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(54) ENHANCED POOL BOILING SYSTEM AND METHOD

(71) Applicant: **UT-Battelle, LLC**, Oak Ridge, TN (US)

(72) Inventors: **Kashif Nawaz**, Knoxville, TN (US); **Cheng-Min Yang**, Oak Ridge, TN (US)

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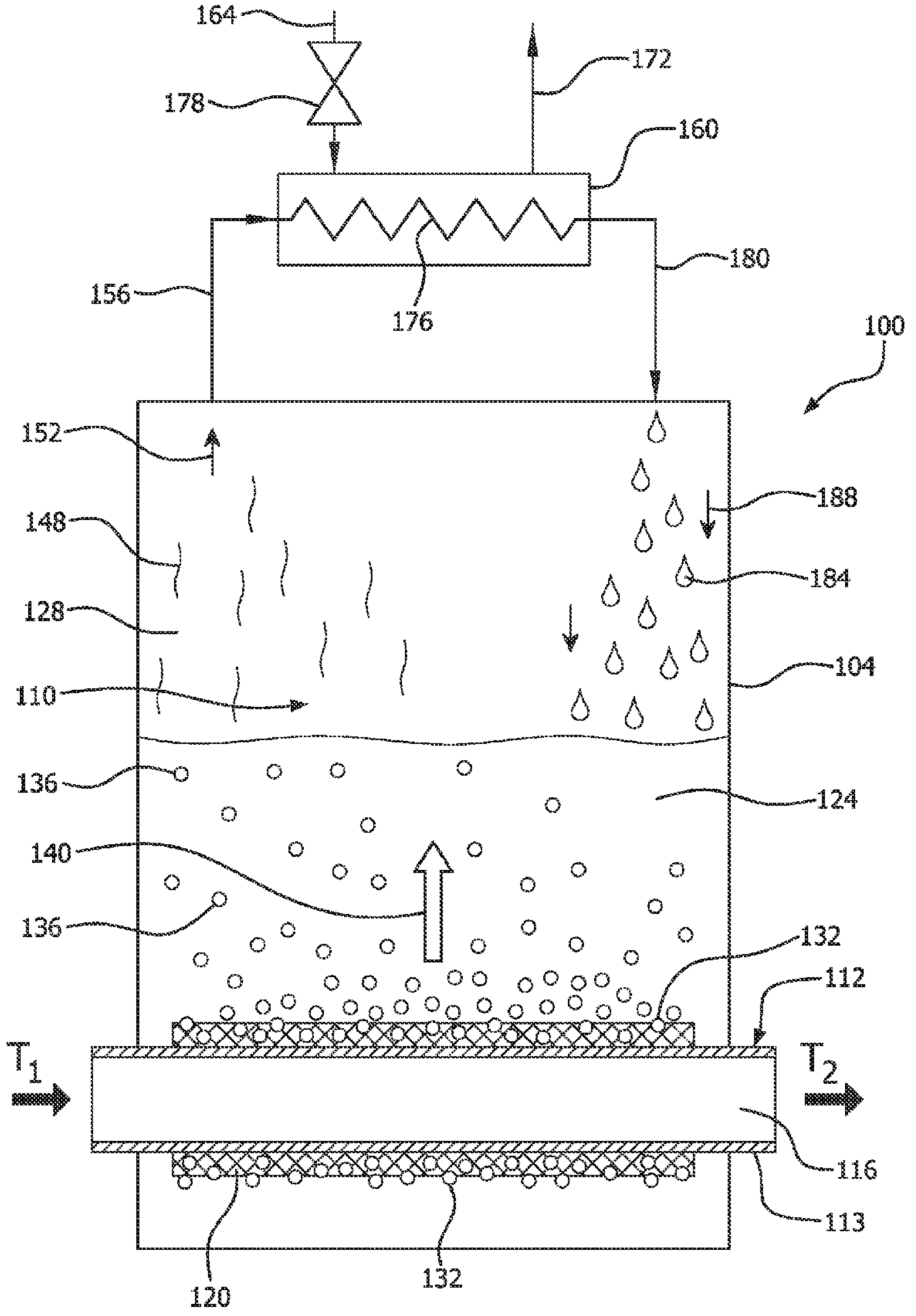
(57) ABSTRACT

A boiling heat exchange system includes a heat exchanger including a chamber configured to hold a heat exchange fluid including a heat exchange vapor and a pool of heat exchange liquid and an evaporator tube having an outer surface and a thermally conductive open-cell porous material disposed on the outer surface and comprising a plurality of pores. The evaporator tube can be immersed in the heat exchange liquid held in the chamber and the heat exchange liquid will enter the pores. The open-cells of the open-cell porous material will heat the heat exchange liquid to cause the heat exchange liquid to boil to a heat exchange vapor and exchange heat with a source fluid flowing through the evaporator tube or with a component in thermal contact with the evaporator. A method of performing heat exchange is also disclosed.



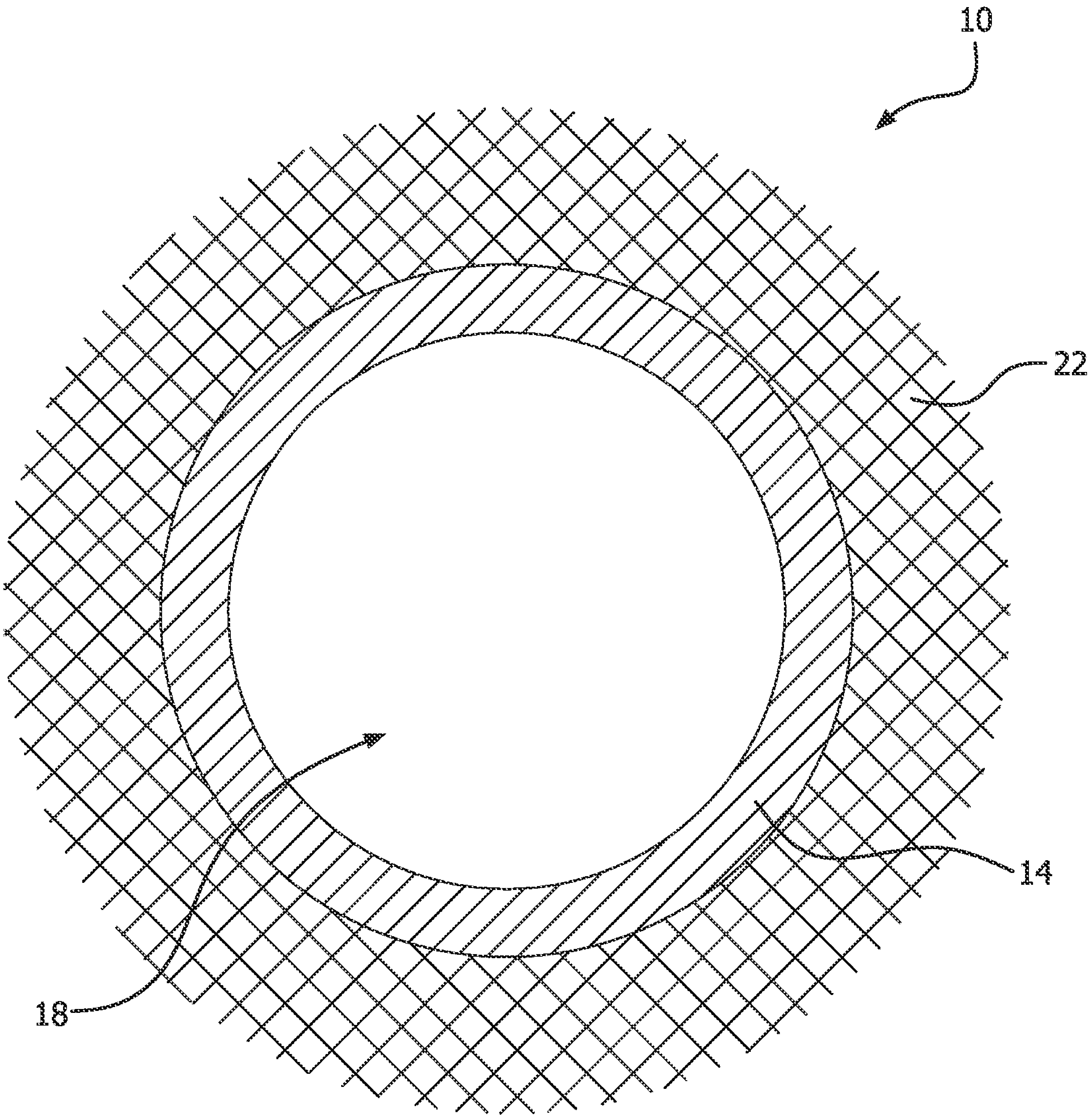


FIG. 1

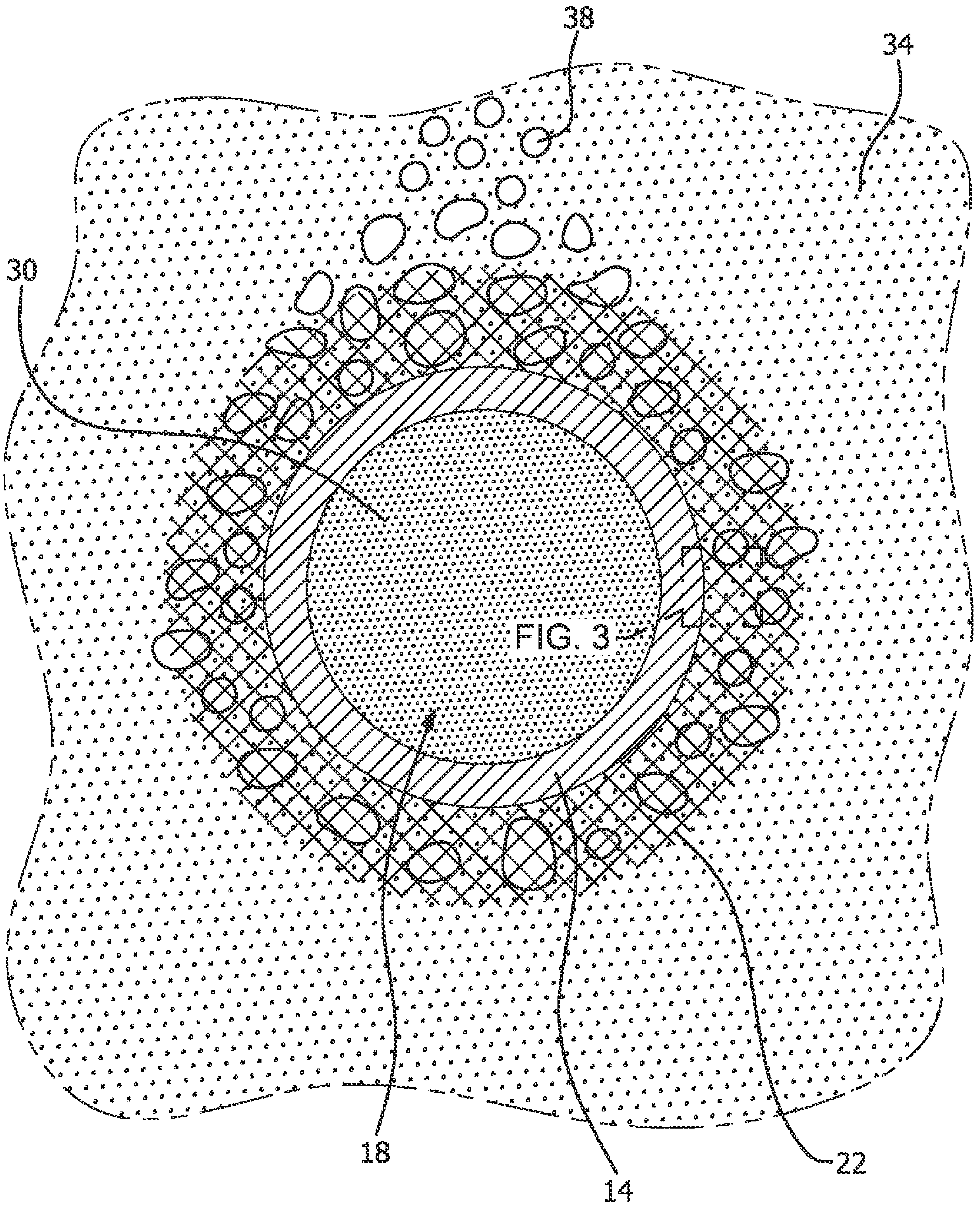


FIG. 2

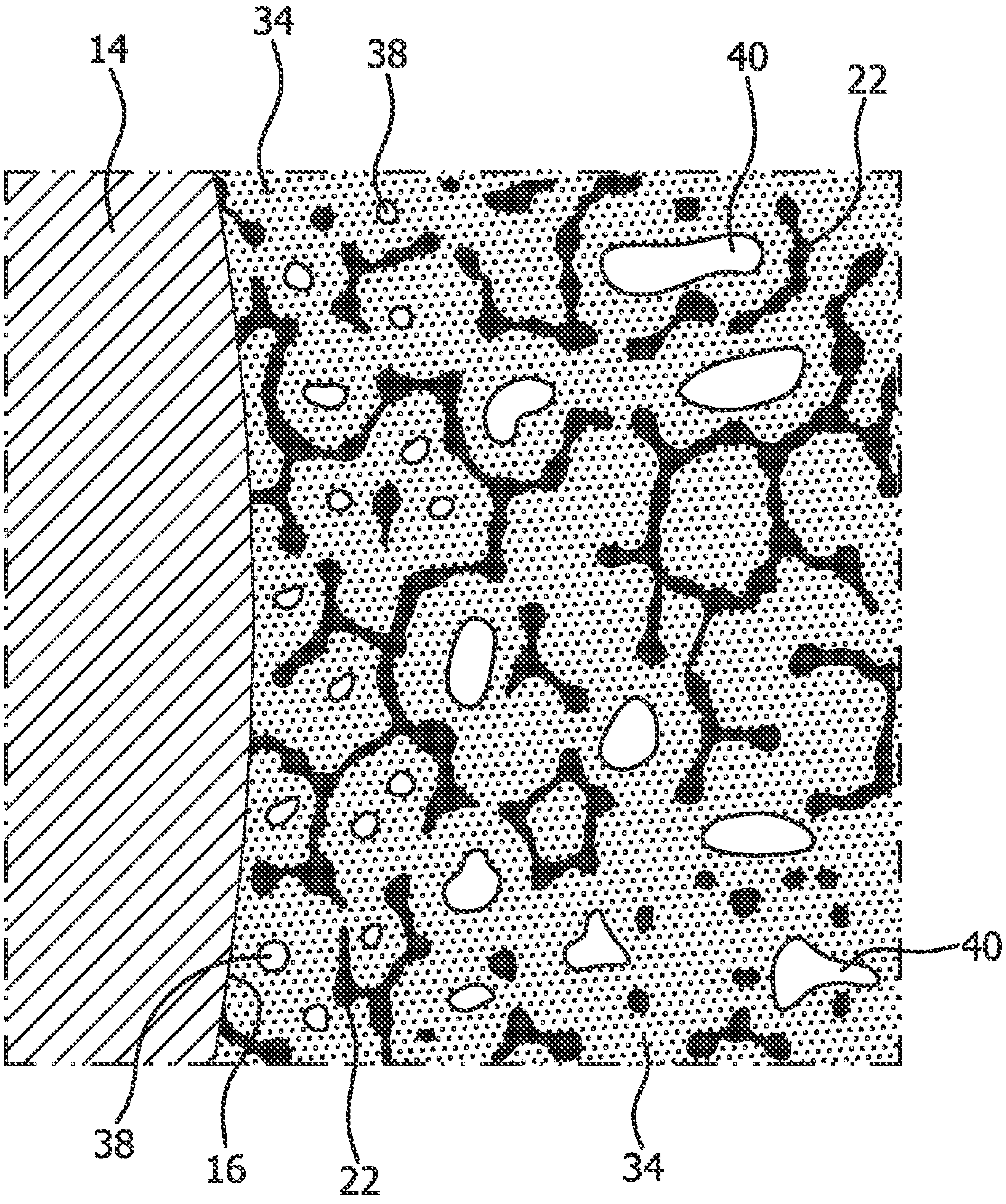
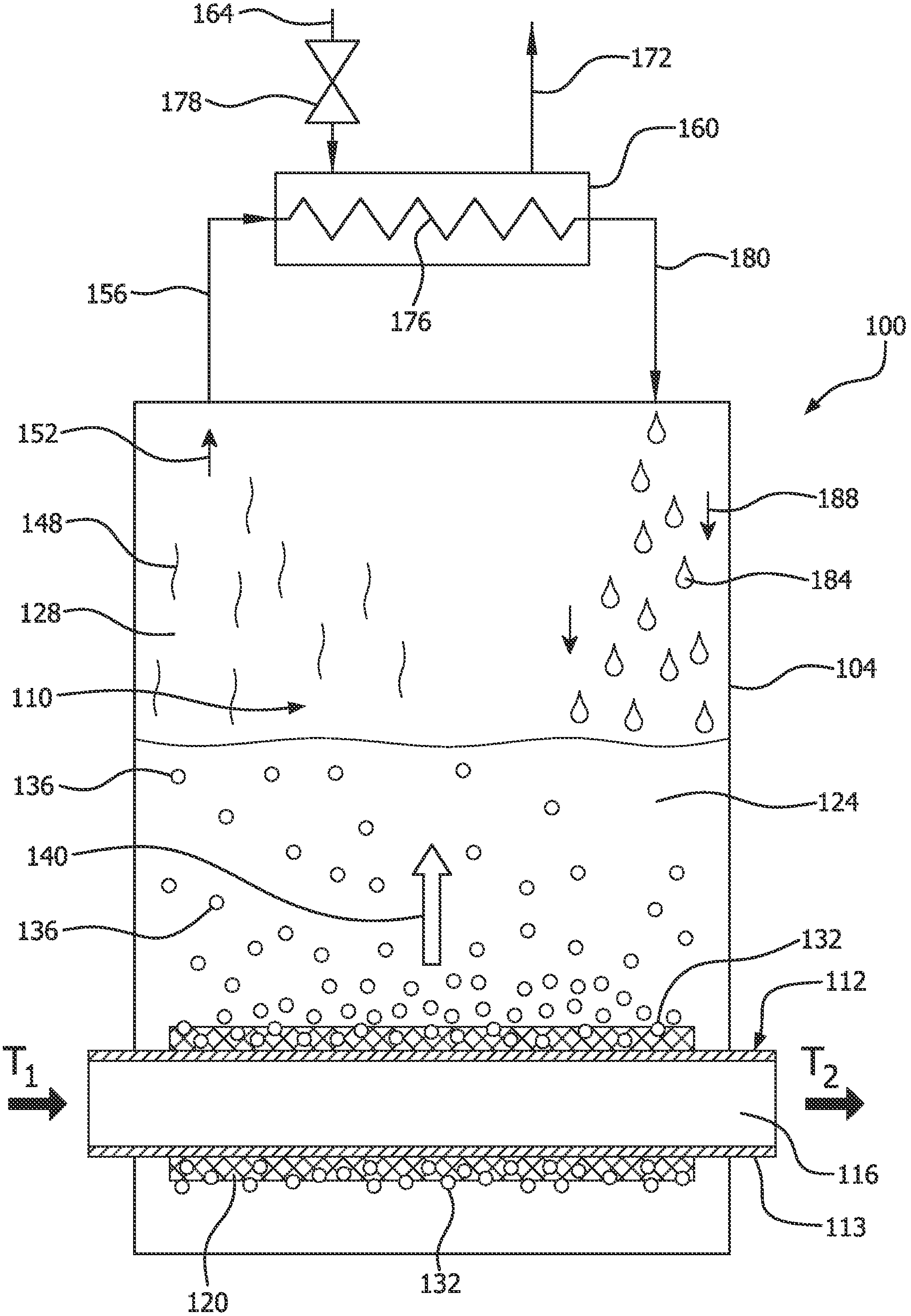


FIG. 3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178
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180
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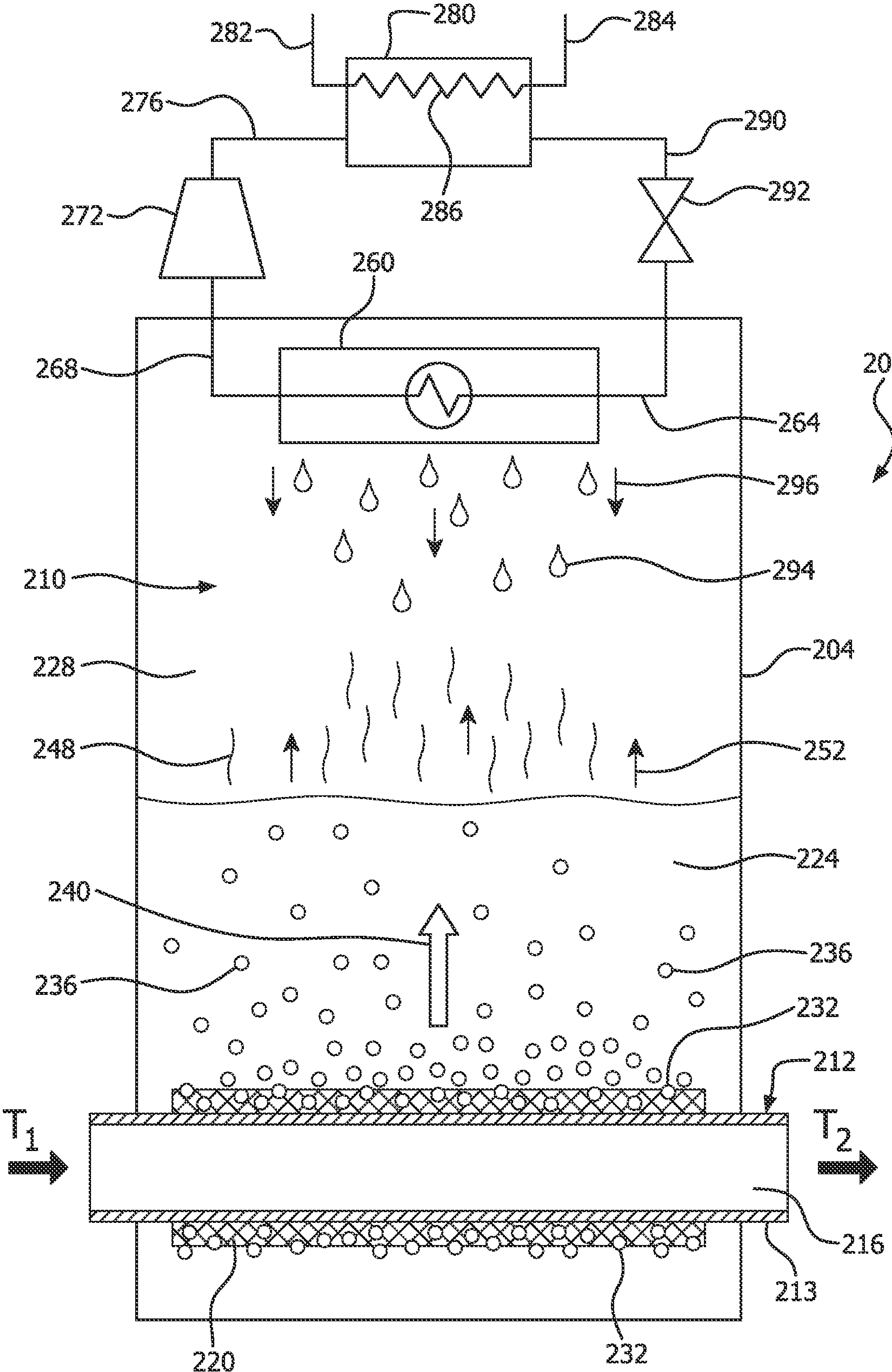
112
T_1
T_2
116
113
120
132

FIG. 4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236
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T1
T2
216
213
220
232

FIG. 5

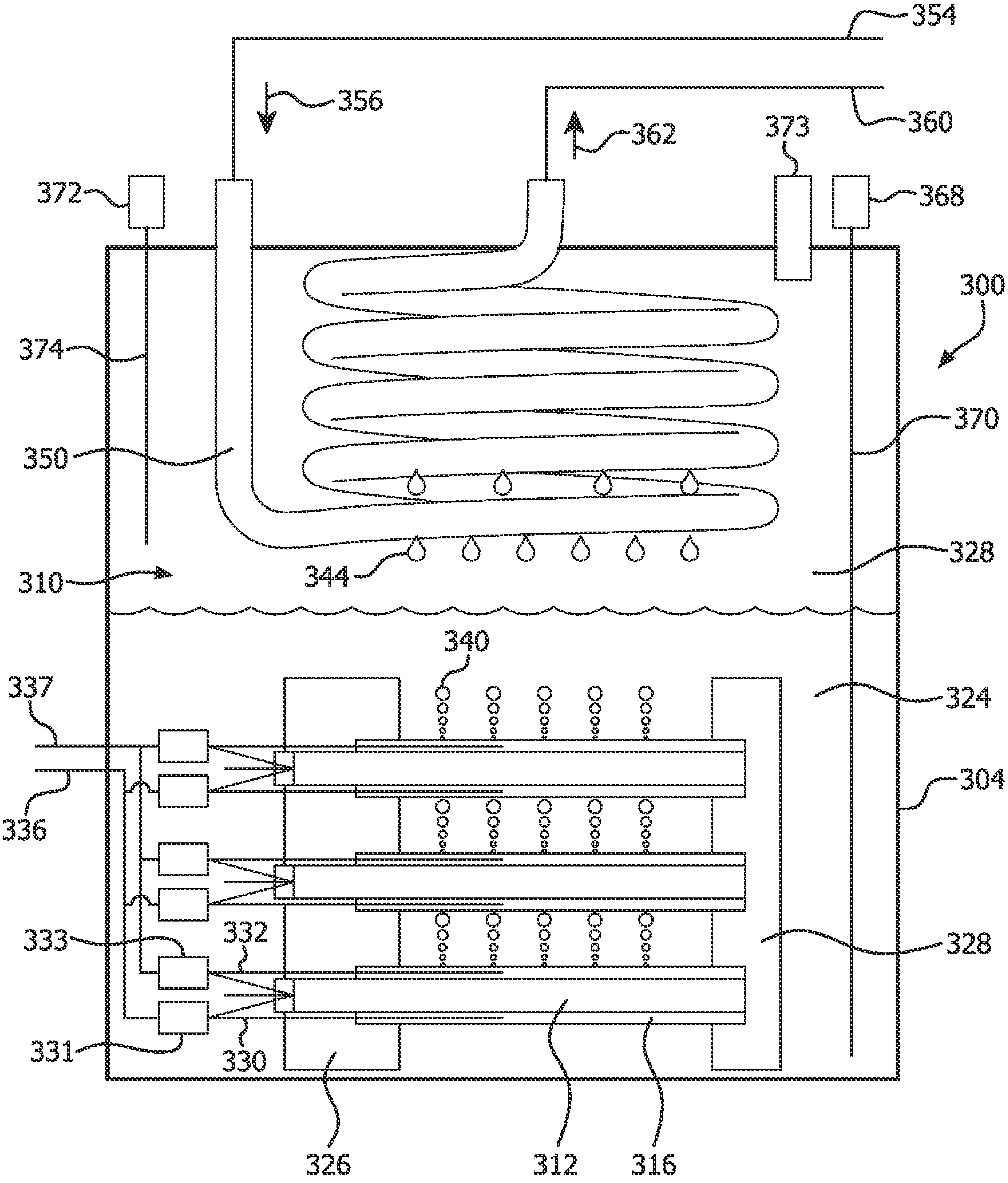
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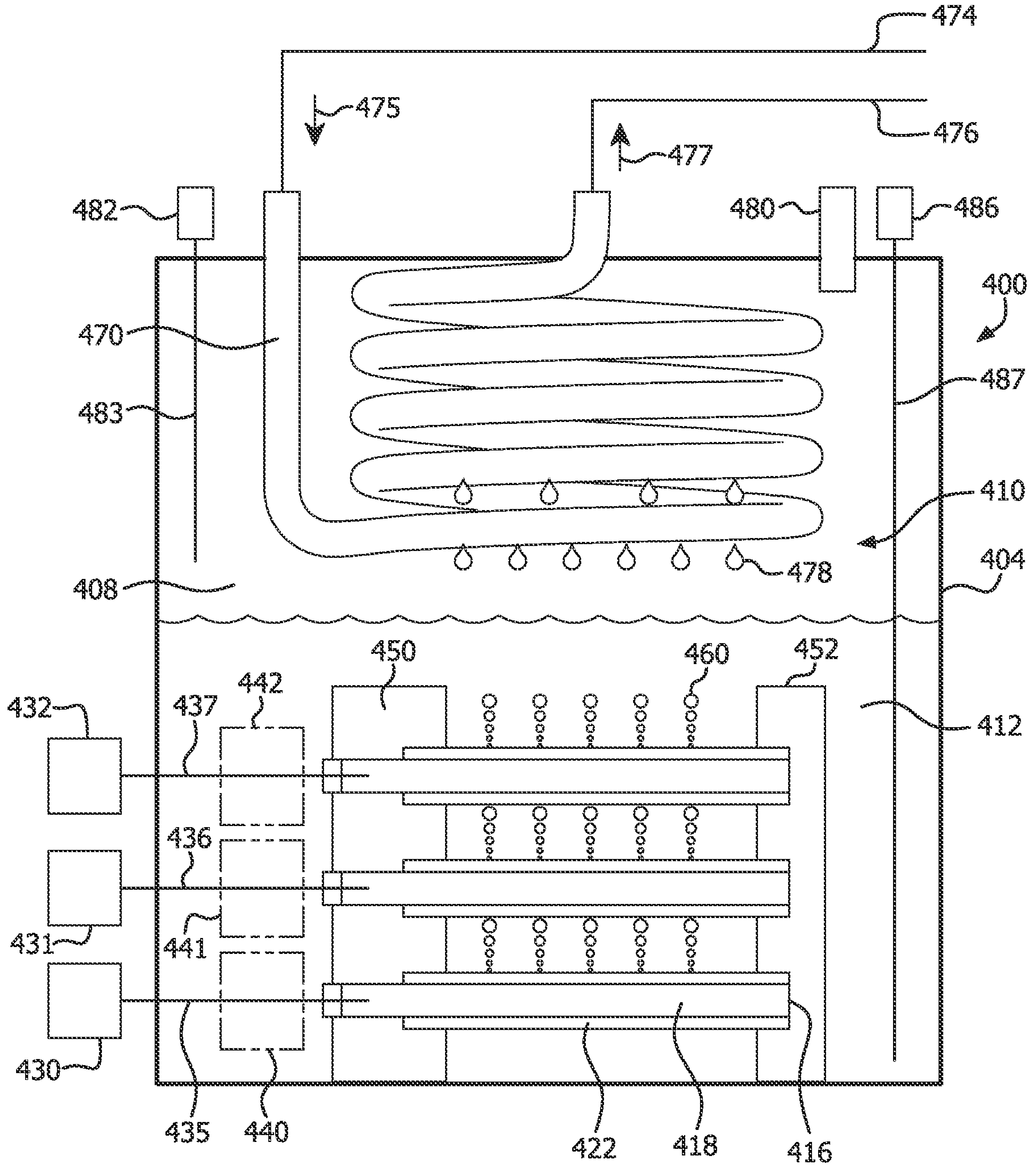
FIG. 6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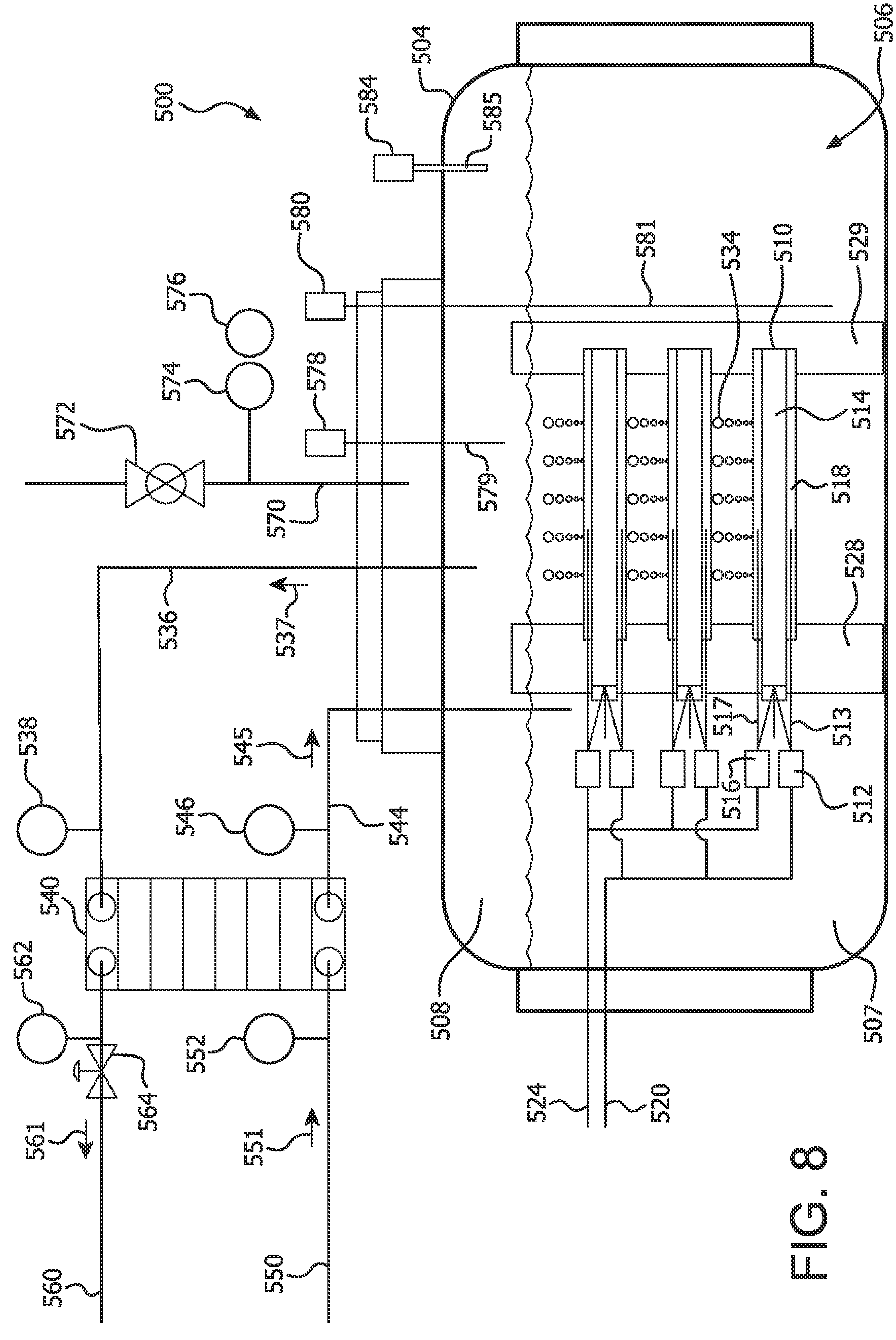
418
416

FIG. 7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536
537
538
545
546
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517
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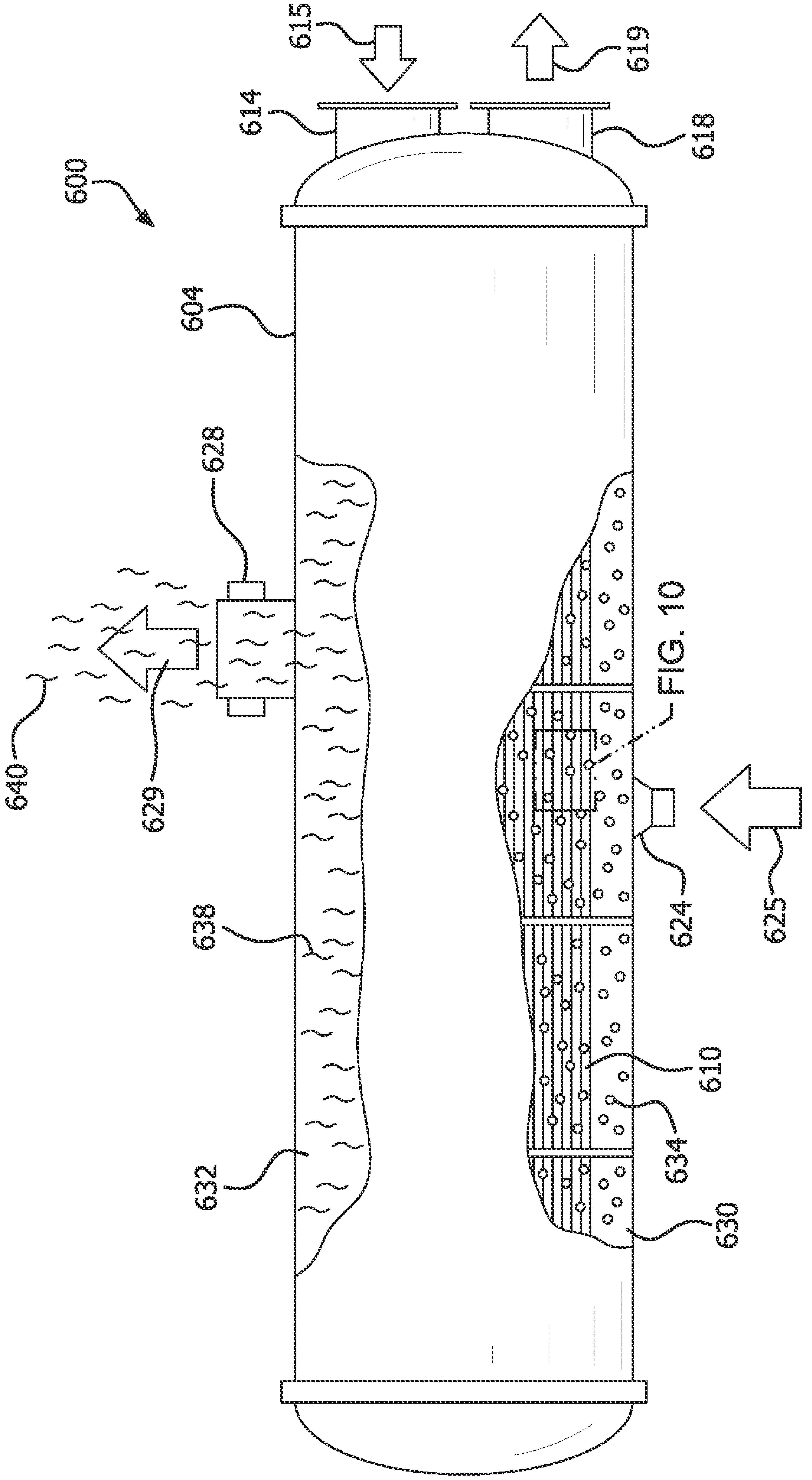
564
561
552
551
508
507
524
520
560
550

FIG. 8


615
619
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618
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638
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FIG. 10
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FIG. 9

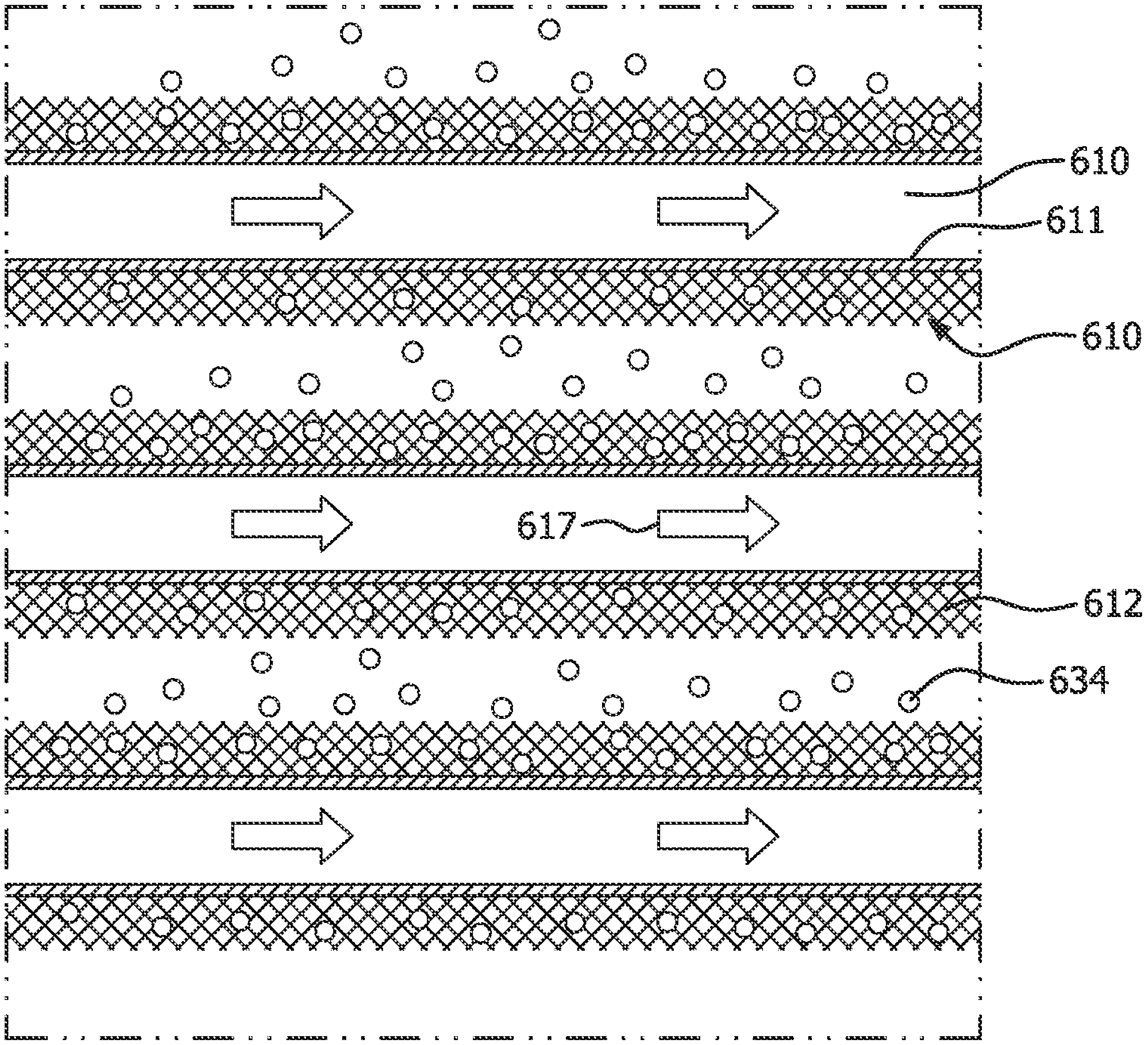

FIG. 10

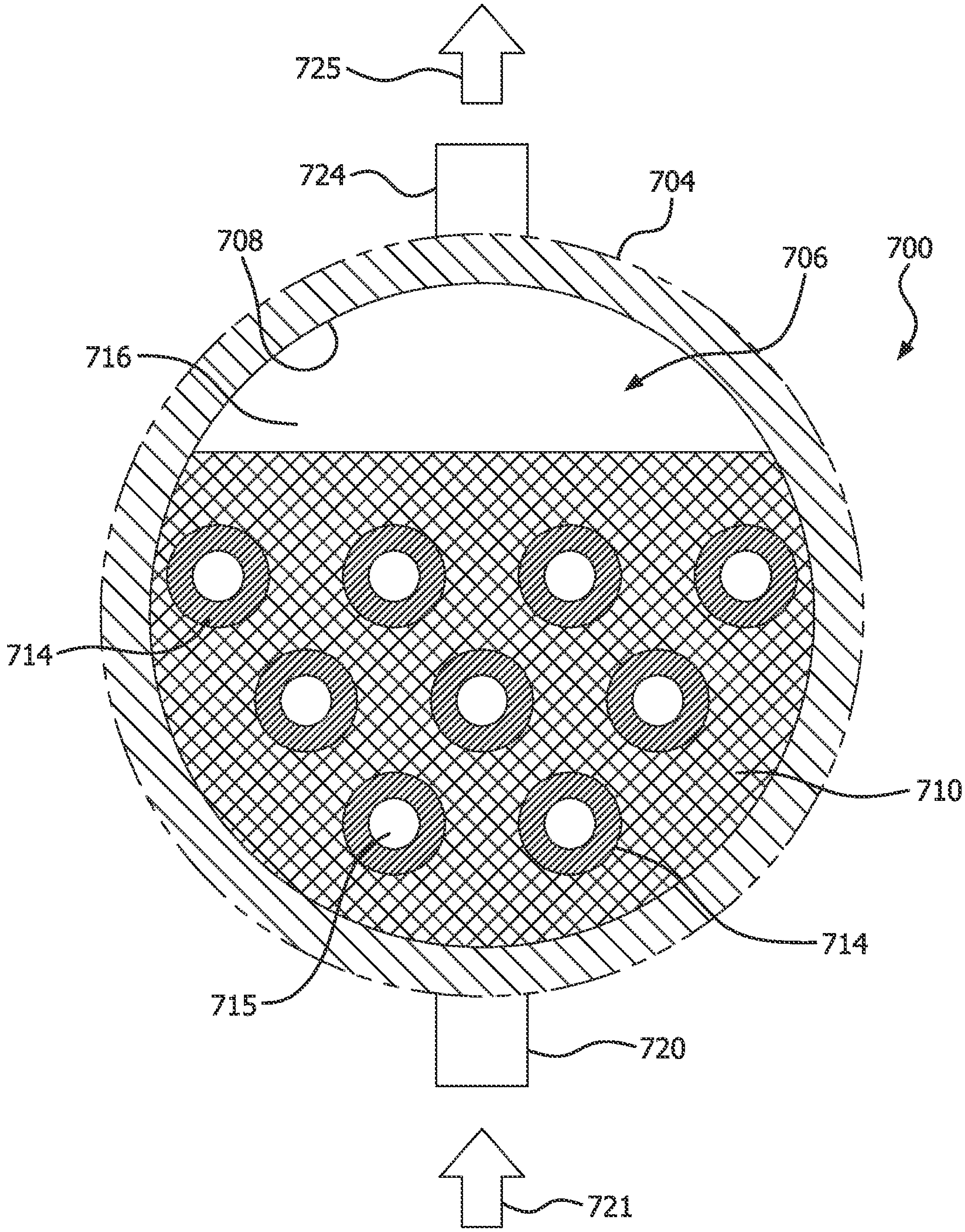

FIG. 11

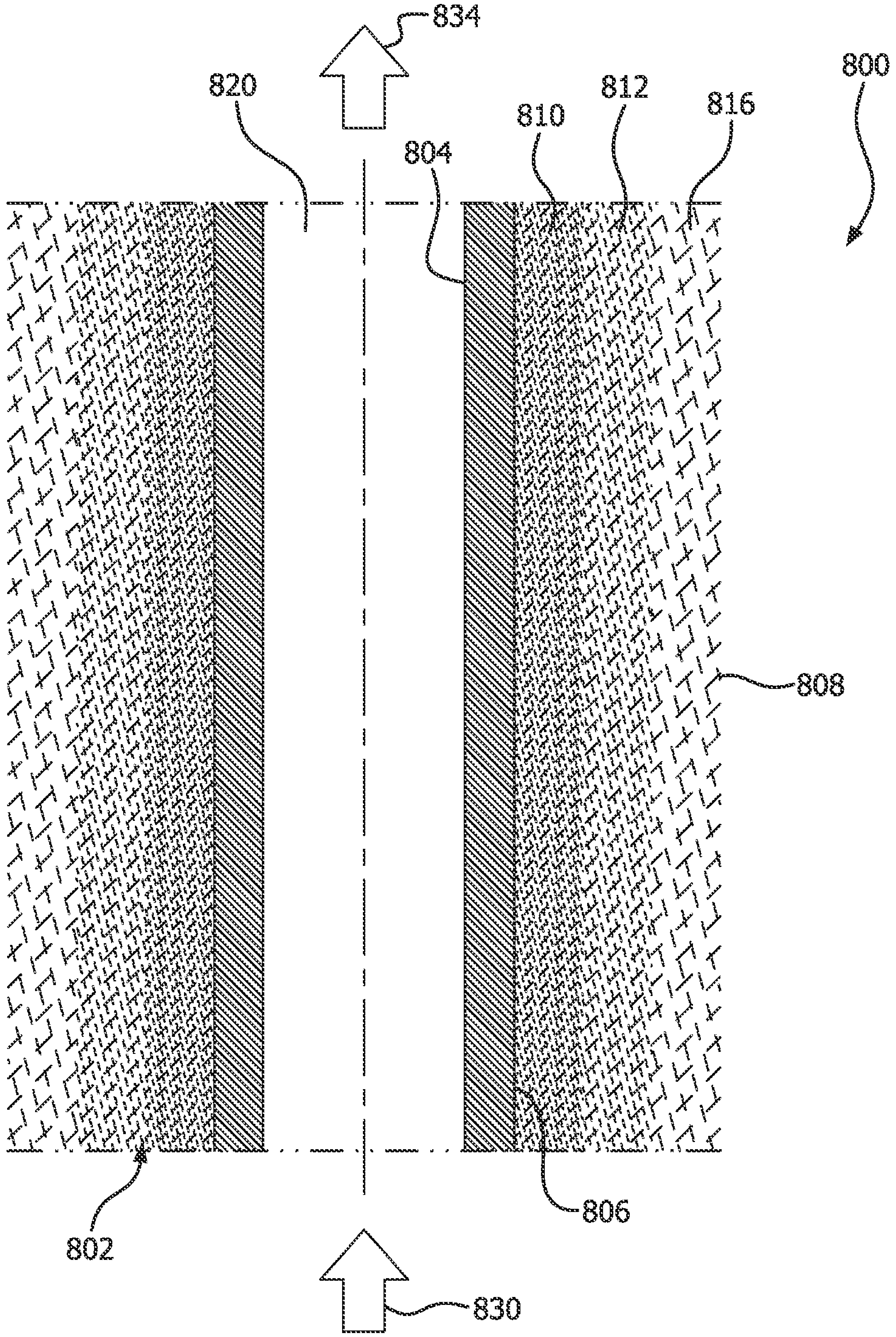

FIG. 12

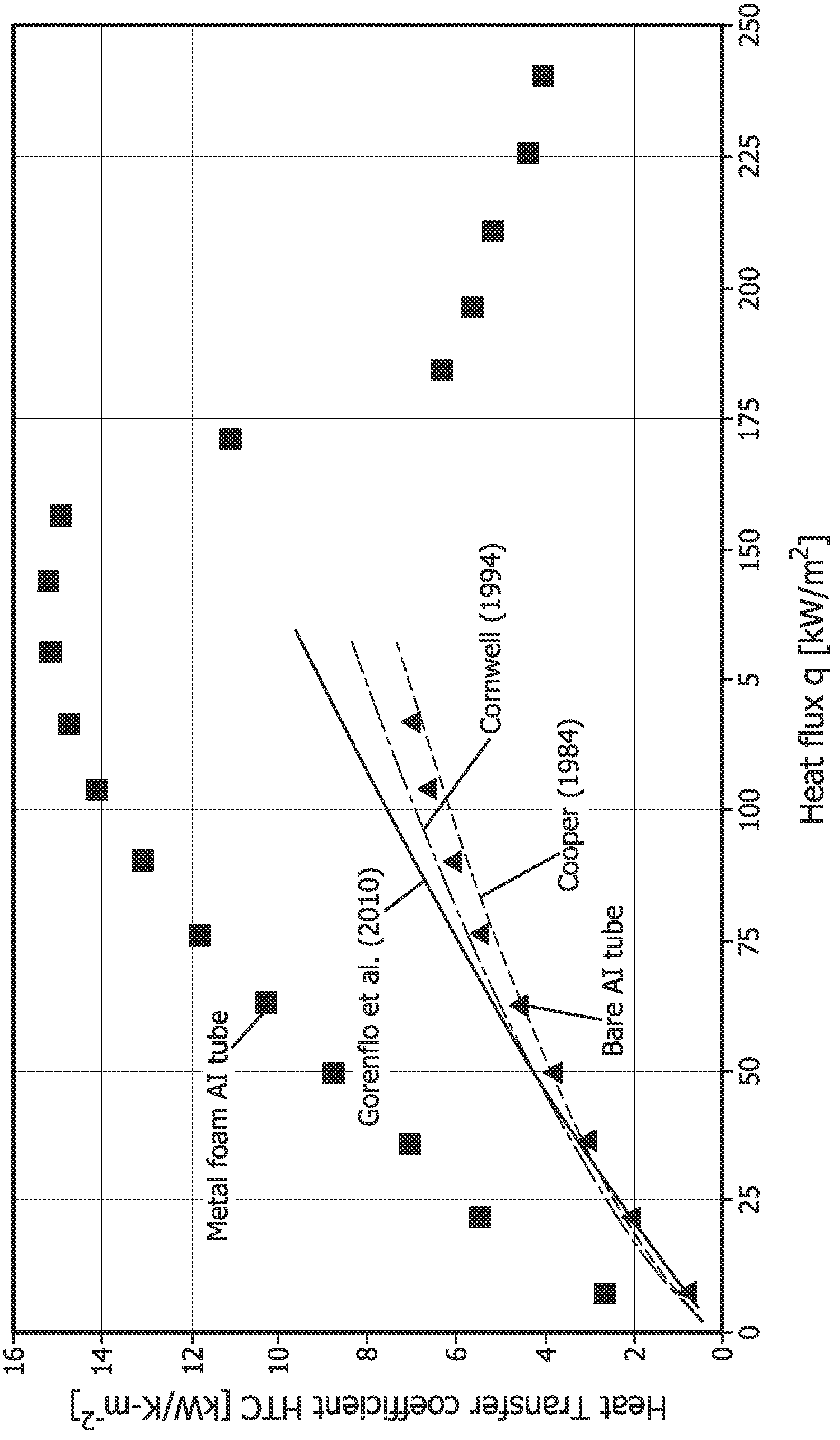
Heat Transfer coefficient HTC [kW/K-m^{-2}]
0
2
4
6
8
10
12
14
16
Heat flux q [kW/m^2]
0
25
50
75
100
5
150
175
200
225
250
Metal foam Al tube
Gorenflo et al. (2010)
Cornwell (1994)
Cooper (1984)
Bare Al tube

FIG. 13

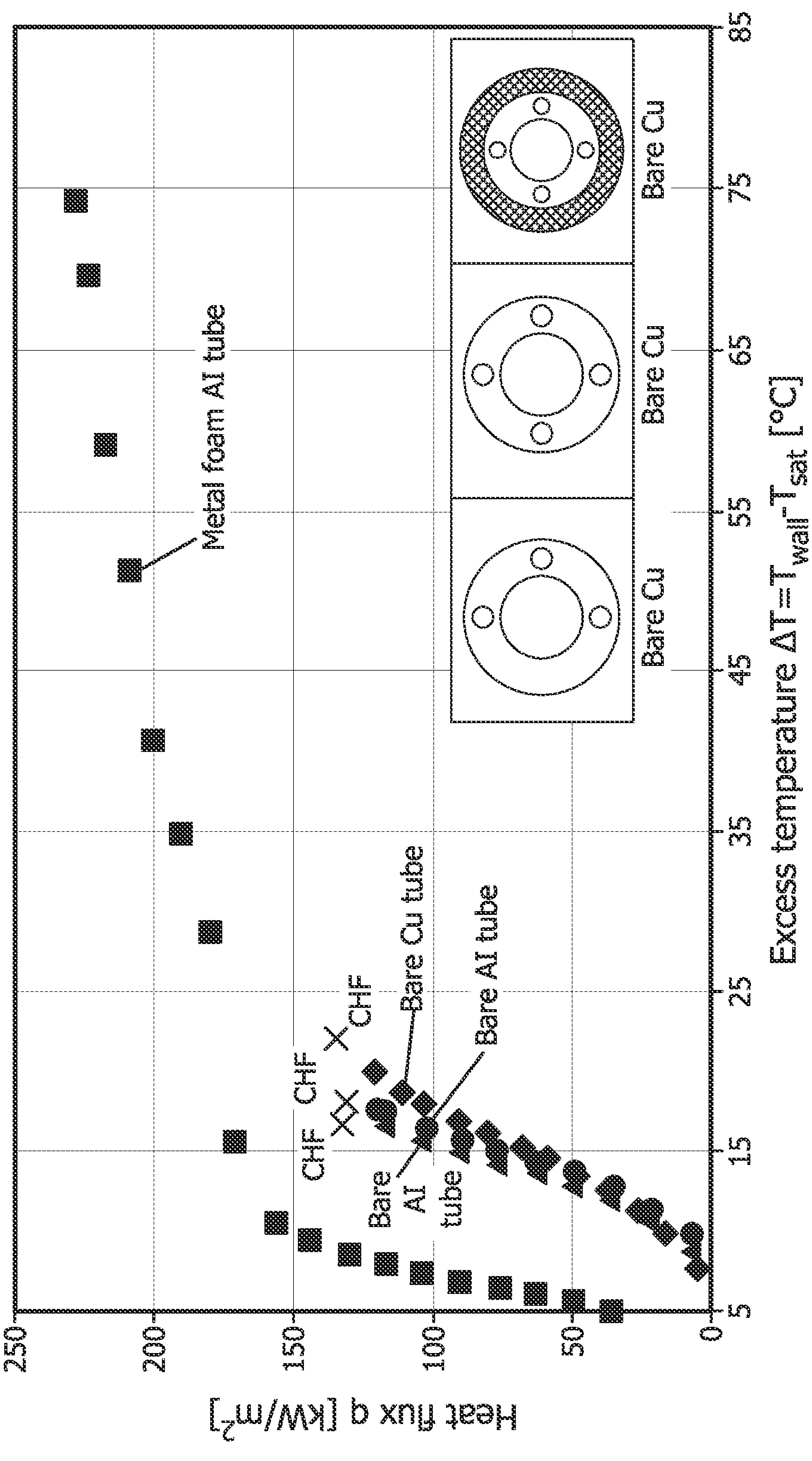
Heat flux q [kW/m^2]
250
200
150
100
50
0
Excess temperature ΔT=T$_{wall}$-T$_{sat}$ [°C]
5
15
25
35
45
55
65
75
85
Metal foam Al tube
CHF
CHF
CHF
Bare Cu tube
Bare Al tube
Bare Al tube
Bare Cu
Bare Cu
Bare Cu

FIG. 14

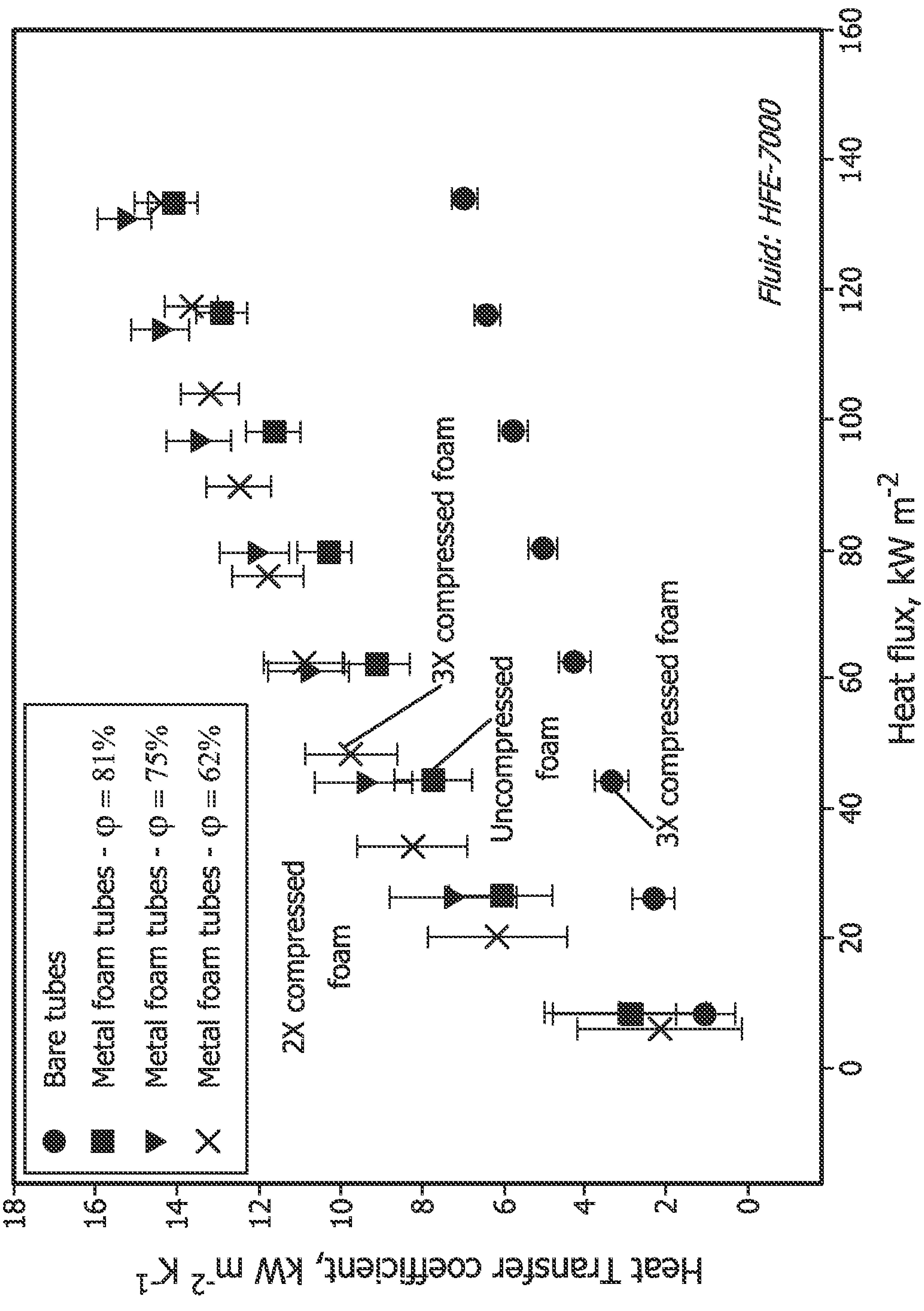
● Bare tubes
■ Metal foam tubes - φ = 81%
▼ Metal foam tubes - φ = 75%
✕ Metal foam tubes - φ = 62%
2X compressed foam
3X compressed foam
Uncompressed foam
3X compressed foam
Fluid: HFE-7000
Heat Transfer coefficient, kW m^{-2} K^{-1}
0
2
4
6
8
10
12
14
16
18
Heat flux, kW m^{-2}
0
20
40
60
80
100
120
140
160

FIG. 15

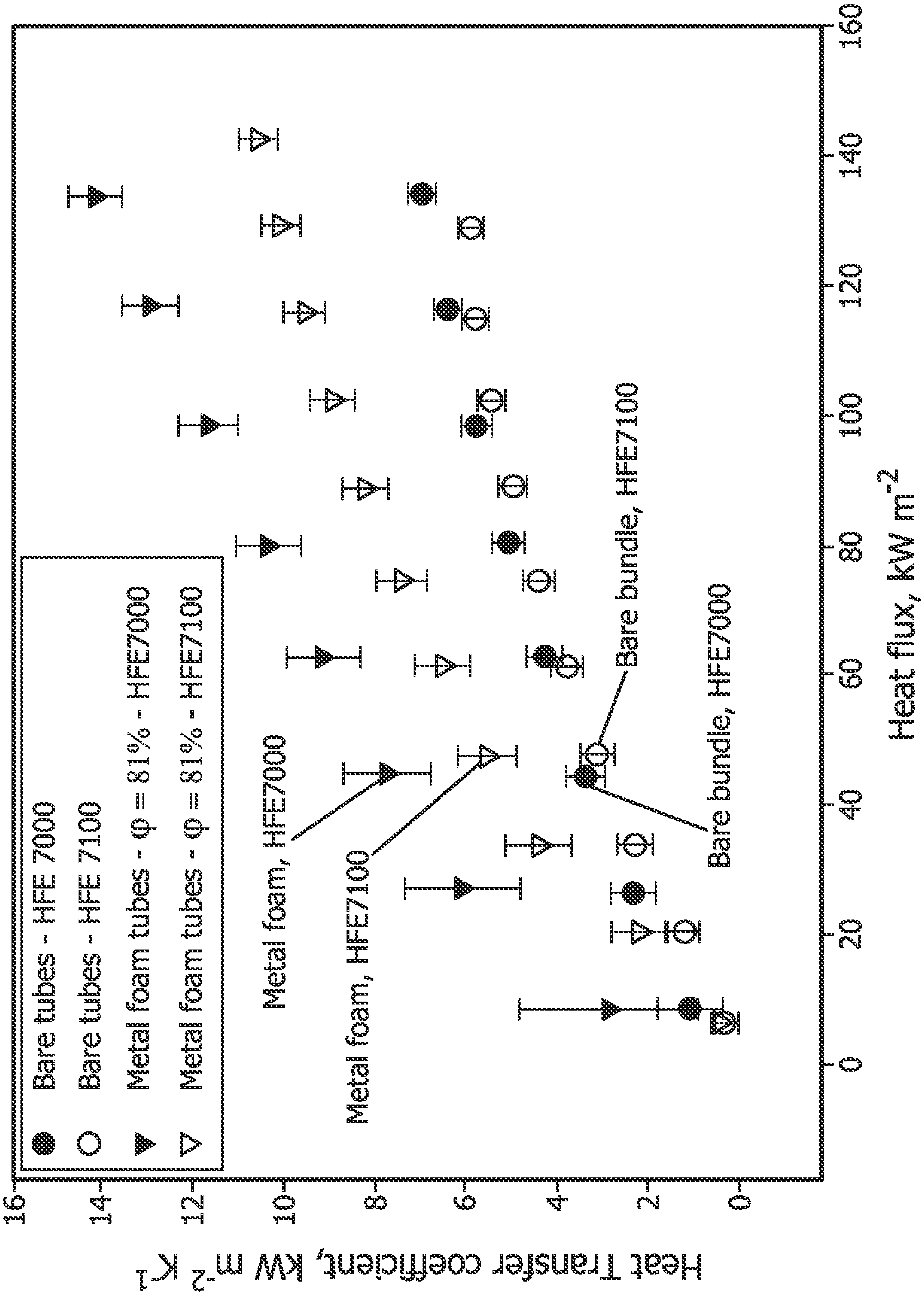
● Bare tubes - HFE 7000
○ Bare tubes - HFE 7100
▲ Metal foam tubes - φ = 81% - HFE7000
△ Metal foam tubes - φ = 81% - HFE7100
Metal foam, HFE7000
Metal foam, HFE7100
Bare bundle, HFE7100
Bare bundle, HFE7000
Heat Transfer coefficient, kW m^{-2} K^{-1}
Heat flux, kW m^{-2}
0
2
4
6
8
10
12
14
16
0
20
40
60
80
100
120
140
160

FIG. 16

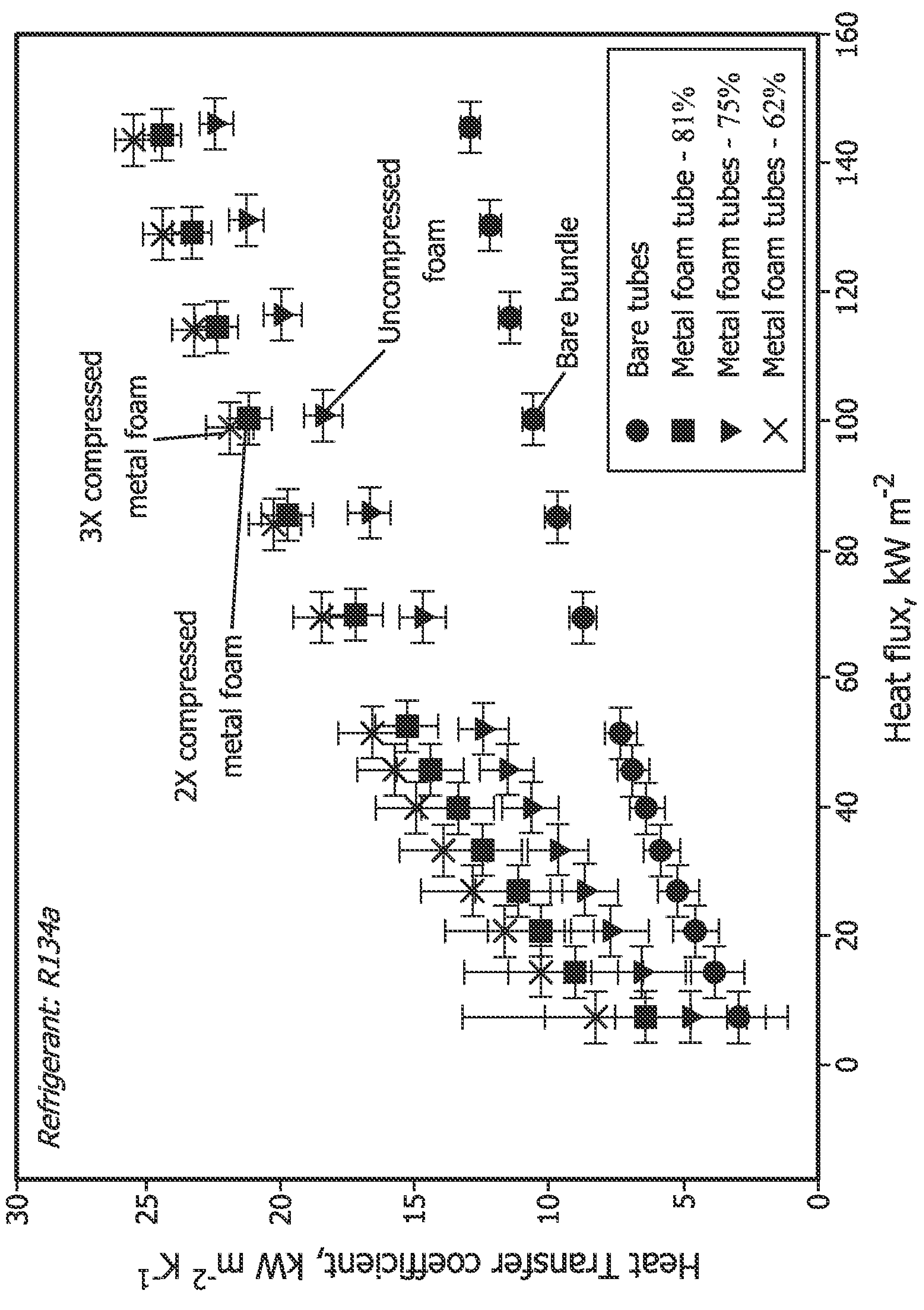
Refrigerant: R134a
3X compressed metal foam
2X compressed metal foam
Uncompressed foam
Bare bundle
● Bare tubes
■ Metal foam tube - 81%
▼ Metal foam tubes - 75%
✕ Metal foam tubes - 62%
Heat Transfer coefficient, kW m^-2 K^-1
Heat flux, kW m^-2
0
5
10
15
20
25
30
0
20
40
60
80
100
120
140
160

FIG. 17

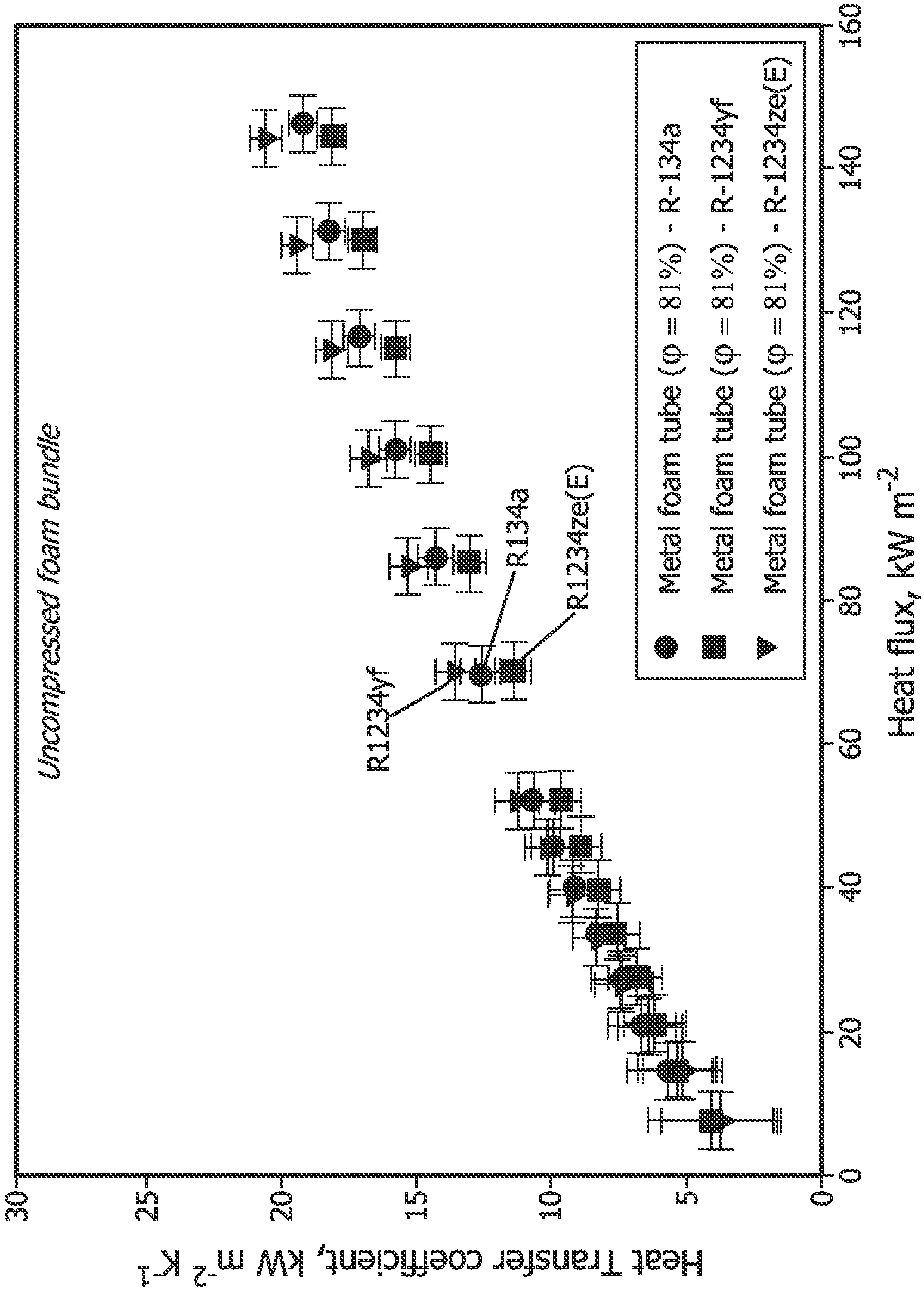
Uncompressed foam bundle
R1234yf
R134a
R1234ze(E)
● Metal foam tube (φ = 81%) - R-134a
■ Metal foam tube (φ = 81%) - R-1234yf
▼ Metal foam tube (φ = 81%) - R-1234ze(E)
Heat flux, kW m-2
0
20
40
60
80
100
120
140
160
Heat Transfer coefficient, kW m-2 K-1
0
5
10
15
20
25
30

FIG. 18

ENHANCED POOL BOILING SYSTEM AND METHOD

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Ser. No. 63/432,405 filed on Dec. 14, 2022, entitled "Enhanced Pool Boiling of Low-Pressure Refrigerants on Round Tubes", the entire disclosure of which incorporated herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

[0002] This invention was made with government support under Contract No. DE-AC05-00OR22725 awarded by the U.S. Department of Energy. The government has certain rights in this invention.

FIELD OF THE INVENTION

[0003] The present invention relates to heat exchange, and more particularly to pool boiling and flooded evaporator systems and methods.

BACKGROUND OF THE INVENTION

[0004] Flooded evaporator or pool boiling heat transfer is one of the most effective heat transfer methods and crucial for several energy conversion processes such as electronic cooling, steam generation, water purification and thermal management. Enhancing boiling heat transfer around tubes enables higher heat flux, which can improve efficiency and lead to compact heat exchangers. Delaying the onset of critical heat flux (CHF) allows for higher CHFs and protects equipment during anomalous transient conditions.

[0005] Boiling is a critical phenomenon for several energy conversion applications and for electronics cooling processes. During the boiling process, extremely high heat transfer rates can be attained at relatively low temperature differences. Enhancing boiling heat transfer has been an active area of research in recent years. Deploying passive techniques, particularly porous structures, has been extensively investigated to enhance boiling heat transfer. Significant advantages of such deployments include lightweight and compact heat exchangers. The enhancement is often attributed to the large surface area per unit volume, potential wicking phenomena to avoid dry-out, and higher nucleation sites density.

[0006] Another type of surface enhancement that is under increasing research is a porous cellular structure, such as porous metal foam. Such foams are described in US Patent Publication 2021/0389061 "HEAT EXCHANGE APPARATUS AND METHOD", the disclosure of which is hereby incorporated fully by reference. These porous structures not only provide a larger surface area for heat transfer to take place, but the many interconnected cells in the mesh help provide fluid channels to prevent dry-out, which should delay the onset of CHF. Porous structures on flat surfaces in water has shown that heat transfer can be increased as much as three times over the value for a plain flat surface, and CHF can be doubled over the plain flat surface. It was also found that pore size and the thickness of the foam layer both had influence on the overall heat transfer enhancement. In addition to water, pool boiling experiments in Novec 7100 on flat copper surfaces enhanced with commercially available copper foam were reported in literature. In those studies, it was found that the copper foam increased the heat transfer through both increased bubble nucleation and enhanced convection, and that increased wickability of the foams improved high heat flux performance.

[0007] As previously seen, most of the literature focuses on flat surfaces, and research into using open-porous structures to enhance the pool boiling heat transfer of tubes appears somewhat limited. As reported in literature, pool boiling studies were performed in R134a on horizontal tubes covered in brazed on open cell copper foam. They found that heat transfer enhancement was greatest below approximately 30 kW/m^2, performing better than some commercially available enhanced tubes. They also found that, at low to medium heat fluxes, thinner foams with higher porosity performed better than thicker, denser foams. At high heat fluxes, smaller pores once again showed increased resistance to bubble departure.

SUMMARY OF THE INVENTION

[0008] A boiling heat exchange system includes a heat exchanger having a chamber and at least one evaporator tube. The chamber is configured to hold a heat exchange fluid including a heat exchange vapor and a pool of heat exchange liquid. The evaporator tube has a wall with an inner surface and an outer surface, and the evaporator tube has an input end and an opposite, output end. A thermally conductive open-cell porous material is disposed on the outer surface and includes a plurality of pores. At least a portion of the evaporator tube can be immersed in the heat exchange liquid held in the chamber and heat exchange liquid will enter the pores and open-cells of the open-cell porous material. The evaporator tube is configured to receive, at the input end, a source fluid to be cooled from a first temperature to a second temperature each higher than a boiling temperature of the heat exchange liquid, and guide the source fluid from the input end through the evaporator tube to the output end. The evaporator tube is immersed in the pool of heat exchange liquid and source fluid is moved through the evaporator tube, and heat from the source fluid will pass through the wall and the thermally conductive open-cell porous material to cause the heat exchange liquid within the open-cells to boil to a heat exchange vapor. The heat exchange vapor will move through the open cells of the thermally conductive porous material and will be replaced in the open-cells by more heat exchange liquid.

[0009] The system can further include a condensing system for condensing the heat exchange vapor to a heat exchange liquid and returning the heat exchange liquid to the pool of refrigerant liquid. The chamber can have a heat exchange vapor outlet to release heat exchange vapor and a heat exchange liquid inlet to receive heat exchange liquid. The condensing system comprises a condensing heat exchanger to receive the heat exchange vapor from the chamber, condense the heat exchange vapor to the heat exchange liquid, and return the heat exchange liquid to the pool of heat exchange liquid in the chamber.

[0010] The thermally conductive open-cell porous material can be a foam of a conductive material. The thermally conductive porous material can include at least one selected from the group consisting of metal, graphite, or carbon foams. The metal foam can include at least one selected from the group consisting of Cu, Al, or Fe, and alloys thereof.

[0011] The open cells of the thermally conductive open-cell porous material can have pore openings between cells. The pore size of the pore openings can be from 0.1 μm to 100 mm. The cell diameter of the open cells can increase from a first size proximate to the evaporator tube to a second size greater than the first size distal to the evaporator. The thermally conductive open-cell porous material can have a porosity in a range of 40%-99%. The thermally conductive porous material can have a pore density in a range of 5-100 pores per inch (PPI). The open cells of the thermally conductive open-cell porous material can have a cell diameter of from 1 μm to 10 mm.

[0012] The thermally conductive open-cell porous material can be provided as a layer surrounding the evaporator tube. The layer of thermally conductive porous material can have a thickness in a range of 10%-100% of an outer radius of the evaporator tube.

[0013] The system can further include a plurality of evaporator tubes embedded in a matrix of the thermally conductive open cell porous material. The thermally conductive open-cell porous material can include a coating to change the surface morphology on the layer of thermally conductive porous material.

[0014] The heat exchange fluid can be any suitable such fluid. IN one aspect, the heat exchange fluid comprises water.

[0015] A method of conducting heat exchange can include the step of providing a heat exchanger that includes a chamber and an evaporator tube. The chamber can be configured to hold heat exchange fluid including heat exchange vapor and a pool of heat exchange liquid. The evaporator tube has a wall with an inner surface and an outer surface, and an input end and an opposite, output end, with a layer of thermally conductive open-cell porous material disposed on the outer surface and comprising a plurality of pores. At least a portion of the evaporator tube can be immersed in the heat exchange liquid held in the chamber. The evaporator tube is configured to receive, at the input end, a source fluid to be cooled from a first temperature to a second temperature each higher than a boiling temperature of the heat exchange liquid, and guide the source fluid from the input end through the evaporator tube to the output end. A pool of heat exchange liquid is provided in the chamber such that when the evaporator tube is immersed in the heat exchange liquid, heat exchange liquid will enter the pores and the open-cells of the thermally conductive open-cell porous material.

[0016] Source fluid at the first temperature is directed through the evaporator. The source fluid exits the evaporator tube at the second temperature. The source fluid exchanges heat with the evaporator tube, the thermally conductive porous material, and thereby with the heat exchange liquid within the pores of the thermally conductive open-cell porous material. The heat exchange liquid will change state to a heat exchange vapor and the heat exchange vapor will move through the open-cells of the thermally conductive open-cell porous material and will be replaced by heat exchange liquid. The heat exchange vapor can contact and release heat to a condensing system, and will be transformed from heat exchange vapor to heat exchange liquid and will return to the pool of heat exchange liquid.

[0017] A method of heating a fluid can include the step of providing a heat exchange tube having a heat exchange wall with an inner surface and an outer surface for separating a first heat exchange fluid from a second heat exchange fluid. The first heat exchange fluid moves in a flow direction relative to the inner surface of the wall. The heat exchange tube includes a layer of thermally conductive open-cell porous metal foam having a plurality of pores. The thermally conductive open-cell porous metal foam is disposed on the outer surface of the heat exchange tube.

[0018] The first heat exchange fluid flows through the tube while the second heat exchange fluid penetrates the pores of the thermally conductive open-cell porous metal foam, such that the first heat exchange fluid exchanges heat with the second heat exchange fluid.

[0019] The thermally conductive open-cell porous metal foam includes open cells having a cell diameter. The cell diameter of the open cells increases from a first size proximate to the wall to a second size greater than the first size distal to the wall. The porous material can include open cells having a cell diameter, and the cell diameter of the open cells can increase from a first size at an upstream location relative to the flow direction to a second size less than the first size downstream relative to the flow direction.

[0020] A component heat exchange system can include a heat exchanger comprising a chamber and an evaporator tube. The chamber is configured to hold a heat exchange fluid including a heat exchange vapor and a pool of heat exchange liquid. The evaporator tube has an outer surface and includes a thermally conductive open-cell porous material disposed on the outer surface and having a plurality of pores. At least a portion of the evaporator tube is immersed in the heat exchange liquid held in the chamber such that heat exchange liquid will enter the pores and open-cells of the thermally conductive open-cell porous material.

[0021] The evaporator tube is thermally connected by a thermal connection to the component such that heat is transferred from the component to the evaporator tube. The temperature of the evaporator tube is higher than a boiling temperature of the heat exchange liquid, wherein heat from the component will pass through the wall and the thermally conductive open-cell porous material to cause the heat exchange liquid within the thermally conductive open-cells to boil to a heat exchange vapor, and the heat exchange vapor will move through the open cells of the thermally conductive open-cell porous material and will be replaced in the open cells by more heat exchange liquid which will then also evaporate.

[0022] The component can be an electrical component such as a processor, a mechanical component such as an internal combustion engine, or a power generation component such as a nuclear reactor. The component can include at least one selected from the group consisting of an electrical component, a mechanical component, a chemical reactor component, and a nuclear reactor component. The electrical component can include a processor. The mechanical component can include an internal combustion engine.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] There are shown in the drawings embodiments that are presently preferred it being understood that the invention is not limited to the arrangements and instrumentalities shown, wherein:

[0024] FIG. **1** is a cross-section of a heat exchange tube according to the invention for pool boiling heat exchange.

[0025] FIG. **2** is the cross-section of FIG. **1** showing the heat exchange tube in a pool boiling operation.

[0026] FIG. **3** is an expanded view of area FIG. **3** in FIG. **2**.

[0027] FIG. **4** is a schematic diagram of a pool boiling heat exchanger with an external heat exchange fluid condenser.

[0028] FIG. **5** is a schematic diagram of a pool boiling heat exchanger with an internal heat exchange fluid condenser.

[0029] FIG. **6** is a schematic diagram of an open-loop pool boiling test system.

[0030] FIG. **7** is a schematic diagram of component cooling using the heat transfer system of the invention.

[0031] FIG. **8** is a schematic diagram of a high-pressure heat exchange system.

[0032] FIG. **9** is a schematic diagram, partially broken away, of a shell and tube pool boiling apparatus.

[0033] FIG. **10** is an expanded view of area FIG. **10** in FIG. **9**.

[0034] FIG. **11** is cross-section of a heat exchange apparatus with heat exchange tubes in a thermally conductive porous open-cell material matrix.

[0035] FIG. **12** is a cross-section of a heat exchange tube with a thermally conductive porous open-cell material having a radial gradient cell size.

[0036] FIG. **13** is plot of heat transfer coefficient HTC (kWm^{-2}K^{-1}) vs. heat flux q (kWm^{-2}).

[0037] FIG. **14** is a plot of heat flux q (kWm^{-2}) vs. excess temperature $\Delta T = T_{wall} - T_{sat}$ (° C).

[0038] FIG. **15** is a plot of heat transfer coefficient kWm^{-}$_{2}$K^{-1} vs. heat flux kWm^{-2}.

[0039] FIG. **16** is a plot of heat transfer coefficient kWm^{-}$_{2}$K^{-1} vs. heat flux kWm^{-2}.

[0040] FIG. **17** is a plot of heat transfer coefficient (kWm^{-}$_{2}$K^{-1}) vs. heat flux kWm^{-2}.

[0041] FIG. **18** is a plot of heat transfer coefficient (kWm^{-}$_{2}$K^{-1}) vs. heat flux (kWm^{-2}).

DETAILED DESCRIPTION OF THE INVENTION

[0042] A boiling heat exchange system includes a heat exchanger with a chamber and an evaporator. The chamber is configured to hold a heat exchange fluid including a heat exchange vapor and a pool of heat exchange liquid. The evaporator tube has a wall with an inner surface and an outer surface, an input end and an opposite, output end. A layer of thermally conductive open-cell porous material is disposed on the outer surface and has a plurality of pores. At least a portion of the evaporator tube can be immersed in the heat exchange liquid held in the chamber and heat exchange liquid will enter the pores and open-cells of the thermally conductive open-cell porous material. The thermally conductive open-cell porous material can extend around the entire perimeter of the evaporator tube, so that when immersed in the heat exchange liquid heat exchange with the thermally conductive open-cell porous material is possible 360° about the perimeter of the evaporator tube.

[0043] The evaporator tube can be configured to receive, at the input end, a source fluid to be cooled from a first temperature to a second temperature each higher than a boiling temperature of the heat exchange liquid. The evaporator tube guides the source fluid from the input end to the output end. The evaporator tube is immersed in the pool of heat exchange liquid. As the source fluid is moved through the evaporator tube, heat from the source fluid will pass through the wall and the thermally conductive open-cell porous material to cause the heat exchange liquid within the thermally conductive open-cells to boil to a heat exchange vapor, and the heat exchange vapor will move through the open cells of the thermally conductive porous material and will be replaced in the open cells by more heat exchange liquid which will then also evaporate.

[0044] The system can be open-loop in which the heat exchange fluid is used only once and then vented or transferred to storage or another process. The system can also be closed-loop, in which the refrigerant is condensed and returned to the pool of heat exchange liquid for reuse. The system can include a condensing system for condensing the heat exchange vapor to a heat exchange liquid and returning the heat exchange liquid to the pool of heat exchange liquid. The chamber can include a heat exchange vapor outlet to release heat exchange vapor and a heat exchange liquid inlet to receive heat exchange liquid. The condensing system can include a condensing heat exchanger to receive the heat exchange vapor from the chamber, condense the heat exchange vapor to the heat exchange liquid, and return the heat exchange liquid to the pool of heat exchange liquid in the chamber. In an alternative embodiment, the condensing heat exchanger can be located in the vapor space within the chamber.

[0045] The thermally conductive open-cell porous material can be a foam of a conductive material. The conductive material can be at least one selected from the group consisting of metal, graphite, or carbon foams. The metal foam can include at least one selected from the group consisting of Cu, Al, or Fe, and alloys thereof. Other thermally conductive open-cell porous materials are possible.

[0046] The open cells have pore openings between cells. The pore size of the pore openings can vary. The pore size of the pore openings can be from 0.1 μm to 100 mm. The pore size of the pore openings can be 0.1 μm, 1 μm, 100 μm, 200 μm, 300 μm, 400 μm, 500 μm, 600 μm, 700 μm, 800 μm, 900 μm, 1 mm, 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm, 50 mm, 55 mm, 60 mm, 65 mm, 70 mm, 75 mm, 80 mm, 85 mm, 90 mm, 95 mm, or 100 mm, and can be within a range of any high value and low value selected from these values.

[0047] The cell diameter and/or the pore size of the open cells can increase from a first size proximate to the evaporator tube outer wall to a second size greater than the first size distal to the evaporator tube wall.

[0048] The thermally conductive open-cell porous material can have a porosity in a range of 40%-99%. The porosity of the foam can be 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 96, 97, 98, or 99%, and can be within a range of any high value and low value selected from these values.

[0049] The thermally conductive open-cell porous material can have a pore density in a range of 5-100 pores per inch (PPI). The pore density of the thermally conductive open-cell porous material can be 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, or 100 pores per inch, and can be within a range of any high value and low value selected from these values.

[0050] The open cells of the thermally conductive open-cell porous material can have any suitable cell diameter. The open cells have a cell diameter of from 1 μm to 10 mm. The cell diameter of the open cells can be 1 μm, 10 μm, 100 μm, 200 μm, 300 μm, 400 μm, 500 μm, 600 μm, 700 μm, 800 μm, 900 μm, 1 mm, 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm, 9 mm, or 10 mm, and can be within a range of any high value and low value selected from these values.

[0051] The thickness of the thermally conductive porous material can vary. The layer of thermally conductive open-cell porous material can have a thickness in a range of 10%-100% of an outer radius of the evaporator tube. The layer of thermally conductive porous material can have a thickness of 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95 or 100% of an outer radius of the evaporator tube, and the thickness can be in a range of any high value and low value selected from these values.

[0052] The invention can take different forms. A plurality of evaporator tubes can be embedded in a matrix of the thermally conductive open cell porous material. The evaporator tubes and matrix of the thermally conductive open cell porous material can be positioned within an outer housing.

[0053] The porous material can have a coating to change the surface morphology on the layer of thermally conductive porous material. This can be to alter the hydrophobic or hydrophilic characteristics of the porous material to suit a particular heat exchange fluid.

[0054] The system can be used with many different heat exchange fluids fluids. The heat exchange fluid should be capable of a phase transition, evaporation or boiling, in the temperature and pressure range that is required. The heat exchange fluid in one example can comprises water. Other heat exchange fluids can be refrigerants. The refrigerant can be pure or can include contaminants such as oil.

[0055] The evaporator tube can have any suitable shape. The evaporator tube will commonly be tubular, but as used herein the term encompasses other shapes such as square, triangular, pentagonal, hexagonal, octagonal, and oval shapes. Still other cross-sectional shapes are possible.

[0056] A method of conducting heat exchange can include the step of providing a heat exchanger with a chamber and an evaporator tube. The chamber is configured to hold a heat exchange fluid including a heat exchange vapor and a pool of heat exchange liquid. The evaporator tube has a wall with an inner surface and an outer surface, an input end and an opposite, output end. A layer of thermally conductive open-cell porous material is disposed on the outer surface and has a plurality of pores. At least a portion of the evaporator tube can be immersed in the heat exchange liquid held in the chamber and heat exchange liquid will enter the pores and open-cells of the thermally conductive open-cell porous material.

[0057] The evaporator tube is configured to receive, at the input end, a source fluid to be cooled from a first temperature to a second temperature each higher than a boiling temperature of the heat exchange liquid. The evaporator tube guides the source fluid from the input end to the output end. The evaporator tube is immersed in the pool of heat exchange liquid. As the source fluid is moved through the evaporator tube, heat from the source fluid will pass through the wall and the thermally conductive open-cell porous material to cause the heat exchange liquid within the thermally conductive open-cells to boil to a heat exchange vapor, and the heat exchange vapor will move through the open cells of the thermally conductive porous material and will be replaced in the open cells by more heat exchange liquid which will then also evaporate.

[0058] The method includes the step of providing a pool of heat exchange liquid in the chamber such that the evaporator tube is immersed at least partially in the heat exchange liquid, and the heat exchange liquid will enter the pores and the open-cells of the thermally conductive porous material.

[0059] The source fluid at the first temperature is directed through the evaporator. The source fluid exits the evaporator tube at the second temperature. The source fluid exchanges heat with the evaporator tube, the thermally conductive porous material, and thereby with the heat exchange liquid within the pores of the thermally conductive porous material. The heat exchange liquid changes state to a heat exchange vapor and the heat exchange vapor moves through the open-cells of the thermally conductive porous material and is be replaced by more heat exchange liquid moving into the open-cells.

[0060] The method can further include the step of providing a condensing system and condensing the heat exchange vapor. The heat exchange vapor will contact and release heat to the condensing system, and is transformed from heat exchange vapor to heat exchange liquid. The condensed heat exchange liquid is then returned to the pool of heat exchange liquid.

[0061] A component heat exchange system can include a chamber and an evaporator in the chamber. The chamber is configured to hold a heat exchange fluid including a heat exchange vapor and a pool of heat exchange liquid. A layer of thermally conductive open-cell porous material is disposed on the outer surface of the evaporator tube and has a plurality of pores. At least a portion of the evaporator tube can be immersed in the heat exchange liquid held in the chamber and heat exchange liquid will enter the pores and open-cells of the thermally conductive open-cell porous material.

[0062] The evaporator tube is thermally connected by a thermal connection to the component such that heat is transferred from the component to the evaporator tube. The evaporator tube does not in this embodiment flow a source fluid through it, but rather can be a solid material or can be filled with a thermally conductive material such that when heat is transferred from the component to the evaporator tube the temperature of the evaporator tube will rise. The temperature of the evaporator tube is higher than a boiling temperature of the heat exchange liquid. The evaporator tube is immersed in the pool of heat exchange liquid within the chamber. Heat from the component will pass to the evaporator tube and through the wall of the evaporator tube to the thermally conductive open-cell porous material to cause the heat exchange liquid within the thermally conductive open-cells to boil to a heat exchange vapor. The heat exchange vapor will move through the open cells of the thermally conductive porous material and will be replaced in the open cells by more heat exchange liquid which will then also evaporate.

[0063] The component that is cooled can any of several different kinds of possible components. The component can be an electrical component such as a processor, a mechanical component such as an internal combustion engine, or a power generation component such as a nuclear reactor.

[0064] There is shown in FIGS. **1-3** an evaporator tube **10** according to the invention. The evaporator tube **10** includes a tube **14** with an open interior **18** and an outer layer of a thermally conductive open-cell porous material **22**. As shown in FIG. **2**, the evaporator tube **10** can be immersed in a heat exchange liquid **34**. A source fluid **30** flows through the tube **14**. The source fluid **30** is at a temperature higher than the boiling temperature of the heat exchange liquid **34**. Heat is transferred from the source fluid **30** to the wall **14** and thereby to the thermally conductive porous material **22**.

The heat exchange liquid **34** enters the pores of the porous material **22** and exchanges heat from the walls of the open cells making up the porous material **22**. The heat exchange liquid **34** within the pores of the porous material **22** encounters an outer surface **16** (FIG. **3**) of the tube **14** and absorbs heat sufficient to change state to heat exchange vapor bubbles **38**. The vapor bubbles **38** progress away from the tube outer surface **16** and can join with other vapor bubbles to form larger vapor bubbles **40** which then leaves the porous material **22** and float to the top of the pool of heat exchange liquid **34**. Additionally, heat exchange vapor bubbles **40** can form some distance from the tube outer surface **16** owing to the thermal conductivity of the porous material **22**. Heat will be exchanged from the walls of the open cells of the porous material **22** directly to heat exchange liquid **34** within the open cells to vaporize the heat exchange liquid **34** into heat exchange vapor bubbles **40**.

[0065] There is shown in FIG. **4** a heat exchange system **100** according to the invention having a chamber **104** defining a interior space **110** for the heat exchange fluid. An evaporator tube **112** is mounted within the interior space **110**. The evaporator tube **112** has a tube **113** with an open interior flow passage **116** and a layer of thermally conductive open cell porous material **120** on an outer surface of the tube **113**. The evaporator tube **112** is immersed in a pool of heat exchange liquid **124** within the chamber **104**. The chamber contains both heat exchange liquid **124** and heat exchange vapor **128**.

[0066] Source fluid flows through the open interior **116** of the evaporator tube **112**, entering at a temperature T_1, which is higher than the boiling point of the heat exchange liquid **124** at the operating pressure of the chamber **104**. Heat exchange vapor bubbles **132** form at the surface of the tube **113** and within the layer of porous material **120**, and heat exchange vapor bubbles **136** rise in the direction shown by arrow **140**. The source fluid exits at temperature T_2 that is less than T_1 but above the boiling point of the heat exchange liquid **124**.

[0067] The vapor bubbles **136** progress into the heat exchange vapor **128** above the heat exchange liquid **124** and some heat exchange vapor **148** progresses in the direction of arrow **152** into a heat exchange vapor outlet **156**. The heat exchange vapor **148** is directed to a condenser **160** having a condensing coil **176** which is contacted by cooling fluid flowing into the condenser **160** through an inlet **164** and through an outlet **172** and can be controlled by a suitable valve **178**. The heat exchange vapor **148** is condensed back into a heat exchange liquid, which is returned through condenser outlet **180** back to the chamber **104** and falls as heat exchange liquid droplets **184** in the direction shown by arrow **188** back to the pool of heat exchange liquid **124**.

[0068] There is shown in FIG. **5** a heat exchange system **200** having a chamber **204** defining an interior space **210** for the heat exchange fluid. An evaporator tube **212** is mounted within the interior space **210**. The evaporator tube **212** has tube core **213** with an open interior flow passage **216** and a layer of thermally conductive open cell porous material **220** on an outer surface of the tube core **212**. The evaporator tube **212** is immersed in a pool of heat exchange liquid **224** within the chamber **204**. The chamber **204** has both heat exchange liquid **224** and heat exchange vapor **228**.

[0069] Source fluid flows through the open interior **216** of the tube **213**, entering at a temperature T_1, which is higher than the boiling point of the heat exchange liquid **224** at the operating pressure of the chamber **204**. Heat exchange vapor bubbles **232** form at the layer of porous material **220**, and heat exchange vapor bubbles **236** rise in the direction shown by arrow **240**. The source fluid exits at temperature T_2 that is less than T_1 but above the boiling point of the heat exchange liquid **224**.

[0070] The vapor bubbles **236** progress into the heat exchange vapor **228** above the heat exchange liquid **224** and some heat exchange vapor **248** progresses upward in the direction of arrow **252** where the heat exchange vapor contacts a heat exchange vapor condenser **260** within the chamber **204**. The condenser **260** is part of a refrigeration cycle which removes the heat that is contained by the heat exchange vapor **248**.

[0071] The refrigeration cycle can be closed-loop and utilize a refrigerant. The refrigeration cycle can include a compressor **272** which receives refrigerant gas from the heat exchange vapor condenser **260** through a connection **268**. The compressed refrigerant gas is passed through a connection **276** to an external heat exchanger **280**, where it is cooled by suitable heat exchanging apparatus such as cooling coils **286**. The heat exchanger **280** receives cooling fluid through inlet **282** and exhausts cooling fluid through exhaust outlet **284**. The refrigerant is passed through a connection **290** and a valve **292** and through the refrigerant inlet **264** to the heat exchange vapor condenser **260**. The heat exchange vapor is condensed by the heat exchange vapor condenser **260** back into a heat exchange liquid, which falls as heat exchange liquid droplets **294** in the direction shown by arrow **296** back to the pool of heat exchange liquid **224**.

[0072] There is shown in FIG. **6** system **300** for pool boiling and particularly for testing pool boiling performance of the system **300** and heat exchange tubes according to the invention. The system **300** includes a chamber **304** having an open interior **310**. A heat exchange liquid **324** and heat exchange vapor **328** are provided in the interior **310**. A plurality of evaporator tubes **312** are provided in the open interior **310**. An outer layer of thermally conductive porous material **316** is provided on an outer surface of the evaporator tube **312**. The evaporator tubes **312** in this embodiment comprise resistive heating elements for heating the thermally conductive porous material **316**. The evaporator tubes **312** can be mounted on suitable supports **326** and **328**.

[0073] Evaporator tubes **312** are connected by suitable electrical connections **330**, **332** to respective electrical buses **331**, **333**. These connect to power supply lead lines **336** and **337**. Power is applied to the resistive heating elements of the evaporator tubes **312** and thereby to the thermally conductive porous material **316** to heat the thermally conductive open-cell porous material to a temperature that is above the boiling temperature of the heat exchange liquid **324**.

[0074] The heat exchange liquid **324** is heated by contact with the heated thermally conductive open-cell porous material **316** and evaporates to form heat exchange vapor bubbles **340**. A heat exchange vapor condenser **350** is provided in the interior **310**. The heat exchange vapor condenser **350** condenses the heat exchange vapor back to heat exchange liquid droplets **344**, which fall back into the pool of heat exchange liquid **324**. The heat exchange vapor condenser **350** receives cooling fluid from connection **354** which flows in the direction of arrow **356**. The cooling fluid absorbs heat as it flows through the heat exchange vapor condenser **350** and exits through heated cooling fluid exhaust connection **360** in the direction shown by arrow **362**. A suitable thermocouple

368 can have a sensor **370** extending into the heat exchange liquid pool **324**. Another thermocouple **372** can have a sensor **374** to monitor temperatures of the heat exchange vapor **328**. A pressure sensor **373** can also be provided.

[0075] There is shown in FIG. **7** a system **400** for cooling various components such as electronic devices. The system includes a chamber **404** having a heat exchange liquid **412** and a heat exchange vapor **408** in an open interior **410** of the chamber **404**. A plurality of evaporator tubes **416** having a thermally conductive core **418** are provided in the open interior **410**. An outer layer of thermally of thermally conductive open-cell porous material **422** is provided on an outer surface of the core **418**. Electrical devices **430-432** or other devices in need of heat management are connected by thermally conductive connections **435-437** to the evaporator tubes **416**. The thermally conductive connections **435-437** can be any suitable thermal conductor. The evaporator tubes **416** can be supported in the heat exchange liquid **412** by suitable supports **450**, **452**. In some cases it may be desirable to place the components that are being cooled directly within the chamber **404** as shown in phantom by electrical devices **440-442**.

[0076] The heat generated by the electrical components **430-432** (or electrical components **440-442**) is transmitted to the evaporator tubes **418** and this heat is transferred to the thermally conductive open-cell porous material **422**. Heat is transferred to the heat exchange liquid **412**, generating heat exchange vapor bubbles **460**. These heat exchange vapor bubbles **460** travel upward and contact a heat exchange vapor condenser **470**. Heat exchange vapor condenser **470** receives cooling liquid through a cooling fluid inlet connection **474** which flows in the direction of arrow **475** and absorbs heat from the heat exchange vapor and exits the heat exchange vapor condenser **470** as cooled heat exchange cooling fluid through a cooling fluid exhaust connection **476** in a direction shown by arrow **477**. The is condensed into heat exchange liquid droplets **478** which drop back into the pool of heat exchange liquid **412**. A thermocouple **482** can have a sensor **483** extending into the heat exchange vapor **408**. A thermocouple **486** can have a sensor **487** which extends into the pool of heat exchange liquid **412**. A pressure sensor **480** can also be provided for sensing the pressure within the chamber **404**.

[0077] There is shown in FIG. **8** a heat exchange system **500** for operation at elevated pressures. The system **500** includes a pressure chamber **504** having an open interior **506** with heat exchange liquid **507** and a heat exchange vapor **508**. A plurality of evaporator tubes **510** having a core **514** comprising resistive heating elements are provided in interior **506**. An outer layer of thermally of thermally conductive open-cell porous material **518** is provided on an outer surface of the core **514**. Electrical buses **512**, **516** receive electrical power from power source connections **520**, **524** and provide this power to the resistive heater elements **514** through suitable electrical connections **513**, **517**. The evaporator tubes can be mounted on suitable supports **528**, **529** so as to be immersed or partially immersed in the heat exchange liquid **507**.

[0078] Heat is transmitted to the thermally conductive open-cell porous material **518** which heats the heat exchange liquid **507** and generates heat exchange vapor bubbles **534**. The exchange vapor bubbles **534** enter a heat exchange vapor outlet connection **536** as shown by arrow **537**. A thermocouple **538** senses temperature in the line **536**. The vapor enters an external condenser **540** such as a plate condenser and leaves as condensed liquid through return heat exchange liquid connection **544** as shown by arrow **545**. A thermocouple **546** can be provided to monitor the temperature of the heat exchange liquid in the heat exchange liquid connection **544**. The external condenser **540** receives cooling fluid through a cooling fluid inlet connection **550** as indicated by arrow **551** and the temperature of the cooling fluid can be monitored by thermocouple **552**. The cooling fluid is exhausted from the external condenser **540** through a cooling fluid exhaust connection **560** as indicated by arrow **561**. A thermocouple **562** can be provided to sense the temperature of the exhausted cooling fluid, and a valve **564** can be provided to control the flow of the cooling fluid.

[0079] A heat exchange fluid charge and vacuum connection **570** can be provided and controlled by valve **572**. A pressures sensor **574** and temperature sensor **576** can be provided to sense the pressure and temperature in the charge or vacuum connection. A thermocouple **578** with sensor **579** can extend into the vapor **508**, and a thermocouple **580** with sensor **581** can extend into the liquid **507**. A pressure gauge **584** can be provided and can have a pressure sensor element **585** extending into the pressure chamber **504**.

[0080] There is shown in FIGS. **9-10** a shell and tube type heat exchange system **600**. The system **600** includes a chamber **604** with a plurality of evaporator tubes **610** mounted therein having a tube core **611** having an open interior **613** and an outer layer of thermally conductive open-cell porous material **612** on an outer surface of the tube core **611**. The chamber receives a source fluid through a port **614** as shown by arrows **615**, flows through the tubes **611** as shown by arrows and exhausts the heat exchange fluid through a port **618** as indicated by arrow **619**. Within the chamber **604** is heat exchange liquid **630** and heat exchange vapor **632**. The heat exchange liquid **630** flows into the chamber **604** through a port **624** as indicated by arrow **625**. Some of the heat exchange vapor **638** rises and exits the chamber **604** through a port **628** as indicated by arrow **629**. The exhausted vapor **640** exiting the port **628** can be condensed and recycled, or in the case of environmentally acceptable materials such as water can be vented directly to the atmosphere. As shown particularly in FIG. **10**, the flow **617** of source fluid heats the tubes **611** and the thermally conductive porous material **612**, which causes the formation of heat exchange vapor bubbles **634** which progress into the vapor space **632** and exits as flowing vapor **638** which exits through the port **628**.

[0081] There is shown in FIG. **11** an alternative embodiment of a heat exchange system **700**. A chamber **704** includes an open interior **706** in which there is a matrix **710** of a thermally conductive open-cell porous material which substantially fills the interior **706** of the chamber **704** and can be secured to the interior wall **708** of the chamber **704**. A vapor space **716** between the top of the matrix **710** and the top of chamber **704** can be provided. A plurality of heat exchange tubes **714** is provided within the matrix **710**. The heat exchange tubes **714** can have open interiors **715** which allow for the passage of a source fluid to exchange heat with a heat exchange fluid within the chamber **704**. The heat exchange fluid enters through an inlet port **720** as indicated by arrow **721** and exits through an exit port **724** is indicated by arrow **725**.

[0082] There is shown in FIG. **12** an embodiment of an evaporator tube **800** with a tube core **804**, A thermally conductive open-cell porous material **802** is provided on an outer surface **806** of the tube core **804**, and has a graduated porosity from a point near the tube outer surface **806** to an outer surface **808** of the thermally conductive open-cell porous material **802**. The evaporator tube **800** has an innermost layer **810** of the thermally conductive open-cell porous material adjoining outer surface **806** of the tube **804** with a smaller porosity that outer layers. The thermally conductive open-cell porous material **802** has a graduated porosity, such that the porosity of a middle layer **812** is greater than the porosity of the innermost layer **810** and less than the porosity of an outermost layer **816**. A source fluid flows in the direction of arrow **830** through open interior **820** of the tube **804** and exhausts as shown by arrow **834**. The graduated porosity allows more space for more vapor which accumulates as the vapor progresses radially outward from the tube surface **806** given that some vapor forms at the outer surface tube **804** and still more vapor is formed by heat transfer with the walls of the open cell porous material some distance from the outer surface **806** of the tube **804**. Although shown with porosity increasing radially outward, the porosity of the thermally conductive open-cell porous material can also or alternatively be increased longitudinally relative to the flow direction of the source fluid.

[0083] One of the applications for the invention is the thermal management of lithium-ion batteries with the two-phase immersion cooling with dielectric fluid. In order to evaluate the potential performance improvement of the proposed enhanced tubes in dielectric fluid, an open-loop pool boiling test rig was built. The apparatus consists of a clear rectangular container, an immersed test section, and a condensing unit, as illustrated in FIG. **6**. The clear container was made of polycarbonate, and the test section was a horizontally mounted round tube immersed in a dielectric liquid pool, which served as the heat exchange liquid. The tube bundle contained four aluminum tubes placed in a staggered tube arrangement, with one of the tubes not being visible in FIG. **6**. For each individual tested tube, four thermocouple holes were drilled alongside the tube wall, Type-T thermocouples were inserted for measuring the wall temperatures. The heat flux for the tube was supplied by a cartridge heater installed in the tube. Power to the tube heater was controlled using pulse width modulation, allowing for different heater outputs to be approximated over a time span of 1 second, and current transformers were used to measure the amp draw of the heater at a specific power setting.

[0084] The heat transfer coefficient of the externally enhanced tube (single tube) at various heat fluxes is compared with that of the bare aluminum tube, as shown in FIG. **13**. The effective heat transfer coefficient of the enhanced tube, determined based on the outer diameter of the round tube, is 2.1~4.8 times higher than the bare aluminum tube, and the metal foam had a better heat transfer enhancement at lower heat fluxes. FIG. **14** shows the comparison of the pool boiling curves for bare copper, bare aluminum, and metal foam enhanced aluminum tubes. For the bare copper and bare aluminum tubes, the critical heat fluxes occur at 135 kW/m^2 and 131 kW/m^2, respectively. However, the metal foam enhanced tube does not reach the critical heat flux during the whole test conditions, where the maximum heating power of the current test facility is 228 kW/m^2. This indicates that the metal foam around the tube sample delays the critical heat flux and maintains a certain level of heat transfer capacity at higher heat fluxes.

[0085] Three enhanced tube bundles with uncompressed, 2×compressed, and 3×compressed metal foams were experimentally evaluated, and the corresponding porosities are 81%, 75%, and 62%, respectively. FIG. 15 shows the comparison of their pool boiling performances in HFE-7000 against that of the bare tube bundle. The metal foam tubes with an 81% porosity showed a 100-166% enhancement in heat transfer coefficient compared to the bare tubes. As the porosity decreases, the heat transfer coefficient increases even more. For example, the metal foam tubes with a 75% porosity showed about a 120-212% improvement in heat transfer coefficient over the bare tubes. The enhanced heat transfer coefficient of the metal foam tubes, compared with the bare tubes, is mainly attributed to the increased surface area and nucleation sites. Experiments with another dielectric fluid, HFE 7100, were also carried out in order to better understand the behavior of metal foam tubes. Similar to the HFE 7000, the HFE 7100 working fluid also showed enhanced heat transfer performance for metal foam tubes, as shown in FIG. 16. The metal foam tubes with 81% porosity offered about 100-166% enhancement for the HFE 7000, whereas the enhancement percentage has been reduced to 70-90% for the HFE 7100.

[0086] Another application for the invention is refrigerant pool boiling in a flooded evaporator. Another apparatus was developed to evaluate the performance of the tube bundle for high-pressure refrigerants. The schematic of the refrigerant boiling set up is shown in FIG. **8**. The main components of the this system are the high pressure chamber **504**, a bundle of the tubes **510**, the plate heat exchanger (condenser) **540**, and a cooling unit. The tube bundle experiment for this application was conducted in the high-pressure chamber **504**. Upon placing the tube bundle, the chamber **504** was vacuumed and charged with refrigerant **507**. The heaters **514** were powered to begin the boiling experiments, and then the heating power was gradually increased to understand the boiling behavior at different heat fluxes. The vapor **508** produced by the boiling process was directed to the plate heat exchanger **540** and was condensed back to liquid by exchanging heat with cooling water flow indicated by arrow **551**. The temperature and the flow rate of the cooling water were controlled to maintain the constant system pressure. The plate heat exchanger **540** was supplied with cooling water from a chiller (not shown) that provided the required cooling capacity to condense the vapor. The condensed refrigerant was passed to the high-pressure chamber **504** through the liquid return line **544**. The temperature of the liquid refrigerant **506** and refrigerant vapor **508** was monitored at the top and bottom of the vessel using T-type thermocouples.

[0087] The average heat transfer coefficients of refrigerant, R134a, over the metal foam tube bundles with different porosities are compared against the plain aluminum tube bundle, as shown in FIG. **17**. Overall, all of the tested metal foam tube bundles showed higher heat transfer coefficients compared to the plain aluminum tube bundle in the refrigerant pool. Among the metal foam tube bundles, 62% porosity exhibited a higher heat transfer coefficient than that of a plain tube, followed by 75% and 81% porosities. The metal foam tubes with 62% improved the heat transfer coefficient by 102-153% and 162-291% over the plain tubes at high (>39 KW m−2) and low (<39 KW m−2) heat fluxes, respectively. Similarly, compared with the plain tube bundle, the metal foam tubes with 75% porosity offered an enhancement of 95-127% and 133-202% at high (>39 KW m−2) and low (<39 KW m−2) heat fluxes, respectively. The metal foam tubes with 81% porosity, exhibited an enhancement of heat transfer coefficient that remained identical at 80-90% over the entire heat flux range. In addition to R134a (GWP=1300), another two low GWP refrigerants R-1234yf (GWP=4) and R-1234ze(E) (GWP=7) were tested. When the heat flux is less than ~50 KW m−2, the HTCs of R-1234yf and R1234ze(E) are quite similar to those of R-134a. However, when heat flux is more than ~50 KW m−2, the HTCs of R-1234yf are nearly 10% higher than those of R-134a for both plain and metal foam tubes, while a 5% reduction in heat transfer coefficient was observed for R-1234ze(E) compared with R-134a.

[0088] The metal foam enhanced tube bundles were able to improve the pool boiling performance for both dielectric fluids and refrigerants due to the larger surface area of the enhanced tube and a greater number of nucleation sites. For the dielectric fluids, the heat transfer coefficient of the metal foam tube bundle offered a 100-212% improvement in heat transfer coefficient compared with the bare tube bundle. The critical heat flux of the enhanced tube is at least double compared to the bare aluminum tube. For the refrigerants, the metal foam enhanced tube bundle provides an 80-291% enhancement in heat transfer coefficient under the current test conditions.

[0089] The invention as shown in the drawings and described in detail herein disclose arrangements of elements of particular construction and configuration for illustrating preferred embodiments of structure and method of operation of the present invention. It is to be understood however, that elements of different construction and configuration and other arrangements thereof, other than those illustrated and described may be employed in accordance with the spirit of the invention, and such changes, alternations and modifications as would occur to those skilled in the art are considered to be within the scope of this invention as broadly defined in the appended claims. In addition, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting.

We claim:

1. A boiling heat exchange system, comprising:

a heat exchanger comprising:

- i) a chamber configured to hold a heat exchange fluid including a heat exchange vapor and a pool of heat exchange liquid; and,
- ii) an evaporator tube having a wall with an inner surface and an outer surface, wherein the evaporator tube has an input end and an opposite, output end and a thermally conductive open-cell porous material disposed on the outer surface and comprising a plurality of pores, wherein at least a portion of the evaporator tube can be immersed in the heat exchange liquid held in the chamber and heat exchange liquid will enter the pores and open-cells of the open-cell porous material, and wherein the evaporator tube is configured to receive, at the input end, a source fluid to be cooled from a first temperature to a second temperature each higher than a boiling temperature of the heat exchange liquid, guide the source fluid from the input end through the evaporator tube to the output end, wherein when the evaporator tube is immersed in the pool of heat exchange liquid and source fluid is moved through the evaporator tube, heat from the source fluid will pass through the wall and the thermally conductive open-cell porous material to cause the heat exchange liquid within the open-cells to boil to a heat exchange vapor, and the heat exchange vapor will move through the open cells of the thermally conductive porous material and will be replaced in the open-cells by more heat exchange liquid.

2. The system of claim **1**, further comprising a condensing system for condensing the heat exchange vapor to a heat exchange liquid and returning the heat exchange liquid to the pool of refrigerant liquid.

3. The system of claim **2**, wherein the chamber comprises a heat exchange vapor outlet to release heat exchange vapor and a heat exchange liquid inlet to receive heat exchange liquid; and the condensing system comprises a condensing heat exchanger to receive the heat exchange vapor from the chamber, condense the heat exchange vapor to the heat exchange liquid, and return the heat exchange liquid to the pool of heat exchange liquid in the chamber.

4. The system of claim **1**, wherein the thermally conductive open-cell porous material comprises a foam of a conductive material.

5. The system of claim **4**, wherein the thermally conductive open-cell porous material comprises at least one selected from the group consisting of metal, graphite, or carbon foams.

6. The system of claim **5**, wherein the metal foam comprises at least one selected from the group consisting of Cu, Al, or Fe, and alloys thereof.

7. The system of claim **4**, wherein the open cells have pore openings between cells, the pore size of the pore openings being from 0.1 μm to 100 mm.

8. The system of claim **7**, wherein the cell diameter of the open cells increases from a first size proximate to the evaporator tube to a second size greater than the first size distal to the evaporator.

9. The system of claim **5**, wherein the foam has a porosity in a range of 40%-99%.

10. The system of claim **5**, wherein the foam has a pore density in a range of 5-100 pores per inch (PPI).

11. The system of claim **4**, wherein the open cells of the thermally conductive open-cell porous material have a cell diameter of from 1 μm to 10 mm.

12. The system of claim **1**, wherein the thermally conductive open cell porous material is provided as a layer surrounding the evaporator tube.

13. The system of claim **12**, wherein the layer of thermally conductive porous material has a thickness in a range of 10%-100% of an outer radius of the evaporator tube.

14. The system of claim **1**, further comprising a plurality of evaporator tubes embedded in a matrix of the thermally conductive open-cell porous material.

15. The system of claim **1**, further comprising a coating to change the surface morphology on the layer of thermally conductive porous material.

16. The system of claim **1**, wherein the heat exchange fluid comprises water.

17. A method of conducting heat exchange, comprising the steps of:

providing a heat exchanger comprising:

i) a chamber configured to hold heat exchange fluid including heat exchange vapor and a pool of heat exchange liquid;

iii) An evaporator tube having a wall with an inner surface and an outer surface, wherein the evaporator tube has an input end and an opposite, output end, and a layer of thermally conductive open-cell porous material disposed on the outer surface and comprising a plurality of pores, wherein at least a portion of the evaporator tube can be immersed in the heat exchange liquid held in the chamber, and wherein the evaporator tube is configured to receive, at the input end, a source fluid to be cooled from a first temperature to a second temperature each higher than a boiling temperature of the heat exchange liquid, guide the source fluid from the input end through the evaporator tube to the output end;

providing a pool of heat exchange liquid in the chamber such that the evaporator tube is immersed in the heat exchange liquid, and heat exchange liquid will enter the pores and the open-cells of the thermally conductive porous material;

directing the source fluid at the first temperature through the evaporator, the source fluid exiting the evaporator tube at the second temperature, the source fluid exchanging heat with the evaporator tube, the thermally conductive open-cell porous material, and thereby with the heat exchange liquid within the pores of the thermally conductive open-cell porous material, whereby the heat exchange liquid will change state to a heat exchange vapor and the heat exchange vapor will move through the open-cells of the thermally conductive open-cell porous material and will be replaced by heat exchange liquid.

18. The method of claim **17**, wherein the heat exchange vapor contacts and releases heat to a condensing system, and is transformed from heat exchange vapor to heat exchange liquid and the heat exchange liquid is returned to the pool of heat exchange liquid.

19. A method of heating a fluid, comprising the steps of:

providing a heat exchange tube, comprising a heat exchange wall with an inner surface and an outer surface for separating a first heat exchange fluid from a second heat exchange fluid, the first heat exchange fluid moving in a flow direction relative to the inner surface of the wall, the heat exchange tube comprising a layer of thermally conductive open-cell porous metal foam having a plurality of pores, the thermally conductive porous metal foam being disposed on the outer surface of the tube; and,

flowing the first heat exchange fluid through the heat exchange tube while permitting the second heat exchange fluid to penetrate the pores of the thermally conductive open-cell porous metal foam, wherein the first heat exchange fluid exchanges heat with the second heat exchange fluid.

20. The method of claim **19**, wherein the thermally conductive open-cell porous metal foam comprises open cells having a cell diameter, and wherein the cell diameter of the open cells increases from a first size proximate to the wall to a second size greater than the first size distal to the wall.

21. The method of claim **19**, wherein the thermally conductive open-cell porous material comprises open cells having a cell diameter, and the cell diameter of the open cells increases from a first size at an upstream location relative to the flow direction to a second size less than the first size downstream relative to the flow direction.

22. A component heat exchange system, comprising:

a heat exchanger comprising a chamber and an evaporator tube, the chamber being configured to hold a heat exchange fluid including a heat exchange vapor and a pool of heat exchange liquid;

the evaporator tube having an outer surface and comprising thermally conductive open-cell porous material disposed on the outer surface and having a plurality of pores;

at least a portion of the evaporator tube being immersed in the heat exchange liquid held in the chamber such that heat exchange liquid will enter the pores and open-cells of the thermally conductive open-cell porous material;

wherein the evaporator tube is thermally connected by a thermal connection to the component such that heat is transferred from the component to the evaporator tube; the temperature of the evaporator tube being higher than a boiling temperature of the heat exchange liquid, wherein heat from the component will pass through the wall and the thermally conductive open-cell porous material to cause the heat exchange liquid within the thermally conductive open-cells to boil to a heat exchange vapor, and the heat exchange vapor will move through the open cells of the thermally conductive porous material and will be replaced in the open cells by more heat exchange liquid which will then also evaporate.

23. The component heat exchange system of claim **22**, wherein the component comprises at least one selected from the group consisting of an electrical component, a mechanical component, a chemical reactor component, and a nuclear reactor component.

24. The component heat exchange system of claim **23**, wherein the electrical component comprises a processor.

25. The component heat exchange system of claim **23**, wherein the mechanical component comprises an internal combustion engine.

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