(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 4 481 313 A1

(12) EUROPEAN PATENT APPLICATION

published in accordance with Art. 153(4) EPC

(43) Date of publication:
25.12.2024 Bulletin 2024/52

(21) Application number: **23756064.4**

(22) Date of filing: **17.01.2023**

(51) International Patent Classification (IPC):
F28D 15/02 *(2006.01)*

(52) Cooperative Patent Classification (CPC):
F28D 15/02

(86) International application number:
PCT/JP2023/001216

(87) International publication number:
WO 2023/157536 (24.08.2023 Gazette 2023/34)

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA
Designated Validation States:
KH MA MD TN

(30) Priority: **15.02.2022 JP 2022020914**

(71) Applicants:
- **Thermal Solutions Co., Ltd.**
  Hachioji-shi, Tokyo 192-0375 (JP)
- **Fumoto, Koji**
  Sagamihara-shi, Kanagawa 252-5258 (JP)

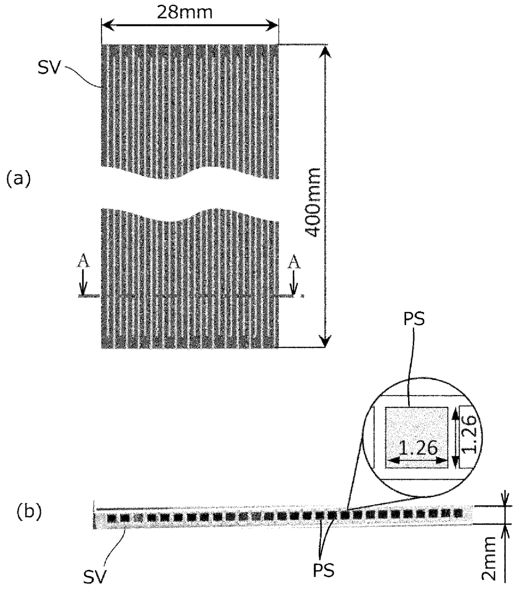
(72) Inventors:
- **ISHII, Keiko**
  Sagamihara-shi, Kanagawa 252-5258 (JP)
- **FUMOTO, Koji**
  Sagamihara-shi, Kanagawa 252-5258 (JP)

(74) Representative: **Wenzel Nemetzade Warthmüller Patentanwälte Part mbB**
Maximilianstraße 2
80539 München (DE)

(54) SELF-REGENERATING BRIDGE-TYPE HEAT PIPE

(57) In order to provide a self-regenerating bridge-type heat pipe capable of effectively transporting heat while maintaining a low filling ratio of a working fluid, in the self-regenerating bridge-type heat pipe made of aluminum in which a working fluid is filled within flow passages which are alternately folded back, inner surfaces of the flow passages are subjected to a water repellent treatment, and the filling ratio of the working fluid is 30 vol.% or less.

FIG. 2



EP 4 481 313 A1

Processed by Luminess, 75001 PARIS (FR)

Description

[Technical Field]

[0001] The present invention relates to a self-regenerating bridge-type heat pipe.

[Background Art]

[0002] Recently, along with the downsizing of electronic devices and improvement of performance thereof, heat generation density of electronic components is rapidly increasing. Heretofore, various types of heat pipes that convey heat through gas-liquid phase change of refrigerants filled therein have been used widely as cooling and heat controlling devices for electronic devices. Further, the use of heat pipes as heat exchange devices that aim at recovering exhaust heat to suppress global warming have been considered. Furthermore, the use of various heat pipes as heat transport devices for performing thermal control of batteries for electric vehicles (EV) has been discussed.

[0003] Heretofore, various types of heat pipes have been proposed, such as a conventional wick heat pipe and a loop heat pipe. Specifically, a self-excited oscillation-type heat pipe (Pulsating Heat Pipe: PHP, or Oscillating Heat Pipe: OHP, hereinafter referred to as PHP) is a heat pipe formed by folding back a narrow flow passage multiple times between a heating section HS and a cooling section CS, as illustrated in FIG. 1, and filling working fluid to approximately half the volume of the flow passage. In the PHP, liquid slags LS formed by surface tension of the working fluid are retained between vapor plugs and moved by self-excited oscillation, according to which a passive and high heat transport is realized.

[0004] The characteristics of PHP include, for example, that it has a high heat transport performance compared to the conventional heat pipe due to the use of sensible heat movement of liquid slags LS accompanying self-excited oscillation, that it is suitable for downsizing since it does not require an internal configuration such as the wick, and that the heat transport performance thereof is not easily affected by gravity.

[0005] Further, the PHP is drawing attention in that it has a high heat transport ability since, unlike the conventional heat pipes, it is free from any liquid reflux limitation due to capillary force limitation and flooding limitation, such that various studies of PHP have been performed. In general, parameters that influence the heat transport ability of PHPs include shapes and number of turns (number of channels) of the flow passage, physical property and filling ratio of the working fluid, setting conditions, and various dimensional ratios.

[0006] However, due to the complexity of the self-excited oscillation structure and the heat transport form, the PHP has not yet achieved design guidelines as a practical device, and even now, there are many ongoing researches, from basic researches to applicational researches, which are aimed at improving the heat transport ability thereof.

[0007] In consideration of the backgrounds described above, researches have been carried out regarding the effect of improvement of the performance of PHPs in a case where a self-rewetting fluid (also referred to as self-wetting solution) is used as the working fluid (refer to Non-Patent Literature 1). Self-rewetting fluid refers to a dilute aqueous solution of alcohol (such as butanol and pentanol) whose carbon number is 4 or more. Unlike other common liquids, these types of fluids are known to have a surface tension that increases with temperature within a certain temperature range.

[Citation List]

[Non-Patent Literature]

[0008] [Non-Patent Literature 1] Fumoto, Koji et al., "Improvement in Pulsating Heat Pipe using a Self-Rewetting Fluid (Cases of Butanol and Pentanol).", Thermal Science & Engineering, Vol. 19, No. 1 (2011)

[Summary of Invention]

[Problem to be Solved by the Invention]

[0009] A number of researchers including the present inventors have reported that the improvement of heat transport ability of PHPs has been achieved by the self-rewetting effect accompanying the unique surface tension characteristics described above, and that an effect to suppress dry-out may also be expected thereby.

[0010] Heretofore, regarding the researches involving PHPs, it has been clarified that an optimum value of filling ratio of working fluid lies within a range of 40 to 60 vol.%. It is known that beyond this range, a sufficient self-excited oscillation may not be achieved and the heat transport ability is deteriorated, which is an obstruction to practical application. Actually, if the filling ratio of the working fluid is equal to or less than 30 vol.%, the amount of working fluid supplied to the evaporation section is reduced, and finally, results in a dry-out state, such that the operating limit of the heat pipe is reached. Therefore, there is a drawback in that a long length of the flow passage of the heat pipe cannot be ensured.

[0011] However, based on a viewpoint that differs from the conventional technique, the present inventors have successfully realized a heat pipe that can perform heat transport effectively for a long distance even in a state where the filling ratio of the working fluid is 30 vol.% or less.

[0012] The present invention aims at providing a self-regenerating bridge-type heat pipe capable of performing heat transport effectively while suppressing the filling ratio of the working fluid to a low value.

[Means to Solve the Problem]

[0013] In order to solve the problems described above, one of a typical self-regenerating bridge-type heat pipe according to the present invention is a self-regenerating bridge-type heat pipe made of aluminum in which a working fluid is filled within flow passages that are alternately folded back, wherein inner surfaces of the flow passages are subjected to water repellent treatment, and wherein a filling ratio of the working fluid is 30 vol.% or less.

[Effects of Invention]

[0014] The present invention enables to provide a self-regenerating bridge-type heat pipe capable of realizing an effective heat transport while suppressing the filling ratio of the working fluid to a low value.

[0015] Problems, configurations and effects other than those described above will become apparent by the following descriptions of embodiments.

[Brief Description of Drawings]

[0016]

FIG. 1 is a schematic drawing of a conventional PHP.
FIG. 2(a) is a side view of a self-regenerating bridge-type heat pipe according to a present embodiment, and FIG. 2(b) is a cross-sectional view of the configuration of FIG. 2(a) cut at line A-A and viewed in the direction of the arrow.
FIG. 3 is a schematic drawing of an experimental apparatus used by the present inventors.
FIG. 4 is a view schematically illustrating temperature measurement positions and area ratios of an evaporation section and a condensation section of the self-regenerating bridge-type heat pipe.
FIG. 5 is a microscopic image of a cross section of a flow passage of the self-regenerating bridge-type heat pipe.
FIG. 6 is a view illustrating a relationship between an input power to a cartridge heater and a net heat supply.
FIG. 7 is a view illustrating a net heat supply and a temperature history of an evaporation section, a heat insulation section, and a condensation section in a case where a working fluid is filled with a general filling amount (50 vol.%) as comparative example 1 to a self-regenerating bridge-type heat pipe having a water repellent treatment applied to a flow passage surface.
FIG. 8 is a view illustrating a net heat supply and a temperature history of an evaporation section, a heat insulation section, and a condensation section in a case where a working fluid is filled with a filling amount (30 vol.%) as comparative example 2 to a heat pipe without a water repellent treatment applied to a flow passage surface.
FIG. 9 is a view illustrating a temperature history of an evaporation section, a heat insulation section, and a condensation section with respect to a heat transport state in a case where a filing ratio of the working fluid is set to 5 vol.% (first embodiment) in the self-regenerating bridge-type heat pipe according to comparative example 1.
FIG. 10 is a view illustrating a temperature history of an evaporation section, a heat insulation section, and a condensation section with respect to a heat transport state in a case where a filing ratio of the working fluid is set to 10 vol.% (second embodiment) in the self-regenerating bridge-type heat pipe according to comparative example 1.
FIG. 11 is a view illustrating a relationship between the net heat supply and a thermal resistance.
FIG 12 is a view illustrating a relationship between the net heat supply and an effective thermal conductivity.
FIG. 13 is a view schematically illustrating a state of an inner side of the heat pipe.

[Description of Embodiments]

[0017] The present inventors have been inspired by the enhancement of heat transport ability realized by improving wettability of flow passages using a conventional self-rewetting fluid, and have realize a further improvement of heat transport ability of a PHP using a method of modifying a surface of the flow passage directly. Specifically, after subjecting the surface of a flow passage of a heat pipe to water repellent finishing, and in order to more effectively utilize the water repelling effect, a filling ratio of the working fluid is intentionally set to 30 vol.% or less, such as to approximately 10 vol.%, the present inventors have successfully realized a super high-efficiency heat transport without changing the shape of the conventional PHP.

[0018] In such a heat pipe, a heat transfer phenomenon that clearly differs from that of the conventional PHP has been confirmed, so that in order to distinguish the present heat pipe from the conventional PHP, the present heat pipe is referred to as a self-regenerating bridge-type heat pipe. In the self-regenerating bridge-type heat pipe, by setting the filling ratio of the working fluid extremely low, thin liquid films (bridges) in a state of liquid slags formed within the flow passage move at a high vibration frequency, and thereby, a heat transport ability that could not have been achieved by the conventional PHP may be realized. The details of the self-regenerating bridge-type heat pipe will be described below.

(Self-Regenerating Bridge-Type Heat Pipe)

[0019] FIG. 2(a) is a side view of a self-regenerating bridge-type heat pipe SV according to the present embodiment, and FIG. 2(b) is a cross-sectional view illustrating the configuration of FIG. 2(a) cut at line A-A and viewed in the direction of the arrow.

[0020] The self-regenerating bridge-type heat pipe SV is composed of a flat multi-hole tube made of aluminum (also referred to as an aluminum flat multi-hole PHP) schematically illustrated in FIG. 2(a). A main component of the material of the flat multi-hole tube is aluminum (A1297), and in this example, the shape is 400 [mm] in total length, 48 [mm] in width, and 2 [mm] in thickness, but the dimensions are not specifically limited. Flow passages PS formed in an inner side thereof are composed of 28 passages arranged in parallel with respect to the length direction, and adjacent flow passages PS are separated by partition walls, but the number of passages are not specifically limited.

[0021] Further, as illustrated in FIG. 2(a), end surface portions of the flow passages are alternately cut. Specifically, an upper end of an (N+1)th flow passage in a direction of parallel alignment of flow passages and an upper end of an (N)th flow passage are mutually connected and sealed from the atmosphere, and further, a lower end of the (N+1)th flow passage and a lower end of an (N+2)th flow passage are mutually connected and sealed from the atmosphere, by which a continuous and alternately folded-back flow passage PS is obtained. At both end portions, excluding one portion of an injection portion, both end surfaces are pressed and clamped, and thereafter, sealed by a resin adhesive (heat resistant temperature of 200 °C). The shape of the self-regenerating bridge-type heat pipe SV is not limited to the above-described shape, and it is preferable for the distance from one folded-back end to the other folded-back end of the flow passage to be 50 mm or longer, and more preferably, 300 mm or longer.

[0022] The cross section of the flow passage of the self-regenerating bridge-type heat pipe SV is square-shaped, as illustrated in FIG. 2(b), with one side of the cross section being 1.26 mm, and a cross-sectional area thereof being 1.59 mm^2, wherein the cross-sectional area thereof is set to be 0.25 mm^2 or more and 9.0 mm^2 or less, and more preferably 1.0 mm^2 or more and 5.0 mm^2 or less. Further, the cross-sectional shape is not limited to a square, and for example, it may be round.

[0023] The self-regenerating bridge-type heat pipe SV may be formed by folding back a pipe made of aluminum having a continuous flow passage repeatedly for multiple times.

(Experiment)

[0024] Hereafter, the experiments of the self-regenerating bridge-type heat pipe SV performed by the present inventors will be described.

[0025] FIG. 3 is a schematic drawing of an experimental apparatus that the present inventors used. The experimental apparatus includes a heating system HS, an injection system IS, and a measurement system MS. The heating system HS is composed of a copper block CB that holds a lower end side of the self-regenerating bridge-type heat pipe SV, a cartridge heater CH serving as a heater disposed within the copper block CB, and a heat conductive grease (not shown) that comes into contact with the self-regenerating bridge-type heat pipe SV and the cartridge heater CH. The cartridge heater CH generates heat by current supplied from a transformer TF, and the current value thereof may be confirmed through a power meter PM.

[0026] As described in detail later with reference to FIG. 4, an area in which the self-regenerating bridge-type heat pipe SV faces the cartridge heater CH within the copper block CB is referred to as an evaporation section EA, an area excluding the evaporation section of the self-regenerating bridge-type heat pipe SV within the copper block CB is referred to as a heat insulation section AA, and an area of the self-regenerating bridge-type heat pipe SV exposed from the copper block CB and coming into contact with outside air is referred to as a condensation section CA.

[0027] The injection system IS is composed of a vacuum pump PP equipped with a digital vacuum gauge, and a syringe SR for filling working fluid, wherein either one of the vacuum pump and the syringe may be selectively communicated with the injection portion of the self-regenerating bridge-type heat pipe SV by switching of a valve W.

[0028] The measurement system MS includes a plurality of thermocouples TC (type K: φ 0.3 mm) attached to the self-regenerating bridge-type heat pipe SV. The thermocouples TC are connected to a data logger DL, and temperature data measured via the thermocouples TC is processed at high speed.

[0029] The self-regenerating bridge-type heat pipe SV is maintained at a bottom heated state by the heating system HS, and cooling of the upper end side is performed through natural cooling.

[0030] FIG. 4 schematically illustrates temperature measurement positions of the self-regenerating bridge-type heat pipe SV, and area ratio of the evaporation section EA and the condensation section CA. The unit of numerical values shown in FIG. 4 is mm. Three thermocouples TC that output measured values T_{e1}, T_{e2}, and T_{e3} are arranged in the evaporation section EA (three points at a position of 10 mm from the lower end), a thermocouple TC that outputs a measured value T_{ad} is arranged in the heat insulation section AA (at a center position of the heat insulation section AA), and five thermocouples that output measured values T_{c1} to T_{c5} are arranged in the condensation section CA (three points at a position of 10 mm from the upper end and two points at a center portion of the flow passage direction). The respective thermocouples TC are fixed to a surface of the self-regenerating bridge-type heat pipe SV, and an outside air side thereof is covered by a heat insulating material, by which the influence of outside air temperature is eliminated.

[0031] The area ratio of the evaporation section EA, the heat insulation section AA, and the condensation section CA according to the present experiment was respectively fixed to 20%, 30%, and 50%, based on the overall length of the self-regenerating bridge-type heat pipe SV. Distilled water is used as the working fluid. All surfaces of the self-regenerating bridge-type heat pipe SV used in the present experiment excluding the condensation section EA (one side of the natural air-cooled portion) and the heating system HS are covered with a heat insulating material (heat insulating foam with a thickness of 10 mm). In the present experiment, a hard aluminum anodizing treatment is applied to the surface of the flow passage to enhance the water repellency of the surface of the flow passage of the self-regenerating bridge-type heat pipe SV.

[0032] FIG. 5 is a microscopic image of a cross section of the flow passage of the self-regenerating bridge-type heat pipe SV. As illustrated in FIG. 5, a hard anodized aluminum layer, i.e., alumite layer, of approximately 5 pm is formed on the inner surface of the flow passage PS.

[0033] Hereafter, experiments performed by the present inventors are described. As a preparation for the experiment, the inner side of the self-regenerating bridge-type heat pipe SV is set to a vacuum state of -0.099 MPa or lower in gauge pressure by the vacuum pump PP, and thereafter, the valve W is switched, and a working fluid is filled using a micro-syringe SR so as not to allow non-condensable gas (air) from entering the pipe. Considering that the working fluid also contains dissolved gas, the working fluid itself is subjected to deaeration processing. The filling ratio (FR) of the working fluid is defined by the following equation (1).

[Equation 1]

$$FR = \frac{V_{fluid}}{V_{PHP}} \times 100 \qquad [\text{vol.\%}] \qquad (1)$$

[0034] In the equation, V_{fluid} [mm^3] represents a volume of the filled working fluid, and V_{PHP} [mm^3] represents a total flow passage capacity ($=1.75 \times 10^{-5}$ m^3) of the self-regenerating bridge-type heat pipe SV confirmed in advance. According to the present experiment, the filling ratio is respectively set to 0 (no working fluid), 5, 10, and 50 [vol.%]. Measurement error of the filling amount of the working fluid may be estimated as being within ±0.2% based on the measurement accuracy of an electronic precision gravimeter.

[0035] The experiment repeated a process of increasing an applied power to the cartridge heater after confirming that temperatures of respective parts of the self-regenerating bridge-type heat pipe SV have become stationary. From the viewpoint of safety, the experiment was ended when a generation of dry-out has been confirmed and when the temperature of the evaporation section has reached approximately 120 °C.

[0036] As a preliminary test performed prior to the main experiment, a heat flux sensor was inserted between the self-regenerating bridge-type heat pipe SV and the cartridge heater CH to an empty self-regenerating bridge-type heat pipe SV with no working fluid filled therein (filling ratio 0 [vol.%]), and power supplied to the cartridge heater CH and net heat supply transmitted to the self-regenerating bridge-type heat pipe SV were measured.

[0037] FIG. 6 is a view illustrating a relationship between the input power to the cartridge heater CH and the net heat supply. FIG. 6 also illustrates a temperature difference between the net heat supply and a heat insulation section, and an effective thermal conductivity of the empty self-regenerating bridge-type heat pipe SV computed based on the cross-sectional area of the heat pipe.

[0038] Based on FIG. 6, it may be recognized that the net heat supply transmitted from the cartridge heater CH to the self-regenerating bridge-type heat pipe SV is increased linearly along with the increase of supply power. Further, the effective thermal conductivity of an empty self-regenerating bridge-type heat pipe SV is recognized to be 206.8 [W/(m K)] in average regardless of the input power, and compared to the thermal conductivity of 220 to 230 [W/(m·K)], which is the thermal conductivity of aluminum alloy (A1297) serving as the material of the self-regenerating bridge-type heat pipe SV, it is suppressed to 6% or less, such that the accuracy of the present experimental apparatus and the measurement system was confirmed. In the following description, the net heat supply is used to evaluate the heat supply.

[0039] As an overall performance evaluation, a thermal resistance value (R) and an effective thermal conductivity (Keff) are used. The thermal resistance value is computed using equation (2).

[Equation 2]

$$R = \frac{(T_e - T_c)}{Q} \quad (2)$$

[0040] In Equation 2, T_e and T_c [°C] respectively denote calculated mean temperatures of measured values (T_{e1}, T_{e2}, and T_{e3}) in the evaporation section EA and measured values (thermocouples T_{c1}, T_{c2}, and T_{c3}) in the condensation section CA respectively illustrated in FIG. 4. Reference Q [W] represents a net heat supply. The effective thermal conductivity (K_{eff}) is calculated based on equation (3).

[Equation 3]

$$K_{eff} = \frac{L_{eff}}{A_{cr}} \frac{Q}{(T_e - T_c)} = \frac{L_{eff}}{A_{cr}} \frac{1}{R} \qquad (3)$$

[0041] In Equation 3, L_{eff} [m] refers to a temperature measurement distance (0.38 [m]) of the evaporation section EA and the condensation section CA. A_{cr} represents a cross-sectional area (0.002×0.048 [m^2]) of the self-regenerating bridge-type heat pipe SV.

[0042] Next, the experimental accuracy will be described. The accuracy of thermal resistance (R) is defined by Equation (4).

[Equation 4]

$$\frac{\delta R}{R} = \sqrt{\left(\frac{\delta(\Delta T)}{\Delta T}\right)^2 + \left(\frac{\delta Q_H}{Q_H}\right)^2} \qquad (4)$$

[0043] The data accuracy of the thermal resistance R is ±1.6%. Next, the accuracy of the effective thermal conductivity K_{eff} is defined by Equation (5).

[Equation 5]

$$\frac{\delta K_{eff}}{K_{eff}} = \sqrt{\left(\frac{\delta L_{eff}}{\Delta L_{eff}}\right)^2 + \left(\frac{\delta A_{cr}}{A_{cr}}\right)^2 + \left(\frac{\delta(\Delta T)}{\Delta T}\right)^2 + \left(\frac{\delta Q_H}{Q_H}\right)^2} \qquad (5)$$

[0044] Since the measurement error in a pipe axis direction distance L_{eff} between the evaporation section EA and the condensation section CA is ±3.0%, the data accuracy of the effective thermal conductivity K_{eff} is ±3.3%.

(Experimental Results and Consideration)

(1) Comparative Example 1

[0045] FIG. 7 illustrates a net heat supply and a temperature history of the evaporation section EA (T_{e2}), the heat insulation section AA (T_{ad}), and the condensation section CA (T_{c2}) in a case where a typical filling amount (50 vol.%) of working fluid is filled in the self-regenerating bridge-type heat pipe SV whose flow passage surface has been subjected to water repellent treatment. Distilled water is used as the working fluid.

[0046] In FIG. 7, the vertical axis indicates temperature, and the horizontal axis indicates experimental time. In the drawing, the value of the net heat supply is also indicated, and in this example, the heat supply was gradually increased in stepped sections of 10.0 W, 15.2 W, 20.3 W, 25.4 W, and 30.6 W. Based on FIG. 7, when the heat supply was 15.2 W, oscillation was confirmed in the measured value (T_{c2}) of the condensation section EA, and it may be easily recognized that self-excited oscillation has occurred within the self-regenerating bridge-type heat pipe SV. However, since the temperature difference between the evaporation section EA and the condensation section CA (T_{e2} - T_{c2}) is relatively great, it is assumed that no continuous and significant oscillation has occurred.

[0047] Meanwhile, when the heat supply was 20.3 W or higher, the temperature difference (T_{e2} - T_{c2}) between the evaporation section EA and the condensation section CA was maintained to approximately 7.3 K (heat supply 25.4 W), such that it may be recognized that heat transport from the evaporation section EA to the condensation section CA has been realized by significant self-excited oscillation. Further, these tendencies indicate a similar tendency to the conventional report of a case where the filling amount of working fluid is 50 vol.%. In addition, when the heat supply was 30.6 W, a tendency was recognized where the temperature of the condensation section CA is reduced and the temperature difference with the evaporation section EA was increased after 16500 seconds, and the occurrence of a dry-out was confirmed thereafter.

(2) Comparative Example 2

[0048] FIG. 8 illustrates a net heat supply and a temperature history of the evaporation section EA (T_{e2}), the heat insulation section AA (T_{ad}), and the condensation section CA (T_{c2}) in a case where working fluid is filled with a filling amount (30 vol.%) in a heat pipe whose flow passage surface has not been subjected to water repellent treatment. Distilled water is used as the working fluid. The shape and temperature measurement positions of the heat pipe are the same as those of comparative example 1.

[0049] According also to FIG. 8, the vertical axis indicates temperature, and the horizontal axis indicates experimental time. In the drawing, the value of net heat supply is also indicated, and in this example, the heat supply was gradually increased in stepped sections of 10.0 W, 12.0 W, 13.8 W, 15.0 W, and 16.0 W.

[0050] According to FIG. 8, along with the elapse of experimental time, the temperature of the respective sections (T_{e2}, T_{ad}, and T_{c2}) rises, but compared to the evaporation section (heating section: T_{e2}), the temperature of the condensation section (cooling section: T_{c2}) is not raised as much. This means that the heat transport from the evaporation section is not performed efficiently. Further, after the elapse of 20250 seconds (16 W), the temperature of the condensation section (cooling section: T_{c2}) drops while the temperature of the evaporation section (heating section: T_{e2}) rises rapidly, which is an indication of a typical temperature history caused by the occurrence of a dry-out (operating limit = phenomenon in which the inner side of an evaporation section of a heat pipe is dried).

(First Embodiment)

[0051] FIG. 9 illustrates a temperature history of the evaporation section EA (T_{e2}), the heat insulation section AA (T_{ad}), and the condensation section CA (T_{c2}) regarding a heat transport state in a case where the working fluid is filled at a filling ratio of 5 vol.% to the self-regenerating bridge-type heat pipe SV according to the comparative example. Distilled water is used as the working fluid. The indication of the vertical axis, the horizontal axis, and the net heat supply are the same as those of FIGs. 7 and 8.

[0052] Based on FIG. 9 indicating that when the heat supply is 15.2 W and beyond, the temperature of the evaporation section EA (T_{e2}) and the temperature of the condensation section CA (T_{c2}) become substantially the same temperature, it may be recognized that a significant heat transport has occurred within the self-regenerating bridge-type heat pipe SV from the evaporation section EA to the condensation section CA. If this heat quantity is considered as the starting of heat transport of the self-regenerating bridge-type heat pipe SV, it may be recognized that it has been started at the evaporation section EA at approximately 60 °C (40 °C difference from the room temperature of 20 °C). Further, it may be recognized that along with the increase of heat supply, the temperatures of the evaporation section EA, the heat insulation section AA, and the condensation section CA are transited in a corresponding state.

[0053] Especially, it has been discovered that the temperature difference between the evaporation section EA and the condensation section CA around 8000 seconds where a heat quantity of 20.3 W is supplied is 1.0 K or less, and further, around 10000 seconds where a heat quantity of 25.4 W is supplied, the temperature difference is reduced to 0.69 K.

(Second Embodiment)

[0054] FIG. 10 illustrates a temperature history of the evaporation section EA (T_{e2}), the heat insulation section AA (T_{ad}), and the condensation section CA (T_{c2}) regarding a heat transport state in a case where the working fluid is filled at a filling ratio of 10 vol.% to the self-regenerating bridge-type heat pipe SV according to the comparative example. Distilled water is used as the working fluid. The indication of the vertical axis, the horizontal axis, and the net heat supply are the same as those of FIG. 9.

[0055] Based on FIG. 10 indicating that when the heat supply reaches 10.0 W and beyond, the temperature of the evaporation section EA (T_{e2}) and the temperature of the condensation section CA (T_{c2}) rapidly approximate each other, and it may be recognized that a heat transport has occurred within the self-regenerating bridge-type heat pipe SV from the evaporation section EA to the condensation section CA. If this heat quantity is considered as the starting of heat transport of the self-regenerating bridge-type heat pipe SV, it may be recognized that it has been started at the evaporation section

EA at a temperature of approximately 50 °C (30 °C difference from the room temperature of 20 °C), lower than the first embodiment. Further, it may be recognized that along with the increase of heat supply, the temperatures of the evaporation section EA, the heat insulation section AA, and the condensation section CA are transited in a corresponding state.

[0056] Especially, it has been discovered that the temperature difference between the evaporation section EA and the condensation section CA around 12300 seconds where a heat quantity of 20.3 W is supplied is 0.77 K or less, and further, it is reduced to 0.63 K around 15000 seconds where a heat quantity of 30.6 W is supplied. In the present experiment, from the viewpoint of safety management, a maximum temperature of 120 °C is set as the experiment termination temperature, but upon terminating the experiment, no dry-out has been confirmed for both cases where the filling ratio of working fluid was set to 5 vol.% and to 10 vol.%, such that a possibility of a further heat transport was suggested.

(Comparison of Comparative Example and Embodiment)

[0057] As can be seen clearly from the experimental results (comparative example 2) of FIG. 8, it is recognized that the heat pipe that has not been subjected to the water repellent treatment will not operate normally when the filling ratio of the working fluid is 30 vol.% (or less). Further, as can be recognized clearly by comparing the graph of FIG. 8 with the graphs of FIGs. 9 and 10, the heat supply (W in the drawings) and the level of temperature rise differ completely. Specifically, in FIG. 8, the temperature of the evaporation section (heating section: T_{e2}) has reached approximately 120 °C at 15.0 W, and a temperature difference of approximately 20 °C has occurred from the condensation section (low temperature section: T_{c2}), such that may be recognized that there is a failure in the heat transport function. Meanwhile, in FIG. 7 illustrating the comparative example 1 (filling ratio 50 vol.%), the heat supply is 15.2 W and the temperature of the evaporation section (heating section: T_{e2}) is approximately 70 °C. The reason why the temperature is somewhat lower in comparative example 1 than comparative example 2 under similar conditions is that heat is transported from the evaporation section (heating section) to the condensation section (low temperature section) by the self-excited oscillation phenomenon of the heat pipe. That is, in the case of a heat pipe to which water repellent treatment has been performed and filled at a filling ratio of 50 vol.%, it may be recognized that some level of heat transport function is realized, but which is not sufficient. In contrast, in the self-regenerating bridge-type heat pipe of the first and second embodiments with a lower filling ratio, as illustrated in FIGs. 9 and 10, the temperature of the evaporation section (heating section: T_{e2}) is somewhat lower than 70 °C at 15.2 W, and the temperature is similar to the condensation section temperature, such that it is clear that a significant heat transport is performed.

(Thermal Resistance and Effective Thermal Conductivity)

[0058] FIG. 11 illustrates a relationship between the net heat supply and the thermal resistance. The vertical axis represents a thermal resistance value in logarithmic display. The horizontal axis represents a net heat supply. The parameters are filling ratios of working fluid, including 0 [vol.%] (empty self-regenerating bridge-type heat pipe SV). According to the comparative example in which the self-regenerating bridge-type heat pipe SV is filled with a working fluid at a typical filling ratio of 50 [vol.%], the thermal resistance took a value of 2.1 [K/W] at a heat supply of 10 [W] before the thermal resistance dropped along with the increase of heat supply, and reached a lowest value of 0.19 [K/W]. Thereafter, the thermal resistance showed a tendency to increase at a heat supply of 30.6 W where the tendency of a dry-out has been recognized.

[0059] Meanwhile, in the case of the first embodiment in which the self-regenerating bridge-type heat pipe SV is filled with a working fluid of 5 [vol.%], the thermal resistance took a value of 0.86 [K/W] at a heat supply of 10 [W] before the thermal resistance dropped significantly along with the increase of heat supply, and the thermal resistance reached 0.022 [K/W] at a heat supply of 30.6 [W].

[0060] Further, in the case of the second embodiment in which the self-regenerating bridge-type heat pipe SV is filled with a working fluid of 10 [vol.%], the thermal resistance took a value of 0.36 [K/W] at a heat supply of 10 [W] before the thermal resistance dropped significantly along with the increase of heat supply, and the thermal resistance reached 0.021 [K/W] at a heat supply of 30.6 [W].

[0061] Based on the above description, it has been recognized that by filling the working fluid at a filling ratio of 5 and 10 [vol.%], a value of 1/10 or smaller of the filling ratio (such as 50 [vol.%]) may be obtained.

[0062] FIG. 12 illustrates a relationship between the net heat supply and the effective thermal conductivity. The parameters are filling ratios of the working fluid. In a case where the self-regenerating bridge-type heat pipe SV was filled with a working fluid at a typical filling ratio of 50 [vol.%], the effective thermal conductivity took a highest value of 21498.6 [W/(m K)] at a heat supply of 25 [W] before showing a tendency to drop. In contrast, in a case where the pipe was filled with a working fluid of 5 [vol.%], the effective thermal conductivity took a value of 176171.8 [W/(m K)] at a heat supply of 30.6 [W], and further, in a case where the pipe was filled with a working fluid of 10 [vol.%], the effective thermal conductivity took a value of 191068.1 [W/(m·K)] at a heat supply of 30.6 [W].

[0063] FIG. 13 schematically illustrates an inner side of the heat pipe.

[0064] Conventionally, based on various experiments including the visualization of PHP, the most suitable filling ratio of the working fluid was considered to be approximately 50 [vol.%]. In this case, when the PHP was made to come into contact with a high temperature section and a low temperature section, as illustrated in 50 [vol.%] of FIG. 12, vapor plugs VP and liquid slags LS are randomly formed at a volume ratio of approximately half the flow passage (FIG. 13(b)).

[0065] Meanwhile, in the self-regenerating bridge-type heat pipe SV with a low filling ratio, when the PHP was made to come into contact with a high temperature section corresponding to the evaporation section and a low temperature section corresponding to the condensation section, as illustrated in 5 - 10 [vol.%] of FIG. 12, liquid slags LS formed within the flow passage are short and formed at an extremely low ratio within the flow passage (FIG. 13(c)).

[0066] Further, the short liquid slags LS are mainly formed in the condensation section by the fluid being in a dropwise condensation state DP (FIG. 13(d)) due to the water repellent treatment effect on the surface of the flow passage, which is grown to form a bridge BG in the shape of a thin film so as to act as a lid within the flow passage (FIGs. 13(e) and (f)). That is, if the filling ratio of the working fluid is not sufficiently low, such as 30 [vol.%] or lower, the liquid slags LS will form a relatively large lump, such that the forming of bridges BG will be obstructed.

[0067] The bridge BG is defined to have a film thickness that is 1/2 or less of a maximum length of a surface facing the vapor plug VP. In order to effectively form the bridges BG, it is preferable for the cross-sectional area of the flow passage having been subjected to water repellent treatment of the self-regenerating bridge-type heat pipe SV to be 0.25 mm^2 or more and 9.0 mm^2 or less, in consideration of the surface tension of the working fluid.

[0068] In the conventional PHP, liquid slags LS having a relatively large volume exist within the flow passage, and such liquid slags LS are flown or oscillated to realize heat transport, such that there is a need to apply a large pressure difference to the ends of the liquid slags LS. In contrast, according to the self-regenerating bridge-type heat pipe SV having a low filling ratio as according to the present embodiment, liquid slags which are extremely short and which have an extremely small volume (thin film-shaped bridges BG which shield the cross section of the flow passage) are formed within the flow passage. Therefore, the inertia of the liquid slag LS is small compared to the conventional PHP, such that the flowing or oscillating of the liquid slag LS is enabled by a relatively small pressure difference that occurs on both sides thereof. Therefore, even in a flow passage having a length of 400 mm or longer from one folded-back end to the other folded-back end, the movement of bridges BG is enabled. Further, the generated bridges BG may maintain their shape in the condensation section to oscillate and flow, but when they reach the evaporation section, the bridges are considered to collapse in a short time along with evaporation, by which the pressure to move other bridges BG may be created and transmitted.

[0069] Thermal performance of a self-regenerating bridge-type heat pipe SV, that has been subjected to water repellent treatment by performing aluminum anodizing treatment to the flow passage of an aluminum flat multi-hole PHP, and to which distilled water serving as working fluid is filled at an extremely low filling ratio, was studied experimentally, and the following conclusions had been reached.

(1) It had been clarified that by subjecting the flow passage surface of the aluminum flat multi-hole PHP to water repellent treatment, self-excited oscillation occurred even at an extremely low filling ratio of working fluid, and that a high heat transport efficiency was realized.
(2) In the self-regenerating bridge-type heat pipe SV having a total length of 400 [mm], when the filling ratio of working fluid was set to 5 [vol.%], it has been confirmed that the temperature difference between the evaporation section and the condensation section was 1 [K] or less.
(3) As a result of evaluating the heat transport ability based on thermal resistance and effective thermal conductivity, a maximum thermal resistance value of 0.019 [K/W] was obtained. This is 1/10 or less of the thermal resistance value according to the conventional PHP in which the filling ratio of working fluid is 50 [vol.%],

[0070] According to the embodiments described above, the inner surface of the flow passage of the aluminum flat multi-hole PHP is subjected to aluminum anodizing treatment to thereby provide water repellent treatment thereto, but it has been confirmed that a similar result may be achieved using a PHP having been subjected to water repellent treatment by performing a boehmite treatment, in which an aluminum flat multi-hole plate that has not been subjected to surface treatment is immersed in warm water (90 °C).

[Reference Signs List]

[0071] HS: heating system, IS: injection system, MS: measurement system, BG: bridge, CB: copper block, CH: cartridge heater, DL: data logger, PM: power meter, PP: vacuum pump, PS: flow passage, SR: syringe for filling working fluid, SV: self-regenerating bridge-type heat pipe, TC: thermocouple, TF: transformer, W: valve

Claims

1. A self-regenerating bridge-type heat pipe made of aluminum in which a working fluid is filled within flow passages which are alternately folded back,
   wherein inner surfaces of the flow passages are subjected to a water repellent treatment, and wherein a filling ratio of the working fluid is 30 vol.% or less.

2. The self-regenerating bridge-type heat pipe according to claim 1, wherein the filling ratio of the working fluid is 5 to 10 vol.%.

3. The self-regenerating bridge-type heat pipe according to claim 1 or claim 2, wherein a cross-sectional area of the flow passages is 0.25 mm^2 or more and 9.0 mm^2 or less.

4. The self-regenerating bridge-type heat pipe according to any of claims 1 to 3, wherein, in a state where the self-regenerating bridge-type heat pipe is made to come into contact with a high temperature section and a low temperature section, a bridge of the working fluid is formed within the flow passages.

5. The self-regenerating bridge-type heat pipe according to any of claims 1 to 4, wherein the water repellent treatment is either an aluminum anodizing treatment or a boehmite treatment.

6. The self-regenerating bridge-type heat pipe according to any of claims 1 to 5, wherein a distance from one folded-back end to the other folded-back end of the flow passages is 50 mm or more.

FIG. 1

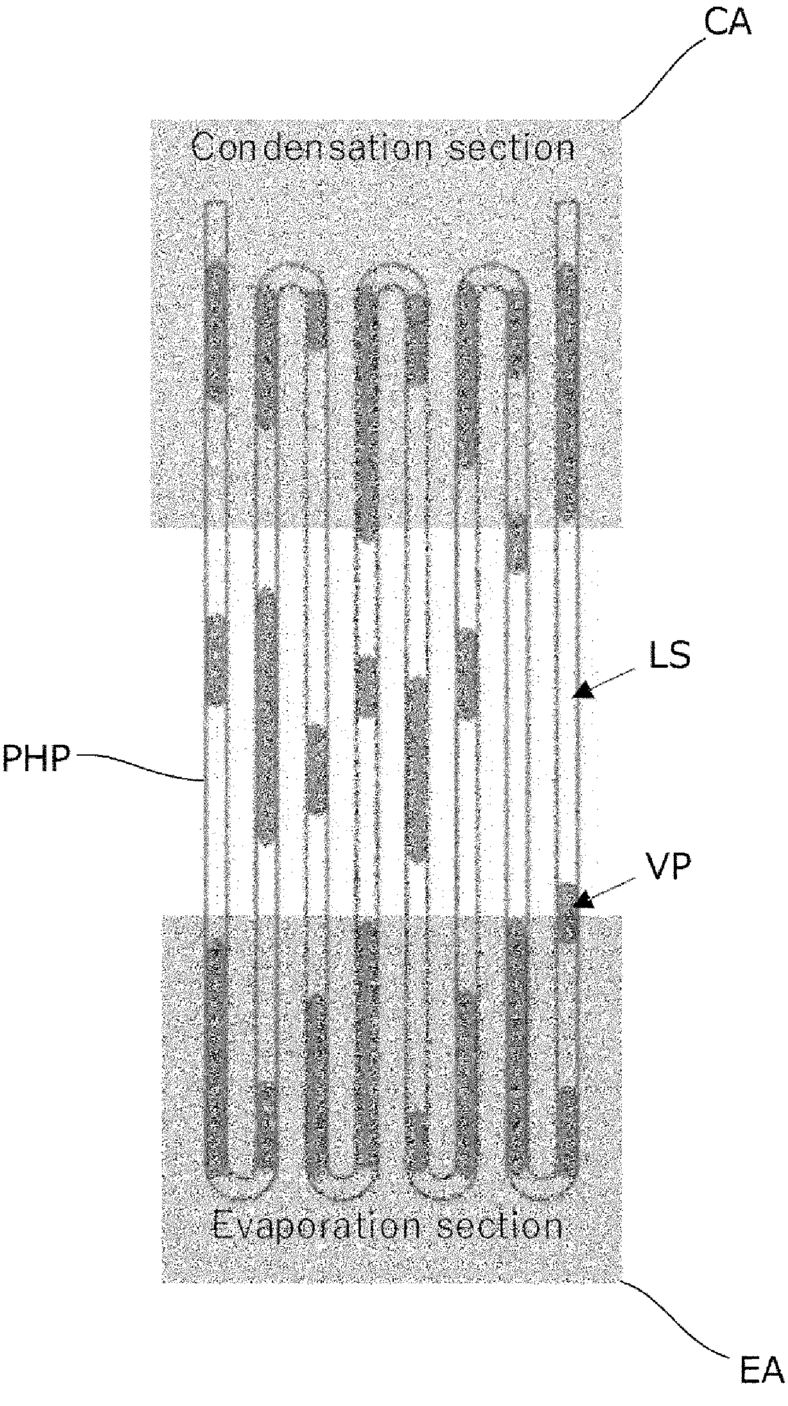


FIG. 2

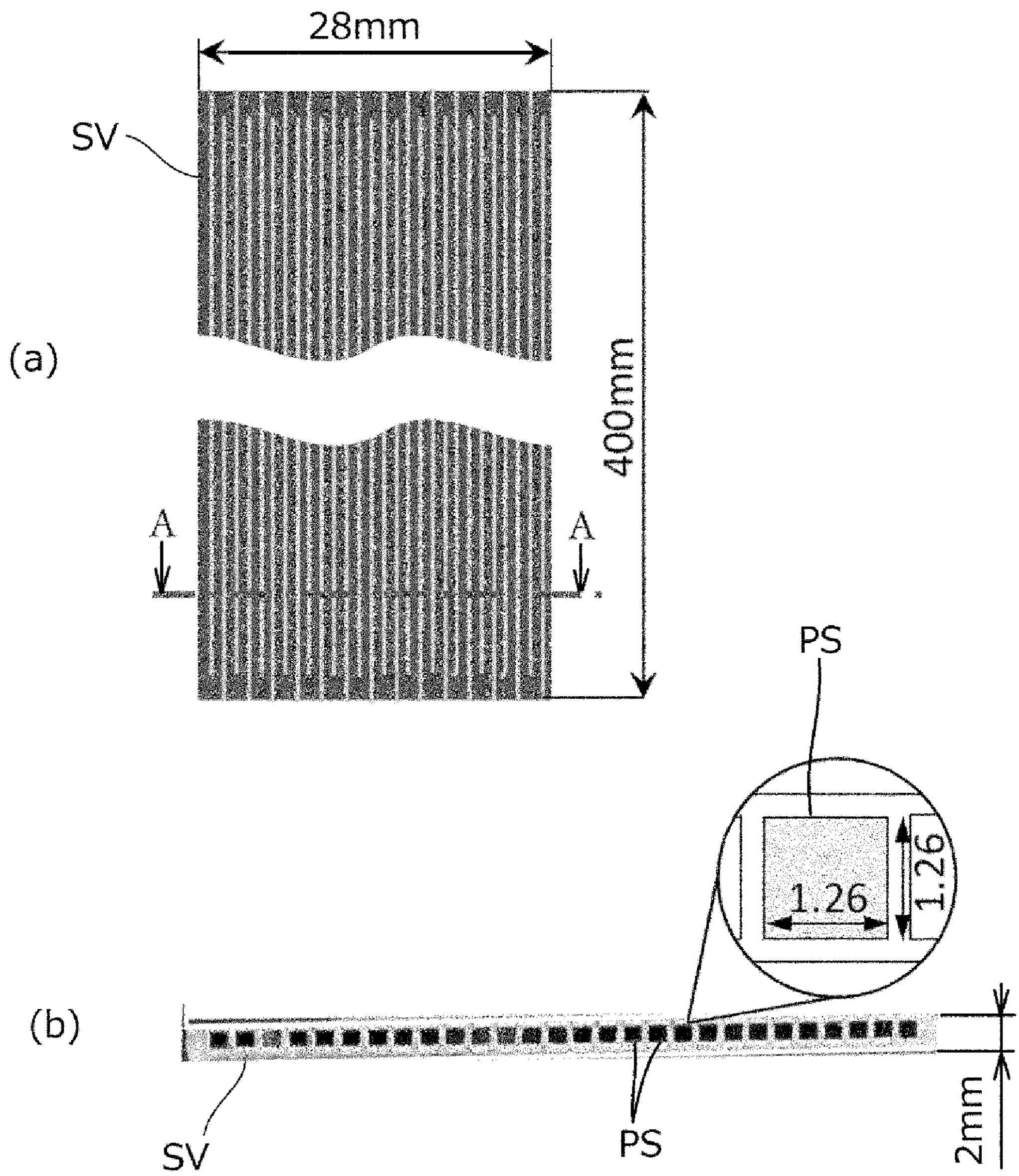


FIG. 3

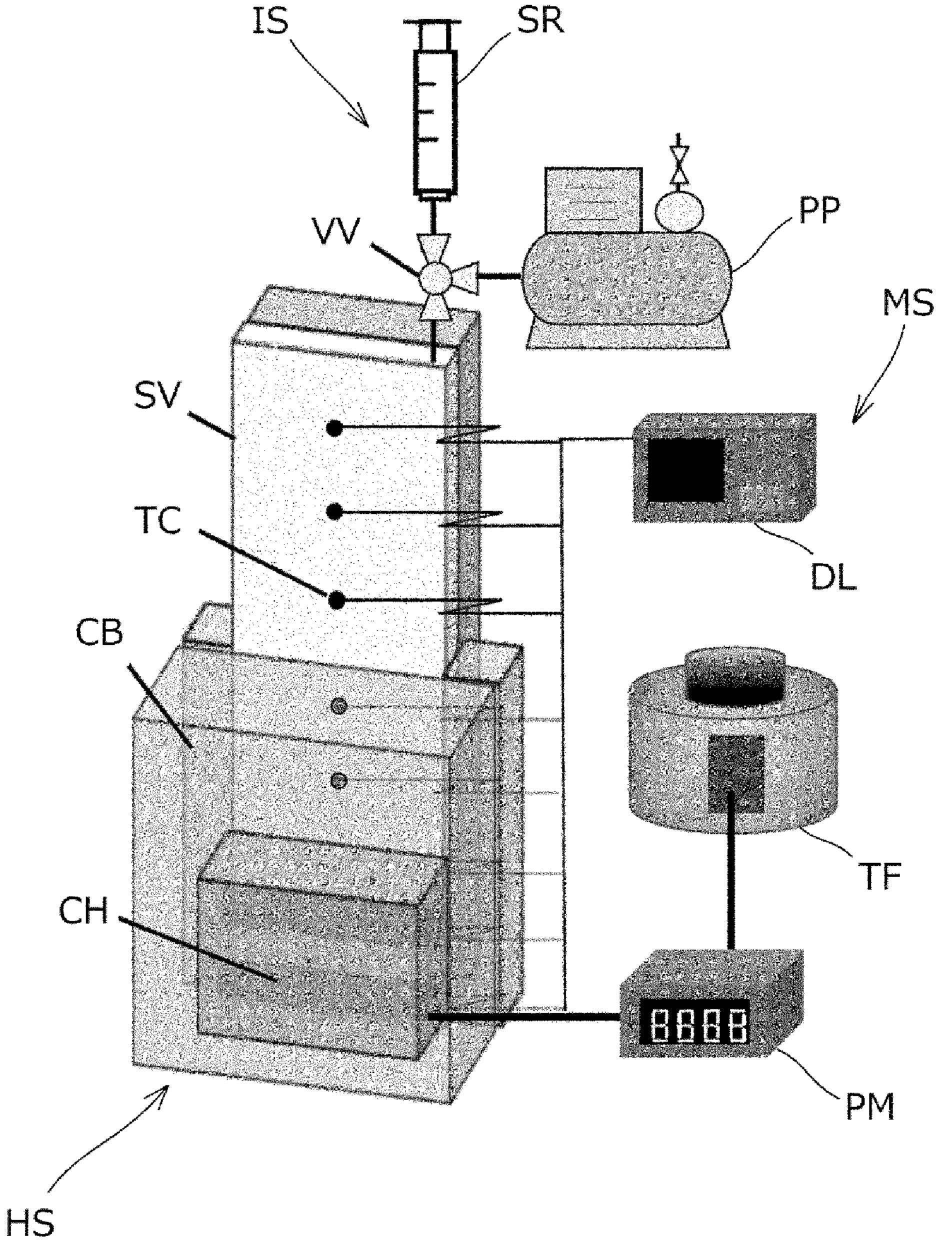


FIG. 4

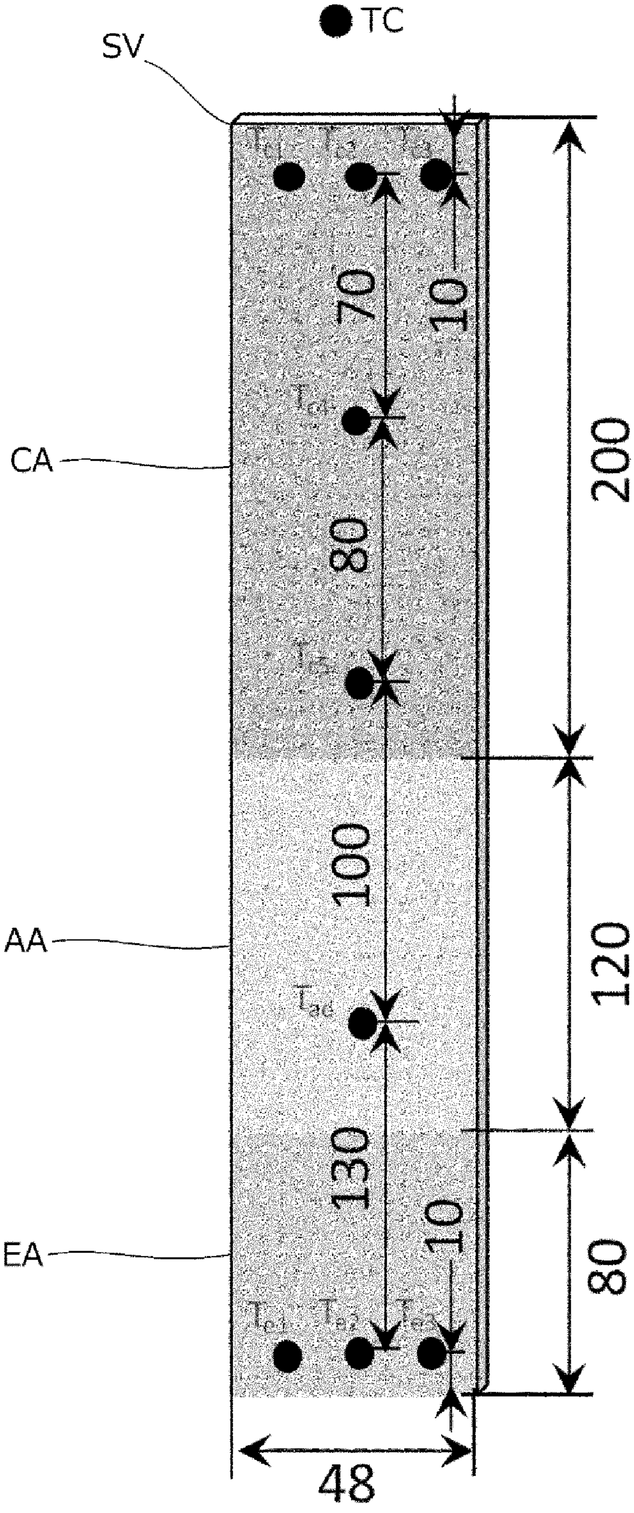

TC
SV
T_{c1}
T_{c2}
T_{c3}
70
10
T_{c4}
CA
200
80
T_{c5}
100
AA
120
T_{ac}
130
10
EA
80
T_{e1}
T_{e2}
T_{e3}
48

FIG. 5

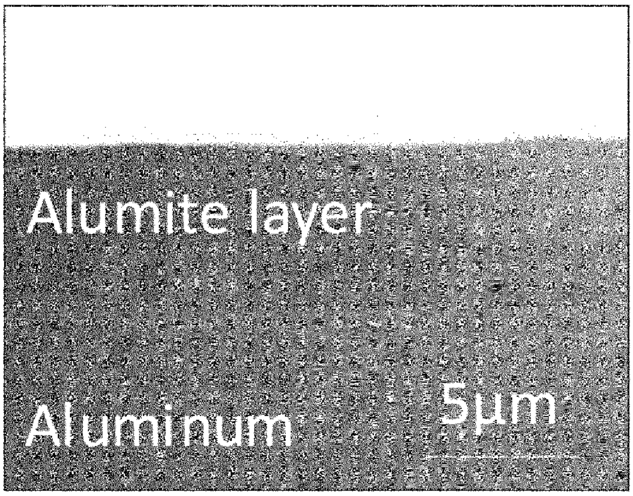

Alumite layer
Aluminum
5μm

FIG. 6

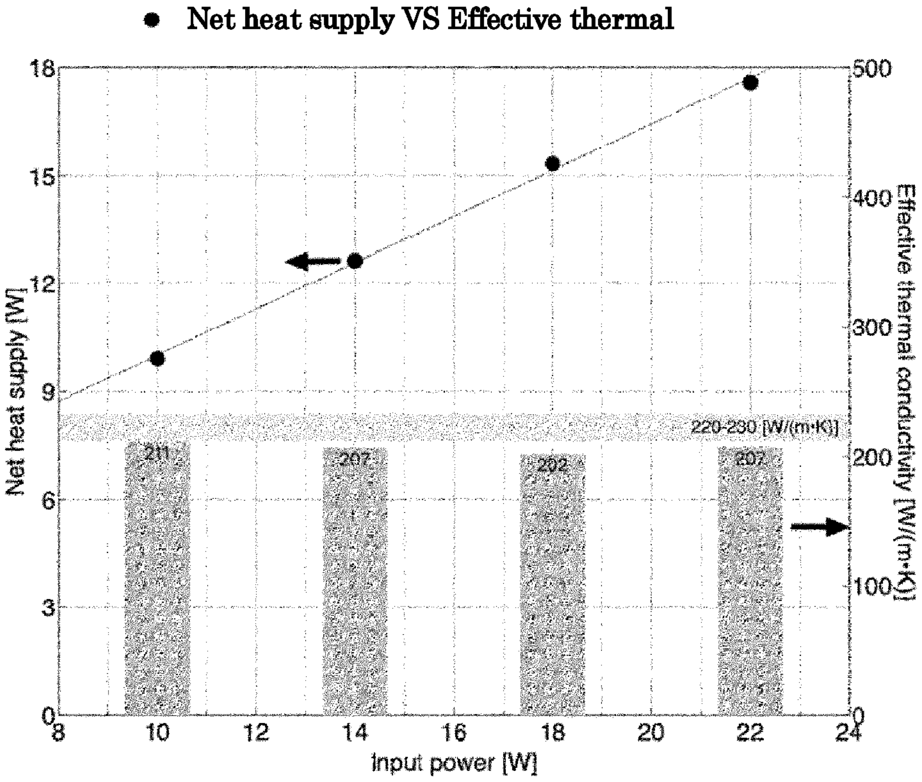

● Net heat supply VS Effective thermal
Net heat supply [W]
0
3
6
9
12
15
18
Effective thermal conductivity [W/(m•K)]
0
100
200
300
400
500
220-230 [W/(m·K)]
211
207
202
207
Input power [W]
8
10
12
14
16
18
20
22
24

FIG. 7

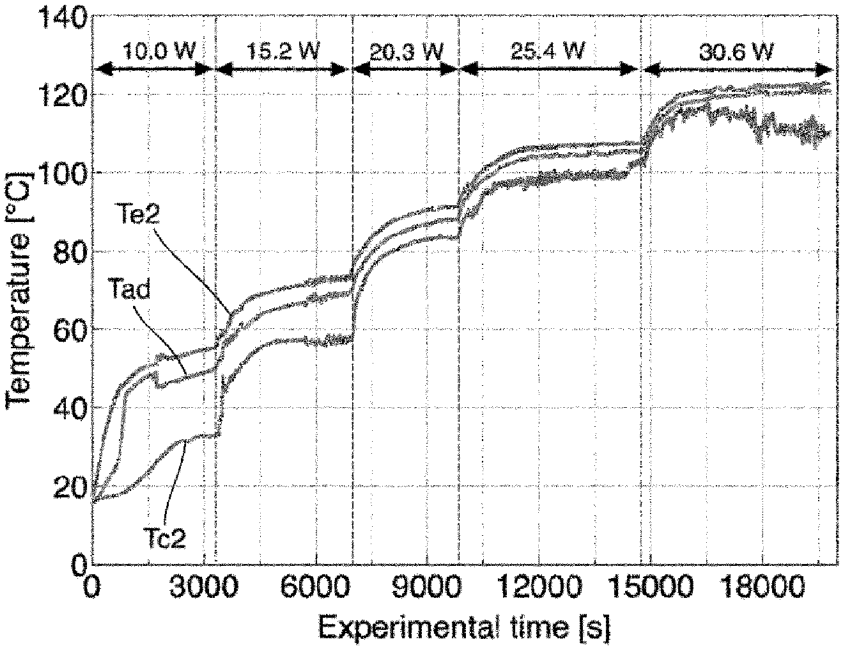

10.0 W
15.2 W
20.3 W
25.4 W
30.6 W
Te2
Tad
Tc2
Temperature [°C]
0
20
40
60
80
100
120
140
0
3000
6000
9000
12000
15000
18000
Experimental time [s]

FIG. 8

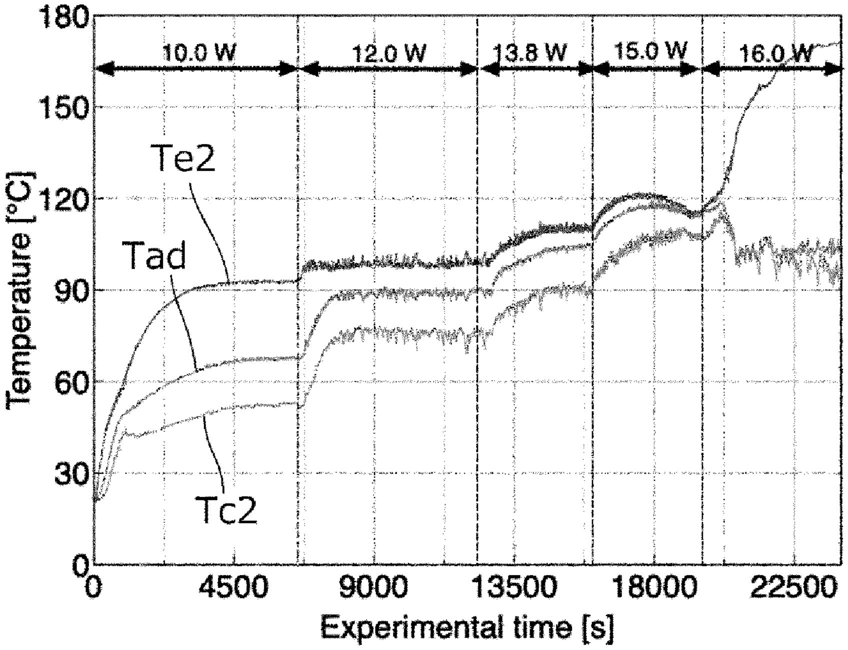

10.0 W
12.0 W
13.8 W
15.0 W
16.0 W
Te2
Tad
Tc2
Temperature [°C]
0
30
60
90
120
150
180
0
4500
9000
13500
18000
22500
Experimental time [s]

FIG. 9

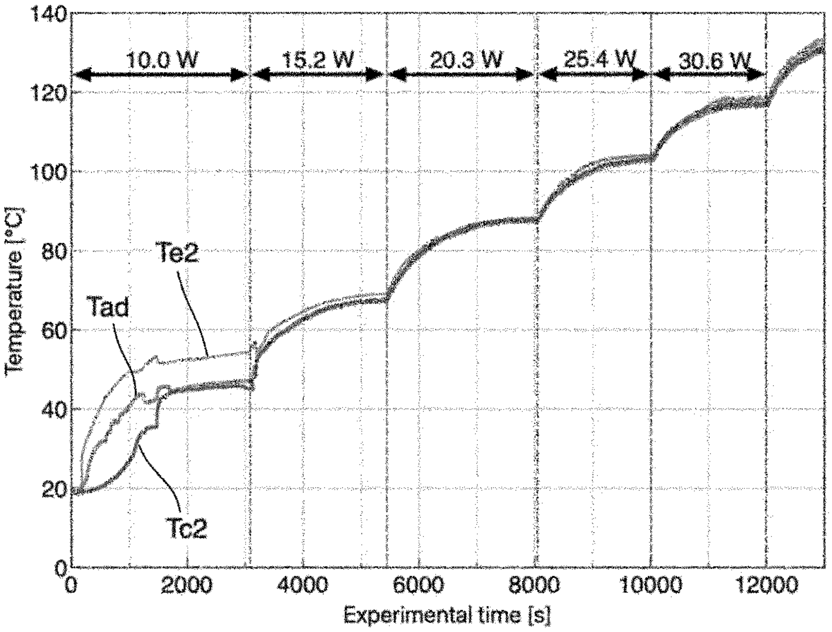

10.0 W
15.2 W
20.3 W
25.4 W
30.6 W
Te2
Tad
Tc2
Temperature [°C]
0
20
40
60
80
100
120
140
0
2000
4000
6000
8000
10000
12000
Experimental time [s]

FIG. 10

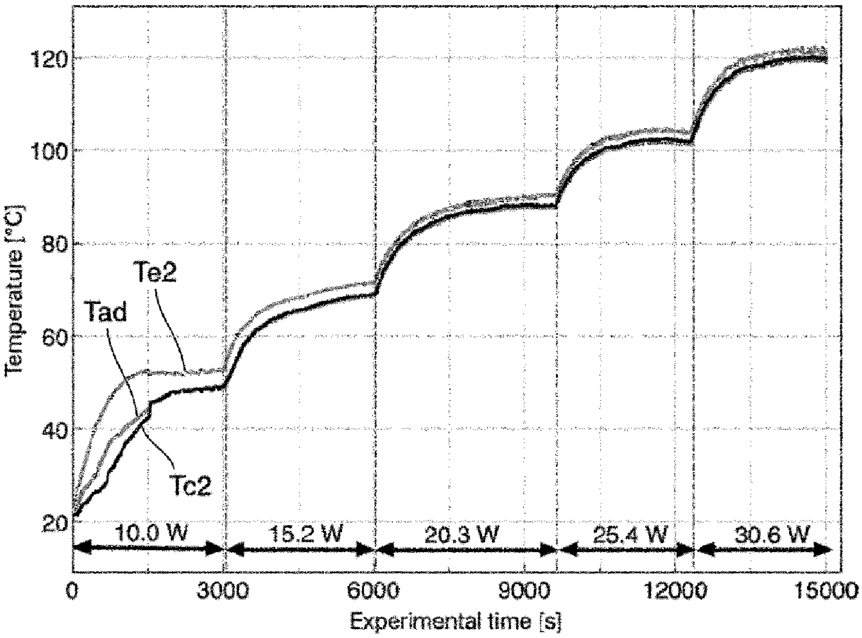

Te2
Tad
Tc2
Temperature [°C]
20
40
60
80
100
120
10.0 W
15.2 W
20.3 W
25.4 W
30.6 W
0
3000
6000
9000
12000
15000
Experimental time [s]

FIG. 11

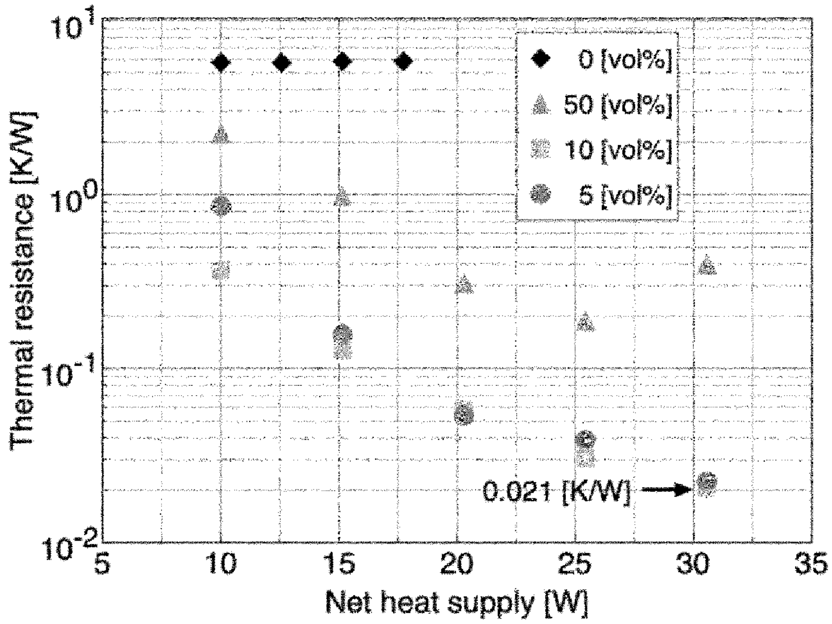

10^1
10^0
10^{-1}
10^{-2}
Thermal resistance [K/W]
0 [vol%]
50 [vol%]
10 [vol%]
5 [vol%]
0.021 [K/W]
5
10
15
20
25
30
35
Net heat supply [W]

FIG. 12

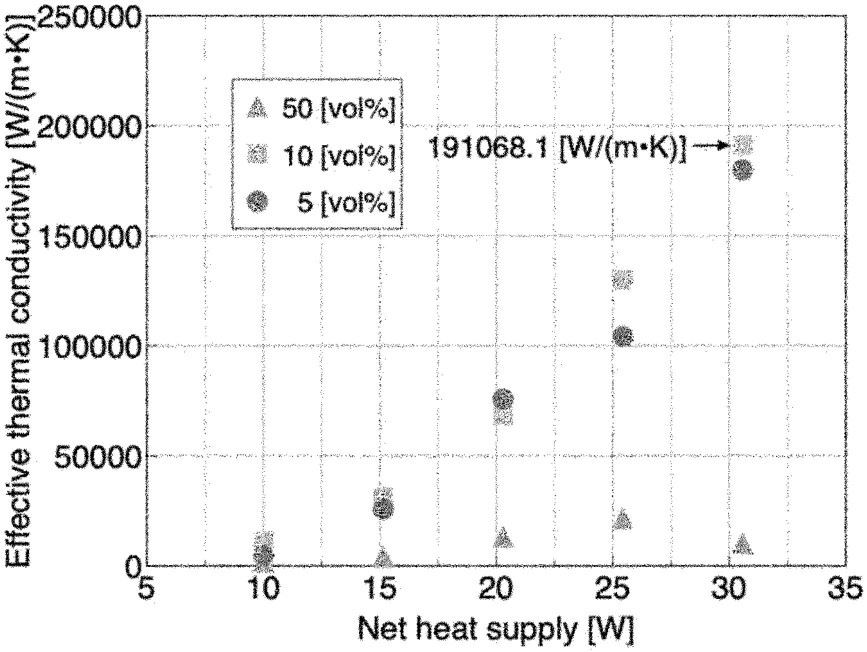
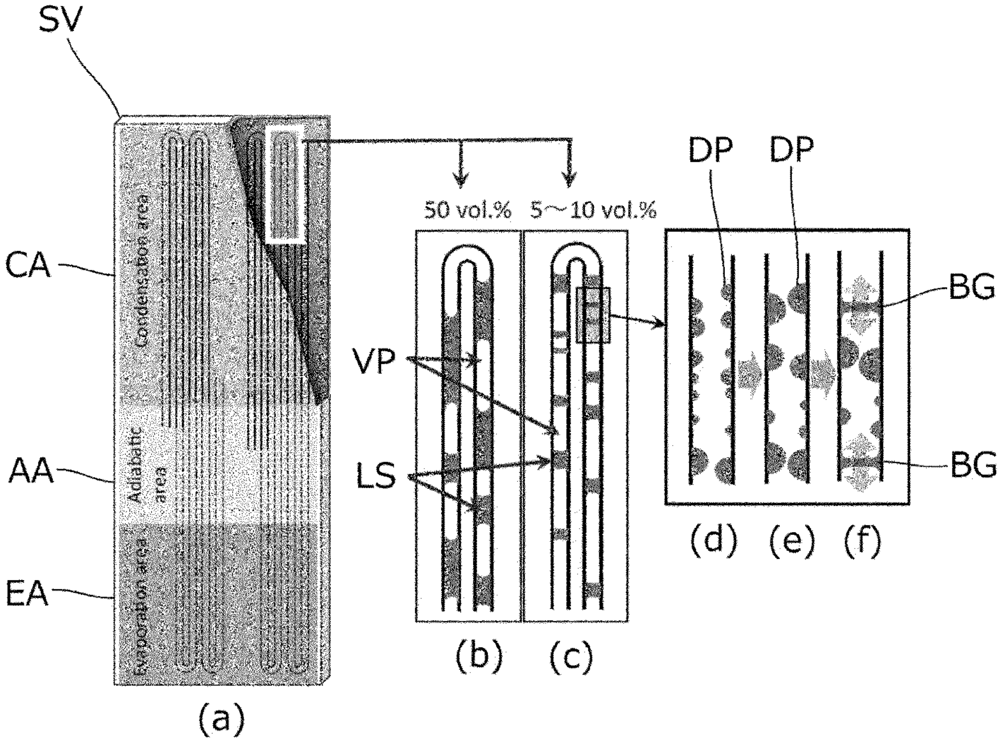

250000
200000
150000
100000
50000
0
Effective thermal conductivity [W/(m•K)]
50 [vol%]
10 [vol%]
5 [vol%]
191068.1 [W/(m•K)]
5
10
15
20
25
30
35
Net heat supply [W]

FIG. 13


SV
CA
AA
EA
Condensation area
Adiabatic area
Evaporation area
50 vol.%
5～10 vol.%
VP
LS
DP
DP
BG
BG
(a)
(b)
(c)
(d)
(e)
(f)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2023/001216

A. CLASSIFICATION OF SUBJECT MATTER

F28D 15/02(2006.01)i
FI: F28D15/02 102G; F28D15/02 M; F28D15/02 101L; F28D15/02 104A

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F28D15/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2023
Registered utility model specifications of Japan 1996-2023
Published registered utility model applications of Japan 1994-2023

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 2014-47979 A (TOYOTA CENTRAL R&D LABS INC) 17 March 2014 (2014-03-17) paragraphs [0026]-[0057], [0142]-[0147], fig. 1-3	1-6
Y	JP 2002-168578 A (NTT ADVANCED TECHNOLOGY CORP) 14 June 2002 (2002-06-14) paragraph [0026]	1-6
Y	JP 2021-32558 A (DALIAN MARITIME UNIVERSITY) 01 March 2021 (2021-03-01) claims 1-7, paragraph [0007]	1-6
Y	JP 3170057 U (KIKO KAGI KOFUN YUGENKOSHI) 01 September 2011 (2011-09-01) paragraphs [0017]-[0023]	5-6
A	JP 2015-194315 A (DENSO CORP) 05 November 2015 (2015-11-05) paragraphs [0014]-[0022], [0051]-[0055], fig. 1-3	1-6

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier application or patent but published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search **02 March 2023**	Date of mailing of the international search report **14 March 2023**
Name and mailing address of the ISA/JP **Japan Patent Office (ISA/JP)** **3-4-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8915** **Japan**	Authorized officer Telephone No.

Form PCT/ISA/210 (second sheet) (January 2015)

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2023/001216

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
JP 2014-47979 A	17 March 2014	(Family: none)	
JP 2002-168578 A	14 June 2002	(Family: none)	
JP 2021-32558 A	01 March 2021	US 2021/0055058 A1 claims 1-7, paragraph [0005] CN 110472352 A	
JP 3170057 U	01 September 2011	(Family: none)	
JP 2015-194315 A	05 November 2015	(Family: none)	

Form PCT/ISA/210 (patent family annex) (January 2015)

REFERENCES CITED IN THE DESCRIPTION

Non-patent literature cited in the description

- **FUMOTO, KOJI et al.** Improvement in Pulsating Heat Pipe using a Self-Rewetting Fluid (Cases of Butanol and Pentanol).. *Thermal Science & Engineering*, 2011, vol. 19 (1) **[0008]**