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(54) Method and apparatus for controlling cooling with coolant at a subambient pressure

(57) According to one embodiment of the invention a method for controlling cooling of a heat-generating structure disposed in an environment having an ambient pressure includes providing a fluid coolant and reducing the 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. The method further includes boiling and vaporizing coolant to absorb heat from the heat-generating structure by bringing the coolant into thermal communication with the heat generating structure. The method also includes measuring a parameter indicative of a pressure of the coolant and adjusting the pressure of the coolant in response to control the cooling of the heat-generating structure.

To be accompanied, when published, by Figure 1 of the drawings.

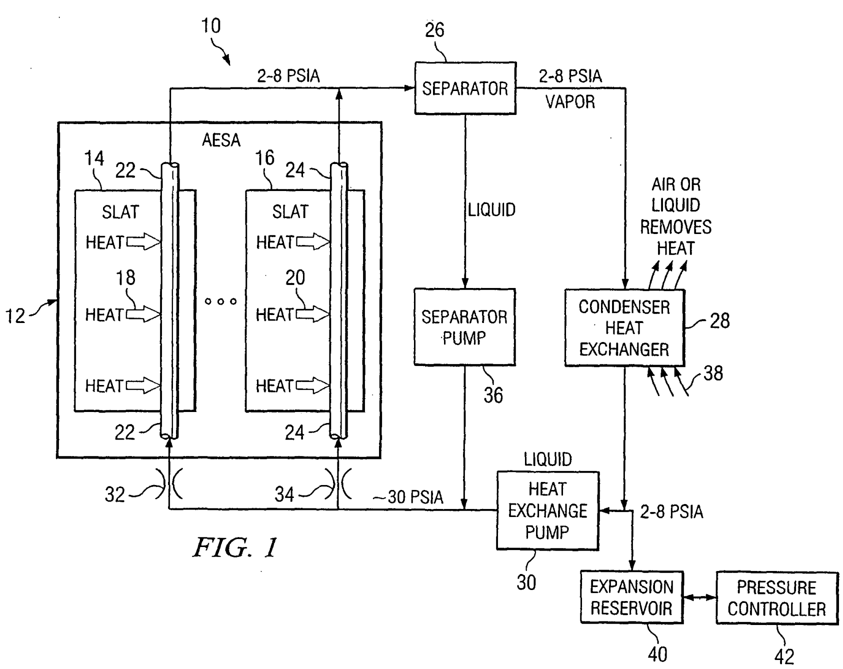

FIG. 1

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Description

TECHNICAL FIELD OF THE INVENTION

[0001] This invention relates in general to cooling techniques and, more particularly, to a method and apparatus for controlling cooling of a system that generates a substantial amount of heat through use of coolant at a subambient pressure.

BACKGROUND OF THE INVENTION

[0002] 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.
[0003] 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

[0004] According to one embodiment of the invention a method for controlling cooling of a heat-generating structure disposed in an environment having an ambient pressure includes providing a fluid coolant and reducing the 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. The method further includes boiling and vaporizing coolant to absorb heat from the heat-generating structure by bringing the coolant into thermal communication with the heat generating structure. The method also includes measuring a parameter indicative of a pressure of the coolant and adjusting the pressure of the coolant in response to control the cooling of the heat-generating structure.
[0005] 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 heat-generating device, such as a phase array antenna, may be maintained at a desired temperature through a control system that feeds back an indication of pressure of a coolant. Such an approach avoids complex control schemes that must take into account thermal delay associated with feeding back the temperature of the heat-generating device. Such an approach may avoid instability problems and provides a stable thermal environment during startup and when heat load environments change.
[0006] Other advantages may be readily ascertainable by those skilled in the art.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] 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 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;

FIGURE 2 is a block diagram of the apparatus of FIGURE 1 showing additional details related to the control of the system of FIGURE 1;

FIGURE 3 is a block diagram of the system of FIGURE 2 showing yet additional details related to the control of the system of FIGURE 1; and

FIGURE 4 is a diagram of an example linear actuated bellows that may be used in conjunction with the teachings of the present invention.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS OF THE INVENTION

[0008] Example embodiments of the present invention and their advantages are best understood by referring to FIGURES 1-4 of the drawings, like numerals being used for like and corresponding parts of the various drawings.
FIGURE 1 is a block diagram of an apparatus 10 that includes a phased array antenna system 12. 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 in-

vention involves techniques for controlling cooling the slats 14 and 16, so as to remove appropriate amounts of heat generated by electronic circuitry therein.

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 FIGURE 1, for example by the arrows at 18 and 20.

[0009] 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 FIGURE 1. In the embodiment of FIGURE 1, the pump 30 consumes only about 0.1 kilowatts to 2.0 kilowatts of power.

[0010] 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.

[0011] 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.

[0012] 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 18 and 20 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.

[0013] 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.

[0014] 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 FIGURES 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 18 and 20 at a desired temperature. According to the teachings of the invention, slats 18 and 20 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 18 and 20. 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.

[0015] 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.

[0016] The coolant used in the disclosed embodiment of FIGURE 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 100ºC 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 60ºC. When water is subjected to a subambient pressure of about 3 psia, its boiling temperature decreases to approximately 60ºC. Thus, in the embodiment of FIGURE 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.

[0017] Water flowing from the pump 30 to the orifices 32 and 34 has a temperature of approximately 60ºC to 65ºC, 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 60ºC to 65ºC, 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.

[0018] 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 55ºC, and typically has an ambient temperature below 40ºC. 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 60ºC to 65ºC, 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.

[0019] It will be noted that the embodiment of FIGURE 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.

[0020] As mentioned above, the coolant used in the embodiment of FIGURE 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, or a mixture of water and ethylene glycol (WEGL). 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.

[0021] 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 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.

[0022] FIGURE 2 is a block diagram of the apparatus 10 of FIGURE 1 showing additional details related to the control of apparatus 10. FIGURE 2 additionally illustrates a pressure transducer 44 that measures the pressure of the coolant within tubes 22 and 24. Thus, pressure transducer 44 measures the pressure at which coolant within tubes 22 and 24 boils. Alternatively, any transducer capable of providing an indication of the pressure at which coolant within tubes 22 and 24 boils may be utilized. One example of such an alternative transducer is a temperature transducer, because the pressure at which coolant in tubes 22 and 24 boils may be determined by the temperature of such coolant. Temperature transducer 44 provides a signal 46 indicative of the pressure coolant in tubes 22 and 24 to controller 42. Controller 42 controls pressure of coolant in tubes 22 and 24 by either introducing additional coolant or removing coolant from the portion of the control loop between tubes 22 and 24 and heat exchange pump 30. In this particular example, expansion reservoir 40 includes a pump motor 48 having a reversible shaft 50 driving a positive displacement charge pump 52. If it is determined that the pressure in tubes 22 and 24 needs to be increased, controller 42 commands (via command 60) the pump motor 48 to drive the positive displacement charge pump 52 to provide additional coolant to the coolant loop. If it is desired that the coolant pressure in tubes 22 and 24 be lowered, controller 42 commands pump motor 48 to drive positive displacement discharge pump 52 to remove coolant from the coolant loop and store it in a holding reservoir 54. Controller 42 also receives a level indication 56 indicative of the level of holding reservoir 54. Pump meter feeds back its speed to controller 42 via signal 62.

[0023] According to the teachings of the invention, either removing or increasing coolant within the coolant loop effectively changes the pressure of the coolant in tubes 22 and 24. This change in pressure results in a desired change in temperature of phased array antenna system 12. In one embodiment, controller 42 also receives a signal 58 indicative of the heat load of base array antenna system 12. Because the relationship between the temperature of antenna array 12 and the pressure within tubes 22 and 24 depends upon the amount of heat being generated by antenna array 12, this signal may be utilized by controller 42 to determine whether the pressure in the cooling system loop should be increased or decreased. However, controller 42 may be appropriately programmed to provide the correct pressure adjustment based upon anticipated heat loads without receiving an indication of the actual heat load of antenna system 12. By controlling the temperature of antenna array system 12 through feedback and control of the pressure of the coolant in tubes 22 and 24, control loop complications associated with the thermal delay involved in feeding back temperature (and associated stability problems) can be avoided.

[0024] FIGURE 3 is a block diagram of the system of FIGURE 1 showing yet even further details related to the control of apparatus 10. In this example, controller 42 receives a plurality of additional signals. These signals include a slat temperature level set 64, an ambient temperature 66, an ambient air pressure 68, slat temperatures 70, heat exchanger temperature and pressures 70, and a fan speed 74. In addition, controller 42 also is shown as generating a plurality of additional signals, including a separator pump control signal 76, a heat exchange pump control signal 78, and a fan control signal 80. Slat temperature level signal 64 presents a desired temperature for slats 18 and 20. In this particular embodiment, the slat temperature level is set and controller 42 utilizes the desired set level in determining any appropriate changes to the pressure of the coolant in tubes 22 and 24 to maintain this temperature. Such calculations may also include the heat load indicator 58. The ambient air temperature signal 66 is used to set the speed of a fan 82 to ensure that the correct air mass flow rate through heat exchanger 28 occurs for a specific heat load relative to the temperature of the ambient air entering the heat exchanger 28.

[0025] The ambient air pressure may vary as a function of the operating altitude of apparatus 10. Signal 68, which is indicative of the ambient air pressure is used to set the fan 82 motor speed to ensure the correct air mass flow through the heat exchanger regardless of altitude. The ambient air pressure signal 68 is also used to compensate for pressure variations in the holding reservoir 54 until an optimum pressure is maintained.

[0026] The heat exchanger temperatures, represented by numeral 72, at the heat exchanger inlet and outlet are provided to controller 42 to indicate the performance of the heat exchanger and to see if the heat exchanger 28 is reaching its maximum capacity, as indicated by the outlet temperature being close to or the same as the inlet temperature. The associated heat exchanger pressures, also represented by reference numeral 72, is provided to controller 42 on both sides of the heat exchanger 38. These pressures are used to determine the air mass flow rate through the heat exchanger and determine the desired fan motor speed. In addition, these pressures are used with the measured fan speed to assess if the heat exchanger 28 is getting clogged with trash or debris.

[0027] Fan control signal 80 and the associated fan speed 74 are provided by and to controller 42 to control the fan speed to regulate the air mass flow through heat exchanger 28. Slat temperature level set 64 is a signal provided to controller 42 that informs controller 42 that it should raise the saturation pressure in the loop to raise its boiling temperature during periods of low heat load. This is performed to hold the temperature of the slat assembly constant over a range of heat loads.

[0028] Controller 42 also generates halt and status reporting signals, represented collectively by reference numeral 84. Signals 84 communicate the operational status of the cooling system and reports whether the cooling system is operating within set limits based on the heat load being removed. Controller 42 also reports if any alarm or shutdown limits have been reached.

[0029] FIGURE 4 is a diagram of an example linear actuated bellows-like reservoir 86 that may be used as an alternative approach for moving fluid into or out of the control loop to control the loop's pressure. Reservoir 86 includes a linear actuator 88 that may pull or push on a free end 90 of the bellows 92 to evacuate the loop or to let coolant flow back into the loop. Reservoir 86 combines the functions of holding reservoir 54 and dispositive displacement charge pump 52.

[0030] Although the present invention has been disclosed in the context of a phased array antenna system, 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.

Claims

1. An apparatus (10), comprising a heat-generating structure (12) disposed in an environment having an ambient pressure and a cooling system for removing heat from said heat-generating structure (12), said cooling system including:

a fluid coolant;
structure that reduces 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 (12);
structure that directs a flow of the coolant in the form of a liquid in a manner causing the liquid coolant to be brought into thermal communica-

tion with the heat-generating structure (12), the heat from the heat-generating structure (12) causing the liquid coolant to boil and vaporize so that the coolant absorbs from the heat-generating structure (12) as the coolant changes state;
a pressure transducer (44) disposed within the passageway (22, 24) and operable to measure a pressure of the coolant in the passageway (22,24);
a controller (42) operable to receive the pressure of the coolant in the passageway (22, 24) and generate a control signal based at least in part on a desired temperature of a portion of the heat-generating structure and the amount of heat generated by the heat-generating structure;
a positive displacement pump (52) responsive to the control signal operable to adjust a pressure of the coolant to control cooling of the heat-generating structure (12);

wherein the heat-generating structure (12) includes a passageway (22,24) having a surface that extends along a length of the passageway (22,24); and

wherein heat (18,20) generated by the heat-generating structure (12) is supplied to the surface of the passageway (22,24) along the length of the surface, the portion of the coolant flowing through the passageway and engaging the surface so as to absorb heat from the surface.

2. A method for controlling cooling of a heat-generating structure (12) disposed in an environment having an ambient pressure, comprising:

providing a fluid 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 (12);
boiling and vaporizing the coolant to absorb heat from the heat-generating structure (12) by bringing the coolant into thermal communication with the heat-generating structure (12);
measuring a parameter indicative of a pressure of the coolant; and
adjusting the pressure of the coolant in response to the measuring to control the cooling of the heat-generating structure.

3. A method according to claim 2, wherein adjusting the pressure of the coolant comprises adjusting the pressure of the coolant based at least in part on a heat load of the heat-generating structure (12).

4. A method according to claim 2, or claim 3, wherein the parameter indicative of a pressure of the coolant is one of pressure of the coolant and a temperature of the coolant.

5. A method according to any of claims 2 to 4, wherein adjusting the pressure of the coolant comprises adjusting the pressure of the coolant by a positive displacement pump (52).

6. A method according to any one of claims 2 to 5, wherein adjusting the pressure of the coolant comprises adjusting the pressure of the coolant by a linear actuated bellows (86).

7. A method according to any one of claims 2 to 6, including:

configuring the heat-generating structure (12) to include a passageway (22,24) having a surface that extends along a length of the passageway (22,24);
supplying the heat (18,20) generated by the heat generating structure to the surface of the passageway (22,24) along the length thereof; and
causing the portion of the coolant to flow through the passageway (22,24) and engage the surface.

8. A method according to any one of claims 2 to 7, wherein adjusting the pressure of the coolant comprises adjusting the pressure of the coolant based in part on a desired temperature of a portion of the heat-generating structure (12).

9. A method according to claim 7, wherein the parameter indicative of a pressure of the coolant is a parameter indicative of a pressure of the coolant in the passageway (22,24).

10. A method according to any one of claims 2 to 9, including selecting for use as the coolant one of water, methanol, a fluorinert, and a mixture of water and ethylene glycol.

11. A method according to any one of claims 2 to 10, including circulating the coolant through a flow loop.

12. A method according to claim 11, including configuring the loop to include a heat exchanger (28) for removing heat from said coolant so as to condense the coolant.

13. A method according to claim 12, including causing the heat exchanger (28) 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 pressure of the coolant.

14. An apparatus (10), comprising heat-generating structure (12) disposed in an environment having an ambient pressure, and a cooling system for removing heat from the heat-generating structure (12), the cooling system including:

a fluid coolant;
structure that reduces 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 (12);
structure that directs a flow of the coolant in a manner causing the liquid coolant to be brought into thermal communication with the heat-generating structure (12), the heat from the heat-generating structure (12) causing the liquid coolant to boil and vaporize so that the coolant absorbs heat from the heat-generating structure (12) as the coolant changes state;
a transducer (44) in operative communication with the coolant and operable to measure a parameter indicative of a pressure of the coolant;
a controller (42) operable to receive the parameter indicative of a pressure of the coolant and generate a control signal; and
structure responsive to the control signal that is operable to adjust a pressure of the coolant to control cooling of the heat-generating structure (12).

15. An apparatus (10) according to claim 14, wherein the controller (42) is further operable to generate a control signal based at least in part on a desired temperature of the heat-generating structure (12).

16. An apparatus (10) according to claim 14, or claim 15, wherein the controller (42) is further operable to generate a control signal based at least in part on a heat load of the heat-generating structure (12).

17. An apparatus (10) according to any one of claims 14 to 16, wherein the transducer (44) is one of a pressure transducer and a temperature transducer.

18. An apparatus (10) according to any one of claims 14 to 17,

wherein the heat-generating structure (12) includes a passageway (22,24) having a surface that extends along a length of the passageway (22,24); and

wherein heat (18,20) generated by the heat generating structure (12) is supplied to the surface of the passageway (22,24) along the length of the surface, the portion of the coolant flowing through the passageway (22,24) and engaging the surface so as to absorb heat from the surface.

19. An apparatus (10) according to claim 18, wherein the transducer (44) is a pressure transducer disposed in the passageway (22,24).

20. An apparatus (10) according to any one of claims 14 to 19, wherein the structure responsive to the control signal is a positive displacement pump (52).

21. An apparatus (10) according to any one of claims 14 to 19, wherein the structure responsive to the control signal is a linear actuated bellows (86).

22. An apparatus (10) according to any one of claims 14 to 21, wherein the structure that directs a flow of the coolant is configured to circulate the coolant through a flow loop.

23. An apparatus (10) according to Claim 22, including a heat exchanger (28) for removing heat from the coolant flowing through the loop so as to condense the coolant to a liquid.

24. An apparatus (10) according to Claim 23, wherein the heat exchanger (28) transfers heat from the coolant to a further medium having an ambient temperature less than the boiling temperature of the coolant at the pressure of the coolant.

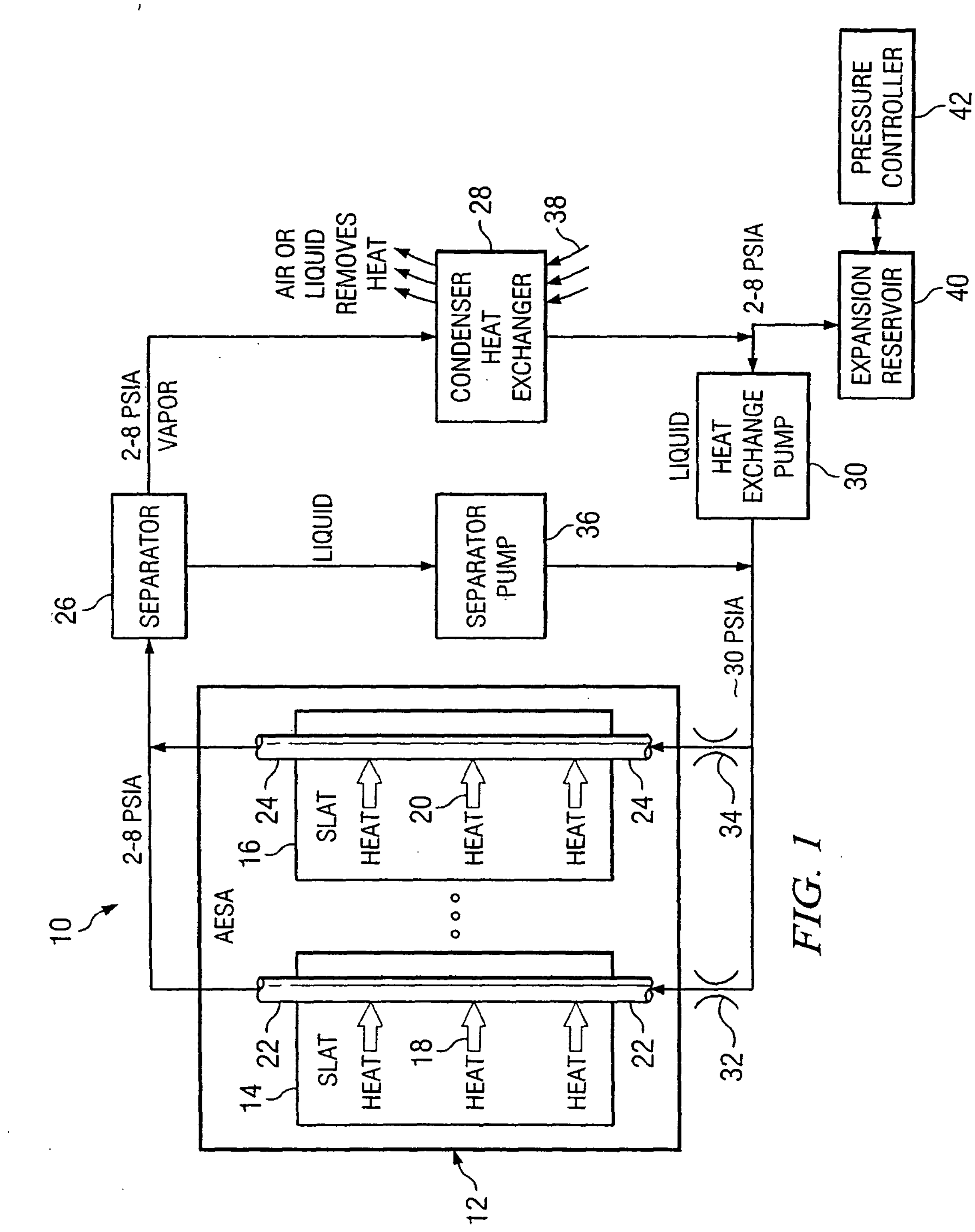
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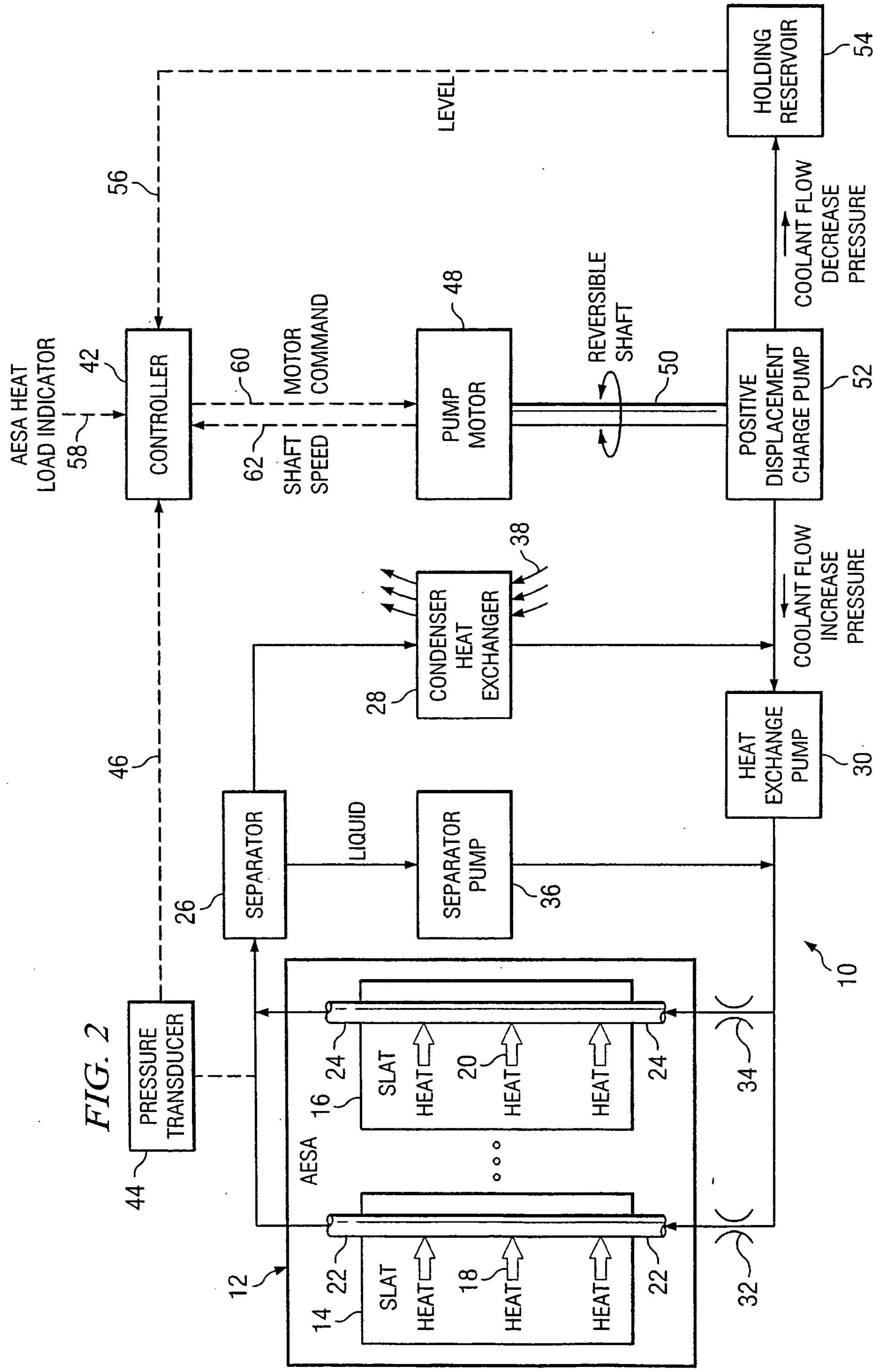
FIG. 1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DECREASE
PRESSURE
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PRESSURE
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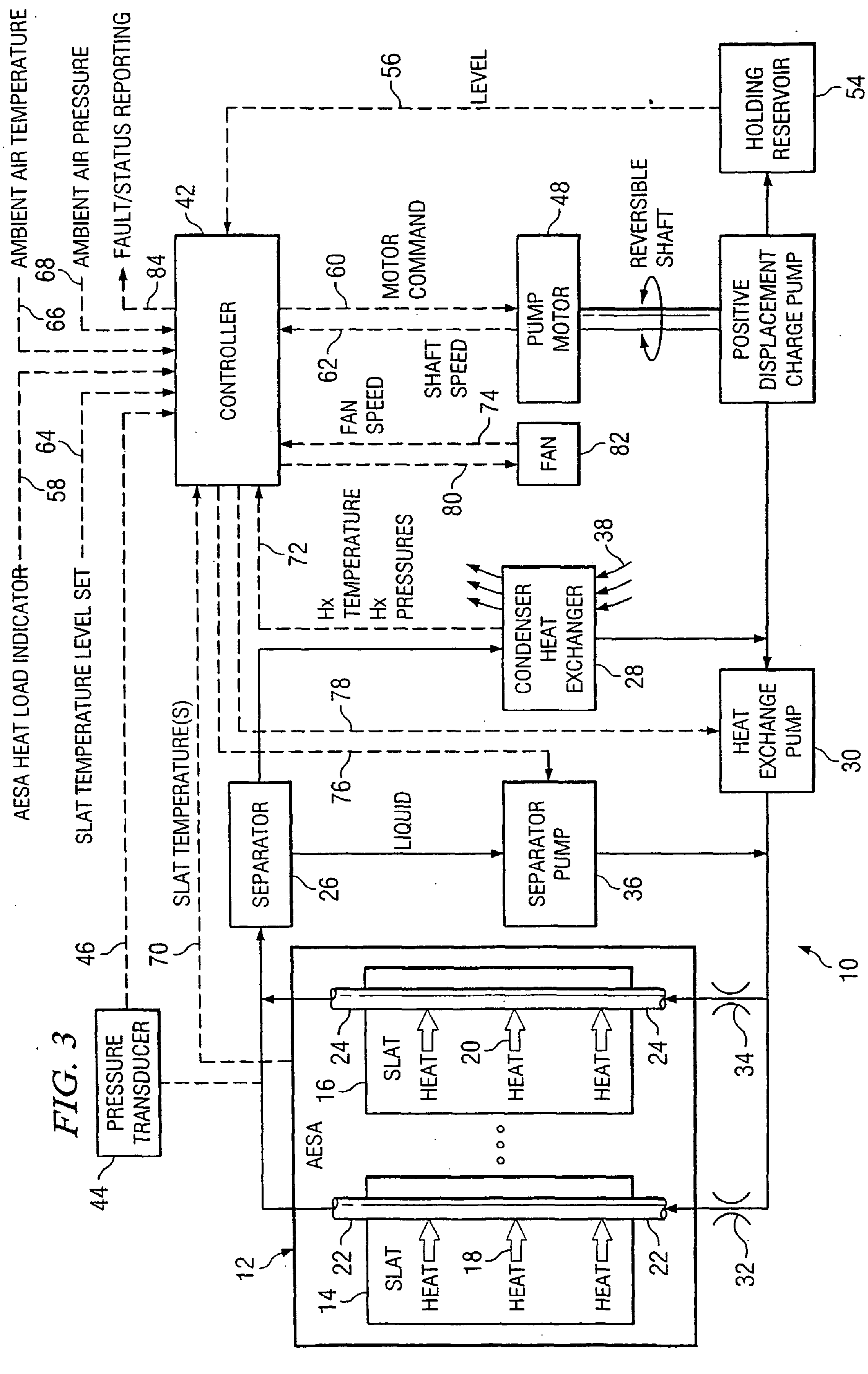
FIG. 2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AMBIENT AIR PRESSURE
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CONTROLLER
MOTOR COMMAND
SHAFT SPEED
FAN SPEED
PUMP MOTOR
REVERSIBLE SHAFT
POSITIVE DISPLACEMENT CHARGE PUMP
HOLDING RESERVOIR
LEVEL
FAN
Hx TEMPERATURE
Hx PRESSURES
CONDENSER HEAT EXCHANGER
HEAT EXCHANGE PUMP
SEPARATOR
LIQUID
SEPARATOR PUMP
PRESSURE TRANSDUCER
AESA
SLAT
HEAT
10
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FIG. 3

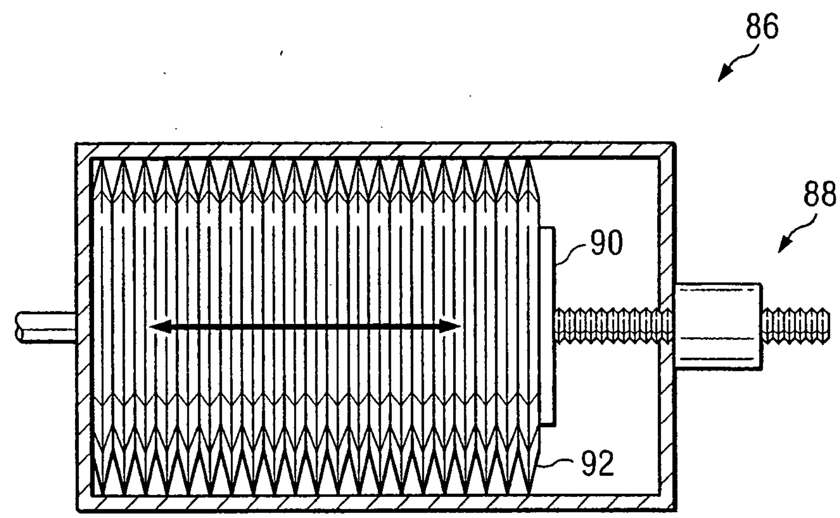

FIG. 4