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(54) **A heat transfer apparatus**

(57) An apparatus comprises a housing having a wall, at least a portion of the wall is thermally conductive. A working fluid is enclosed within the housing and can change phase between a liquid phase and a vapor phase when it exchanges heat with the thermally conductive portion of the wall. The apparatus further has an electrode located inside the housing. When a voltage is applied between the electrode and an electrically conductive portion of the wall an electric field is generated which capable of exerting a force on the working fluid to thereby cause the working fluid to move under the effect of said force.

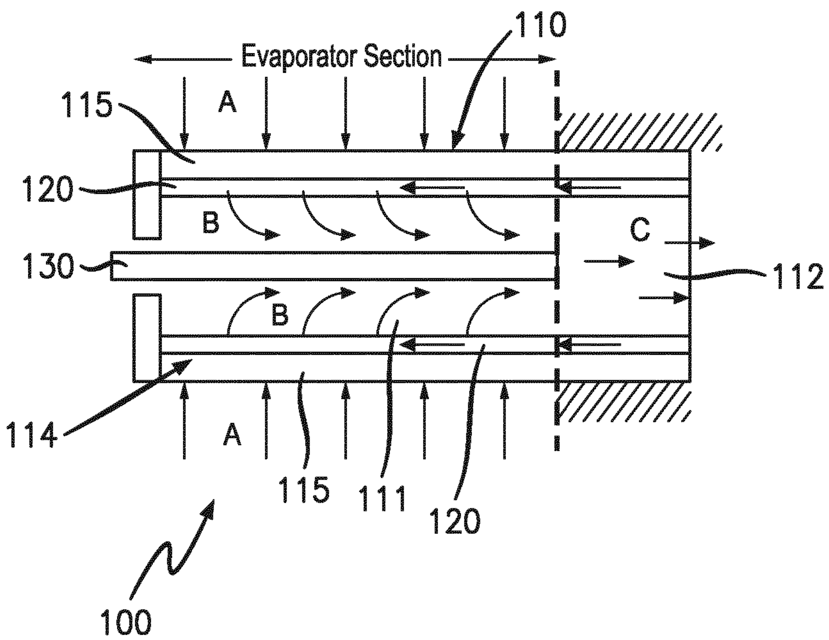

FIG. 2

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Description

BACKGROUND

[0001] Apparatus for transferring heat, such as heat pipes and thermosyphons are used extensively in a variety of thermal management applications to effectively transfer heat from heat sources, such as electronic components to heat sinks which are typically located at moderate distances from the heat source. The ability to control heat transfer characteristics or effective thermal resistance of such apparatus would allow for improved heat source temperature control and device reliability.

SUMMARY

[0002] Some embodiments feature An apparatus comprising:

- a housing having a wall, at least a portion of the wall being thermally conductive;
- a working fluid enclosed within the housing and configured to change between a liquid phase and a vapor phase in response to exchange of heat with the thermally conductive portion of the wall; and
  an electrode located inside the housing;
  wherein the apparatus is configured to generate an electric field in response to applying a voltage between the electrode and an electrically conductive portion of the wall, said electric field being capable of exerting a force on the working fluid.

[0003] According to some specific embodiments, the fluid is in liquid phase and the apparatus is configured to attract the liquid to the electrode.
[0004] According to some specific embodiments, the fluid is in liquid phase containing bubbles and the apparatus is configured to repel the bubbles away from the electrode.
[0005] According to some specific embodiments, the attraction of the liquid to the electrode causes reduction in a thickness of a layer of the liquid on the thermally conductive wall.
[0006] According to some specific embodiments, the attraction of the liquid to the electrode causes generation of one or more dry areas on the thermally conductive wall.
[0007] According to some specific embodiments, the housing comprises an evaporation section configured to evaporate a liquid phase fluid upon receiving heat from the thermally conductive wall and a condenser section configured to condense into liquid a vapor phase fluid by emitting heat to the thermally conductive wall. According to some specific embodiments, the apparatus is configured to attract the liquid phase of the fluid to the electrode in the condenser section such that flow of the liquid phase fluid to the evaporator section is substantially avoided. According to some specific embodiments, the apparatus further comprises an adiabatic section located between the evaporator section and the condenser section and, wherein the electrode is located in the adiabatic section and is configured to attract the liquid phase of the fluid to the electrode such that flow of the liquid phase fluid to the evaporator section is reduced.
[0008] According to some specific embodiments, the electrode comprises a plurality of segments, configured to be individually energized by applying a voltage thereto such that a voltage applied to one segment is different from a voltage applied to another segment.
[0009] According to some specific embodiments, the plurality of segments are sequentially energized such that the fluid receives a plurality of sequential forces. According to some specific embodiments, various electrodes are placed in various sections inside the housing.
[0010] According to some specific embodiments, an electrode is extended into a plurality of the sections inside the housing.
[0011] According to some specific embodiments, the electrode has a shape with one or more sharp edges.
[0012] According to some specific embodiments, the apparatus is a heat pipe. According to some specific embodiments, the apparatus is a thermosyphon.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013]

Figure 1 is an exemplary schematic representation of a known heat transfer apparatus.
Figure 2 is an exemplary schematic representation of a portion of an apparatus in which the principles of the disclosure are implemented.
Figures 3A and 3B are exemplary schematic representations of an apparatus according to some embodiments.

Figures 4A and 4B are exemplary schematic representations of an apparatus according to some embodiments.
Figures 5A and 5B are exemplary schematic representations of an apparatus according to some embodiments.
Figures 6A and 6B are exemplary schematic representations of an apparatus according to some embodiments.
Figures 7A and 7B are exemplary schematic representations of an apparatus according to some embodiments.

[0014] These and further features and advantages of the present invention are described in more detail, for the purpose of illustration and not limitation, in the following description as well as in the claims with the aid of the accompanying drawings.

[0015] It is to be noted that these figures are provided only for illustrative purposes and are not necessarily represented in scale.

DETAILED DESCRIPTION

[0016] Some known heat transfer apparatus, such as heat pipes or thermosyphons, typically operate through the principle of vaporization and condensation of a working fluid within a closed-loop.

[0017] Figure 1 is an exemplary schematic representation of a heat transfer apparatus, in this case a heat pipe. The heat pipe 100 includes a housing 110 having an interior space which is typically divided into three sections: evaporator section 111, adiabatic section 112 and condenser section 113. The boundaries of the three sections are represented by dashed lines. The housing comprises thermally conductive walls. A working liquid, herein also referred to as liquid, is contained inside the housing. The working liquid is capable of vaporizing and condensing under appropriate temperatures which are imposed on the heat pipe 100. Typically a heat pipe also comprises a wick structure 120 which is useful for conveying the working liquid. However, in some cases the apparatus may not include wick structures such as for example in thermosyphons. Herein the term thermosyphon is to be understood to refer to a heat pipe containing a working liquid and having a condenser and an evaporator but without a wick, which operate in an orientation with the evaporation section positioned below the condenser section, such that gravity force drives the liquid flow from the condenser back to the evaporator.

[0018] In operation, the heat pipe is installed next or close to the heat source (e.g. an electronic device to be cooled) such that the evaporator section 111, having thermally conductive walls, is typically placed at a position where it can receive the heat emitted from the heat source. This is shown in the figure by means of arrows A. The heat received causes the liquid located in the evaporator section 111 to evaporate as shown by arrows B. The vapor thus generated then flows to the adiabatic section 112 of the heat pipe 100 where there is typically no or negligible exchange of heat between the vapor and the surroundings. This movement is shown in the figure by arrows C. Next the vapor reaches the condenser section 113 where the vapor is condensed and converted to liquid phase formed on the inner surfaces of the walls of the heat pipe, or the wick structure 120 as is the case in the example of figure 1. The condensation process is represented in figure 1 by arrows D. The condensation is achieved due to a heat transfer effect in the vicinity of the condenser section 113 to remove heat from the thermally conductive walls of the housing of the heat pipe 100. Such removal of heat may be performed using external active cooling mechanisms such as a fan to blow cool air over the external surface of the condenser section 113 to remove heat from the latter as shown by arrows E. The condensed liquid present on the wick structure 120 (or the inner surfaces of the walls of the housing, if wick is not used) is then moved back to the evaporator section 111, passing through the adiabatic section 112. After reaching the evaporator section 111, the liquid undergoes another evaporation/condensation cycle in similar fashion as described above. The combined evaporation/condensation process contributes to transferring heat from the heat source and dissipating the heat to the surroundings, e.g. ambient air.

[0019] However, the thermal resistance of a heat pipe or thermosyphon of the type described above is typically not constant or linear and can vary depending on the operating conditions imposed. Furthermore, the thermal resistance of such apparatus is typically not known (at least with accuracy) prior to installation. Such thermal resistance can in fact change over the life of the heat pipe or thermosyphon. In a practical use, the heat source temperature of the device being cooled and the heat transport rate of the heat transfer apparatus assembled onto the device cannot be accurately predicted at the beginning of the life of the assembly. This is because these parameters can vary as input powers or ambient conditions change and they can drift over time. These problems can have a critical effect on the performance and reliability of the electronic components intended to be cooled, in particular those that require effective cooling and are sensitive to temperature changes.

[0020] The use of external effects or mechanisms to limit or enhance heat transfer from the heat pipe or thermosyphon may also involve drawbacks. For example, the use of variable speed fans, or other mechanisms of such type, to increase convection coefficients may have drawbacks due to added complexity associated to the use of moving parts and may pose a reliability concern for certain practical applications (for example rotary fans are typically not reliable for a relatively long lifetime). Furthermore, this option would not be viable in cases where the heat must be dissipated to the air without the assistance of fans, such as systems relying on buoyant natural convection or in vacuum or space-based applications where radiation is the only dissipation mechanism.

[0021] Another known approach for controlling the temperature of the heat source in heat pipe or thermosyphon systems is based on the use of so-called variable conductance heat pipes. In these designs, a quantity of non-condensable gas (NCG) such as for example air, nitrogen, argon and helium is added to the heat pipe to effectively "block off" part of the internal condenser section thereby limiting the area of condensation to occur within the heat pipe or thermosyphon. As the operating temperature of the heat pipe changes, the NCG volume either expands or contracts to block more or less of the condenser section. Careful design of these heat pipes allows for somewhat improved consistency of heat pipe conductance or linearity. More complex active systems employ an additional reservoir of NCG beyond the condenser and a heater is typically used to actively expand the NCG into the condoner section as required.

[0022] Embodiments of the disclosure are based on the use of Electrohydrodynamics (EHD) in a heat transfer apparatus, such as for example a heat pipe or a thermosyphon, to achieve control on heat transfer. EHD is the study of electric fields on fluid dynamics which is already known to those of skill in the pertinent arts. According to some studies, it is believed that imposing an electric field on dielectric fluids can introduce forces, in particular at liquid-gas interfaces, that alter the mechanics of the these processes and can significantly enhance or diminish heat transfer rates. Some examples of such studies are H. Sadek, A.J. Robinson, J.S. Cotton, C.Y. Ching, M. Shoukri, (2006) "Electrohydrodynamic Enhancement of In-Tube Convective Condensation Heat Transfer," International Journal of Heat and Mass Transfer, 49, (9-10), pp. 1647-1657; and J.S. Cotton, A.J. Robinson, M. Shoukri, J.S. Chang, (2005) "A Two-Phase Flow Pattern Map for Annular Channels with and without a DC Applied Voltage and the Application to Electrohydrodynamic Convective Boiling Analysis," International Journal of Heat and Mass Transfer, 48 (25-26), pp. 5536-5579, the contents of both of which are incorporated herein by reference in their entirety.

[0023] The above-identified references propose the use of EHD to enhance or control convective boiling or convective condensation in heat exchanger applications where the purpose is apparently to transfer heat from inside to outside a tube (or vice-versa). These techniques relate to open loop systems that typically rely on external pumping to drive the two-phase flow. Additionally, in these applications, the objective appears to be that of introducing EHD forces to enhance boiling or condensation in order to improve the performance of the heat exchanger. These effects usually target the entire heat transfer surface of the device.

[0024] However, in the present disclosure it is proposed that EHD effects be employed within a heat transfer apparatus which is a closed, two-phase heat transport loops where, in operation, both boiling and condensation can occur simultaneously in different regions of the device. Examples of such apparatus are heat pipes and thermosyphons. This enables the transport of heat from one location to another relatively distant location with low-effective thermal resistance, typically without requiring external pumping mechanism as is the case of the previously referenced techniques (it is however noted that heat pipes typically require an internal wick structure and rely on capillary forces to move the liquid while thermosyphons typically rely on gravity to drive the liquid flow). Furthermore, as will be described in further detail below, in the present disclosure EHD effects may be used to enhance or mitigate the internal heat transfer and two-phase flow mechanisms in heat pipes or thermosyphons, or other closed-loop, two-phase heat transfer apparatus, in order to provide an active control technique in the system where these devices are employed. This would allow for selectively varying the maximum heat transport capability or the effective thermal resistance of the device depending on system operating conditions.

[0025] Herein, the term two-phase as referred to in heat transfer is to be understood to refer to situations in which heat transfer uses a phase of liquid and a phase of vapor which may be present simultaneously or interchangeably. Furthermore, the term closed-loop is to e understood to refer to a situation where a fluid, in liquid or in vapor phase, is located inside an enclosure within the apparatus without having the possibility of flowing out of the enclosure.

[0026] Embodiments of the disclosure propose the use of EHD effects employed inside a closed-loop, two-phase, heat transfer apparatus, such as a heat pipe or a thermosyphon, to actively influence the internal fluid mechanics and thereby improve the heat transfer mechanisms.

[0027] In two phase systems, it is known that EHD can augment the flow field in such a way as to realize significant enhancement in the heat transfer. Examples of studies in this regard are W. Panofsky, M. Phillips, "Classical Electricity and Magnetism", 2nd ed., Addison-Wesley, Pub. Co., Reading, Massachusetts, 1962; and J.S. Chang, A. Watson, "Electromagnetic hydrodynamics", IEEE Transactions on Dielectrics and Electrical Insulation 1 (15) (1994) 871-895, the contents of both of which are incorporated herein by reference in their entirety.

[0028] These documents, among others, propose the following expression related to the forces induced on a dielectric medium within an electric field;

$$f_e = \rho_e \overline{E} - \frac{1}{2} E^2 \nabla \varepsilon + \frac{1}{2} \nabla \left[\rho E^2 \left(\frac{\delta \varepsilon}{\delta \rho} \right)_T \right] \qquad (1)$$

[0029] The three terms on the right hand side of equation (1), as seen from left to right represent the electrophoretic, dielectrophoretic and electrostrictive components of the EHD force respectively.

[0030] The electrophoretic force is considered to be a force that acts on the net free charge within the fluid and is dependent on the polarity of the electric field. This force will cause charged particles to move from an emitter pole to a collector pole within an electric field generated between said poles and draw neutral molecules in the same direction causing a net flow of fluid.

[0031] The dielectrophoretic force is known to arise due to spatial gradients of the permittivity. In a two phase flow the difference in permittivity of the two phases at the extremely thin liquid-vapour interface may cause this force to be significant. The last term is the electrostrictive force which is known to arise due to inhomogeneity of the permittivity with density at constant temperature. Here again, when two phases are involved, the density change can be quite large at the liquid-vapor interface and cause this force to be large as well. As expressed in equation (1), the dielecrophoretic and electrorestrictive forces depend on the electric field raised to the power of two (squared), and thus do not depend on the polarity of the electric field.

[0032] It is further known that, when electric field is applied by an energized electrode on a liquid-vapor interface, liquid extraction occurs towards the electrode. Conversely, such electric filed on a bubble will force the bubble to move away from the electrode. Reference in this regard is, for example, made to J. E. Bryan and J. Seyed-Yagoobi, "Influence of Flow Regime, Heat Flux, and Mass Flux on Electrohydrodynamically Enhanced Convective Boiling," Journal of Heat Transfer, vol. 123, pp. 355-367, 2001 the contents of which are incorporated herein by reference in its entirety.

[0033] The present disclosure relies on the concept according to which the dielectrophoretic and electrorestrictive components act in such a way as to modify the level of heat transfer in a closed-loop, two-phase heat transfer apparatus, such as a heat pipe or a thermosyphon. In particular the disclosure addresses the possibility of enhancing, deteriorating (i.e. reducing) or in the extreme case inhibiting heat transfer, using the above referenced properties related to extracting a liquid to an energized electrode or repelling bubbles from it.

[0034] Figure 2 represents a schematic example of a portion of an apparatus in which the principles of the disclosure are implemented. In figure 2, like elements have been provided with like reference numerals as those of figure 1. The apparatus may be a heat pipe, a thermosyphon or any other apparatus configured to remove heat from a heat source by an evaporation/condensation process imposed on a working liquid which is inside a closed housing. However, for simplicity, only a portion of a complete heat pipe 100 is shown in figure 2. The shown portion includes a part of a housing 110 having an interior space including an evaporator section 111 l and a portion of an adiabatic section 112. The boundary between the two sections is schematically represented a by dashed line. The housing 110 comprises walls 115 which are thermally conductive at least in the evaporator section and the condenser section of the housing. The walls 115 are also electrically conductive at least in selected portions thereof. A working liquid is contained inside the housing (it is however understood that the complete housing is a closed and substantially hollow structure). The working liquid is capable of vaporizing and condensing under appropriate temperatures which are imposed on the heat pipe 100. In the example of figure 2, the heat pipe also comprises a wick structure 120. However, in some cases the apparatus may not include wick structures such as for example in thermosyphons.

[0035] As used herein, a thermally conductive material is to be understood to refer to any material having a thermal conductivity greater than about 1W/mK (Watts per Meter Kelvin) may be considered as a thermally conductive material. Conversely, any material having a thermal conductivity of less than about 1W/mK may be considered as thermally non-conductive. Within the thermal conductivity range described above, a thermal conductivity greater than 100W/mK may be considered as a high thermal conductivity value and one within the range of 1-100W/mK may be considered as an acceptable value.

[0036] In addition, and differently from the known apparatus of figure 1, the apparatus of figure 2 includes an EHD electrode 130 located in the evaporator section 111. However, it is to be noted that the location of the EHD electrode is not limited to be inside the evaporator section and based on the requirements of each specific design requirements, the EHD electrode may also be located in the adiabatic section, or in the condenser section of the apparatus. Likewise an EHD electrode may extend into more than one of such sections, or different EHD electrodes may be located in respective different ones of the evaporator, adiabatic or condenser sections.

[0037] The EHD electrode may be any electrode made of an electrically conductive material, or a material coated with an electrically conductive layer.

[0038] Furthermore, the EHD electrode may have any suitable shape and cross-section. However, as EHD effect depends on electric field gradients, the presence of sharp corners may influence the EHD forces as such sharp corners may have high spatial gradients. Examples of electrodes with sharp corners are triangular, square, rectangle or star-shaped structures.

[0039] The EHD electrode 130 is used as an element capable of influencing the evaporation mechanisms in the evaporator section 111. In operation, the apparatus 100 is installed next or close to the heat source (e.g. an electronic device to be cooled) such that the evaporator section 111 is placed at a position where it can receive the heat emitted from the heat source. This is shown in the figure by means of arrows A (the heat source is not shown). The heat received by the apparatus causes the liquid located in the evaporator section 111 to evaporate as shown by arrows B. However, in the apparatus of figure 2 a voltage may be applied between the EHD electrode 130 and an electrically conductive internal wall 114 of the housing 110. Such voltage generates an electric field that influences the liquid evaporation mechanisms. Depending on the strength of the electric field, the geometry of the electrode and the exact nature of the EHD input signals employed, the EHD effect could serve to either enhance or reduce and even inhibit the evaporative heat transfer in the region under the effect of the electric field, as will be described in further detail below. This effect may then be used for changing the effective thermal resistance of the evaporator and the heat transport characteristics of the apparatus as a whole. Some possible configurations for enabling enhancement, reduction or inhibition of heat transfer, according to embodiments of the disclosure, are given below by way of non-limiting examples with reference to figures 3A- 3B, 4A-4B, 5A-5B and 6A-6B. Figures 3A and 3B illustrate scenarios of an exemplary configuration whereby heat transfer may be enhanced. In particular, figure 3A shows an EHD electrode 210 located proximate to a heat transfer wall 220. Furthermore, a liquid 230 is present between the heat transfer wall and the EHD electrode 210. The liquid may be contained within a wick structure (in a heat pipe) or a liquid film or pool (in a thermosyphon). The heat transfer wall 220 may be for example a portion of a wall of a heat pipe or a thermosyphon and may be in thermal contact with a heat source (e.g. an electronic component) to absorb heat therefrom, or it may be in thermal contact with a cooling source (e.g. a heat sink) to transfer the heat thereto and thereby condense the vapor back into liquid.

[0040] The heat transfer wall 220 may be totally or partially electrically conductive. In the scenario of figure 3A, no voltage is applied between the EHD electrode 210 and the electrically conductive wall 220. As a result of receiving heat from the heat source, the heat transfer wall 220 transfers such heat to the liquid 230. When the liquid reaches a sufficiently high temperature, it starts to evaporate.

[0041] In the scenario of figure 3B, in which like elements have been identified with like reference numerals, a voltage is applied between the EHD electrode 210 and the electrically conductive wall 220. An electric field is generated between said electrode 210 and said wall 220. The electric field causes the liquid to be attracted toward the energized electrode 210. The liquid attracted to the EHD electrode 210, or put differently, extracted from the heat transfer wall 220, is shown in figure 3B by reference numeral 231. It may be further observed that liquid 230 is accumulated on the EHD electrode 210 as a result of such extraction. The process of liquid extraction from the heat transfer 230 causes the thickness of the layer of the liquid 230 on the heat transfer wall 210 to decrease which in turn gives rise to a subsequent enhancement in the heat transfer. As the liquid layer gets thinner, it has a lower thermal resistance. However, once the evaporator dries out the thermal resistance increases drastically because there is no longer any liquid available to evaporate.

[0042] The scenario of figure 3B was described in relation to an evaporation process However, similar effects apply to condensation processes, where the presence of an electric field between the EHD electrode 210 and heat transfer wall 220 may cause the droplets created as a result of condensation be attracted to the EHD electrode more rapidly form the liquid which is transferred to the evaporation section, thereby enhancing heat transfer process. Similarly, using EHD to attract droplets to the electrode during condensation would serve the same purpose: namely to thin the condensate layer and lower thermal resistance.

[0043] Figures 4A and 4B are scenarios of another exemplary configuration whereby heat transfer may be enhanced. In these figures, like elements have been provided with like reference numerals as those of figures 3A and 3B. The arrangement and configuration of the EHD electrode 210, the heat transfer wall 220 and the liquid 230 is similar to those of figures 3A and 3B and therefore a detailed description thereof is considered not necessary. However, the scenarios of figures 4A and 4B differ from those of figures 3A and 3B in that in the case of figures 4A and 4B, bubbles 240 are present in the liquid 230.

[0044] Referring in particular to figure 4A, where no voltage is applied between the EHD electrode 210 and the heat transfer wall 220, the behavior of the bubbles 240 present within the liquid 230 is as in a normal condition of operation in which bubbles are formed on the hot surface of the heat transfer wall 220 and subsequently move to the surface of the liquid 230.

[0045] In the scenario of figure 4B, a voltage is applied to the EHD electrode 210 thereby generating an electric field. Such electric field exerts forces, namely EHD forces, on the bubbles which, as previously described, are in a direction to repel the bubbles away from the EHD electrode. Therefore, by applying a voltage to the EHD electrode which is capable of generating a force that is stronger than buoyancy, the bubbles are forced to move away from the electrode, and therefore away from the surface of the liquid. An interaction between this repelling force with the buoyancy which tends to force the bubbles toward the surface imposes two substantially opposite movements on the bubbles causing the bubbles to move in multi-directional patterns as represented in figure 4B by reference numeral 250. Such multi-directional movement in turn gives rise to considerable mixing which enhances the heat transfer from the heat transfer wall 220.

[0046] Referring now to figures 5A and 5B a possible example of a configuration for enabling reduction or inhibition of heat transfer is provided. In these figures, like elements have been provided with like reference numerals as those of figures 3A and 3B. The arrangement and configuration of the EHD electrode 210, the heat transfer wall 220 and the liquid 230 is similar to those of figures 3A and 3B and therefore a detailed description thereof is considered not necessary.

However, the scenarios of figures 5A and 5B differ from those of figures 3A and 3B in that in the case of figure 5B, the surface 221 of the heat transfer wall 220 is exposed to vapor phase. This may occur when a considerable amount of liquid is extracted from the heat transfer wall 220 to the EHD electrode 210 as shown by liquid droplets 231. It may be observed in figure 5B that liquid 230 is accumulated on the EHD electrode 210 as a result of such extraction. Similar to the effect shown in figure 3B, as a result of liquid extraction from the heat transfer 230, the thickness of the layer of the liquid 230 on the heat transfer wall 210 decreases. However, in the example of figure 5B the amount of exaction is such that at least portions of the surface 221 of the heat transfer wall 220 are completely left without liquid thereby generating dry patches on the surface 221 which cause the heat transfer rate to decrease. In order to achieve the scenario of figure 5B, various parameters may be adjusted individually or in combination. For example one parameter which may give rise to considerable liquid attraction toward the electrode 210 may be the voltage applied to the electrode 210. An increase in this voltage may cause stronger forces to be exerted on the liquid and thereby attract higher amounts of liquid as compared to the voltage applied on the electrode 210 in the example of figure 3B, assuming other conditions are equivalent. Another parameter which may be adjusted is the amount of the liquid present in the heat transfer apparatus so as to allow faster creation of dry patches on the surface 221. A further parameter may be the geometry of the electrode, for example a larger electrode or a sharp-edged electrode (as mentioned above) may influence the liquid attraction effects. If substantially all the liquid 230 on the surface 221 is extracted toward the EHD electrode 230, then heat transfer process may be considered to have been inhibited. In this manner, it becomes possible to design heat transfer apparatus, e.g. heat pipes or thermosyphons, which are capable of reducing or inhibiting the transfer of heat as desired.

[0047] A further possibility is the use of EHD technique in a thermosyphon or heat pipes causing it to behave as a thermal switch. Figures 6A and 6B illustrate scenarios of an exemplary configuration for such use. Referring first to figure 6A, a thermosyphon 300 is shown comprising a housing 360. A working liquid 330 is provided inside the housing 360. The housing 360 comprises an evaporator section 361, an adiabatic section 363 and a condenser section 362. The three sections are separated in the figure by dashed lines. For simplicity of illustration only portions of the walls 320 of the housing 360 are shown in the figure; however it is understood that the housing defines a closed space in which the liquid 330 is contained. Walls 320 are configured to transfer heat.

[0048] The thermosyphon 300 further comprises an EHD electrode 310 located substantially along central longitudinal axis of the thermosyphon, however this is only exemplary and the disclosure is not so limited.

[0049] In the scenario of figure 6A, no voltage is applied between the electrode 310 and an electrically conductive portion of the heat transfer walls 320. As a result of receiving heat from a heat source, as shown by arrow A, the heat transfer wall 320 transfers heat to the liquid 330 located within the evaporator section 361. When the liquid reaches a sufficiently high temperature, the liquid starts to evaporate and the resulting vapor moves toward the condenser section 362. In the condenser section 362 the vapor is condensed and converted into droplets formed on the inner surfaces of the walls 320 of the thermosyphon. The condensation may be achieved due to a heat transfer effect in the vicinity of the condenser section 362 to remove heat from the thermosyphon. The condensed liquid 331 formed on the inner surfaces of the walls of the thermosyphon then moves back, due to gravity, to the evaporator section 361.

[0050] Referring now to figure 6B, a scenario is described in which a voltage is applied between the EHD electrode 310 and an electrically conductive part of the heat transfer walls 320. The arrangement and configuration of the EHD electrode 310, the heat transfer wall 320 and the liquid 330 is similar to those of figure 6A and therefore a detailed description thereof is considered not necessary. However, in the scenario of figure 6B, by applying a voltage to the EHD electrode, an electric field is generated which would extract the liquid in the condenser section 362 toward the EHD electrode 310 and therefore avoid the liquid to fall toward the evaporator section 361, as schematically shown in the upper part of figure 6B, reference numerals 330 and 332. Although in figures 6A and 6B, the electrode is shown to be located along the entire length of the thermosyphon, the embodiments are no so limited. In some embodiments, the electrode may be located in the condenser section or in both the condenser section and adiabatic section of the apparatus. This effect therefore thermally isolates the evaporator section from the condenser section, thus breaking the evaporation-condensation loop. In this manner by selectively applying and removing a voltage to the EHD electrode, the thermosyphon may be configured to behave as a thermal switch such that applying no voltage may be considered as a situation in which the switch is in closed position (i.e. normal heat transfer operation) and a predetermined voltage applied to the electrode may be considered as a situation in which the switch in open (i.e. no or negligible heat transfer).

[0051] In an alternative embodiment, using a heat pipe having a wick structure, it may possible to provide an EHD electrode only in the evaporator section. In this case when the electrode is energized, the generated EHD forces extract the liquid out of the wick in the evaporator section prior to evaporation thereby causing premature dry-out in the evaporator and hence effectively shutting off the heat pipe. This effect can also be used to provide a thermal switch.

[0052] Similarly, an EHD electrode may be installed in the condenser section of a heat pipe in order to setup similar electric fields and EHD forces for the purposes of controlling the condensation mechanisms and condenser effective thermal resistance.

[0053] Figures 7A and 7B illustrate a further example of a thermosyphon according to some embodiments of the disclosure.

[0054] Referring to figure 7A, a thermosyphon 400 is shown comprising a housing 460. A working liquid 430 is provided inside the housing 460. The housing 460 comprises an evaporator section 461, a condenser section 462 and an adiabatic section 463 located between the condenser section 462 and the evaporator section 461. The three sections are separated in the figure by dashed lines. The thermosyphon 400 further comprises an EHD electrode 410 installed in the adiabatic section 463. In figure 7A (and also 7B) the EHD electrode 410 is shown to have a plurality of segments 411. The use of a plurality of segment may be advantageous as will be described further below, however the disclosure is not so limited and electrodes having only one segment may likewise be used.

[0055] With continued reference to figure 7A, it is assumed that the EHD electrode 410 is not energized. The thermosyphon would therefore operate in the known manner in which heat is transferred from a heat source (not shown) to the evaporator section 461 as shown by arrows A. The heat received causes the liquid located in the evaporator section 461 to evaporate as shown by arrows B which then flows by convection, through the adiabatic section 463 as shown by arrows C until it reaches the condenser section 462 where the vapor is condensed and converted into droplets formed on the inner surfaces of the walls of the thermosyphon as represented by arrows D. The removal of heat from the condenser section is represented by arrows E. The condensed liquid 431 then flows downward, driven by gravity, on the inner surfaces of walls 420 of the thermosyphon and toward the evaporator section 461 where the liquid undergoes another evaporation/condensation cycle in a similar fashion as described above. Figure 7B shows only the adiabatic section 463 of the thermosyphon of figure 7A with the difference that in figure 7B the EHD electrode is energized by applying a voltage between the EHD electrode 410 and an electrically conductive portion of the walls 420 of the thermosyphon. In figure 7B like elements have been provided by like reference numerals as those of figure 7A. In this situation, the energized EHD electrode exerts an extraction force on the liquid 431 which is flowing downward on the inner surface of the walls 420 thereby attracting the liquid 431 toward the electrode 410 as shown by droplets 432 and further forcing such droplets to move upward as shown by arrows F.

[0056] It is to be noted that, without the presence of EHD forces, there typically exists a certain amount of shear forces between the downward flowing liquid and the upward flowing vapor. This is because the vapor velocity is typically significantly greater due to the density difference between the two phases. Also, the flow velocities depend directly on the heat transfer rate of the device. If the shear forces are sufficiently high, the liquid is entrained into the vapor flow and the evaporator dries out. This is typically known as the entrainment limit of the device. When EHD effect is present, the EHD forces would extract liquid from the surface to encourage entrainment or cause it to happen at reltively much lower velocities (or heat transfer rates) if desired. This is due to the liquid extraction effect described previously. This effect limits the amount of liquid 431 which is allowed to return to the evaporator section 461 by effectively causing the thermosyphon 400 reach its entrainment limit prematurely (as compared to the case where no EHD forces are present). This configuration therefore may be used as another control mechanism for effectively adjusting the heat transfer rate or even "turning off" the thermosyphon.

[0057] As mentioned above, the EHD electrode may comprise a plurality of segments 411 as shown in figures 7A and 7B. The segments 411 of the EHD electrode 410 may be configured such that they may be individually energized in a controlled manner. Therefore different voltages may be applied to different segments to thereby exert different extraction forces on the liquid. For example, in one configuration a sequential activation of the segments may cause the liquid to move at a desired and controllable speed or cause the liquid to move at variable speed or intermittently as a function of time similar to a pumping effect.

[0058] In some embodiments, various electrodes may be placed in various locations inside the housing of the heat transfer apparatus. For example an EHD electrode may be installed in the condenser section and another EHD electrode may be installed in the evaporator section. Each electrode, when energized, may cause extraction of the liquid toward itself thereby thinning the layer of liquid on the inner surfaces of the walls in each respective section. This effect contributes to lowering the overall thermal resistance of the apparatus. Furthermore, a prolonged extraction of the liquid to the EHD electrode in the evaporator section may cause a dry-out in that section and therefore stop the heat transfer process. The apparatus as disclosed herein allows for the active control of the internal hydrodynamic and heat transfer mechanisms of passive two-phase heat transport loops such as heat pipes or thermosyphons.

[0059] The proposed solution offers an advantageous control mechanism as it relies on internal effects produced inside the heat transfer apparatus rather than requiring external elements for such control.

[0060] Another advantage of the proposed solution is that it offers a response time that is significantly quicker than the existing variable conductance heat pipes since it does not rely on the heating and cooling of a non-condensable gas region. This in-turn offers greater control accuracy.

[0061] A still further advantage is that this approach offers a variety of types of control mechanisms depending on how the EHD electrodes are designed and placed within the apparatus (to either enhance or mitigate flows and heat transfer mechanisms) thereby offering flexibility in designing a control system.

[0062] It is to be noted that the list of structures corresponding to the claimed means is not exhaustive and that one skilled in the art understands that equivalent structures can be substituted for the recited structure without departing from the scope of the invention.

[0063] It should further be appreciated by those skilled in the art that any block diagrams herein represent conceptual views of illustrative circuitry embodying the principles of the invention. Similarly, it will be appreciated that any flow charts, flow diagrams, state transition diagrams, pseudo code, and the like represent various processes which may be substantially represented in computer readable medium and so executed by a computer or processor, whether or not such computer or processor is explicitly shown.

Claims

1. An apparatus comprising:

- a housing having a wall, at least a portion of the wall being thermally conductive;
- a working fluid enclosed within the housing and configured to change between a liquid phase and a vapor phase in response to exchange of heat with the thermally conductive portion of the wall; and

an electrode located inside the housing;

wherein the apparatus is configured to generate an electric field in response to applying a voltage between the electrode and an electrically conductive portion of the wall, said electric field being capable of exerting a force on the working fluid.

2. The apparatus of claim 1, wherein the fluid is in liquid phase and the apparatus is configured to attract the liquid to the electrode.

3. 1. The apparatus of claim 1, wherein the fluid is in liquid phase containing bubbles and the apparatus is configured to repel the bubbles away from the electrode.

4. 1. The apparatus of claim 2, wherein the attraction of the liquid to the electrode causes reduction in a thickness of a layer of the liquid on the thermally conductive wall.

5. The apparatus of claim 2, wherein the attraction of the liquid to the electrode causes generation of one or more dry areas on the thermally conductive wall.

6. 1. The apparatus of claim 1, wherein the housing comprises an evaporation section configured to evaporate a liquid phase fluid upon receiving heat from the thermally conductive wall and a condenser section configured to condense into liquid a vapor phase fluid by emitting heat to the thermally conductive wall.

7. The apparatus of claim 6 configured to attract the liquid phase of the fluid to the electrode in the condenser section such that flow of the liquid phase fluid to the evaporator section is substantially avoided.

8. The apparatus of claim 6 further comprising an adiabatic section located between the evaporator section and the condenser section and, wherein the electrode is located in the adiabatic section and is configured to attract the liquid phase of the fluid to the electrode such that flow of the liquid phase fluid to the evaporator section is reduced.

9. The apparatus of claim 1, wherein the electrode comprises a plurality of segments, configured to be individually energized by applying a voltage thereto such that a voltage applied to one segment is different from a voltage applied to another segment.

10. The apparatus of claim 9, wherein the plurality of segments are sequentially energized such that the fluid receives a plurality of sequential forces.

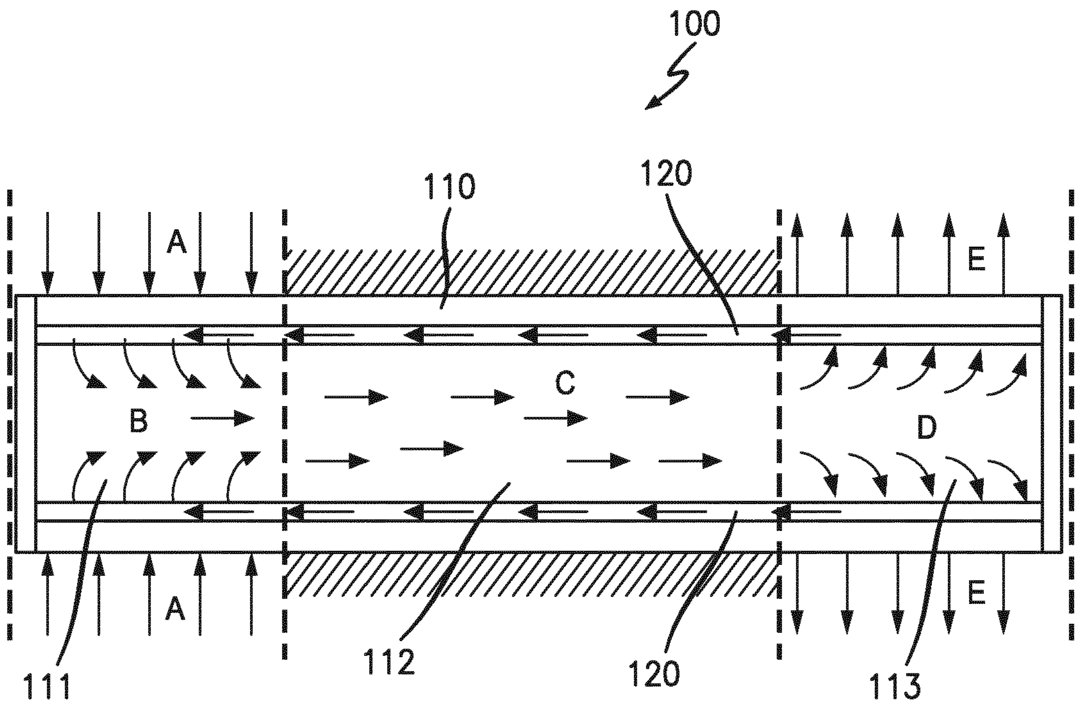
11. The apparatus of claim 1, wherein various electrodes are placed in various sections inside the housing.

12. The apparatus of claim 11 wherein an electrode is extended into a plurality of the sections inside the housing.

13. The apparatus of the any one of the preceding claims wherein the electrode has a shape with one or more sharp edges.

14. The apparatus of the any one of the preceding claims wherein the apparatus is a heat pipe.

15. The apparatus of the any one of the preceding claims wherein the apparatus is a thermosyphon.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D
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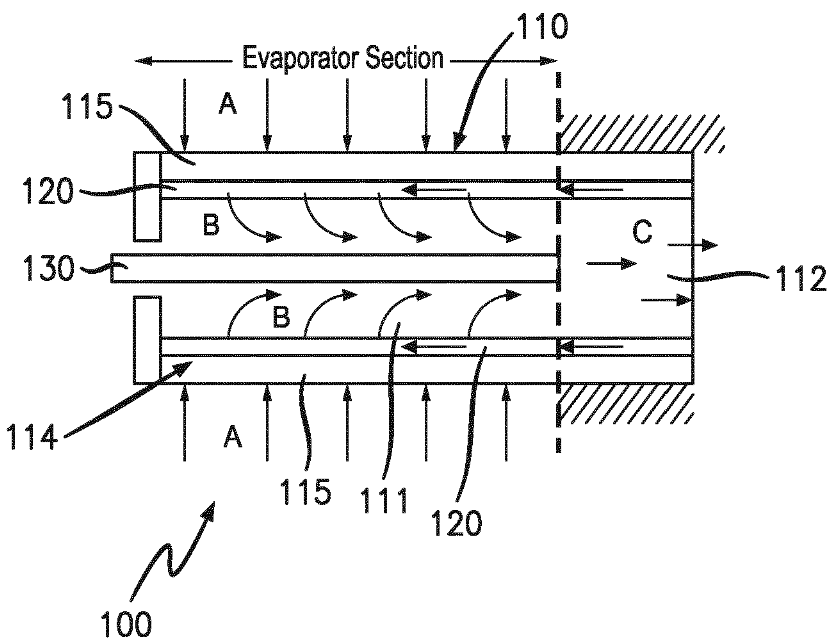
113

FIG. 1


Evaporator Section
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C
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FIG. 2

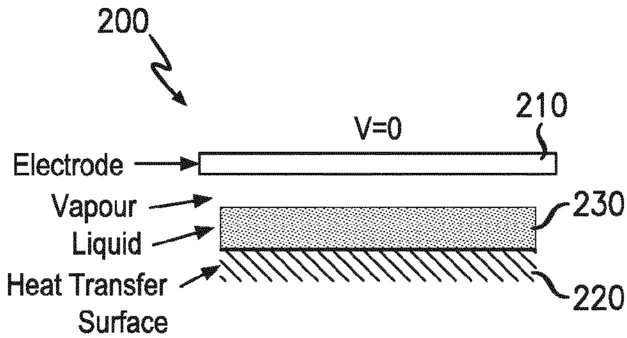


FIG. 3A

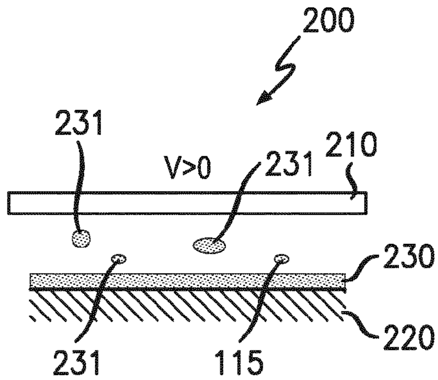


FIG. 3B

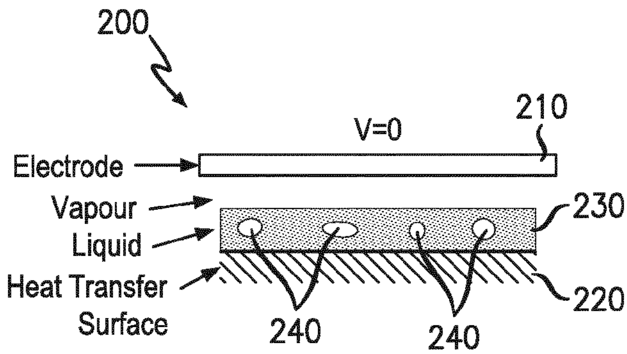


FIG. 4A

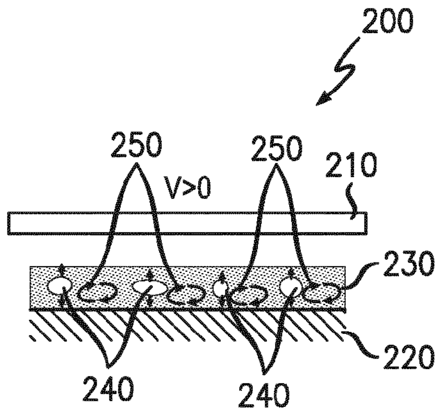


FIG. 4B

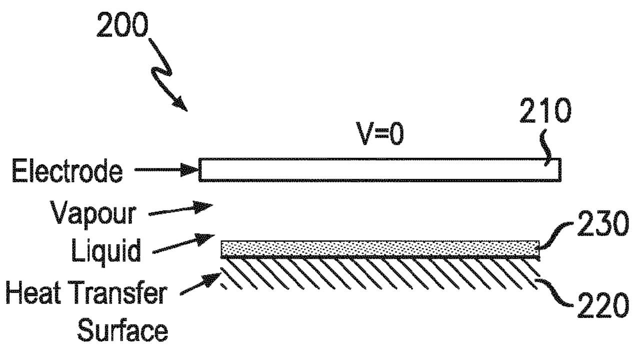


FIG. 5A

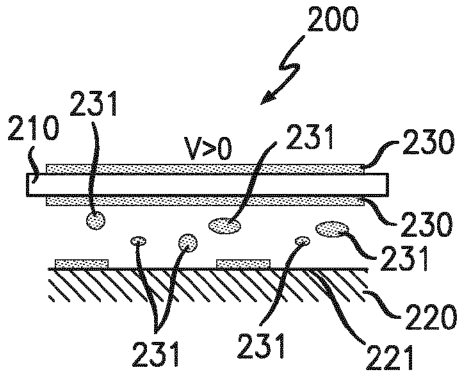


FIG. 5B

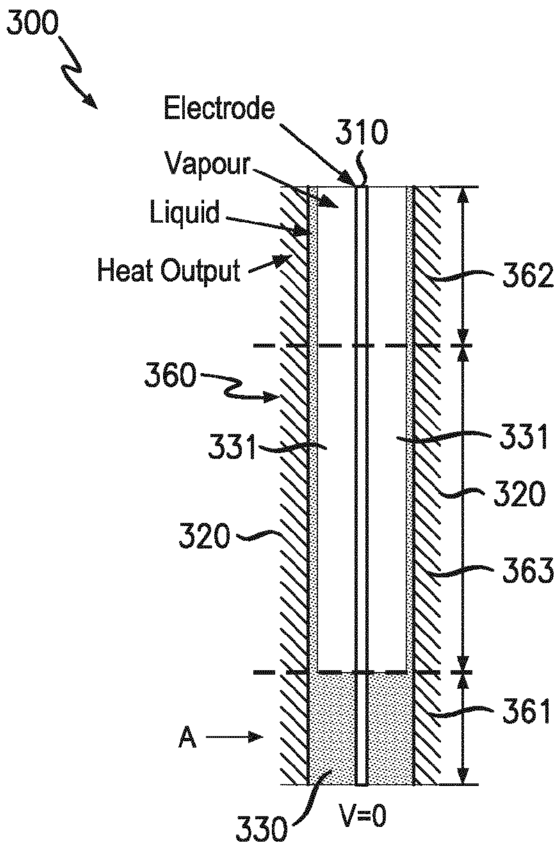


FIG. 6A

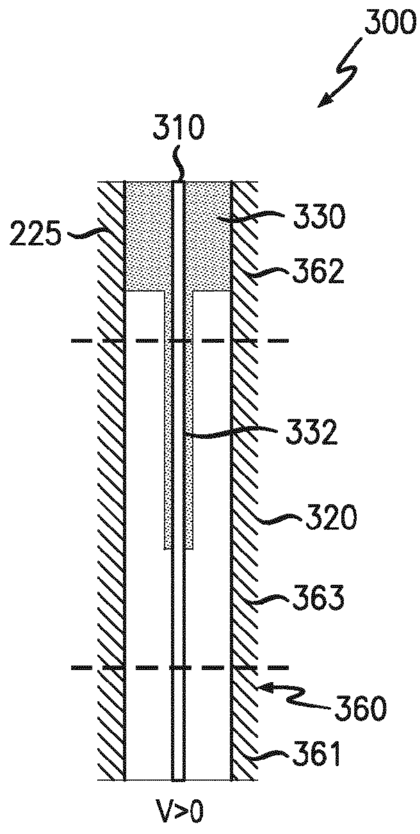
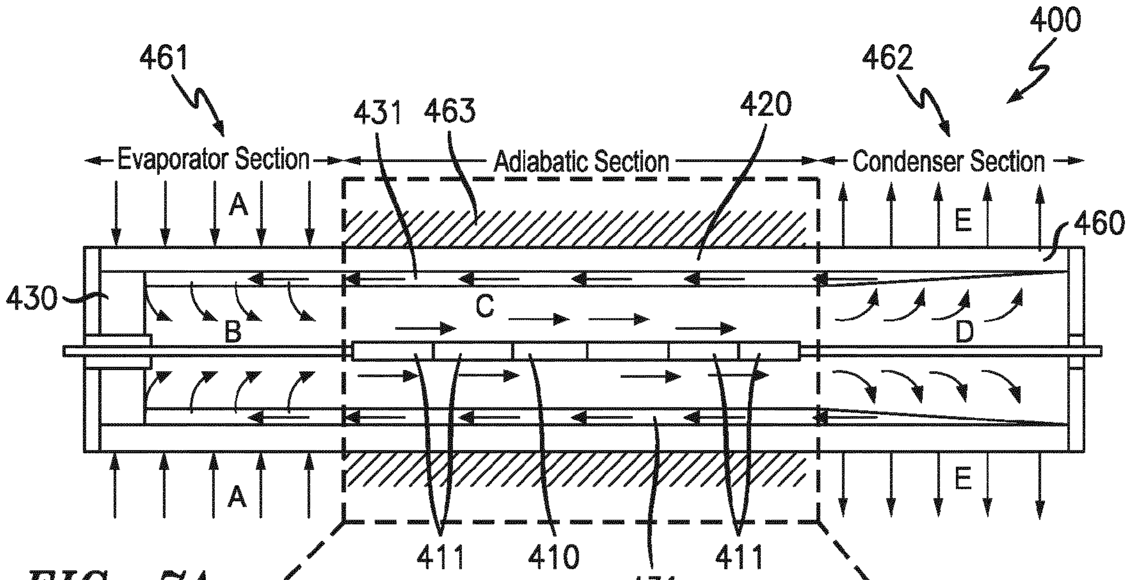


FIG. 6B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Evaporator Section
Adiabatic Section
Condenser Section
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C
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D
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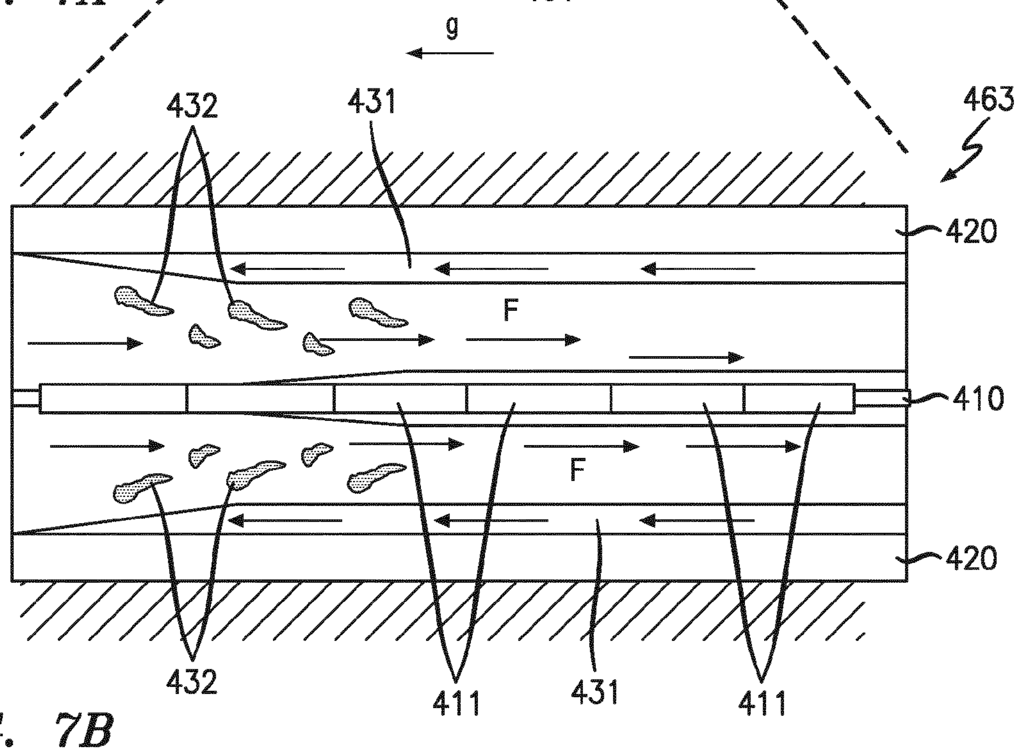
431

FIG. 7A


g
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F
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411

FIG. 7B

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EUROPEAN SEARCH REPORT

Application Number
EP 14 30 5066

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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X	US 3 683 214 A (LEFFERT CHARLES B) 8 August 1972 (1972-08-08) * abstract; figure 2 * * column 2, line 4 - line 61 *	1-15	
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X	US 6 888 721 B1 (MOGHADDAM SAEED [US] ET AL) 3 May 2005 (2005-05-03) * abstract *	1,9-11	

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F28F
F28D

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	6 May 2014	Bain, David

CATEGORY OF CITED DOCUMENTS

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06-05-2014

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