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(54) DUAL-LOOP COOLING SYSTEM

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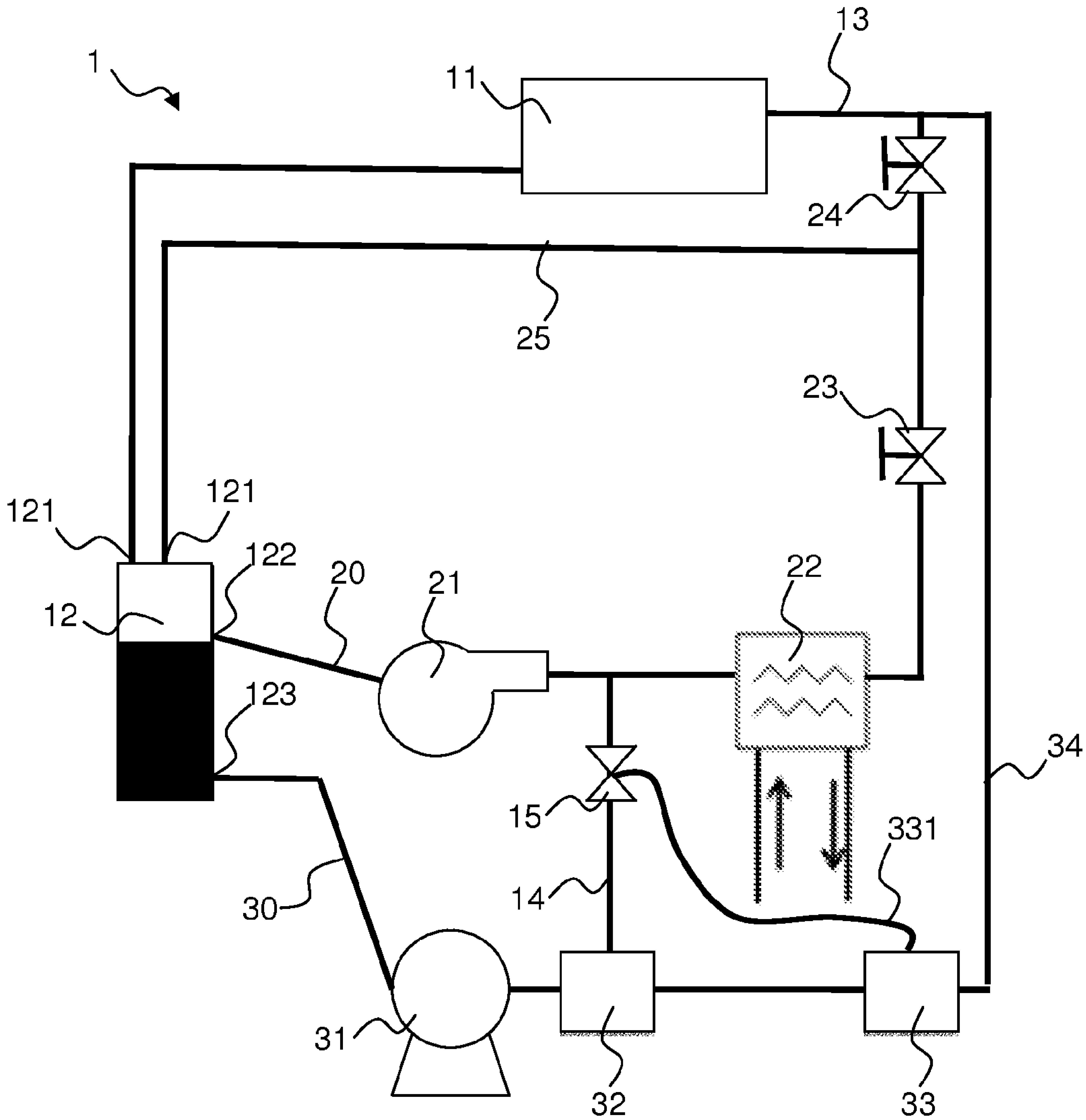
(57) **ABSTRACT**

Disclosed are methods and apparatuses for cooling a work piece surface using a dual-loop cooling system. The system includes a vapor-compression loop and a liquid-evaporation loop. The loops are configured to prepare a coolant at or approximately at saturation for delivery into a chamber for cooling the surface. A preferred liquid-evaporation loop includes a chamber, a phase separator, a liquid pressurizer, and a vapor mixer that heats the coolant to or near its saturation temperature. A preferred vapor-compression loop includes the phase separator, a compressor, a condenser, an expansion valve, and a return line. The vapor mixer preferably heats the coolant by mixing liquid coolant with vapor coolant derived from the vapor-compression loop. A two-phase flow detector may be disposed downstream of the vapor mixer and be in communication with a vapor valve disposed upstream of the vapor mixer to ensure that an appropriate amount of vapor is fed into the vapor mixer to induce evaporation. Methods include cooling a surface by cycling a coolant through the liquid-evaporation loop and preparing the coolant at saturation with vapor derived from the vapor-compression loop.



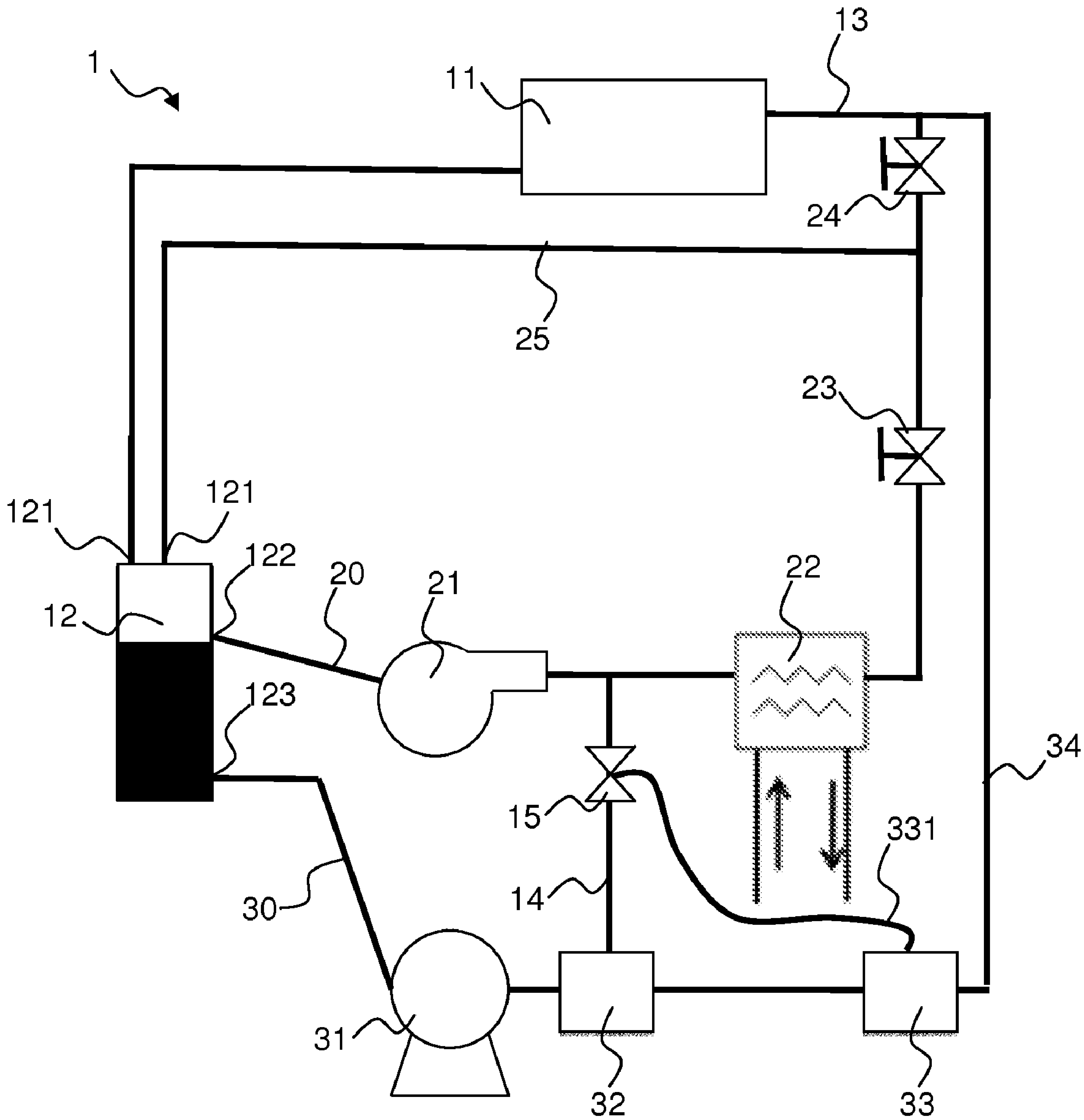


FIG. 1

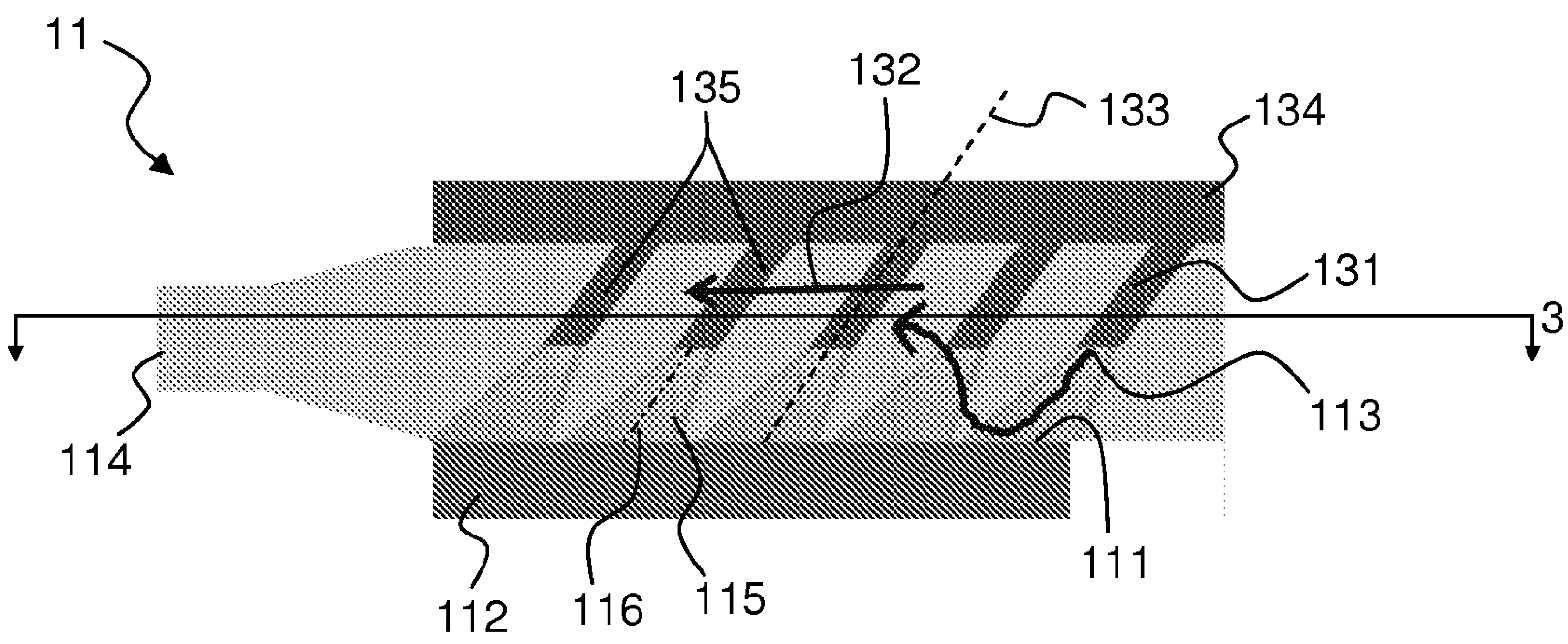

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FIG. 2

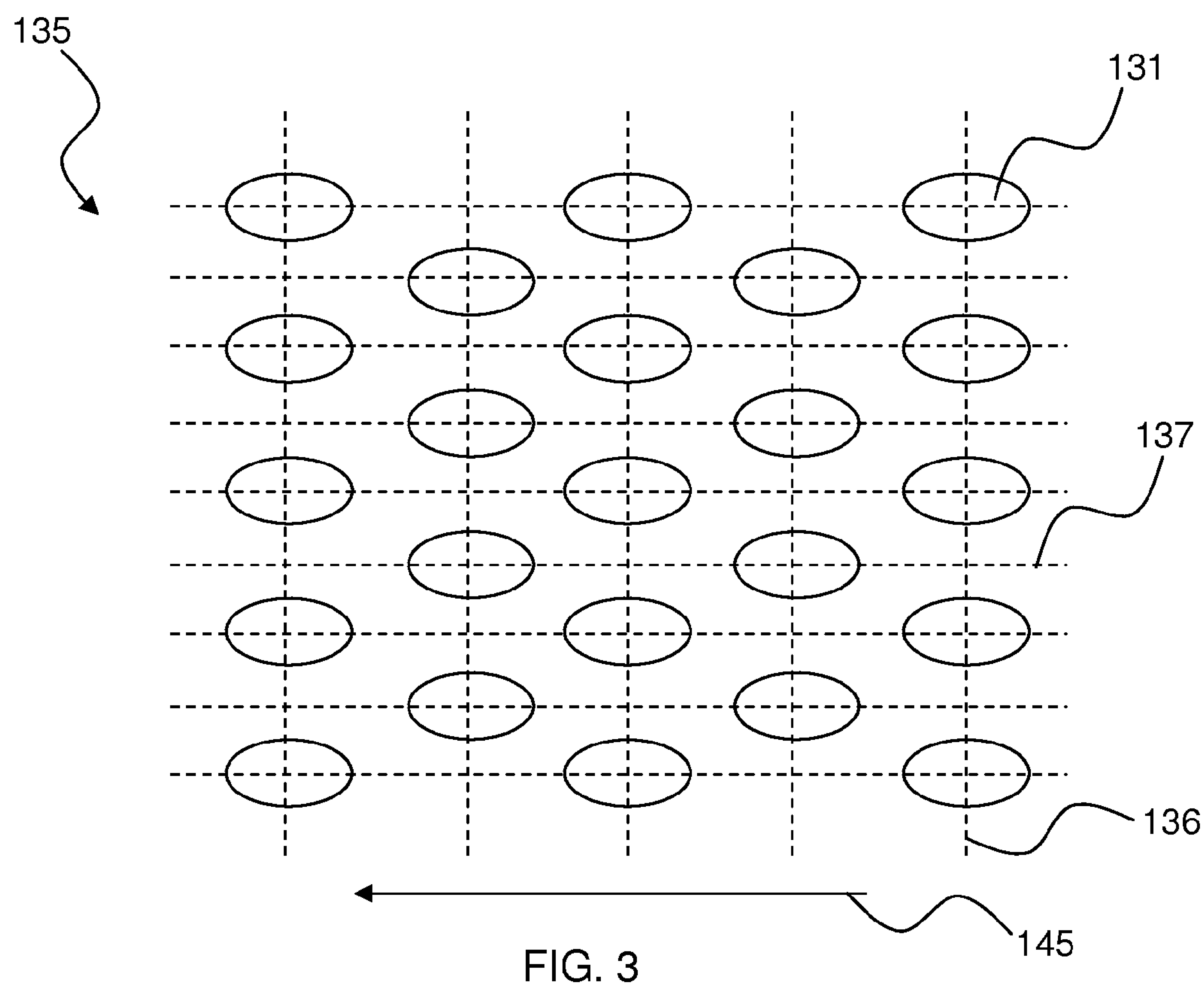
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FIG. 3

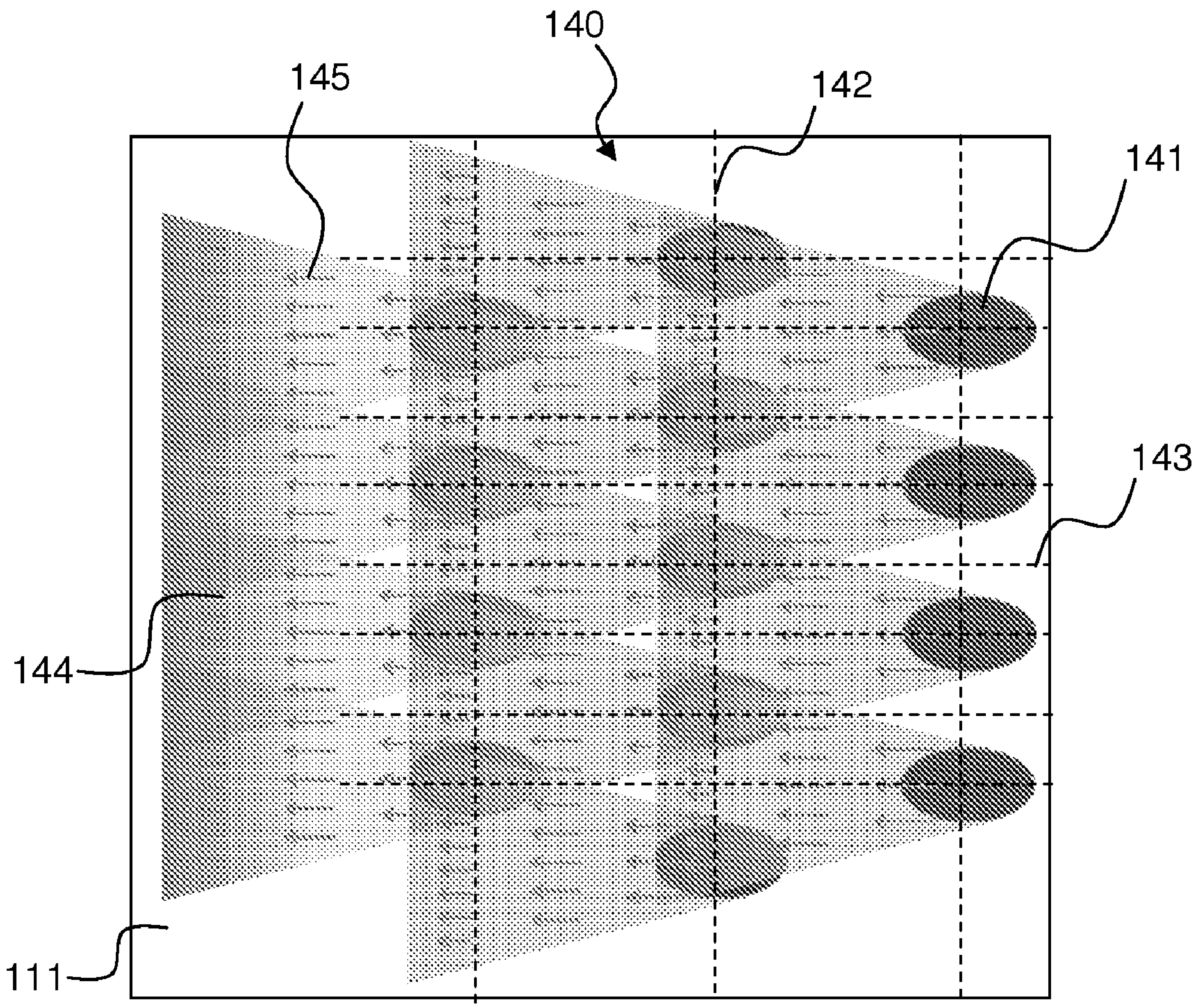

FIG. 4

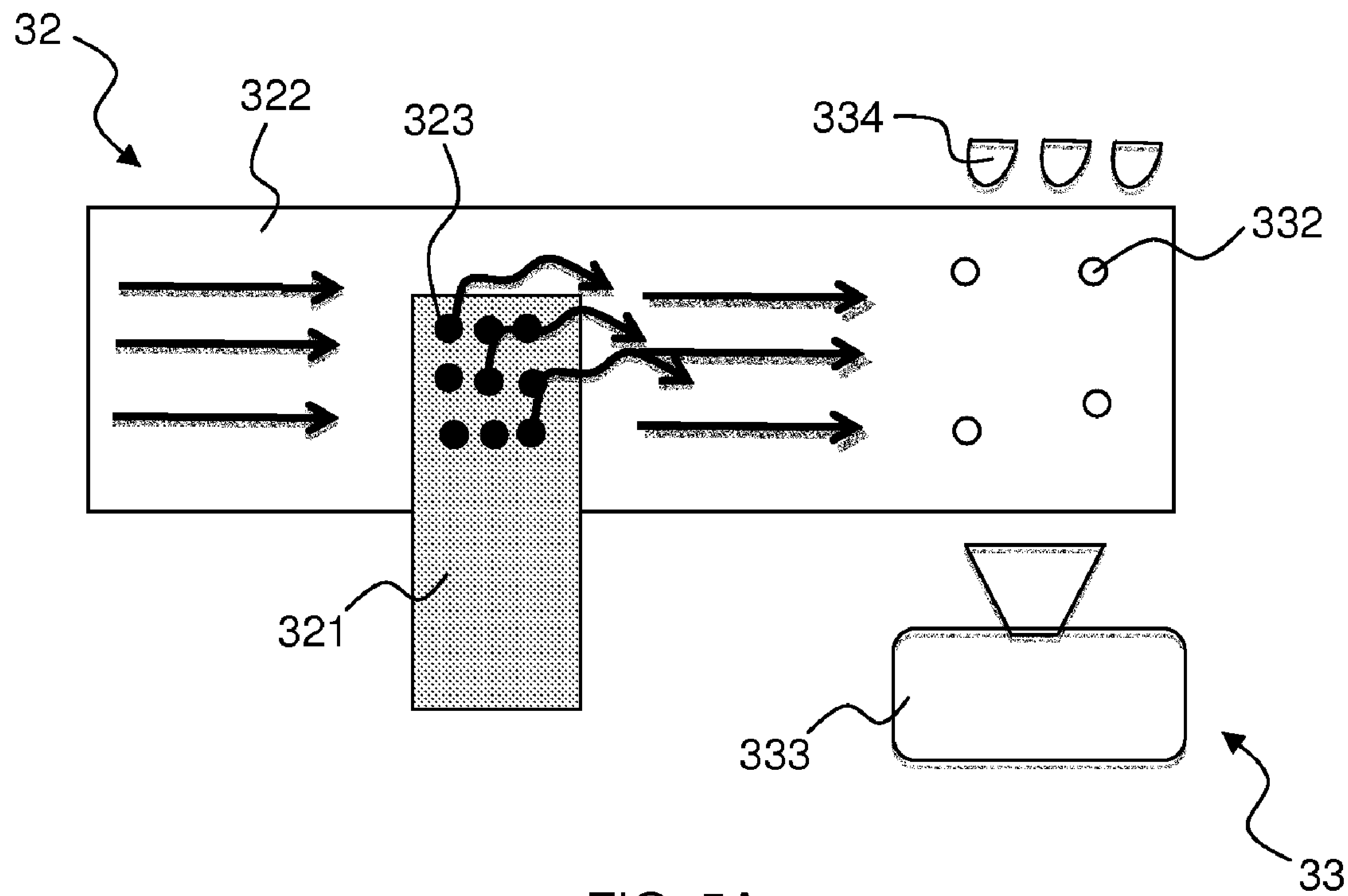
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FIG. 5A

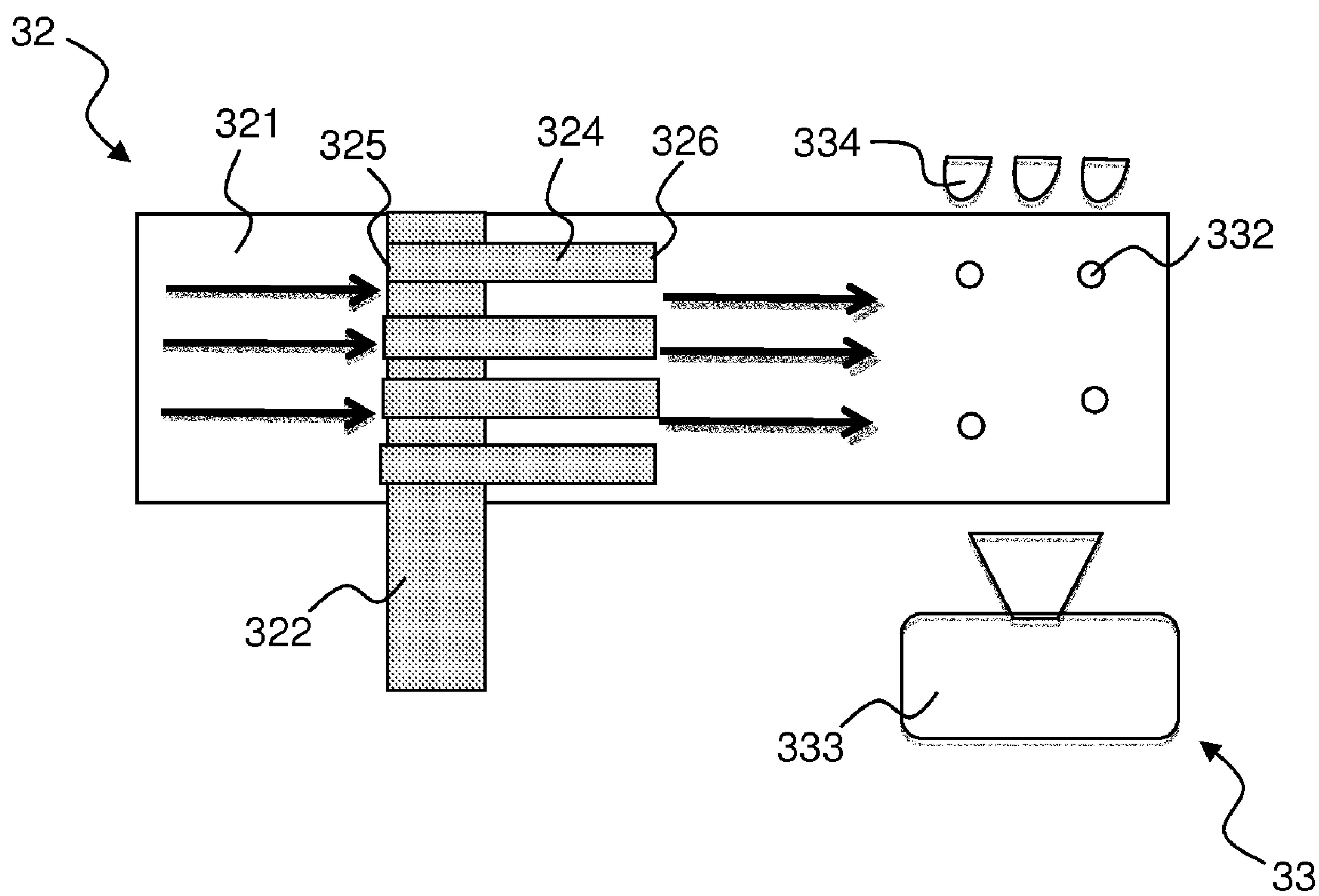
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FIG. 5B

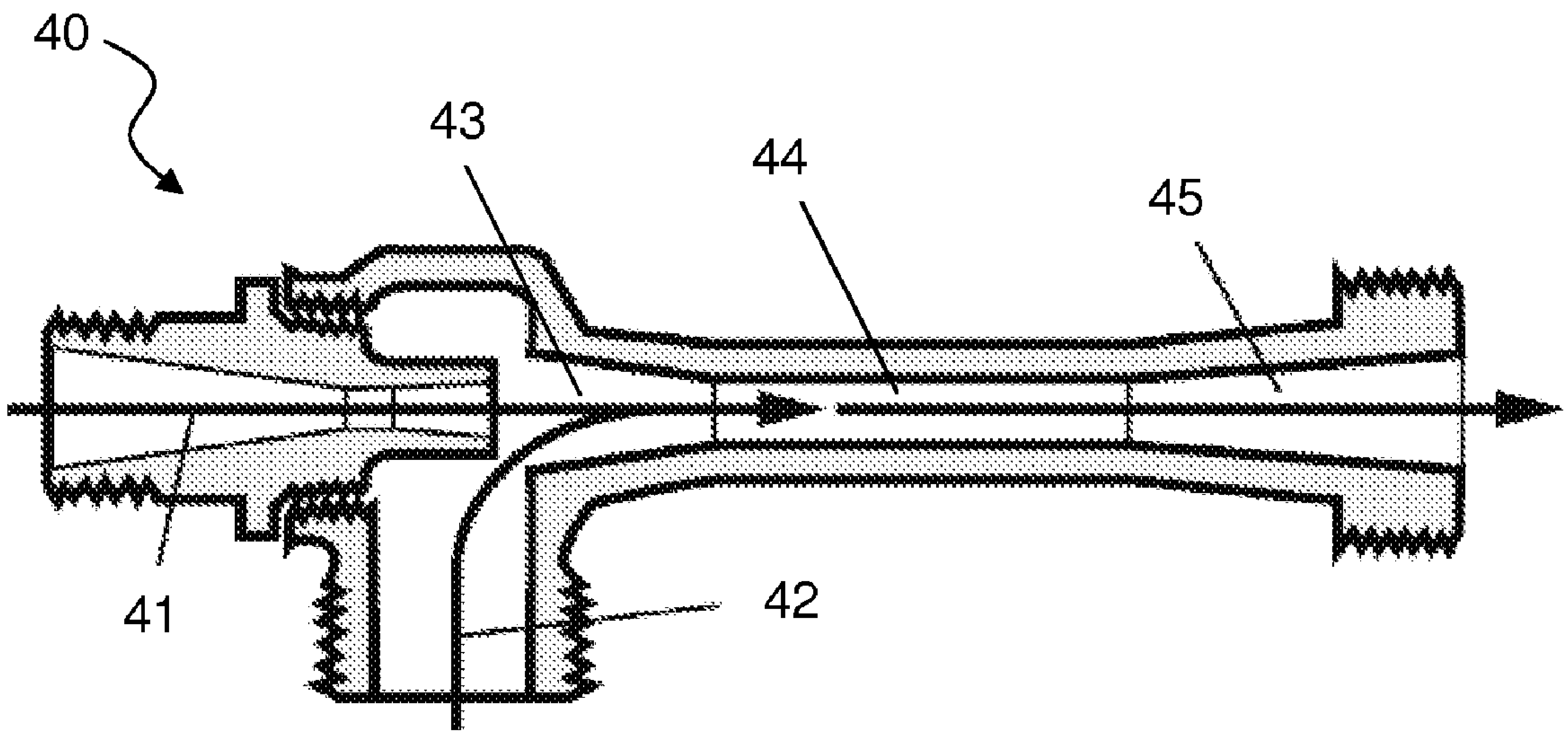

FIG. 6

DUAL-LOOP COOLING SYSTEM

FIELD OF THE INVENTION

[0001] The present invention is directed to methods and apparatuses for cooling work pieces such as processors or other electronic devices.

BACKGROUND

[0002] Methods for maintaining electronic devices within a safe and desirable operating temperature range have been a topic of research since the invention of the transistor. Maintaining such a temperature range is a challenging problem that is only increasing in importance and difficulty as semiconductor technology continues to progress. State of the art microprocessors easily produce more than 40 W of thermal energy per square centimeter of the microchip surface. Power electronics can attain heat densities three times this level.

[0003] In addition to the requirement to manage such high heat intensity, there is a need to remove the thermal energy efficiently, both in terms of energy expended and space required. According to the Department of Energy, approximately 3% of electricity used in the United States is devoted to powering data centers or computer facilities. Approximately half of this electricity goes toward power conditioning and cooling. Increasing the efficiency of cooling would lead to dramatic savings in energy. More efficient cooling is also needed in transportation systems due to the rapidly increased adoption of hybrid and electric vehicles. More efficient cooling of the electronic systems in these vehicles translates into increased range and utility of the vehicles.

[0004] The majority of computer systems are currently cooled using air that is forced through a series of extended metal surfaces coupled to microchips or other electronic work pieces. However, these systems are inherently limited in terms of their performance and efficiency. Due to the very low volumetric heat capacity of air, a large volume of air flow is required to remove the heat load of even one processor. A recommended value is 5 to 10 cubic feet per minute (cfm) per 100 W of heat load. This equates to the equivalent of two air conditioning systems sized for a typical U.S. house being required to cool a rack of computers. A typical data center may have several hundred of these racks.

[0005] Furthermore, air-cooled systems are not only inefficient in themselves but also cause the electronics they cool to operate less efficiently. Because of the low thermal capacity of air, fully utilized microprocessors operate at or near the maximum rated temperature. Reducing the temperature of microprocessors can save at least 25% of the energy they consume at the same level of utilization.

[0006] Numerous liquid cooling schemes have been implemented to address some of the problems associated with air cooling. A majority rely on using water that flows through channels defined by fins, wherein the fins are indirectly coupled to a work piece via a metal base plate, a thermal paste, and a direct bond metal such as copper. This approach can be effective. However, the intervening materials between the water and the work piece induce significant thermal resistance, which reduces the efficiency of the system. In addition to the thermal resistance, the intervening materials add to the cost and time of manufacture, constitute additional points of failure, and provide possible disposal issues. Finally, the intervening materials render the system unable to efficiently deal with local hot spots on a work piece. The entire system must be designed to accommodate the maximum anticipated heat load of one or a few localized hot spots.

[0007] Further improvements have been made to liquid-cooled systems by using a coolant other than water. Dielectric coolants can come into direct contact with the electronic devices and not harm them. Use of such dielectric coolants permits eliminating a significant amount of thermal interface material from the system. However, the dielectric coolants are less efficient coolants than water. More aggressive cooling techniques are therefore required to achieve the necessary performance.

[0008] One approach with dielectric coolants includes direct spray impingement, in which atomized liquid coolant is sprayed directly on a work piece surface through air or vapor. However, spray cooling is limited by several factors. First, spray cooling requires a significant working volume to enable the atomized sprays to form. Second, atomizing the liquid requires a significant amount of pressure upstream of the atomizer. The pressure is required to generate an appropriate pressure drop at the atomizer-air interface. An appropriate pressure drop facilitates atomization by inducing partial evaporation of coolant as the coolant passes through the interface. Maintaining the amount of pressure to ensure the appropriate pressure drop consumes a significant amount of energy. Third, high flow rates are required to prevent critical heat flux, wherein evaporation of coolant on the surface prevents atomized liquid from reaching the surface. In the end, it has proven difficult to design a practical, compact spray cooling system, despite the large amount of effort that has been expended to do so.

[0009] Another approach is to use direct jet impingement, wherein streams of liquid are projected through a liquid medium and impinge directly on a work piece surface. While impinging jets are known to have notable heat transfer performance, impinging jet systems have problems of scalability. To achieve high heat transfer over a large area, arrays of jets must be used. The use of arrays in conventional direct jet impingement systems, however, is problematic. Opposing surface flow of fluid from neighboring jet streams induces stagnant regions on the surface. The heat transfer performance in these stagnant regions can drop to nearly zero. Furthermore, conventional jet impingement systems use nozzles that are part of a large, flat nozzle plate. As fluid from jet streams impinging on the surface flow from the center of the plate flows outward, it can have enough momentum to completely deflect the outermost jets, preventing them from impinging on the heated surface. As a result of these factors, conventional impinging jet systems are limited in size.

[0010] Direct impingement cooling is commonly employed in a vapor-compression cooling cycle. The vapor-compression cooling cycle compresses vapor coolant generated from cooling a surface, condenses the compressed vapor to a liquid while transferring the heat to an external temperature sink, expands the condensed coolant to cause a drop in pressure and temperature, impinges the expanded coolant against the surface for cooling, and re-compresses the vapor generated therefrom and recycles it through the cycle. While vapor-compression cooling cycles are simple and thermodynamically ideal for generating atomized sprays, they are known for circulating oil derived from the condenser, do not operate well when coupled to high temperature sinks, are difficult to adjust with changing heat sink temperatures, and do not provide redundancy within the system.

SUMMARY OF THE INVENTION

[0011] The present invention addresses the shortcomings of conventional cooling systems by providing a dual-loop cooling system that provides at least two, partially parallel cycles that prepare coolant at or approximately at saturation prior to using the coolant for cooling.

[0012] One aspect of the invention comprises an apparatus for cooling a surface. One version of the apparatus comprises at least one chamber with the surface exposed therein. The chamber comprises an inlet and an outlet and is configured for flowing fluid therethrough by entering through the inlet in a stream projected against the surface and exiting through the outlet. The apparatus also comprises a liquid source in fluid communication with the inlet of the chamber. The apparatus also comprises a heat-transfer apparatus configured to transfer heat to liquid derived from the liquid source at a point upstream of the inlet.

[0013] The apparatus may further include a heat-transfer regulator configured to adjust amount of heat transferred via the heat-transfer apparatus to the liquid. The heat-transfer regulator may include a two-phase flow detector disposed between the heat-transfer apparatus and the inlet, wherein the two-phase flow detector is configured to communicate with a device that adjusts an amount of heat transferred via the heat-transfer apparatus to the liquid in response to a signal indicating the presence of two-phase flow, such as an amount of bubbles detected in the liquid.

[0014] In a preferred version of the invention, the heat-transfer apparatus comprises a vapor mixer in fluid communication with the liquid source and a vapor source. A vapor valve configured to adjust flow of vapor to the vapor mixer is disposed between the vapor mixer and the vapor source. A two-phase flow detector in communication with the vapor valve is disposed between the vapor mixer and the inlet. The two-phase flow detector is configured to communicate with the vapor valve to adjust flow of vapor to the vapor mixer in response to a signal indicating the presence of two-phase flow.

[0015] In some versions of the invention, the vapor source comprises a phase separator and a compressor. The compressor is in fluid communication with the phase separator in a configuration to selectively receive vapor therefrom and is also in regulated fluid communication with the vapor mixer to deliver compressed vapor thereto. Such a version may also include a condenser and an expansion valve to prepare substantially saturated coolant. The condenser is in fluid communication with the compressor to receive fluid therefrom and is further in fluid communication with the phase separator via a return line in a configuration to deliver fluid thereto. The expansion valve is disposed between the condenser and the return line. The condenser may further be in regulated fluid communication with the inlet of the chamber to deliver fluid thereto. A circuit valve disposed between the expansion valve and the inlet of the chamber adjusts flow of fluid from the expansion valve to the inlet. The return line recycles to the phase separator fluid that is prevented from reaching the chamber when the circuit valve is closed.

[0016] In some versions of the invention, the liquid source comprises a phase separator and a liquid pressurizer. The phase separator is in fluid communication with the outlet of the chamber and receives fluid therefrom. The fluid pressurizer is in fluid communication with the phase separator in a configuration to selectively receive liquid therefrom and is further in fluid communication with the heat-transfer apparatus as well as the chamber inlet. An exemplary liquid pressurizer is a pump.

[0017] Some versions of the invention comprise a jet pump, wherein the jet pump serves as both a liquid pressurizer and a heat-transfer apparatus.

[0018] A preferred apparatus includes a first fluid loop and a second fluid loop wherein the apparatus is configured to cycle fluid through the first fluid loop and at least intermittently cycle fluid simultaneously through the second fluid loop. The first fluid loop preferably includes the chamber, the phase separator, the liquid pressurizer, and the vapor mixer. The second fluid loop preferably includes the phase separator, the compressor, the condenser, the expansion valve, and the return line. The second fluid loop is configured at least to provide heat to the first fluid loop to prepare coolant substantially at saturation.

[0019] Another aspect of the invention comprises a method of cooling a surface. A preferred method comprises preparing a coolant approximately at saturation, wherein the preparing comprises heating pre-heated coolant to approximately a saturation temperature to generate heated coolant. The method also comprises introducing the heated coolant through an inlet of the chamber which includes projecting a stream of the heated coolant against the surface, wherein the heated coolant at least partially evaporates as it enters the chamber prior to contacting the surface. The method also comprises draining partially evaporated coolant through an outlet of the chamber.

[0020] Some versions of the invention include detecting the amount of vapor phase in the heated coolant and regulating the heating in response to the amount of detected vapor phase.

[0021] In some versions of the invention, heating the pre-heated coolant comprises collecting the partially evaporated coolant draining from the outlet of the chamber to obtain collected coolant, separating the collected coolant into liquid coolant and vapor coolant, selectively pressurizing the liquid coolant to obtain pressurized liquid coolant, and heating the pressurized liquid coolant.

[0022] In some versions of the invention, heating the pre-heated coolant comprises mixing the pre-heated coolant with vapor. One specific version includes collecting vapor-containing coolant to obtain collected coolant, separating the collected coolant into liquid coolant and vapor coolant, selectively compressing the vapor coolant to obtain compressed vapor coolant, and mixing at least a first portion of the compressed vapor coolant with the pre-heated coolant. Such a version may further include condensing at least a second portion of the compressed vapor coolant to generate condensed coolant, expanding the condensed coolant to approximately a saturation pressure of the condensed coolant to generate expanded coolant, and directly recycling at least a first portion of the expanded coolant to be collected and separated and/or mixing at least a second portion of the expanded coolant with the heated coolant prior to the introducing the heated coolant through the inlet of the chamber.

[0023] The system described herein minimizes circulating oil through the chamber by providing circulation routes that bypass the chamber, adjusts to warm or varying sink temperatures by providing for decoupling from the temperature sink (i.e., the ambient), and provides redundant cooling mechanisms.

[0024] The objects and advantages of the invention will appear more fully from the following detailed description of the preferred embodiment of the invention made in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] FIG. **1** depicts a schematic of an apparatus of the present invention for cooling a work piece surface.

[0026] FIG. **2** depicts a side elevation cutaway view a chamber of the present invention comprising tubular nozzles directed non-perpendicularly at the surface and projecting a stream non-perpendicularly against the surface.

[0027] FIG. **3** depicts a top cutaway view of a portion of an array of tubular nozzles as taken from line **3** in FIG. **2**.

[0028] FIG. **4** depicts a top plan view of a surface upon which an array of streams impinges non-perpendicularly.

[0029] FIG. **5**A depicts a cutaway view of one version of a vapor mixer.

[0030] FIG. **5**B depicts a cutaway view of another version of a vapor mixer.

[0031] FIG. **6** depicts a jet pump, which may be used as both a liquid pressurizer and a vapor mixer in the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0032] One aspect of the present invention involves cooling a surface in a chamber with a liquid coolant wherein the coolant at least partially undergoes a phase change to a vapor (i.e., evaporates) upon entering the chamber and prior to contacting the surface. This is achieved by preparing coolant to be introduced in the chamber at or approximately at the coolant's saturation condition.

[0033] The general term "coolant" refers to any fluid capable of undergoing a phase change from liquid to vapor or vice versa at or near the operating temperatures and pressures of an apparatus as described herein. The term refers herein to the fluid in the liquid phase, the vapor phase, and mixtures thereof. A number of coolants may be selected for use within the apparatus described herein depending on cost and level of optimization desired. Non-limiting examples include water, HFE-7000, R-245fa, FC-72, and FC-40. Other coolants are known in the art. Water is readily abundant and inexpensive. However, it does not change phase at a low temperature (such as 40° C. or 50° C.) without operating at very low pressures that can be difficult to maintain. In addition, water as a coolant requires a number of additives and absorbs a range of materials from the surfaces with which it comes into contact. During phase change, these materials may come out of solution, causing fouling or other issues. Therefore, it is preferred that a pure dielectric fluid, such as HFE-7000 or R-245fa, is used as a coolant. Such coolants are preferably used in direct contact with the processor package or surface. This eliminates the requirement for thermal interference materials between the coolant and the work piece to be cooled and thereby eliminates their associated resistances.

[0034] "Preparing," used with reference to preparing coolant at or slightly below saturation, refers to any physical manipulation that renders a coolant at its saturation condition. Non-limiting examples of such physical manipulations include expanding (i.e., de-pressurizing) and/or heating a coolant.

[0035] "Saturation" or "saturation condition," used with respect to a coolant at saturation or at its saturation condition, respectively, refers to a temperature and pressure at which a liquid is in equilibrium with its vapor phase. "Saturation temperature" refers to a particular temperature at a given pressure at which a liquid is in equilibrium with its vapor phase. "Saturation pressure" refers to a particular pressure at a given temperature at which a liquid is in equilibrium with its vapor phase. A liquid at saturation evaporates into its vapor phase as additional thermal energy (heat) is applied or as pressure is reduced. Similarly, a vapor at saturation condenses into its liquid phase as thermal energy is removed or as pressure is increased. The saturation temperature can be increased by increasing the pressure in the system. Conversely, the saturation temperature can be lowered by decreasing the pressure in the system. The saturation pressure can be increased by increasing the temperature in the system. Conversely, the saturation pressure can be lowered by decreasing the temperature in the system. Establishing a temperature of coolant to be introduced in a chamber at or approximately at the saturation condition of the coolant provides for at least a portion of the coolant entering the chamber to evaporate as a result of undergoing a pressure drop upon entering the chamber, with the coolant further evaporating upon being heated by the surface.

[0036] In specific versions of the invention, a coolant "approximately at" the coolant's saturation condition refers to the coolant being slightly below the coolant's saturation temperature and slightly above the coolant's saturation pressure. "Slightly below the coolant's saturation temperature" refers to a temperature about 0.5° C., about 1° C., about 3° C., about 5° C., about 7° C., about 10° C., about 15° C., or about 20° C. below the saturation temperature. "Slightly above the coolant's saturation pressure" refers to a pressure about 1 kPa, about 3 kPa, about 5 kPa, about 7 kPa, about 10 kPa, about 15 kPa, or about 20 kPa above the saturation pressure.

[0037] "Fluid communication" between two or more elements refers to a configuration in which fluid can be communicated between or among the elements and does not preclude the possibility of having a filter, flow meter, a closable valve, or other devices disposed between such elements.

[0038] "Regulated fluid communication" between two or more elements refers to fluid communication between or among the elements that can be increased, decreased, and/or closed, such as with an adjustable valve.

[0039] "Liquid source" refers to any source of a liquid, such as liquid coolant, without limitation. The liquid source preferably includes a phase separator that collects cycling coolant in a closed fluidic system and separates liquid from vapor, as described below. However, the liquid source may also comprise a liquid reservoir in an open fluidic system, wherein coolant is not cycled through the system.

[0040] "Vapor source" refers to any source of vapor, such as vapor coolant, without limitation. The vapor source preferably includes a phase separator that collects cycling coolant in a closed fluidic system and separates liquid from vapor, as described below. However, the vapor source may also comprise a vapor tank or reservoir in an open fluidic system wherein coolant is not cycled through the system.

[0041] "Heat-transfer apparatus" refers to any device capable of transferring heat to liquid coolant. Suitable heat-transfer apparatuses for use in the present invention include, without limitation, vapor mixers, condensers, heat exchangers, and jet pumps.

[0042] "Heat-transfer regulator" refers to any device capable of adjusting, or causing to adjust, an amount of heat transferred via the heat-transfer apparatus to a liquid. Suitable heat-transfer regulators may include, without limitation, any or all of a vapor valve, a two-phase flow detector, and/or a processor in communication with the vapor valve and the two-phase flow detector.

[0043] "Downstream" and "upstream" are used herein in relation to the direction of flow of coolant within the apparatus. As is known in the art, fluid flows from areas of higher pressure to areas of lower pressure.

[0044] "Selectively," used in reference to selectively performing an action on or with liquid, refers to performing that action on or with liquid substantially devoid of vapor. "Selectively" used in reference to selectively performing an action on or with vapor refers to performing that action on or with vapor substantially devoid of liquid.

[0045] "Pressurizing" a substance refers to increasing the pressure of a substance. "De-pressurizing" refers to decreasing the pressure of a substance.

[0046] "Operationally connected" refers to a configuration in which one device monitors, regulates, or controls the operation or functioning of another device or is in communication with another device.

[0047] An exemplary apparatus **1** of the present invention is shown in FIG. **1**. The apparatus **1** comprises two fluid loops, a liquid-evaporation loop **30** and a vapor-compression loop **20**. The liquid-evaporation loop **30** includes a chamber **11**, a phase separator **12**, a liquid pressurizer **31**, a vapor mixer **32**, a distal portion of the inlet feed line **34**, and a proximal portion of the inlet feed line **13**, all in fluid communication. The liquid-evaporation loop **30** also includes a two-phase flow detector **33** operationally connected with the distal portion of the inlet feed line **34** and disposed downstream of the vapor mixer **32**. The vapor-compression loop **20** includes the phase separator **12**, a compressor **21**, a condenser **22**, an expansion valve **23**, and a return line **25**, all in fluid communication.

[0048] The phase separator **12** serves as the only point of mutual convergence between the vapor-compression loop **20** and the liquid-evaporation loop **30**. Here, the phase separator **12** accepts coolant draining from the chamber of the liquid-evaporation loop **30** as well as coolant recycling from the return line **25** of the vapor-compression loop **20**. The phase separator **12** also serves as the only point of mutual divergence, wherein accumulated coolant is separated within the phase separator **12** into vapor coolant and liquid coolant. The vapor coolant is selectively diverted to the compressor **21** of the vapor-compression loop **20**. The liquid coolant is selectively diverted to the liquid pressurizer **31** of the liquid-evaporation loop **30**.

[0049] The vapor mixer **32** of the liquid-evaporation loop **30** serves as one of two points where the vapor-compression loop **20** feeds into the liquid-evaporation loop **30**. The vapor-compression loop **20** unidirectionally feeds into the vapor mixer **32** in a regulated manner through the vapor-mixer feed line **14**. In this manner, hot vapor coolant from the compressor **21** mixes with liquid coolant from the liquid pressurizer **31** in the vapor mixer **32**, thereby heating the liquid. It is preferred that the hot vapor coolant heats the liquid coolant to its saturation temperature. The degree to which the liquid is heated is a function, in part, of the amount of hot vapor diverted from the vapor-compression loop **20** into the vapor mixer **32** and the amount of thermal energy contained by the vapor. The amount of vapor coolant diverted from the vapor-compression loop **20** into the vapor mixer **32** is regulated by a vapor valve **15**. The vapor valve **15** can continuously open or close to allow more or less vapor, respectively, to flow into the vapor mixer **32**, or can completely close.

[0050] The vapor valve **15** itself is further regulated by the two-phase flow detector **33**, the latter of which is in configured in communication **331** with the vapor valve **15**. The two-phase flow detector **33** detects whether or not two-phases (i.e., liquid and vapor bubbles) are present within the coolant in the distal portion of the inlet feed line **34**, thereby indicating whether or not the coolant heated by the vapor coolant is at saturation. If bubbles are not detected, the two-phase flow detector **33** can communicate with the vapor valve **15** to progressively open and allow more vapor to mix with the liquid coolant until bubbles are detected. The two-phase flow detector **33** also preferably detects the amount or concentration of bubbles within the coolant in the distal portion of the inlet feed line **34**, thereby determining the amount of vapor within the liquid. The two-phase flow detector **33** can then communicate with the vapor valve **15** to either open or close in a continuous manner until a pre-defined level of evaporation is achieved. If there is too much vapor detected by the two-phase flow detector **33**, the two-phase flow detector **33** communicates with the vapor valve **15** to close in a continuous manner until the pre-defined level of vapor is achieved. If there is too little vapor, the two-phase flow detector **33** communicates with the vapor valve **15** to open in a continuous manner until the pre-defined level of evaporation is achieved. Various exemplary pre-defined levels of evaporation include about 1% vapor, about 2.5% vapor, about 5% vapor, about 7.5% vapor, about 10% vapor, about 15% vapor, about 20% vapor or more. The vapor valve **15** preferably includes a manual override function, wherein an operator can manually open or close the valve independently of the other components of the apparatus **1**. The vapor valve **15** can also be completely closed to permit cooling with only the liquid-evaporation loop **30** in certain desired circumstances.

[0051] The proximal portion of the inlet feed line **13** serves as the second of the two points where the vapor-compression loop **20** feeds into the liquid-evaporation loop **30** in a regulated manner. Here, the vapor-compression loop **20** at a point downstream of the expansion valve **23** feeds into the liquid-evaporation loop **30** at a point downstream of the two-phase flow detector **33**. A circuit valve **24** regulates the amount of condensed, expanded coolant from the vapor-compression loop **20** that merges with the liquid-evaporation loop **30**. The circuit valve **24** is capable of completely closing to permit cooling with the liquid-evaporation loop **30** only, if desired, but is otherwise continuously adjustable. The circuit valve **24** is preferably independently adjustable with respect to other components of the apparatus **1**. Allowing condensed, expanded coolant from the vapor-compression loop **20** to merge with the liquid-evaporation loop **30** by opening or otherwise adjusting the circuit valve **24** helps to regulate the pressure in the chamber **11**. The portion of the condensed, expanded coolant that is not merged to the proximal portion of the inlet feed line **13** is recycled to the phase separator **12** via the return line **25**.

[0052] An exemplary version of a chamber **11** is shown in FIG. **2**. The chamber **11** includes a surface **111** to be cooled exposed therein, one or more inlets **113** to permit fluid to enter the chamber **11**, and one or more outlets **114** to permit fluid to exit the chamber **11**. In this manner, the chamber **11** is configured to permit fluid to flow therethrough. The inlets **113** are preferably configured to project a stream **115** of a fluid, such as a coolant, against the surface **111**. The stream **115** of fluid projected against the surface **111** is preferably a spray stream but may also be a jet stream. As used herein, a "spray" or "spray stream" refers to a substantially atomized liquid fluid projected through a vapor medium. "Spray" or "spray stream" is contrasted with "jet" or "jet stream," wherein "jet" or "jet stream" refers to a substantially liquid fluid filament that is projected through a substantially liquid or vapor medium or mixture thereof.

[0053] The surface **111** exposed within the chamber **11** preferably comprises a surface portion of a work piece **112**, such that the streams **115** of coolant impinge directly on the work piece **112** without thermal interference materials disposed between the work piece **112** and the coolant. As used herein, "work piece" refers to any electronic or non-electronic device having a surface that generates heat and that is desired to be cooled. Non-limiting, exemplary work pieces **112** include microprocessors, microelectronic circuit chips in supercomputers, or any other electronic circuits or devices requiring cooling such as diode laser packages. The surface **111** can be exposed within the chamber **11** by constructing the chamber **11** around the work piece **112** to include the surface **111** within the chamber **11**. Thus, the work piece **112** or the surface **111** thereof constitutes one wall of the chamber **11**.

[0054] The one or more inlets **113** of the chamber **11** may comprise any inlets known in the art, including any slits, apertures, or nozzles suitable for generating a stream **115** of coolant against a surface **111**. See, e.g., U.S. Pat. Pub. 2006/0196627 to Shedd et al. and U.S. Pat. No. 6,993,926 to Rini et al. Various types of nozzles include pressure atomizer nozzles, vapor assist nozzles, and vapor atomizer nozzles. The inlets **113** may comprise apertures in a generally flat nozzle plate but preferably comprise one or more tubular nozzles **131** that extend into the chamber **11**. The tubular nozzles **131** provide a drainage path **132** for vapor or liquid coolant through the chamber **11**. The drainage path **132** provided by the tubular nozzles **132** prevents exiting coolant from substantially interfering with the streams **115** projected from the inlet **113** and thereby substantially protect the incoming streams **115** from the exiting, warm coolant. The tubular nozzles **131** and optional associated inlet manifold **134** may be made from a variety of materials selected for ease of manufacture and compatibility with the chosen coolant. They may even be injection molded to cut manufacturing costs significantly.

[0055] Each tubular nozzle **131** comprises a central axis **133** defined by the extended dimension of the tubular nozzle **131**. The central axis **133** of the tubular nozzle **131** may either be angled perpendicularly with respect to the surface **111** or angled non-perpendicularly with respect to the surface **111**, the latter of which is shown in FIG. **2**. If angled non-perpendicularly with respect to the surface **111**, the central axis **133** may define any angle between 0° and 90° with respect to the surface **111**, such as about 5°, about 10°, about 15°, about 20°, about 25°, about 30°, about 35°, about 40°, about 45°, about 50°, about 55°, about 60°, about 65°, about 70°, about 75°, about 80° or about 85° or any range therebetween. The tubular nozzles **131** may comprise any cross-sectional shape when viewed along the central axis **133**. Various versions include a circular shape, an oval shape (to generate a fin-shaped nozzle), and virtually any other cross-sectional shape.

[0056] The chamber **11** preferably includes an array **135** of tubular nozzles **131**. The central axes **133** of the tubular nozzles **131** in the array **135** may define different angles with respect to the surface **111**. A preferred arrangement is wherein the central axis **133** of each tubular nozzle **131** in the array **135** comprises the same angle with respect to surface **111**, as shown in FIG. **2**.

[0057] The array of tubular nozzles **131** may be arranged in any configuration suitable for cooling the surface **111**. In a version of the invention depicted in FIG. **3**, the arrays **135** are organized into staggered columns **136** and rows **137**. The staggering of tubular nozzles **131** in the array **135** is such that a given tubular nozzle **131** in a given column **136** and row **137** does not have a corresponding tubular nozzle **131** in a neighboring row **137** in the given column **136** or a corresponding tubular nozzle **131** in a neighboring column **136** in the given row **137**. If the tubular nozzles **131** are configured to induce a substantially same direction of flow **145** along the surface **111** (see below), either the columns **136** or the rows **137** are preferably oriented substantially perpendicularly to the substantially same direction of flow **145**. Arrays **135** of tubular nozzles **131** in a non-staggered arrangement can also be used in the present invention.

[0058] The tubular nozzle **131** may be configured to project a stream **115** having any of a variety of shapes and any of a variety of trajectories. With regard to shape, the stream **115** is preferably a symmetrical stream. As used herein, "symmetrical stream," refers to a stream **115** that is symmetrical in cross section. Examples of symmetrical streams include linear streams, fan-shaped streams, and conical streams. Linear streams have a substantially constant cross section along their length. Conical streams have a round cross section that increases along their length. Fan-shaped streams have a cross section along their length with one cross-sectional axis being significantly longer than a second, perpendicular cross-sectional axis. In some versions of the conical streams, at least one and possibly both of the cross-sectional axes increase in length along the length of the stream. With regard to trajectory, the stream **115** preferably comprises a central axis **116** (see FIG. **2**). For the purposes herein, the "central axis **116** of the stream **115**" is the line formed by center points of a series of transverse planes taken along the length of the stream **115**, wherein each transverse plane is oriented to overlap with the smallest possible surface area of the stream **115**, and each center point is the point on the transverse plane that is equidistant from opposing edges of the stream **115** along the transverse plane. In preferred versions, the tubular nozzle **131** projects a stream **115** having a central axis **116** that is substantially collinear with the central axis **133** of the tubular nozzle **131**. However, the tubular nozzle **131** may also project a stream **115** having a central axis **116** that is angled with respect to the central axis **133** of the tubular nozzle **131**. The angle of the central axis **116** of the stream **115** with respect to the central axis **133** of the tubular nozzle **131** may be any angle between 0° and 90°, such as about 1°, about 2°, about 3°, about 4°, about 5°, about 7°, about 10°, about 15°, about 20°, about 25°, about 30°, about 35°, about 40°, about 45°, about 50°, about 55°, about 60°, about 65°, about 70°, about 75°, or about 80° or any range therebetween. In such versions, the tubular nozzle **131** preferably projects a stream **115** wherein at least one portion of the stream **115** is projected along the central axis **133** of the tubular nozzle **1310**. However, the tubular nozzle **131** may also project a stream **115** wherein no portions of the stream **115** are projected along the central axis **133** of the tubular nozzles **131**.

[0059] Similarly, the tubular nozzle **131** may be configured to project a stream **115** that impinges on the surface **111** at any of a variety of angles. In some versions, the tubular nozzle **131**

projects a stream **115** at the surface **111** such that the entire stream (in the case of a linear stream), or at least the central axis **116** of the stream **115** (in the case of conical or fan-shaped streams), impinges perpendicularly on the surface **111** (i.e., at a 90° angle with respect to the surface). Perpendicular impingement upon a surface **111** induces radial flow of coolant **144** from contact points **141** along the surface **111**. While arrays **140** of perpendicularly impinging streams **115** are suitable for some applications, they are not optimal in efficiency. This is because opposing coolant flow from neighboring contact points interacts to form stagnant regions. Heat transfer performance in these stagnant regions can fall to nearly zero.

[0060] In a preferred version of the invention, the tubular nozzles **131** are configured to project a stream **115** that impinges on the surface **111** such that at least the central axis **116** of the stream **115**, and more preferably the entire stream **115**, impinges non-perpendicularly on the surface **111** (i.e, at an angle other than 90° with respect to the surface). As a non-limiting example, the central axis **116** of the stream **115** may impinge on the surface **111** at any angle between 0° and 90°, such as about 1°, about 2°, about 3°, about 4°, about 5°, about 7°, about 10°, about 15°, about 20°, about 25°, about 30°, about 35°, about 40°, about 45°, about 50°, about 55°, about 60°, about 65°, about 70°, about 75°, or about 80° or any range therebetween. FIG. **4** depicts a top plan view of a surface **111** on which each stream **115** of an array of streams impinges non-perpendicularly on the surface **111**. Such impingement creates a flow pattern in which all the coolant **144** flows along the surface **111** in the substantially same direction **145**. In some versions of patterns flowing in the substantially same direction **145**, flow of coolant **144** at each portion of the surface **111** comprises a common directional vector component along a plane defined by the surface **111**. In other versions, coolant **144** at no two points on the surface **111** flows in opposite directions. In yet other versions, coolant **144** at no two points on the surface **111** flows in opposite directions or flows in perpendicular directions. Flowing coolant **144** in the substantially same direction eliminates stagnant regions on the surface **111**.

[0061] As further shown in FIG. **4**, tubular nozzles **131** in an array **140** are preferably configured to impinge streams **115** on the surface **111** in an array **140** of contact points **141** comprising staggered columns **142** and rows **143**. The staggering is such that a given contact point **141** in a given column **142** and row **143** does not have a corresponding contact point **141** in a neighboring column **142** in the given row **143** or a corresponding contact point **141** in a neighboring row **143** in the given column **142**. If the coolant **144** is induced to flow across the surface **111** in a substantially same direction **145**, as in FIG. **4**, either the columns **142** or the rows **143** are preferably oriented substantially perpendicularly to the substantially same direction **145** of flow. Arrays **140** of contact points **141** arranged in this manner permit coolant **144** emanating from each contact point **141** in a given column **142** or row **143** to flow substantially between contact points **141** in a neighboring column **142** or row **143**, respectively, as shown in FIG. **4**. Even, consistent flow of coolant **144** over a surface **111** without stagnant regions as provided by this configuration encourages bubble generation and evaporation of coolant **144** contacting the surface **111** whereby the heat transfer performance increases significantly.

[0062] The phase separator **12**, or vapor-liquid separator, includes any device capable of separating the vapor and liquid phases of coolant exiting from the chamber **11** and selectively distributing each separated phase to a downstream device. The phase separator **12** is preferably also capable of collecting, accumulating, and storing coolant when not cycling through the device. The phase separator **12** in this respect also serves as a volume buffer, which is useful in accommodating varying heat loads. A preferred phase separator **12** is an accumulator, many versions of which are known in the art. In one version, an accumulator is a vertical vessel comprising one or more inlets **121**, a vapor outlet **122** on an upper portion of the vessel and a liquid outlet **123** near a lower portion of the vessel (see FIG. **1**). Mixed-phase fluid enters the inlet **121** or inlets **121**. The liquid portion of the mixed-phase fluid settles to the bottom of the vessel by gravity, wherein it is withdrawn through the liquid outlet **123**. The vapor travels upward, preferably at a design velocity which minimizes entrainment of liquid droplets as the vapor exits through the vapor outlet **122**. Phase separators are also known in the art as flash drums, knock-out drums, knock-out pots, compressor suction drums, accumulators, receivers or compressor inlet drums.

[0063] The compressor **21** includes any device capable of compressing, or pressurizing, a vapor. Common suitable compressors include reciprocating, rotary screw, scroll, centrifugal, diaphragm, axial-flow, diagonal or mixed-flow, liquid-ring, or roots blower compressors. Reciprocating compressors are piston-style, positive displacement compressors. Rotary screw compressors are also positive displacement compressors, but employ two meshing screw-rotors that rotate in opposite directions to trap vapor and reduce the volume of the vapor along the rotors to a discharge point. Scroll compressors are also positive displacement compressors, wherein vapor is compressed when one spiral orbits around a second stationary spiral, thereby creating smaller and smaller pockets and higher pressures. Centrifugal compressors are dynamic compressors that raise the pressure of the vapor by imparting velocity to a vapor, typically using a rotating impeller, and converting the velocity to pressure. Diaphragm, axial-flow, diagonal or mixed-flow, liquid-ring, and roots blower compressors are well-known in the art and are not described in detail herein. The compressor **21** can be open, hermetic, or semi-hermetic, with respect to how the compressor and/or motor is situated in relation to the refrigerant being compressed. Typically in hermetic, and most semi-hermetic compressors (sometimes known as accessible hermetic compressors), the compressor and motor driving the compressor are integrated and operate within the coolant system. The motor is hermetic and is designed to operate, and be cooled by, the coolant being compressed. An open compressor has a motor drive which is outside of the coolant system, and provides drive to the compressor by means of an input shaft with suitable gland seals. Open compressor motors are typically air cooled.

[0064] The condenser **22** includes any device capable of cooling and condensing the compressed vapor into a liquid form. The condenser **22** may therefore include any heat exchanger known in the art. Suitable heat exchangers may exchange heat from the compressed vapor exiting the compressor to an external cooling fluid and/or air. Non-limiting examples include shell-and-tube, fin-and-tube, micro-channel, plate, adiabatic-wheel, plate-fin, pillow-plate, fluid, dynamic-scraped-surface, phase-change, direct-contact, and spiral heat exchangers. The heat exchanger may operate by parallel flow or counter flow.

[0065] The expansion valve **23** is preferably configured to expand in a manner that forces a drop in pressure of the cooled, condensed liquid coolant to induce evaporation of the coolant. The expansion valve **23** ensures that coolant being recycled to the phase separator **12** includes at least a minimal amount of vapor, the latter of which is separated in the phase separator **12** and diverted from the vapor-compression loop **20** to the vapor mixer **32**, if required. The expansion valve **23** also ensures that coolant diverted from the vapor-compression loop **20** to the chamber **11** is in a saturated condition. The expansion valve **23** is preferably configured to induce the compressed liquid to evaporate to about 1% vapor, about 2.5% vapor, about 5% vapor, about 7.5% vapor, about 10% vapor, about 15% vapor, about 20% vapor or more. Expansion of the coolant in the expansion valve **23** is accompanied by a drop in temperature.

[0066] The liquid pressurizer **31** includes any device capable of pressurizing liquid coolant to a level sufficient to force the coolant through the inlets **113** and against the surface **111**. The liquid pressurizer **31** is preferably a pump. Suitable pumps include gear pumps, variable speed positive displacement pumps, peristaltic pumps, centrifugal pumps coupled with a back pressure regulator, or any other pump known in the art. An example of a suitable pump includes the "MICROPUMP"-brand gear pump (Cole-Parmer, Vernon Hills, Ill.). A variable liquid pressurizer, such as a variable speed pump, enables the flow of coolant to be set at a rate required to meet the expected heat load at the surface **111**. The liquid pressurizer **31** may further include a controller with a variable speed drive. See, e.g., U.S. Pat. Pub. 2006/0196627 to Shedd et al., incorporated herein by reference. These elements enable the liquid pressurizer **31** to operate at a lower power when the thermal load falls. In place of or in addition to a pump, the liquid pressurizer **31** may comprise a reservoir of pressurized coolant. Alternatively, the liquid pressurizer **31** may comprise a jet pump, as described in more detail below.

[0067] The vapor mixer **32** includes any device capable of mixing vapor with liquid coolant. The vapor mixer **32** preferably introduces heat to liquid and thereby increases the enthalpy of the liquid coolant at a substantially constant pressure. Various exemplary versions are shown in FIGS. **5**A-B. In FIG. **5**A, a vapor fluid line **321** carrying pressurized, hot vapor, such as that generated by a compressor **21**, terminates in a perforated diffuser **323**. The perforated diffuser **323** is disposed within a liquid fluid line **322** carrying pressurized liquid, such as that generated by a liquid pressurizer **31**, and diffuses the hot vapor therein. In this version, a vapor valve **15** upstream of the diffuser **323** may be replaced with a plunger in the perforated diffuser to regulate the amount of vapor delivered to the liquid. In FIG. **5**B, an array of tubes **324** is disposed within a vapor fluid line **321** carrying pressurized hot vapor in a configuration that permits the vapor to enter a first end **325** of the array **324** and exit a second end **326** of the array **324**. A liquid fluid line **322** carrying pressurized liquid terminates in the tubes at perforations in the walls of the tubes. The liquid enters the tubes through the perforations and mixes with the vapor passing through.

[0068] In some versions of the invention, the liquid pressurizer **31** and vapor mixer **32** can be replaced with a single device that fulfills both the pressurizing and mixing functions, such as a jet pump **40**. A suitable exemplary jet pump is shown in FIG. **6**. The jet pump **40** uses the Venturi effect of a converging-diverging nozzle to convert the pressure energy of compressed vapor **41** entering the jet pump **40** to a velocity energy within the jet pump **40**. The velocity energy creates a low-pressure zone **43** within the jet pump **40** that draws in and entrains liquid coolant **42**. The liquid coolant **42** and the vapor **41** mix, pass through a converging "throat" section **44**, and subsequently pass through a diverging section **45**, wherein the velocity energy is converted back to pressure energy. Use of a jet pump **40** permits simultaneous pressurizing and mixing of fluid and vapor and can therefore serve both the liquid pressurizing and vapor mixing functions in the apparatus **1**. Jet pumps are otherwise known in the art as an injector, ejector, steam injector, steam ejector, eductor-jet pump, or thermocompressor.

[0069] The two-phase flow detector **33**, non-limiting examples of which are shown in FIGS. **5**A and **5**B, includes any device capable of detecting presence, absence, and/or amount of bubbles **332** in a fluid line or tubing. The two-phase flow detector **33** is preferably capable of monitoring fluid in real-time. The two-phase flow detector **33** preferably runs to a processor (not shown) that determines whether or not there are bubbles **332** in liquid coolant or the degree of bubbles **332** in the liquid coolant. The presence of small bubbles **332** indicates that the liquid coolant is at saturation (no more vapor will condense). The processor then sends a control signal to the vapor valve **15** to adjust accordingly. Examples of suitable two-phase flow detectors include optical bubble detectors such as a digital camera **333**. The digital camera **333** may be coupled with an LED strobe **334** to provide light for capturing images. Other exemplary bubble detectors include "LIQUID-EYE"-brand (Ivek Corporation, North Springfield, Vt.) and "LIFEGUARD"-brand (Moog, Inc., Salt Lake City, Nev.) bubble detectors. Non-optical detectors include an orifice plate with a pressure sensor to measure increased pressure loss due to bubbles, a fiber optic whose light-carrying properties change when in contact with the vapor of a bubble, or a temperature/pressure sensor combination that determines when the temperature no-longer changes independently from the pressure.

[0070] Additional chambers **11** may be added to the apparatus **1**. The additional chambers **11** are preferably, but not necessarily, added in parallel such that they are serviced by the same vapor-compression loops **20** and liquid-evaporation loops **30**. Alternatively or in addition, the apparatus **1** may include additional liquid pressurizers **31**, compressors **21**, condensers **22**, two-phase flow detectors **33**, vapor mixers **32**, etc., in parallel for the purpose of redundancy, reliability, or enhanced cooling effectiveness. As used herein, an additional component "in parallel" refers to a component in fluid communication with the other components in a manner that bypasses only components of the same type without bypassing different types of components. For example, an additional chamber **11** may be added to the apparatus **1** as shown in FIG. **1** by having the proximal portion of the inlet feed line **13** split downstream from where the vapor-compression loop **20** merges with it, such that the split portion of the inlet feed line **13** feeds into two separate chambers **11**. Fluid lines in fluid communication with the outlets **114** of the chambers **11** would then either converge before feeding into the phase separator **12** or would both separately feed into the phase separator **12**.

[0071] In a variation of the exemplary apparatus **1** described herein, the pressurized liquid may be heated by an alternative heat-transfer apparatus, such as one comprising a heat exchanger. The heat exchanger may comprise the heat exchanger of the vapor-compression loop **20** or be coupled thereto, wherein at least some of the heat removed from the compressed vapor during the condensing step is transferred to the liquid coolant to generate saturated liquid coolant. The heat exchanger is preferably configured to vary the amount of heat transferred in accordance with a signal sent from the two-phase flow detector **33** or a processor operationally connected thereto.

[0072] In another variation of the exemplary apparatus **1** described herein, the liquid loop **30** also includes a circuit valve, which enables the vapor-compression loop **20** to cool the chamber **11** in the manner of a conventional vapor-compression cooling system without the aid of the liquid-evaporation loop **30**.

[0073] In yet another variation of the exemplary apparatus **1** described herein, the expansion valve **23** may be adjustable to vary the degree of expansion. In addition, a second two-phase flow detector **33** may be disposed downstream of the adjustable expansion valve **23** to regulate the degree of evaporation in expanded coolant, thereby providing an additional control to ensure that coolant entering the phase separator **12** or the chamber **11** is at saturation.

[0074] An exemplary method of cooling a surface **111** includes collecting in a phase separator **12**, such as an accumulator, coolant draining from an outlet **114** of the chamber **11**. The phase separator **12** separates collected vapor coolant from collected liquid coolant. The phase separator **12** then delivers the separated vapor coolant to the compressor **21** for circulation in a vapor-compression loop **20** and delivers the separated liquid coolant to the liquid pressurizer **31** for circulation in a liquid-evaporation loop **30**.

[0075] In the vapor-compression loop **20** the compressor **21** compresses the separated vapor coolant and simultaneously increases its temperature as well. An amount of the heated, compressed vapor is diverted to the vapor mixer **32** of the liquid-evaporation loop as needed to ensure two-phase flow in the liquid-evaporation loop. The remaining heated, compressed vapor proceeds to the condenser **22**, where it is cooled and condensed into a liquid. The cooled and condensed liquid proceeds through the expansion valve **23**, wherein it undergoes an abrupt reduction in pressure, resulting in evaporation of the liquid and a further reduction in temperature. The coolant at this point is at its saturation state. Depending on the degree at which the circuit valve **24** is opened, a certain proportion (0-100%) of the saturated coolant is diverted to the liquid-evaporation loop **30** through the proximal portion of the inlet feed line **13** and the chamber **11** before being recycled back to the phase separator **12**. This diverted saturated coolant is used to regulate the pressure in the chamber **11**. The diverted saturated coolant also aids the liquid-evaporation loop **30** in cooling the surface **111** in the manner of a conventional refrigeration cycle. The degree to which the circuit valve **24** is opened or closed is preferably a function of the pressure required for cooling the surface **111** in the chamber **11**. The remaining proportion (0-100%) of the saturated coolant is directly recycled back to the phase separator **12** via the return line **25**. The recycled saturated coolant ensures that a certain degree of vapor is supplied to the phase separator **12** for downstream use.

[0076] In the liquid-evaporation loop **30**, the liquid pressurizer **31** pressurizes the separated liquid coolant. The pressurized liquid coolant is then heated. The pressurized liquid coolant is preferably heated by mixing with the hot, compressed vapor emerging from the compressor **21** in the vapor mixer **32**, wherein the vapor is diverted to the vapor mixer **32** by virtue of the vapor valve **15** being open. The heated coolant then passes the two-phase flow detector **33**. If the heated coolant does not contain bubbles **332**, the two-phase flow detector **33** communicates to the vapor valve **15**, such as through a processor, to progressively open and increase the amount of vapor passing into the vapor mixer **32** to increase heating of the liquid coolant. If the heated coolant contains too many bubbles **332**, the two-phase flow detector **33** communicates to the vapor valve **15** to progressively close to reduce the amount of vapor passing into the vapor mixer **32** to decrease heating of the liquid coolant. In this manner, the two-phase flow detector **33** and vapor valve **15** regulate the heating of the liquid coolant. The detection of bubbles **332** ensures that the liquid coolant is heated to its saturation temperature prior to entering the chamber **11**. After being heated to its saturation temperature, the heated coolant is either injected directly into the chamber **11** or mixed with the saturated coolant from the vapor-compression loop **20** before being injected into the chamber **11**.

[0077] The coolant is introduced in the chamber **11** and projected against the surface **111** either as a spray stream or as a jet stream. It is preferred that the coolant being introduced is at or approximately at saturation such that it at least partially evaporates upon entering the chamber **11**. The evaporation is induced by the pressure drop that the coolant undergoes upon passing into the chamber **11** from the inlets **113**. The evaporation is particularly preferred for spray streams, wherein the evaporation aids in atomizing the coolant. The evaporation cools the coolant prior to contacting the surface **111**. Further evaporation of the coolant upon contacting the surface **111** and subsequently being heated by it results in efficient cooling of the surface **111**. The vapor coolant and remaining liquid coolant then drain from the chamber **11** through the outlet **114** and return to the phase separator **12** for further cycles.

[0078] In a preferred version of the invention, the cooling system is designed herein to permit cycling of coolant through the liquid-evaporation loop **30** simultaneously and in parallel with the vapor-compression loop **20**, wherein the liquid-evaporation loop **30** is primarily responsible for cooling the surface **111**, and the vapor-compression loop **20** aids the liquid-evaporation loop **30** by regulating pressure in the chamber **11**, maintaining desired conditions in the phase separator **12**, and providing heated, compressed vapor to the liquid-evaporation loop **30** to ensure saturated coolant enters the chamber **11**. The vapor-compression loop can also contribute to providing saturated coolant to the chamber **11** when and to the degree that the circuit valve **24** is open. With the supporting role of the vapor-compression loop **20** in this version, it is not necessary that coolant is constantly cycled through the vapor-compression loop **20**. Coolant may instead be cycled through the vapor-compression loop **20** intermittently and only as needed to fulfill its supporting roles.

[0079] The present invention is directed, in part, to preparing coolant so that it evaporates upon entering the chamber **11** and prior to contacting the surface **111**. This is distinct from evaporation that occurs after the coolant contacts the surface **111** and is heated by it.

[0080] The elements and method steps described herein can be used in any combination whether explicitly described or not. All combinations of method steps as described herein can be performed in any order, unless otherwise specified or clearly implied to the contrary by the context in which the referenced combination is made.

[0081] As used herein, the singular forms "a," "an," and "the" include plural referents unless the content clearly dictates otherwise.

[0082] Numerical ranges as used herein are intended to include every number and subset of numbers contained within that range, whether specifically disclosed or not. Further, these numerical ranges should be construed as providing support for a claim directed to any number or subset of numbers in that range. For example, a disclosure of from 1 to 10 should be construed as supporting a range of from 2 to 8, from 3 to 7, from 5 to 6, from 1 to 9, from 3.6 to 4.6, from 3.5 to 9.9, and so forth.

[0083] All patents, patent publications, and peer-reviewed publications (i.e., "references") cited herein are expressly incorporated by reference to the same extent as if each individual reference were specifically and individually indicated as being incorporated by reference. In case of conflict between the present disclosure and the incorporated references, the present disclosure controls.

[0084] The methods and compositions of the present invention can comprise, consist of, or consist essentially of the essential elements and limitations described herein, as well as any additional or optional steps, ingredients, components, or limitations described herein or otherwise useful in the art.

[0085] The present disclosure is filed simultaneously with U.S. application Ser. No. ______ to Timothy A. Shedd, filed Apr. ______, 2011 under Attorney Docket Number 09820.948, and entitled High Efficiency Thermal Management System, the entirety of which is incorporated herein by reference.

[0086] It is understood that the invention is not confined to the particular construction and arrangement of parts herein illustrated and described, but embraces such modified forms thereof as come within the scope of the claims.

I claim:

1. An apparatus for cooling a surface comprising:
- at least one chamber with the surface exposed therein, the chamber comprising an inlet and an outlet and being configured for flowing fluid therethrough by entering through the inlet in a stream projected against the surface and exiting through the outlet;
- a liquid source in fluid communication with the inlet of the chamber; and
- a heat-transfer apparatus configured to transfer heat to liquid derived from the liquid source upstream of the inlet.

2. The apparatus of claim **1** further comprising a heat-transfer regulator configured to adjust amount of heat transferred via the heat-transfer apparatus to the liquid.

3. The apparatus of claim **2** wherein the heat-transfer regulator comprises a two-phase flow detector disposed between the heat-transfer apparatus and the inlet, the two-phase flow detector configured to communicate with a device that adjusts an amount of heat transferred via the heat-transfer apparatus to the liquid in response to an amount of vapor phase detected in the liquid.

4. The apparatus of claim **1** wherein the heat-transfer apparatus comprises a vapor mixer in fluid communication with the liquid source and a vapor source.

5. The apparatus of claim **4** further comprising a vapor valve disposed between the vapor mixer and the vapor source, the vapor valve configured to adjust flow of vapor to the vapor mixer.

6. The apparatus of claim **5** further comprising a two-phase flow detector in communication with the vapor valve and disposed between the vapor mixer and the inlet, the two-phase flow detector configured to communicate with the vapor valve to adjust flow of vapor to the vapor mixer in response to an amount of vapor phase detected in the liquid.

7. The apparatus of claim **1** wherein the liquid source comprises:
- a phase separator in fluid communication with the outlet of the chamber; and
- a liquid pressurizer in fluid communication with the phase separator in a configuration to selectively receive liquid therefrom, the liquid pressurizer further being in fluid communication with the heat-transfer apparatus.

8. The apparatus of claim **1** wherein the heat-transfer apparatus comprises a vapor mixer in fluid communication with the liquid source and a vapor source, wherein the vapor source comprises:
- a phase separator; and
- a compressor in fluid communication with the phase separator in a configuration to selectively receive vapor therefrom, the compressor further being in regulated fluid communication with the vapor mixer.

9. The apparatus of claim **8** further comprising:
- a condenser in fluid communication with the compressor in a configuration to receive fluid therefrom and further in fluid communication with the phase separator via a return line in a configuration to deliver fluid to the phase separator; and
- an expansion valve disposed between the condenser and the return line.

10. The apparatus of claim **9** wherein the condenser is further in fluid communication with the inlet of the chamber to deliver fluid thereto, the chamber is in fluid communication with the phase separator to deliver fluid thereto, and the apparatus further comprises:
- a circuit valve disposed between the expansion valve and the inlet, the circuit valve configured to adjust flow of fluid from the expansion valve to the inlet.

11. The apparatus of claim **10** further comprising:
- a first fluid loop comprising:
  - the chamber;
  - a phase separator as the liquid source, wherein the phase separator is in fluid communication with the outlet of the chamber;
  - a liquid pressurizer in fluid communication with the phase separator in a configuration to selectively receive liquid therefrom, the liquid pressurizer further being in fluid communication with the heat-transfer apparatus; and
  - the vapor mixer; and
- a second fluid loop comprising:
  - the phase separator;
  - the compressor;
  - the condenser;
  - the expansion valve; and
  - the return line,
- wherein the apparatus is configured to cycle fluid through the first fluid loop and at least intermittently cycle fluid simultaneously through the second fluid loop.

12. The apparatus of claim **1** wherein the heat-transfer apparatus comprises a heat exchanger.

13. The apparatus of claim **1** wherein the heat-transfer apparatus comprises a jet pump.

14. A method of cooling a surface within a chamber comprising:

preparing a coolant approximately at saturation, wherein the preparing comprises heating pre-heated coolant to approximately a saturation temperature to generate heated coolant;

introducing the heated coolant through an inlet of the chamber which includes projecting a stream of the heated coolant against the surface, wherein the heated coolant at least partially evaporates as it enters the chamber prior to contacting the surface; and

draining partially evaporated coolant through an outlet of the chamber.

15. The method of claim **14** further comprising detecting amount of vapor phase in the heated coolant and regulating the heating in response to the amount of detected vapor phase.

16. The method of claim **14** wherein the heating comprises:

collecting the partially evaporated coolant draining from the outlet of the chamber to obtain collected coolant;

separating the collected coolant into liquid coolant and vapor coolant;

selectively pressurizing the liquid coolant to obtain pressurized liquid coolant; and

heating the pressurized liquid coolant.

17. The method of claim **14** wherein the heating comprises mixing the pre-heated coolant with vapor.

18. The method of claim **17** wherein the heating comprises:

collecting vapor-containing coolant to obtain collected coolant;

separating the collected coolant into liquid coolant and vapor coolant;

selectively compressing the vapor coolant to obtain compressed vapor coolant; and

mixing at least a first portion of the compressed vapor coolant with the pre-heated coolant.

19. The method of claim **18** further comprising:

condensing at least a second portion of the compressed vapor coolant to generate condensed coolant;

expanding the condensed coolant to approximately a saturation pressure of the condensed coolant to generate expanded coolant; and

performing a process selected from the group consisting of:

recycling at least a first portion of the expanded coolant, wherein the first portion of the expanded coolant comprises at least a portion of the vapor-containing coolant in the collecting step; and

mixing at least a second portion of the expanded coolant with the heated coolant prior to the introducing the heated coolant through the inlet of the chamber, wherein the collecting the vapor-containing coolant includes collecting the partially evaporated coolant draining from the outlet of the chamber.

20. A method of cooling a surface within a chamber comprising cycling fluid through a first loop and at least intermittently cycling fluid simultaneously through a second loop, wherein:

the cycling through a first loop comprises:

introducing a substantially saturated coolant through an inlet of the chamber which includes projecting a stream of the substantially saturated coolant against the surface, wherein the substantially saturated coolant at least partially evaporates as it enters the chamber prior to contacting the surface;

draining partially evaporated coolant through an outlet of the chamber;

collecting the partially evaporated coolant to obtain collected coolant;

separating the collected coolant into liquid coolant and vapor coolant;

selectively pressurizing the liquid coolant to obtain pressurized liquid coolant prior to the introducing; and

the cycling through the second loop comprises:

the collecting, wherein the collecting further comprises collecting vapor-containing coolant;

the separating;

selectively compressing the vapor coolant to obtain compressed vapor coolant;

mixing at least a first portion of the compressed vapor coolant with the pressurized liquid coolant to generate the coolant substantially at saturation;

condensing at least a second portion of the compressed vapor coolant to generate condensed coolant;

expanding the condensed coolant to approximately a saturation pressure of the condensed coolant to generate expanded coolant; and

performing a process selected from the group consisting of:

recycling at least a first portion of the expanded coolant, wherein the first portion of the expanded coolant comprises at least a portion of the vapor-containing coolant; and

mixing at least a second portion of the expanded coolant with the coolant substantially at saturation prior to the introducing, wherein the collecting the vapor-containing coolant includes collecting the partially evaporated coolant draining from the outlet of the chamber.

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