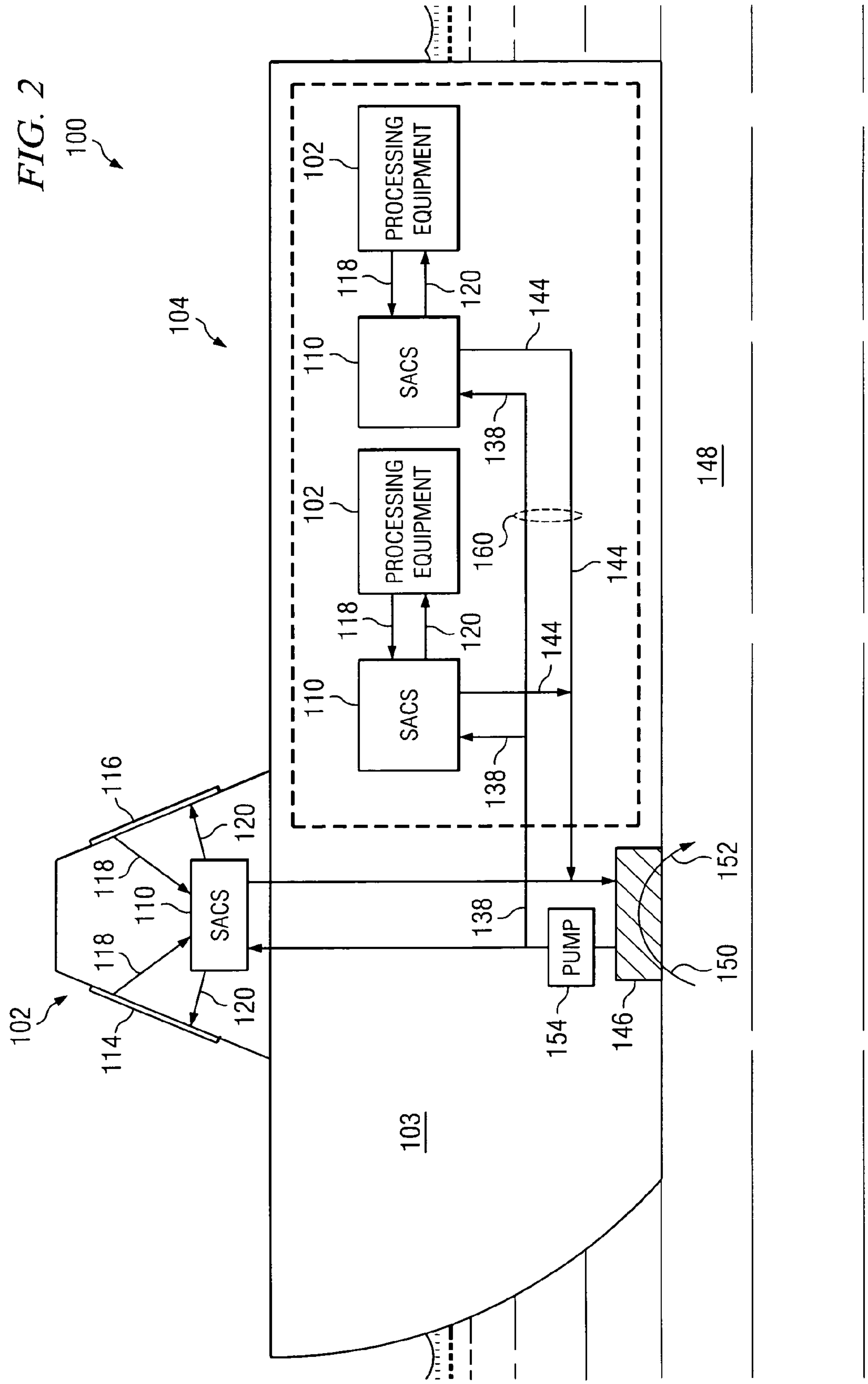
100
104
102
PROCESSING EQUIPMENT
118
120
110
SACS
144
138
160
148
116
114
146
150
152
154
PUMP
103

FIG. 2

METHOD AND APPARATUS FOR COOLING WITH 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 a system that generates a substantial amount of heat through use of 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 that consume large amounts of power, and produce large amounts of heat. One example is the circuitry used in a phased array antenna system.

More specifically, a modern phased array antenna system can easily produce 25 to 30 kilowatts of heat, or even more. One known approach for cooling this circuitry is to incorporate a refrigeration unit into the antenna system. However, suitable refrigeration units are large, heavy, and consume many kilowatts of power in order to provide adequate cooling. For example, a typical refrigeration unit may weigh about 200 pounds, and may consume about 25 to 30 kilowatts of power in order to provide about 25 to 30 kilowatts of cooling. Although refrigeration units of this type have been generally adequate for their intended purposes, they have not been satisfactory in all respects.

In this regard, the size, weight and power consumption characteristics of these known refrigeration systems are all significantly larger than desirable for an apparatus such as a phased array antenna system. And given that there is an industry trend toward even greater power consumption and heat dissipation in phased array antenna systems, continued use of refrigeration-based cooling systems would involve refrigeration systems with even greater size, weight and power consumption, which is undesirable. In such systems, it is often important that stable cooling is achieved during both startup and when the cooled device is subjected to wide swings in required cooling capacities.

SUMMARY OF THE INVENTION

According to one embodiment an apparatus includes a fluid coolant and structure which reduces a pressure of the fluid coolant through a subambient pressure at which the coolant has a cooling temperature less than a temperature of the heat-generating structure. The apparatus also includes structure that directs a flow of the fluid coolant in the form of a liquid at a subambient pressure in a manner causing the liquid coolant to be brought into thermal communication with the heat-generating structure. The heat from the heat-generating structure causes the liquid coolant to boil and vaporize so that the coolant absorbs heat from the heat-generating structure as the coolant changes state. The structure is configured to circulate the fluid coolant through a flow loop while maintaining the pressure of the fluid coolant within a range having an upper bound less than ambient pressure. The apparatus also includes a first heat exchanger for exchanging heat between the fluid coolant flowing through the loop and a second coolant in an intermediary loop so as to condense the fluid coolant flowing through the loop to a liquid. The apparatus also includes a second heat exchanger for exchanging heat between the second coolant in the intermediary cooling loop and a body of water on which the ship is disposed.

According to another embodiment, a method for cooling includes providing a primary fluid coolant in reducing a pressure of the primary fluid coolant to a subambient pressure at which the primary coolant has a cooling temperature less than a temperature of the heat of the heat-generating structure. The method also includes bringing the primary coolant at the subambient pressure into thermal communication with the heat-generating structure so that the primary coolant boils and vaporizes to thereby absorb heat from the heat-generating structure. The method also includes circulating the primary coolant through a flow loop while maintaining the pressure of the primary coolant within a range having an upper bound less than the ambient pressure. The flow loop is in thermal communication with a heat exchanger for removing heat from the primary coolant so as to condense the primary coolant to a liquid. The method also includes providing an intermediary cooling loop in thermal communication with the heat exchanger and exchanging, by the heat exchanger, heat from the primary coolant with an intermediary loop coolant in the intermediary cooling loop. The method also includes exchanging heat from the intermediary cooling loop coolant with a sink fluid.

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, the temperature of a plurality of heat-generating devices on a ship, such as phase array antennas, may be maintained at a desired temperature through a subambient cooling system that sinks the generated heat to the body of water through an intermediary cooling loop. Such an approach can in some embodiments result in substantial heat dissipation without use of compressors. The avoidance of the use of compressors frees up valuable space on the ship. Further, in some embodiments, large vapor lines can be avoided.

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:

FIG. **1** is a block diagram of an apparatus that includes a phased array antenna system and an associated cooling arrangement that embodies aspects of the present invention; and

FIG. **2** is a block diagram of the apparatus of FIG. **1** showing additional details related to the control of the system of FIG. **1**.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS OF THE INVENTION

Example embodiments of the present invention and their advantages are best understood by referring to FIGS. **1**-**2** of the drawings, like numerals being used for like and corresponding parts of the various drawings.

FIG. **1** is a block diagram of an apparatus **10** that includes a phased array antenna system **12**. In one embodiment, the antenna system **12** includes a plurality of identical modular parts that are commonly known as slats, two of which are depicted at **14** and **16**. A feature of the present invention involves techniques for controlling cooling the antenna system **12**, or other heat-generating structure, so as to remove appropriate amounts of heat generated therein.

In the illustrated embodiment, the electronic circuitry within the antenna system **12** has a known configuration, and is therefore not illustrated and described here in detail. Instead, the circuitry is described only briefly here, to an extent that facilitates an understanding of the present invention. In particular, the antenna system **12** includes a two-dimensional array of not-illustrated antenna elements, each column of the antenna elements being provided on a respective one of the slats, including the slats **14** and **16**. Each slat includes separate and not-illustrated transmit/receive circuitry for each antenna element. It is the transmit/receive circuitry which generates most of the heat that needs to be withdrawn from the slats. The heat generated by the transmit/receive circuitry is shown diagrammatically in FIG. **1**, for example by the arrows at **18** and **20**.

Each of the slats is configured so that the heat it generates is transferred to a tube **22** or **24** extending through that slat. Alternatively, the tube **22** or **24** could be a channel or passageway extending through the slat, instead of a physically separate tube. A fluid coolant flows through each of the tubes **22** and **24**. As discussed later, this fluid coolant is a two-phase coolant, which enters the slat in liquid form. Absorption of heat from the slat causes part or all of the liquid coolant to boil and vaporize, such that some or all of the coolant leaving the slats **14** and **16** is in its vapor phase. This departing coolant then flows successively through a separator **26**, a heat exchanger **28**, a pump **30**, and a respective one of two orifices **32** and **34**, in order to again reach the inlet ends of the tubes **22** and **24**. The pump **30** causes the coolant to circulate around the endless loop shown in FIG. **1**. In the embodiment of FIG. **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 flowing through tubes **22** and **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 tubes **22** and **24** circulates this fluid back through tubes **22** and **24** via orifices **32** and **34**.

The orifices **32** and **34** facilitate proper partitioning of the coolant among the respective slats, and also help to create a large pressure drop between the output of the pump **30** and the tubes **22** and **24** in which the coolant vaporizes. It is possible for the orifices **32** and **34** to have the same size, or to have different sizes in order to partition the coolant in a proportional manner which facilitates a desired cooling profile.

Ambient air or liquid **38** is caused to flow through the 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. 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.

The liquid coolant exiting the heat exchanger **28** is supplied to the expansion reservoir **40**. Since fluids typically take up more volume in their vapor phase than in their liquid phase, the 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 the coolant that is in its vapor phase can vary over time, due in part to the fact that the amount of heat being produced by the antenna system **12** will vary over time, as the antenna system operates in various operational modes.

Pressure controller **42** maintains the coolant at a desired subambient pressure in portions of the cooling loop downstream of the orifices **32** and **34** and upstream of the pump **30**, as described in greater detail in conjunction with FIGS. **2** and **3**. Typically, the ambient air pressure will be that of atmospheric air, which at sea level is 14.7 pounds per square inch area (psia).

When antenna system **12** (or any other heat-generating device) undergoes transient heat loads, this subambient pressure may need to be adjusted to allow greater or lesser amounts of heat transfer from slats **14** and **16** at a desired temperature. According to the teachings of the invention, slats **14** and **16** are maintained at a desired temperature by feeding back the pressure of the coolant as it exits passageways **22** and **24**. This pressure is indicative of the temperature at slats **14** and **16**. In response, pressure controller **42** may respond by raising or lowering the pressure of the coolant, which affects the boiling temperature of the coolant and therefore the rate of heat transfer. By feeding back the coolant pressure, as opposed to the temperature of the slats, associated thermal delay is eliminated from the control loop, permitting direct control of pressure without taking into account the thermal delay.

Turning now in more detail to the coolant, one highly efficient technique for removing heat from a surface is to boil and vaporize a liquid which is in contact with the surface. As the liquid vaporizes, it inherently absorbs heat. The amount of heat that can be absorbed per unit volume of a liquid is commonly known as the latent heat of vaporization of the liquid. The higher the latent heat of vaporization, the larger the amount of heat that can be absorbed per unit volume of liquid being vaporized.

The coolant used in the disclosed embodiment of FIG. **1** is water. Water absorbs a substantial amount of heat as it vaporizes, and thus has a very high latent heat of vaporization. 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 such as the phased array antenna system **12**, the coolant needs to boil at a temperature in the range of approximately 60° 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 FIG. **1**, the orifices **32** and **34** permit the coolant pressure downstream from them to be substantially less than the coolant pressure between the pump **30** and the orifices **32** and **34**.

Water flowing from the pump **30** to the orifices **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 orifices **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 8 psia. Due to this reduced pressure, some or all of the water will boil as it passes through and absorbs heat from the tubes **22** and **24**, and some or all of the water will thus vaporize. After exiting the slats, the water vapor (and any remaining liquid water) will still have the reduced pressure of about 2 psia to 8 psia.

When this subambient coolant water reaches the heat exchanger **28**, heat will be transferred from the water 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 water coolant, 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 8 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 FIG. **1** operates without any refrigeration system. In the context of high-power electronic circuitry, such as that utilized in the phased array antenna system **12**, 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 antenna system.

As mentioned above, the coolant used in the embodiment of FIG. **1** is water. However, it would alternatively be possible to use other coolants, including but not limited to methanol, a fluorinert, a mixture of water and methanol, a mixture of water and ethylene glycol (WEGL), or a mixture of water and propylene. These alternative coolants each have a latent heat of vaporization less than that of water, which means that a larger volume of coolant must be flowing in order to obtain the same cooling effect that can be obtained with water. As one example, a fluorinert has a latent heat of vaporization which is typically about 5% of the latent heat of vaporization of water. Thus, in order for a fluorinert to achieve the same cooling effect as a given volume or flow rate of water, the volume or flow rate of the fluorinert would have to be approximately 20 times the given volume or flow rate of water.

Despite the fact that these alternative coolants have a lower latent heat of vaporization than water, there are some applications where use of one of these other coolants can be advantageous, depending on various factors, including the amount of heat which needs to be dissipated. As one example, in an application where a pure water coolant may be subjected to low temperatures that might cause it to freeze when not in use, a mixture of water and ethylene glycol or water and propylene glycol could be a more suitable coolant than pure water, even though the mixture has a latent heat of vaporization lower than that of pure water.

The cooling system of FIG. **1**, also referred to herein as a Subambient Cooling System, or "SACS," may be used in a plurality of contexts. The teachings of the invention recognize that one or a plurality of SACS may be used to provide desired cooling. One such application and associated method and architecture is described below in conjunction with FIG. **2**.

FIG. **2** is a schematic diagram illustrating a ship **100** floating on seawater **148** that includes a plurality of process equipment units **102**, also referred to herein as heat-generating structures. One example of process equipment unit **102** is a phased array antenna system such as described above in conjunction with FIG. **1**. Process equipment units **102** may generate substantial amounts of heat that require cooling. Ship **100** also includes a cooling system **104** for cooling the plurality of heat-generating structures **102**.

Cooling system **104** includes a plurality of subambient cooling systems **110**, an intermediary cooling loop **160**, and a heat exchanger **146**. The plurality of subambient cooling systems **110** are disposed on ship **100** in relation to respective heat-generating structures **102**.

Each subambient cooling system **110** may be as described in conjunction with FIG. **1** and operate generally to cool using a coolant at subambient temperatures. As illustrated, any given heat-generating structure **102** may exchange heat with respective subambient cooling system **110**, as indicated by lines **118** and **120**. In one embodiment, cooling tubes are positioned within heat-generating structures **114** and **116** of phased arrays **102** in an analogous manner to that described above in conjunction with FIG. **1**.

According to the teachings of the invention, it is recognized that a single large subambient cooling system **110** that could be centrally located within ship **100** may be used, but in some implementations the size of associated vapor return lines may be too large that they are not practical for certain applications. The teachings of the invention further recognize that the use of smaller higher pressure liquid lines within an intermediary loop between the heat exchanger of the subambient cooling systems **110**, such as condenser heat exchanger **28** (FIG. **1**), and the ambient seawater may be used to transport heat from the subambient cooling systems **110** to a heat exchanger associated with a sink, such as the seawater, such as heat exchanger **146**. The teachings of the invention further recognize that one or more heat exchangers **146** may be used in conjunction with that intermediary loop.

As illustrated, intermediary loop **160** includes a hot side line **144** and a cold side line **138**. Hot side line **144** contains heat received from the associated condenser heat exchanger (such as heat exchanger **28**) of each subambient cooling system and provides it to heat exchanger **146**. The cold side line **138** of intermediary loop **160** provides a cooling fluid to each subambient cooling system to allow condensation of the vapor created during cooling of phased arrays of the heat-generating structure, as described above. In that connection, a pump **154** may be provided to pump the cooling fluid through intermediary loop **160**. Although any suitable cooling fluid may be used, water is one particularly suitable cooling fluid, as are the coolants described above in connection with FIG. **1**. In some embodiments it may be desirable to use the same coolant in the SACS loop and the intermediary loop **160** to simplify the logistics associated with maintaining the two loops.

When not in use, the SACS **110** loop may be drained to an elastic bladder used as a storage tank. The use of an elastic storage tank alleviates concerns over freezing of the coolant and resultant breakage of the associated lines in the SACS or an inelastic storage tank. An elastic tank may also be used for the coolant used in intermediary loop **160**. Upon startup, the coolant stored in such a bladder may be heated and melted for use in the appropriate loop.

Heat exchanger **146** exchanges heat between intermediary loop **160** and the seawater **148**. In particular, a cool side inlet **150** provides seawater at ambient temperature, which may be approximately 35° C., and hot side outlet **152** provides heated seawater back to the sea. In this manner, each of the subambient cooling systems **110** may exchange heat generated by process equipment **102** with the eventual heat sink of the sea or ocean. It will be recognized that instead of one heat exchanger **146**, a plurality of heat exchangers may also be used. In such a case, intermediary loop **160** may comprise a single loop with multiple outlets to each heat exchanger **146**, or may be replaced with a plurality of intermediary loops connecting respective subambient cooling systems

110 with respective heat exchangers **146**. The size of lines **138** and **144** may be selected based on the particular heat transfer needs of heat generating structures **102**, subambient cooling systems **110**, and the temperature of seawater **148**.

Although the present invention has been disclosed in the context of a plurality of phased array antenna systems on a ship, it will be recognized that it can be utilized in a variety of other contexts, including but not limited to a power converter assembly, or certain types of directed energy weapon (DEW) systems. Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions, and alterations can be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

What is claimed is:

1. A system for cooling a plurality of heat-generating structures on a ship, the plurality of heat-generating structures each disposed in respective environments having a respective ambient pressure, the system comprising:

for each heat generating structure:

a respective fluid coolant;

structure which reduces a pressure of said respective coolant to a subambient pressure at which said respective coolant has a boiling temperature less than a temperature of said heat-generating structure;

structure which directs a flow of said respective coolant in the form of a liquid at said subambient pressure in a manner causing said liquid coolant to be brought into thermal communication with said heat-generating structure, the heat from said heat-generating structure causing said liquid coolant to boil and vaporize so that said respective coolant absorbs heat from said heat-generating structure as said respective coolant changes state, wherein said heat-generating structure includes a plurality of sections which each generate heat, and wherein said structure for directing the flow of said coolant brings respective portions of said coolant into thermal communication with respective said sections of said heat-generating structure;

a heat exchanger for removing heat from said respective coolant flowing through said loop so as to condense said coolant to a liquid; and

at least one intermediary cooling loop operable to thermally couple the respective coolants with a body of water on which the ship floats, the at least one intermediary cooling loop comprising at least one intermediary cooling loop heat exchanger operable to exchange heat between the body of water and an intermediary cooling fluid in the intermediary cooling loop.

2. A system according to claim **1**, wherein the at least one intermediary cooling loop comprises a single intermediary cooling loop thermally coupling each respective coolant to the body of water.

3. A system according to claim **1**, wherein said respective coolant is one of water, methanol, a fluorinert, and a mixture of water and ethylene glycol.

4. A system according to claim **1**, wherein the intermediary cooling fluid is selected from the group consisting of water, methanol, a fluorinert, a mixture of water and ethylene glycol, and a mixture of water and propylene glycol.

5. An apparatus, comprising heat-generating structure disposed in an environment having an ambient pressure, and a cooling system for removing heat from said heat-generating structure, said heat-generating structure disposed on a ship, said cooling system including:

a first fluid coolant;

structure which reduces a pressure of said first coolant to a subambient pressure at which said coolant has a boiling temperature less than a temperature of said heat-generating structure;

structure which directs a flow of said first coolant in the form of a liquid at said subambient pressure in a manner causing said liquid coolant to be brought into thermal communication with said heat-generating structure, the heat from said heat-generating structure causing said liquid coolant to boil and vaporize so that said first coolant absorbs heat from said heat-generating structure as said coolant changes state, wherein said structure is configured to circulate said first coolant through a flow loop while maintaining the pressure of said first coolant within a range having an upper bound less than said ambient pressure;

a first heat exchanger for exchanging heat between said first coolant flowing through said loop and a second coolant in an intermediary loop so as to condense said first coolant flowing through said loop to a liquid; and

a second heat exchanger for exchanging heat between said second coolant in the intermediary cooling loop and a body of water on which the ship is disposed.

6. An apparatus according to claim **5**,

wherein said heat-generating structure includes a passageway having a surface which extends along a length of said passageway; and

wherein heat generated by said heat generating structure is supplied to said surface of said passageway along the length of said surface, said portion of said coolant flowing through said passageway and engaging said surface so as to absorb heat from said surface.

7. An apparatus according to claim **5**, wherein said coolant is one of water, methanol, a fluorinert, and a mixture of water and ethylene glycol.

8. An apparatus according to claim **5**, wherein said structure for directing the flow of said fluid includes a plurality of orifices and causes each said portion of said coolant to pass through a respective said orifice before being brought into thermal communication with a respective said section of said heat-generating structure.

9. An apparatus according to claim **5**, and further comprising a pump for circulating the second coolant.

10. A method for cooling heat-generating structure on a ship on a body of water, the heat-generating structure disposed in an environment having an ambient pressure, the method comprising:

providing a primary fluid coolant;

reducing a pressure of said primary fluid coolant to a subambient pressure at which said primary coolant has a boiling temperature less than a temperature of said heat-generating structure;

bringing said primary coolant at said subambient pressure into thermal communication with said heat-generating structure, so that said primary coolant boils and vaporizes to thereby absorb heat from said heat-generating structure;

circulating said primary coolant through a flow loop while maintaining the pressure of said primary coolant within a range having an upper bound less than said ambient pressure, said flow loop in thermal communication with a heat exchanger for removing heat from said primary coolant so as to condense said primary coolant to a liquid;

providing an intermediary cooling loop in thermal communication with said heat exchanger;

exchanging, by the heat exchanger, heat from said primary coolant with an intermediary loop coolant in said intermediary cooling loop; and

exchanging heat from said intermediary cooling loop coolant with a sink fluid.

11. A method according to claim **10**, wherein the sink fluid is a portion of the body of water on which the ship is disposed.

12. A method according to claim **10**, and further comprising selecting for use as said primary coolant one of water, methanol, a fluorinert, a mixture of water and ethylene glycol, and a mixture of water and propylene glycol.

13. A method according to claim **10**, and further comprising:

providing a plurality of orifices; and

causing each said portion of said primary coolant to pass through a respective said orifice before being brought into thermal communication with a respective said section of said heat-generating structure.

14. A method according to claim **10**, and further comprising configuring said intermediary cooling loop to include a pump for circulating said intermediary loop coolant through said intermediary cooling loop.

15. A method for cooling a plurality of heat-generating structures on a ship on a body of water, the plurality of heat-generating structures each disposed in respective environments having a respective ambient pressure, the method comprising:

for each heat-generating structure;

providing a respective fluid coolant;

reducing a pressure of said respective fluid coolant to a subambient pressure at which said respective coolant has a boiling temperature less than a temperature of said heat-generating structure;

bringing said respective coolant at said subambient pressure into thermal communication with said heat-generating structure so that said coolant boils and vaporizes to thereby absorb heat from said heat-generating structure; and

circulating said respective coolant through a respective flow loop while maintaining the pressure of said respective coolant within a range having an upper bound less than said respective ambient pressure, said respective flow loop in thermal communication with a respective heat exchanger for removing heat from said respective coolant so as to condense said respective coolant to a liquid;

providing at least one intermediary cooling loop;

exchanging, by each respective heat exchanger, heat from each respective coolant with said at least one intermediary cooling loop so as to condense at least a portion of said respective coolant to a liquid; and

exchanging heat from said at least one intermediary cooling loop with the body of water.

16. A method according to claim **15**, wherein the at least one intermediary cooling loop comprises a single intermediary cooling loop thermally coupling each respective coolant to the body of water.

17. The method of claim **16**, and further comprising configuring said single intermediary cooling loop to include an intermediary cooling loop fluid coolant selected from the group consisting of water, methanol, a fluorinert, a mixture of water and ethylene glycol, and a mixture of water and propylene glycol.

18. The method of claim **15**, and further comprising for each heat-generating structure,

providing a plurality of orifices; and

causing each said portion of said coolant to pass through a respective said orifice before being brought into thermal communication with a respective said section of said heat-generating structure.

19. The method of claim **15**, and further comprising configuring said at least one intermediary cooling loop to include a pump for circulating said coolant through said intermediary cooling loop.

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