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(54) **HEAT EXCHANGER FOR A MOLTEN SALT STEAM GENERATOR IN A CONCENTRATED SOLAR POWER PLANT (III)**

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(56) References cited:
WO-A1-2008/095248 WO-A1-2019/115306
CN-U- 206 755 944 US-A- 4 557 322
US-A- 5 261 485 US-A1- 2015 260 464

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Description

Field of the Invention

[0001] The present invention is related to the field of heat exchangers, in particular heat exchangers such as evaporators, superheaters, reheaters, and economizers intended to be used in thermal fluid steam generators such as Molten Salt Steam Generators (MSSG) of Concentrated Solar Power plants (CSP).

Prior Art

[0002] It is known that the CSP tower plants generally comprise one or more solar receivers which are situated at the apex of a central tower. These solar receivers are heated by concentrated incident solar rays and they generate a hot fluid that will be further used to produce high-pressure steam capable of driving a turbine and of producing electricity.

[0003] More specifically the CSP tower plant has as main components, namely, at least a heliostat solar field, a solar receiver installed on the top of the tower, a steam generator, a steam turbine and a storage system. In molten salt technology, the molten salt is heated typically to 565 °C in the solar receiver and stored in the hot storage tank. When a production of electricity is required, the hot salt flows from the hot tank to the Molten Salt Steam Generator (MSSG) to generate steam which will be injected into the steam turbine.

[0004] FIG. 1 diagrammatically shows the components of a typical so-called heat exchanger train for MSSG. The hot molten salt flows, from an inlet 100, through a reheater 101 (or a preheater with or without a reheater) and a superheater 104 to enter in an evaporator 102. Thereafter, the hot salt flows from the outlet of the evaporator 102 to the economizer 103 and further to the outlet 105.

[0005] So-called "shell and tube" heat exchangers refer in prior art to a class of heat exchanger designs suitable for higher pressure applications. This type of heat exchanger is consisting of a large pressure vessel called a "shell" having a set of tubes, called "bundle", inside it. A first fluid runs through the tubes while a second fluid flows inside the shell over the tubes, the first and the second fluid having different temperatures, with the aim of transferring heat from the second fluid to the first fluid or vice versa.

[0006] There are many variations on the shell and tube design. As an example, FIG. 2 diagrammatically shows a straight-tube heat exchanger (two pass tube-side). The ends of each tube 21 are connected to water boxes or plenums 29 through holes provided in separating plates called "tube sheets" 27. The tubes 21 may be straight, as depicted in FIG. 2, or bent in "U" (U-tubes).

[0007] To provide an improved heat exchange between the two fluids, the flow path of the second fluid is often determined by intermediate baffles 28 forming respective passages so that the second fluid flow changes

its direction in passing from one passage to the next one. The baffles are usually under the form of partial circular segments or annular rings and disks, installed perpendicular to the longitudinal axis of the shell 22 to provide a zigzag flow of the second fluid.

[0008] A prior art alternative of the above design, depicted in FIG. 3, is the horizontal hairpin heat exchanger. Hair pin heat exchanger 1 has two shells 22 containing the straight part of U-tubes. The head of the hairpin contains the 180° U-bent part of the tubes. The advantages of this hairpin design are :

- no need for a joint expansion system, as thermal expansion is naturally managed by the hairpin design ;
- easier draining and venting of the exchanger owing to the straight tubes and to the horizontal position of the exchanger.

[0009] Different concepts of steam generator are already known. A synthesis of these different concepts is reported in the Sandia report 93-7084 "Investigation of thermal storage and steam generator issues, Bechtel Corporation", in which are listed advantages and drawbacks of the existing steam generators.

[0010] In order to improve efficiency of the heat transfer in the heat exchangers, it is known since the 1920s that baffles mounted in the shell can have a specific shape intended to guide the fluid in a helical path. Moreover, with a continuous helical baffle, the heat transfer rate increases of about 10% compared with that of conventional segmental baffles for the same shell-side pressure drop (J. Heat Transfer (2007), Vol. 129(10), 1425-1431). This pattern allows to reduce leakage streams occurring in segmental baffles and further to increase the heat transfer coefficient greatly (J. Heat Transfer (2010), Vol. 132(10), 101801). Also, the flow stratification and stagnant zone are avoided (according to calculations), which allows a complete draining and decreases fouling susceptibility (lower fouling resistance and lower heat transfer area).

[0011] Document WO 2009/148822 discloses baffles mounted in the shell to guide the fluid into a helical flow pattern, with different helix angles when the baffle is proximate the inlet and the outlet respectively. Documents US 2,384,714, US 2,693,942, US 3,400,758, US 4,493,368 and WO 2005/019758 each disclose each different kinds of baffles, but with the same aim of providing a helical flow pattern of the fluid. Document US 1,782,409 discloses a continuous helical baffle.

[0012] Document GB 2 020 793 A discloses a counterflow heat exchanger, in particular a steam generator, having two fixed tube plates, an upper tube plate and a lower tube plate, arranged to face each other in parallel and coaxial relationship and having different mean diameters of the bored areas, a nest of tubes extending between said upper and lower tube plates, the tubes being connected to the tube plates and distributed substantially

in a polar symmetry arrangement and having at one end an S-like bent portion, the rectilinear portion of the tube nest substantially comprising the thermal exchange zone being enclosed with substantially uniform distribution within an annular interspace defined between an inner jacket and an outer shroud attached to the tube plates. In use a heating fluid such as liquid sodium passes through the annular space to heat the fluid flowing in the tubes.

[0013] Document WO 2008/095248 A1 discloses a heat exchanger in the form of a barrel heater comprising a cylindrical shell containing at least one tube located therein and extending therealong. The cylindrical shell and the at least one tube are secured to flanged end plates located at each end of said heat exchanger. The flanged end plates are each arranged to connect with a flanged connector for fluid communication with said at least one tube. The shell is provided with at least two external restraints spaced apart from each other, for restraining the heat exchanger on a support frame. The heat exchanger is also provided with a plurality of internal restraints, spaced apart from each other, to locate and restrain the at least one tube relative to the shell.

[0014] Document US 5,261,485 A discloses an apparatus for distributing a slurry comprising a first section having a dome or cone shape and a plurality of passageways, and a second flat section located below the first section and having a plurality of passageways.

[0015] The current solutions are not satisfactory for example in terms of thermal gradient flexibility, efficiency (pressure drop, heat transfer coefficient), drainability, natural circulation, absence of corrosion and leakage, etc. and newly designed steam generator and/or individual heat exchangers thereof should meet technical requirements such as :

- improved thermal efficiency by reducing internal leakages and bypass streams ;
- improved pressure drop by reducing local stream obstacles ;
- improved ramp-up capability ;
- improved reliability ;
- improved fouling behavior, etc.

[0016] Moreover fast start-up usually leads to leakage in particular at the connection between the tubes and the tube sheet.

Aims of the Invention

[0017] The present invention aims to overcome the drawbacks of the heat exchangers of prior art intended for steam generators.

[0018] In particular, the invention aims to obtain a reduced-size heat exchanger presenting high flexibility in terms of thermal gradient as well as improved efficiency thanks to optimized hydrodynamic salt flow leading to lower pressure drop, lower internal leakage (by-pass),

improved heat transfer coefficient, lower tendency to foul, easily drainable molten salt, natural circulation (i.e. without circulation pump), long lifetime, and competitive cost.

Summary of the Invention

[0019] The present invention relates to a heat exchanger comprising:

10 a first straight section, a second straight section and a bent section or elbow linking the first straight section and the second straight section, each straight section comprising a part of an external cylindrical shell;

15 a bundle of parallel U-bent tubes having each a first and a second straight part respectively located in said first straight section and second straight section of the exchanger and a 180°-bent part located in said bent section or elbow of the exchanger, so that, in use, a first fluid to be heated and vaporized is flowing in the tubes, said external cylindrical shell being provided respectively at one end with an inlet and at another end with an outlet for a second fluid which is a hot thermal fluid; and

25 baffles configured to guide the second fluid, wherein the bundle of parallel U-bent tubes is connected via a connection to a first end and to a second end; characterised in that each straight section further comprises a part of an internal cylindrical shell, said external cylindrical shell and said internal cylindrical shell cooperating to form an intershell space enclosing the bundle of parallel U-bent tubes, so that, in use, said second fluid is flowing according to an annular flow path within the intershell space and cooling down by exchanging heat with the first fluid flowing in the tubes; and

35 wherein the first end comprises a first hemispherical bonnet for distributing the first fluid to the tubes of the first straight section, and the second end comprises a second hemispherical bonnet for collecting the first fluid under the form of liquid, vapor or a mixture liquid /vapor from the tubes of the second straight section,

40 said intershell space enclosing the baffles, each said connection being made of a tube sheet which is designed to withstand the difference between the second fluid low pressure inside said intershell space and the first fluid high pressure inside the respective bonnet, wherein the tube sheet comprises a circular plate having a central circular orifice and wherein the tube sheet further comprises a hemispherical shell located over said orifice and tightly connected to said circular plate, so as to make a physical separation between the first fluid and the second fluid.

50 **[0020]** According to preferred embodiments of the invention, the hairpin heat exchanger also comprises one of the following characteristics or a suitable combination

thereof:

- the thickness of the circular plate is larger than the thickness recommended by the ASME standard for withstanding the same pressure difference ;
- the interface between the bonnet and the tube sheet circular plate is essentially planar and the hemispherical shell is oriented towards the interior of the heat exchanger and located inside the internal cylindrical shell;
- the thickness of the hemispherical shell is comprised between 20% and 40% of the thickness of the tube sheet plate ;
- said first straight section and said second straight section consist in separated enclosures linked by said elbow, so that to form a hairpin heat exchanger shell ;
- said first straight section, said second straight section and said bent section or elbow consist in one single enclosure or shell enclosing the bundle of parallel U-tubes and wherein the first hemispherical bonnet and the second hemispherical bonnet coincide ;
- the heat exchanger is horizontal and the flow of the second fluid with respect to the flow of the first fluid therein is either co-current or counter-current ;
- said first fluid is a fluid comprising feedwater or supercritical carbon dioxide ;
- said second fluid is a molten salt or a mixture of molten salts, a thermal oil or liquid sodium ;
- the baffles are under the form of a continuous helical baffle ;
- the baffles are assembled, preferably welded or bolted, to the internal cylindrical shell ;
- a sealing means is provided between the external shell and the baffles ;
- the heat exchanger is equipped with a distribution jacket for uniformly feeding the second fluid from the thermal fluid inlet to the heat exchanger;
- the distribution jacket has a plurality of openings distributed at 360° over an internal face thereof, said openings preferably feeding the second fluid into a first turn of the helical baffle.

[0021] A second aspect of the invention relates to an evaporator made of a heat exchanger as described

above.

[0022] A third aspect of the invention relates to a superheater made of a heat exchanger as described above.

[0023] A fourth aspect of the invention relates to a reheater and/or an economizer and/or a preheater made of a heat exchanger as described above.

[0024] A fifth aspect of the invention relates to a molten salt steam generator (MSSG) comprising at least one heat exchanger train made of an evaporator, a superheater, a reheater and/or economizer and/or preheater as described above. Advantageously, the superheater, the reheater and/or the economizer and/or the preheater are running counter-current, while the evaporator is running co-current.

[0025] Still under the scope of the present invention, the molten salt steam generator is a once-through or a forced circulation steam generator.

Brief Description of the Drawings

[0026]

FIG.1 diagrammatically represents the components of a typical heat exchanger train for a Molten Salt Steam Generator.

FIG. 2 schematically represents an embodiment for a "shell-and-tube" straight tube heat exchanger according to prior art.

FIG. 3 represents a perspective view of a horizontal hairpin generator of prior art.

FIG. 4A and 4B respectively show a plane view and an elevation view for a first preferred embodiment of a heat exchanger according to the present invention.

FIG. 5A and 5B respectively show corresponding cross-sectional views of the heat exchanger according to the embodiment of FIG. 4.

FIG. 6A and 6B respectively show views corresponding to FIG. 5 but with a supporting system of the heat exchanger.

FIG. 7 is a longitudinal cross-sectional detailed view of one exchanger end according to the invention, focusing on the particular tube sheet.

FIG. 8A and 8B respectively show a perspective view and a cross-sectional view of the above-mentioned particular tube sheet.

FIG. 9 is a cutaway 3D view for a second embodiment of the present invention showing an evaporator with a U-tube design.

FIG. 10A and 10B show respective thermography

simulation data for a tube sheet according to prior art (A) and to the particular tube sheet of the present invention (B).

Description of Preferred Embodiments of the Invention

[0027] A first preferred embodiment of the present invention relates to a new design for a horizontal hairpin heat exchanger 1, as depicted in FIG. 4 to 9.

[0028] The heat exchanger has a reciprocating flow between two fluids. A first fluid, generally a mixture of water and water steam, circulates through a first bundle of parallel horizontal straight tubes sections 2 located in the first straight part of the hairpin and further through a second bundle of parallel horizontal straight tubes sections 2 located in the second straight part of the hairpin. The tubes 2 of the first bundle are connected to the tubes 2 of the second bundle by 180° bent tube sections located in the head of the hairpin or elbow 32, forming thereby U-bent tube sections.

[0029] Supercritical carbon dioxide is an example of usable alternate first fluid in the present invention.

[0030] According to this embodiment, the bundle of tubes 2 in each straight part is located between an internal cylindrical shell 3 and an external cylindrical shell 4, as represented in FIG. 5 and FIG. 6.

[0031] The internal space 5 delimited by the two shells 3, 4 permits to hold a heat source, preferably a second fluid, within an annular flow path. This second fluid is a thermal fluid, for example molten salt(s) having been heated by the solar receivers at the apex of a CSP tower plant. The thermal fluid, by having its flow in contact with the bundle(s) of tubes 2, will transfer heat to the parallel-flowing first fluid running through the tubes 2. The first fluid and the second fluid can be co-current or counter-current, without departing from the scope of the present invention. Similarly the heat source or the second fluid can be any thermal fluid such as water, thermal oil, liquid sodium, fluidized bed, etc.

[0032] As illustrated by FIG. 4, a first distribution jacket 30 is provided at one end of the heat exchanger 1 with an inlet nozzle 6, respectively an outlet nozzle 6, through which the thermal fluid enters into, respectively leaves the heat exchanger 1. Similarly, an outlet nozzle 7, respectively inlet nozzle 7, is provided on a second distribution jacket 30 at another end of the heat exchanger 1 in order to discharge the cooled thermal fluid, respectively admit the hot fluid.

[0033] Advantageously, the thermal fluid is uniformly distributed on the shell at 360° (inlet, circulation, fluid temperature) thanks to said distribution jacket 30 located at the inlet nozzle of the heat exchanger.

[0034] In order to improve the efficiency of heat transfer, as shown in FIG. 5 and FIG. 6, space 5 is provided in the straight parts of the hairpin exchanger with an enclosed continuous helical baffle 8 allowing to guide the flow of the thermal fluid. The thermal fluid then helically

flows in the heat exchanger, which is for example an evaporator running under natural circulation, between the internal and the external shell, according to an annular flow path. The continuous helical baffle configuration ensures a gentle flowing of the second fluid, thereby avoiding any sharp direction change or dead zones as in the exchangers having flow-perpendicular baffles. In this manner, the heat transfer rate is greatly increased and the pressure drop is greatly lowered compared with that of exchangers with conventional segment baffles (see above).

[0035] According to one embodiment, the internal cylindrical shell 3 and the baffles 8 can be welded or bolted together. Further a sealing means can be provided between the external shell 4 and the baffles 8 to avoid parasitic streams.

[0036] Advantageously the helical baffles are designed using an innovative solution (sealing device and manufacturing, not shown) in order to have the smallest gap possible between baffles and tubes. This allows to suppress or at least strongly reduce the bypass between baffles and through tubes.

[0037] Still according to the invention, as shown on FIG. 7, on each external end of the hairpin exchanger straight part, the annular bundle of parallel straight tubes 2 is connected, through a particular tube sheet 11, 12, to a (hemi) spherical bonnet 16 containing the high pressure fluid (steam/water steam). The specific tube sheet 11, 12 has the following characteristics :

- the tube sheet plate 12 itself is empty in its center, an orifice being machined therein and corresponding to the prolongation of the heat exchanger straight part lacking tubes 2 ;
- the physical tight separation between the molten salt low pressure zone 13 in the heat exchanger straight part and the high pressure water/steam bonnet zone 15 (see rectangular frame) is ensured by a spherical surface head 11 welded or tightly connected to the tube sheet plate 12 above said orifice ;
- the tube sheet plate 12 is thicker than usually designed in prior art, that is according to the recommendation of ASME (for *American Society of Mechanical Engineers*) code.

[0038] According to the above characteristics, the heat exchanger components cooperate so that the heat exchanger operates as follows :

- the spherical bonnet 16 distributes the first fluid (such as water/steam) towards the tube sheet 12 ; the spherical shape of the bonnet allows to design a bonnet which is thinner;
- the tube sheet 12 distributes the first fluid towards, resp. from, the tube bundles 2 at the inlet, respectively the outlet of the heat exchanger;
- the annular salt flow down (of second fluid) is improved by the continuous helical baffles 8 of the shell-

and-tube configuration and the U-tubes design 14 allows to manage the differential thermal expansion of the tubes.

[0039] As in the classical shell-and-tube configuration, the first fluid, usually water, is under high pressure in quasi-spherical vessels or plenums. On the other side of the tube sheet, the salt flowing around the tube bundles is maintained under much lower pressure, requiring very thick tube sheets to withstand the pressure difference.

[0040] It is an unexpected effect or advantage of the invention to propose a tube sheet that is even thicker than the one prescribed in prior art. Oversizing the tube sheet plate 12 helps reducing the bending stress thereof and reduces creep. Moreover, specific machining of the tube sheet and/or the bonnet allows reducing the amount of useless metal.

EXAMPLE

[0041] The present invention is flexible and intended to be applied to a series of heat exchanger design used in MSSG technology, such as reheater, superheater, economizer, preheater and evaporator devices, wherein all the common components are made according to the generic heat exchanger design of the invention.

[0042] As mentioned above (FIG. 1), a hot molten salt with decreasing temperature flows for example firstly in parallel through a reheater and a superheater to recombine and enter into the evaporator and further in the preheater/economizer in series.

[0043] In current embodiments, hot molten salt entering the system at high temperature, for example 563°C (and certainly below 650°C which is the degradation temperature for the usual molten salts) flows in parallel through the superheater and reheater, combines and passes in series through the evaporator and preheater. Cold salt leaves the preheater at a temperature typically in the range of 290-300°C, preferably at about 293°C, or above a minimum temperature which is either the solidification temperature of the heat transfer fluid (as low as 90°C for the molten salts such as sodium derivatives). Alternately any thermal fluid, e.g. thermal oil, can be used instead of molten salt with an operating temperature range in this case going for example from 80°C (condensation and/or crystallization temperature) to 380°C (example of degradation temperature).

[0044] Moreover it is under the scope of the present invention that the thermal fluid can have a temperature up to 700°C. All metal parts are advantageously made of stainless steel or noble metals which can withstand temperatures up to 600°C and above.

[0045] More specifically, according to one embodiment, molten salt coming from the reheater and superheater enter the evaporator through the inlet nozzle, then helically flows in the evaporator in a natural circulation way in the annular space located between an internal pipe and an external shroud, as described above. Satu-

rated water flows from the steam drum (spherical or horizontal) of the evaporator through the downcomers (not shown) and from the hemispherical bonnet to U-tubes inside the heat exchanger for steam generation. In this design, water at high pressure flows in tubes which are not in contact with the shells. Preferably all the heat exchangers are horizontal.

[0046] Although the design of the exchanger according to the present invention is optimized for natural circulation running, it could also be used in once-through or forced circulation steam generators.

[0047] According to one alternate embodiment of the invention shown on FIG. 9, the straight tubes sections of the first tube bundle and of the second tube bundle make one single U-tube bundle located in a single enclosure or shell (not making a hairpin shell), the elbow 32 of the U-tubes 2 being on one side of the exchanger and the entry/exit of the single U-tube bundle located on the other side being connected to a spherical bonnet 16 through a tube sheet 11, 12 according to the invention.

[0048] The present invention advantageously provides particularly high flexibility in terms of thermal gradient thanks to the following features :

- the tube sheet is empty in its center to avoid any harmful thermal gradient inside the tube sheet; it improves the thermal behavior of this component during the start-up so that the lifetime of this component is longer (see FIG. 10B where the thermal gradient *in the tube sheet* is lower for the present invention as compared with prior art in FIG. 10A) ;
- a specific machining may be foreseen between the tube sheet 12 and the inner pipe 3 so as to avoid peak stress and so as to improve the lifetime of this latter component;
- a specific machining may also be foreseen between the tube sheet 12 and the spherical bonnet 16 (absence of flanges) ;
- a spherical bonnet 16 has been selected as a header or end part to avoid any cold area during the startup of the installation ;
- water at high pressure flows in the tubes or pipes 2 not in the shell side 4 which allows lower thickness thereof and consequently a higher thermal gradient capability ;
- traditional straight baffles are replaced by helical baffles 8 which involve that salt is flowing helically while water is restricted to flow in tubes 2 ;
- continuous helical baffles 8 allow smooth flow direction change. At equivalent ΔP , continuous helical baffles 8 ensure higher speed flow, higher exchange surface and smaller heat exchanger design in comparison to conventional baffles. Moreover, the risk of fouling is lower as there is no dead zone with such baffle design.

[0049] Moreover, according to the present invention, particular connection of the tubes to the tube sheet, such

as IBW (internal bore welding) known as such in the art, may provide a corrosion free and leakage free solution (no risk of crevice corrosion, no risk of leak, or of relaxation).

List of reference symbols

[0050]

1	Hairpin heat exchanger	10
2	Straight tube (section)	
3	Internal cylindrical shell	
4	External cylindrical shell	
5	Intershell space	
6	Thermal fluid inlet	15
7	Thermal fluid outlet	
8	Helical baffle	
9	First straight section	
10	Second straight section	
11	Spherical head of tube sheet	20
12	Thick tube sheet	
13	Second low pressure fluid (molten salt)	
14	U-bent tube	
15	High pressure fluid (water/steam)	
16	Bonnet (inlet or outlet)	25
17	Tube passageway	
18	Front closure	
19	Rear closure	
20	Support	
21	Straight tube	30
22	Shell	
23	Shell-side fluid in	
24	Tube-side fluid in	
25	Tube-side fluid out	
26	Shell-side fluid out	35
27	Tube sheet	
28	Straight baffle	
29	Water box or plenum or bonnet	
30	Distribution jacket	
32	Elbow	40
33	Separation plate	
100	Molten salt inlet of the MSSG	
101	Reheater of the MSSG	
102	Evaporator of the MSSG	
103	Economizer of the MSSG	45
104	Superheater of the MSSG	
105	Molten salt outlet of the MSSG	

Claims

1. A heat exchanger (1) comprising:

a first straight section (9), a second straight section (10) and a bent section or elbow (32) linking the first straight section and the second straight section, each straight section (9, 10) comprising a part of an external cylindrical shell (4);

a bundle of parallel U-bent tubes (2) having each a first and a second straight part respectively located in said first straight section (9) and second straight section (10) of the exchanger and a 180°-bent part located in said bent section or elbow (32) of the exchanger, so that, in use, a first fluid to be heated and vaporized is flowing in the tubes (2), said external cylindrical shell (4) being provided respectively at one end with an inlet (6) and at another end with an outlet (7) for a second fluid which is a hot thermal fluid; and baffles (8) configured to guide the second fluid, wherein the bundle of parallel U-bent tubes (2) is connected via a connection to a first end and to a second end;

characterised in that each straight section (9, 10) further comprises a part of an internal cylindrical shell (3), said external cylindrical shell (4) and said internal cylindrical shell (3) cooperating to form an intershell space (5) enclosing the bundle of parallel U-bent tubes (2), so that, in use, said second fluid is flowing according to an annular flow path within the intershell space (5) and cooling down by exchanging heat with the first fluid flowing in the tubes (2); and wherein the first end comprises a first hemispherical bonnet (16) for distributing the first fluid to the tubes (2) of the first straight section (9), and the second end comprises a second hemispherical bonnet (16) for collecting the first fluid under the form of liquid, vapor or a mixture liquid /vapor from the tubes (2) of the second straight section (10),

said intershell space (5) enclosing the baffles (8), each said connection being made of a tube sheet (11, 12) which is designed to withstand the difference between the second fluid low pressure inside said intershell space (5) and the first fluid high pressure inside the respective bonnet (16), wherein the tube sheet comprises a circular plate (12) having a central circular orifice and wherein the tube sheet further comprises a hemispherical shell (11) located over said orifice and tightly connected to said circular plate (12), so as to make a physical separation between the first fluid and the second fluid.

2. The heat exchanger (1) according to claim 1, wherein the thickness of the circular plate (12) is larger than the thickness recommended by the ASME standard for withstanding the same pressure difference.

3. The heat exchanger (1) according to claim 1, wherein the interface between the bonnet (16) and the tube sheet circular plate (12) is essentially planar and wherein the hemispherical shell (11) is oriented towards the interior of the heat exchanger (1) and located inside the internal cylindrical shell (3).

4. The heat exchanger (1) according to claim 1, wherein the thickness of the hemispherical shell (11) is comprised between 20% and 40% of the thickness of the tube sheet plate (12).
5. The heat exchanger (1) according to claim 1, wherein said first straight section (9) and said second straight section (10) consist in separated enclosures linked by said elbow (32), so that to form a hairpin heat exchanger shell.
6. The heat exchanger (1) according to claim 1, wherein said first straight section (9), said second straight section (10) and said bent section or elbow (32) consist in one single enclosure or shell enclosing the bundle of parallel U-tubes (2) and wherein the first hemispherical bonnet (16) and the second hemispherical bonnet (16) coincide.
7. The heat exchanger (1) according to claim 1, wherein it is horizontal and the flow of the second fluid therein with respect to the flow of the first fluid is either co-current or counter-current.
8. The heat exchanger (1) according to claim 1, wherein said first fluid is a fluid comprising feedwater or supercritical carbon dioxide.
9. The heat exchanger (1) according to claim 1, wherein said second fluid is a molten salt or a mixture of molten salts, a thermal oil or liquid sodium.
10. The heat exchanger (1) according to claim 1, wherein the baffles (8) are under the form of a continuous helical baffle.
11. The heat exchanger (1) according to claim 1, wherein the baffles (8) are assembled, preferably welded or bolted, to the internal cylindrical shell (3).
12. The heat exchanger according to claim 1, wherein a sealing means is provided between the external shell (4) and the baffles (8).
13. The heat exchanger according to claim 1, wherein it is equipped with a distribution jacket (30) for uniformly feeding the second fluid from the thermal fluid inlet (6, 7) to the heat exchanger.
14. The heat exchanger according to claim 13, wherein the distribution jacket (30) has a plurality of openings distributed at 360° over an internal face thereof, said openings preferably feeding the second fluid into a first turn of the helical baffle (8).
15. An evaporator made of a heat exchanger according to claim 1.
16. A superheater made of a heat exchanger according to claim 1.
17. A reheater or an economizer and/or a preheater made of a heat exchanger according to claim 1.
18. A molten salt steam generator (MSSG) comprising at least one heat exchanger train made of an evaporator according to claim 15, a superheater according to claim 16, and a reheater and/or economizer and/or preheater according to claim 17.
19. A molten salt steam generator according to claim 18, wherein the superheater, the reheater and/or the economizer and/or the preheater are running counter-current, while the evaporator is running co-current.
20. A molten salt steam generator according to claim 18, wherein it is a once-through or a forced circulation steam generator.

Patentansprüche

1. Wärmetauscher (1), umfassend:

einen ersten geraden Abschnitt (9), einen zweiten geraden Abschnitt (10) und einen gebogenen Abschnitt oder Krümmer (32), der den ersten geraden Abschnitt und den zweiten geraden Abschnitt verknüpft, wobei jeder gerade Abschnitt (9, 10) einen Teil einer äußeren zylindrischen Hülle (4) umfasst;
 ein Bündel paralleler U-förmig gebogener Rohre (2) mit jeweils einem ersten und einem zweiten geraden Teil, die sich in dem ersten geraden Abschnitt (9) bzw. dem zweiten geraden Abschnitt (10) des Tauschers befinden, und einem um 180° gebogenen Teil, der sich in dem gebogenen Abschnitt oder Krümmer (32) des Tauschers befindet, sodass im Gebrauch ein erstes zu erwärmendes und zu verdampfendes Fluid in den Rohren (2) strömt, wobei die äußere zylindrische Hülle (4) jeweils an einem Ende mit einem Einlass (6) und an einem anderen Ende mit einem Auslass (7) für ein zweites Fluid versehen ist, das ein heißes Wärmefluid ist; und Leitflächen (8), die dazu ausgestaltet sind, das zweite Fluid zu leiten, wobei das Bündel paralleler U-förmig gebogener Rohre (2) über eine Verbindung mit einem ersten Ende und einem zweiten Ende verbunden ist;
dadurch gekennzeichnet, dass jeder gerade Abschnitt (9, 10) ferner einen Teil einer inneren zylindrischen Hülle (3) umfasst, wobei die äußere zylindrische Hülle (4) und die innere zylindrische Hülle (3) zusammenwirken, um einen

- Zwischenhüllenraum (5) zu bilden, der das Bündel paralleler U-förmig gebogener Rohre (2) umschließt, sodass im Gebrauch das zweite Fluid gemäß einem ringförmigen Strömungsweg innerhalb des Zwischenhüllenraums (5) strömt und durch Austauschen von Wärme mit dem ersten Fluid, das in den Rohren (2) strömt, abkühlt; und
- wobei das erste Ende eine erste halbkugelförmige Haube (16) zum Verteilen des ersten Fluids auf die Rohre (2) des ersten geraden Abschnitts (9) umfasst und das zweite Ende eine zweite halbkugelförmige Haube (16) zum Sammeln des ersten Fluids in Form von Flüssigkeit, Dampf oder einer Mischung aus Flüssigkeit/Dampf aus den Rohren (2) des zweiten geraden Abschnitts (10) umfasst,
- wobei der Zwischenhüllenraum (5) die Leitflächen (8) umschließt, wobei jede Verbindung aus einem Rohrboden (11, 12) hergestellt ist, der dazu ausgelegt ist, der Differenz zwischen dem Niederdruck des zweiten Fluids innerhalb des Zwischenhüllenraums (5) und dem Hochdruck des ersten Fluids innerhalb der jeweiligen Haube (16) standzuhalten, wobei der Rohrboden eine kreisförmige Platte (12) mit einer zentralen kreisförmigen Öffnung umfasst und wobei der Rohrboden ferner eine halbkugelförmige Hülle (11) umfasst, die sich über der Öffnung befindet und fest mit der kreisförmigen Platte (12) verbunden ist, um eine physische Trennung zwischen dem ersten Fluid und dem zweiten Fluid herzustellen.
2. Wärmetauscher (1) nach Anspruch 1, wobei die Dicke der kreisförmigen Platte (12) größer als die Dicke ist, die durch den ASME-Standard dafür empfohlen wird, der gleichen Druckdifferenz standzuhalten.
 3. Wärmetauscher (1) nach Anspruch 1, wobei die Schnittstelle zwischen der Haube (16) und der kreisförmigen Rohrbodenplatte (12) im Wesentlichen eben ist und wobei die halbkugelförmige Hülle (11) in Richtung des Inneren des Wärmetauschers (1) ausgerichtet ist und sich innerhalb der inneren zylindrischen Hülle (3) befindet.
 4. Wärmetauscher (1) nach Anspruch 1, wobei die Dicke der halbkugelförmigen Hülle (11) zwischen 20 % und 40 % der Dicke der Rohrbodenplatte (12) beträgt.
 5. Wärmetauscher (1) nach Anspruch 1, wobei der erste gerade Abschnitt (9) und der zweite gerade Abschnitt (10) aus getrennten Gehäusen bestehen, die durch den Krümmer (32) verknüpft sind, um eine Haarnadelwärmetauscherhülle zu bilden.
 6. Wärmetauscher (1) nach Anspruch 1, wobei der erste gerade Abschnitt (9), der zweite gerade Abschnitt (10) und der gebogene Abschnitt oder Krümmer (32) aus einem einzigen Gehäuse oder einer einzigen Hülle bestehen, das bzw. die das Bündel paralleler U-Rohre (2) umschließt, und wobei sich die erste halbkugelförmige Haube (16) und die zweite halbkugelförmige Haube (16) genau entsprechen.
 7. Wärmetauscher (1) nach Anspruch 1, wobei er horizontal ist und die Strömung des zweiten Fluids darin in Bezug auf die Strömung des ersten Fluids entweder im Gleichstrom oder im Gegenstrom ist.
 8. Wärmetauscher (1) nach Anspruch 1, wobei das erste Fluid ein Fluid ist, das Speisewasser oder überkritisches Kohlendioxid umfasst.
 9. Wärmetauscher (1) nach Anspruch 1, wobei das zweite Fluid ein Flüssigsalz oder eine Mischung aus Flüssigsalzen, ein Thermoöl oder flüssiges Natrium ist.
 10. Wärmetauscher (1) nach Anspruch 1, wobei die Leitflächen (8) in Form einer durchgehender spiralförmigen Leitfläche vorliegen.
 11. Wärmetauscher (1) nach Anspruch 1, wobei die Leitflächen (8) an der inneren zylindrischen Hülle (3) montiert, vorzugsweise angeschweißt oder angeschraubt sind.
 12. Wärmetauscher nach Anspruch 1, wobei ein Dichtungsmittel zwischen der Außenhülle (4) und den Leitflächen (8) vorgesehen ist.
 13. Wärmetauscher nach Anspruch 1, wobei er mit einem Verteilmantel (30) zum gleichmäßigen Einspeisen des zweiten Fluids vom Wärmefluideinlass (6, 7) zum Wärmetauscher ausgestattet ist.
 14. Wärmetauscher nach Anspruch 13, wobei der Verteilmantel (30) eine Vielzahl von Öffnungen aufweist, die um 360° über eine Innenfläche davon verteilt sind, wobei die Öffnungen vorzugsweise das zweite Fluid in eine erste Windung der spiralförmigen Leitfläche (8) einspeisen.
 15. Verdampfer, der aus einem Wärmetauscher nach Anspruch 1 hergestellt ist.
 16. Überhitzer, der aus einem Wärmetauscher nach Anspruch 1 hergestellt ist.
 17. Zwischenüberhitzer oder Economizer und/oder Vorüberhitzer, die aus einem Wärmetauscher nach Anspruch 1 hergestellt sind.

18. Flüssigsalzdampferzeuger (MSSG) mit mindestens einer Wärmetauscherkette, die aus einem Verdampfer nach Anspruch 15, einem Überhitzer nach Anspruch 16 und einem Zwischenüberhitzer und/oder Economizer und/oder Vorüberhitzer nach Anspruch 17 hergestellt ist. 5
19. Flüssigsalzdampferzeuger nach Anspruch 18, wobei der Überhitzer, der Zwischenüberhitzer und/oder der Economizer und/oder der Vorüberhitzer im Gegenstrom laufen, während der Verdampfer im Gleichstrom läuft. 10
20. Flüssigsalzdampferzeuger nach Anspruch 18, wobei er ein Durchlauf- oder Zwangsumlaufdampferzeuger ist. 15

Revendications

1. Échangeur de chaleur (1) comprenant : 20

une première section droite (9), une seconde section droite (10) et une section courbée ou coude (32) reliant la première section droite et la seconde section droite, chaque section droite (9, 10) comprenant une partie d'une coque cylindrique externe (4) ; 25

un faisceau de tubes parallèles courbés en U (2) comprenant chacun une première et une seconde partie droite respectivement situées dans ladite première section droite (9) et dans ladite seconde section droite (10) de l'échangeur et une partie courbée à 180° située dans ladite section courbée ou dans ledit coude (32) de l'échangeur, pour que, en cours d'utilisation, un premier fluide à chauffer et à vaporiser s'écoule dans les tubes (2), ladite coque cylindrique externe (4) étant dotée respectivement à une extrémité d'une entrée (6) et à une autre extrémité d'une sortie (7) destinée à un second fluide qui est un fluide thermique chaud ; et 30

des déflecteurs (8) conçus pour guider le second fluide, le faisceau de tubes parallèles courbés en U (2) étant raccordé par l'intermédiaire d'un raccord à une première extrémité et à une seconde extrémité ; 35

caractérisé en ce que chaque section droite (9, 10) comprend en outre une partie d'une coque cylindrique interne (3), ladite coque cylindrique externe (4) et ladite coque cylindrique interne (3) coopérant pour former un espace intercoque (5) confinant le faisceau de tubes parallèles courbés en U (2), pour que, en cours d'utilisation, ledit second fluide s'écoule selon une voie annulaire d'écoulement à l'intérieur de l'espace intercoque (5) et refroidisse par échange de chaleur avec le premier fluide s'écoulant 40

45 50 55

dans les tubes (2) ; et 5

dans lequel la première extrémité comprend un premier chapeau hémisphérique (16), permettant de distribuer le premier fluide dans les tubes (2) de la première section droite (9), et la seconde extrémité comprend un second chapeau hémisphérique (16), permettant de collecter le premier fluide sous la forme de liquide, de vapeur ou d'un mélange liquide /vapeur provenant des tubes (2) de la seconde section droite (10), ledit espace intercoque (5) confinant les déflecteurs (8), chacun desdits raccords étant constitué d'une enveloppe pour tube (11, 12), conçue pour résister à la différence entre la basse pression de second fluide à l'intérieur dudit espace intercoque (5) et la haute pression de premier fluide à l'intérieur du chapeau (16) respectif, l'enveloppe pour tube comprenant une plaque circulaire (12) comportant un orifice central circulaire et l'enveloppe pour tube comprenant en outre une coque hémisphérique (11) située au-dessus dudit orifice et raccordée fermement à ladite plaque circulaire (12), de manière à produire une séparation physique entre le premier fluide et le second fluide. 10

2. Échangeur de chaleur (1) selon la revendication 1, dans lequel l'épaisseur de la plaque circulaire (12) dépasse l'épaisseur recommandée par la norme de l'ASME pour résister à la même différence de pression. 15
3. Échangeur de chaleur (1) selon la revendication 1, dans lequel l'interface entre le chapeau (16) et la plaque circulaire d'enveloppe pour tube (12) est sensiblement plane et dans lequel la coque hémisphérique (11) est orientée vers l'intérieur de l'échangeur de chaleur (1) et située à l'intérieur de la coque cylindrique interne (3). 20
4. Échangeur de chaleur (1) selon la revendication 1, dans lequel l'épaisseur de la coque hémisphérique (11) est comprise entre 20 % et 40 % de l'épaisseur de la plaque d'enveloppe pour tube (12). 25
5. Échangeur de chaleur (1) selon la revendication 1, dans lequel ladite première section droite (9) et ladite seconde section droite (10) consistent en enceintes séparées reliées par ledit coude (32), de façon à former une coque d'échangeur de chaleur en épingle à cheveux. 30
6. Échangeur de chaleur (1) selon la revendication 1, dans lequel ladite première section droite (9), ladite seconde section droite (10) et ladite section courbée ou coude (32) sont constituées d'une seule enceinte ou coque confinant le faisceau de tubes parallèles en U (2) et dans lequel le premier chapeau hémis- 35

phérique (16) et le second chapeau hémisphérique (16) coïncident.

7. Échangeur de chaleur (1) selon la revendication 1, lequel il est horizontal et l'écoulement du second fluide à l'intérieur de celui-ci par rapport à l'écoulement du premier fluide est soit cohérent soit opposé. 5
8. Échangeur de chaleur (1) selon la revendication 1, dans lequel ledit premier fluide est un fluide comprenant de l'eau d'alimentation ou du dioxyde de carbone supercritique. 10
9. Échangeur de chaleur (1) selon la revendication 1, dans lequel ledit second fluide est un sel fondu ou un mélange de sels fondus, de pétrole thermique ou de sodium liquide. 15
10. Échangeur de chaleur (1) selon la revendication 1, dans lequel les déflecteurs (8) sont sous la forme d'un déflecteur hélicoïdal continu. 20
11. Échangeur de chaleur (1) selon la revendication 1, dans lequel les déflecteurs (8) sont assemblés, de préférence soudés ou boulonnés, à la coque cylindrique interne (3). 25
12. Échangeur de chaleur selon la revendication 1, dans lequel un moyen d'étanchéité est prévu entre la coque externe (4) et les déflecteurs (8). 30
13. Échangeur de chaleur selon la revendication 1, dans lequel il est équipé d'une chemise de distribution (30) permettant l'alimentation uniforme du second fluide de l'entrée pour fluide thermique (6, 7) à l'échangeur de chaleur. 35
14. Échangeur de chaleur selon la revendication 13, dans lequel la chemise de distribution (30) comporte une pluralité d'ouvertures distribuées à 360° sur sa face interne, lesdites ouvertures alimentant de préférence le second fluide dans une première spire du déflecteur hélicoïdal (8). 40
15. Évaporateur constitué d'un échangeur de chaleur selon la revendication 1. 45
16. Surchauffeur constitué d'un échangeur de chaleur selon la revendication 1. 50
17. Réchauffeur ou économiseur et/ou préchauffeur constitué d'un échangeur de chaleur selon la revendication 1.
18. Générateur de vapeur de sel fondu (MSSG) comprenant au moins un train d'échangeurs de chaleur constitué d'un évaporateur selon la revendication 15, d'un surchauffeur selon la revendication 16 et

d'un réchauffeur et/ou d'un économiseur et/ou d'un préchauffeur selon la revendication 17.

19. Générateur de vapeur de sel fondu selon la revendication 18, dans lequel le surchauffeur, le réchauffeur et/ou l'économiseur et/ou le préchauffeur fonctionnent à contre-courant, tandis que l'évaporateur fonctionne selon le courant.
20. Générateur de vapeur de sel fondu selon la revendication 18, dans lequel il est un générateur de vapeur à circulation à passage unique ou forcée.

PRIOR ART

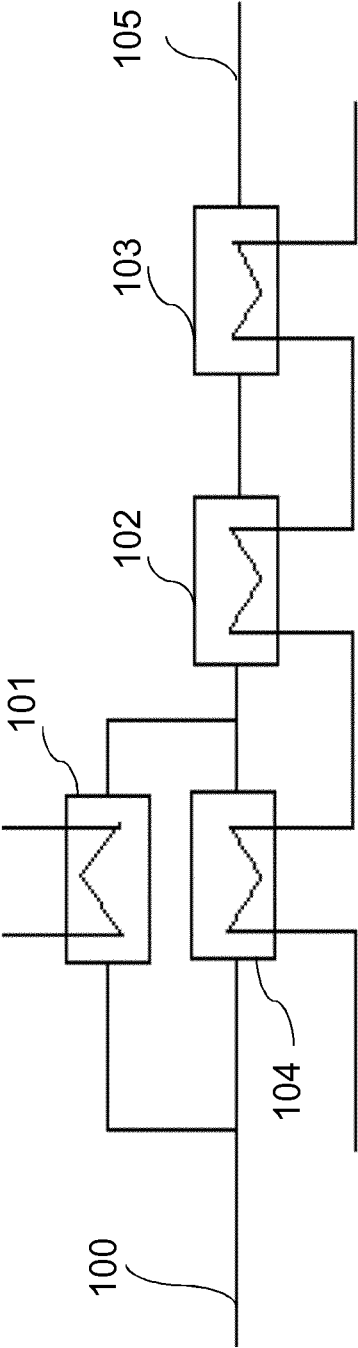


FIG. 1

PRIOR ART

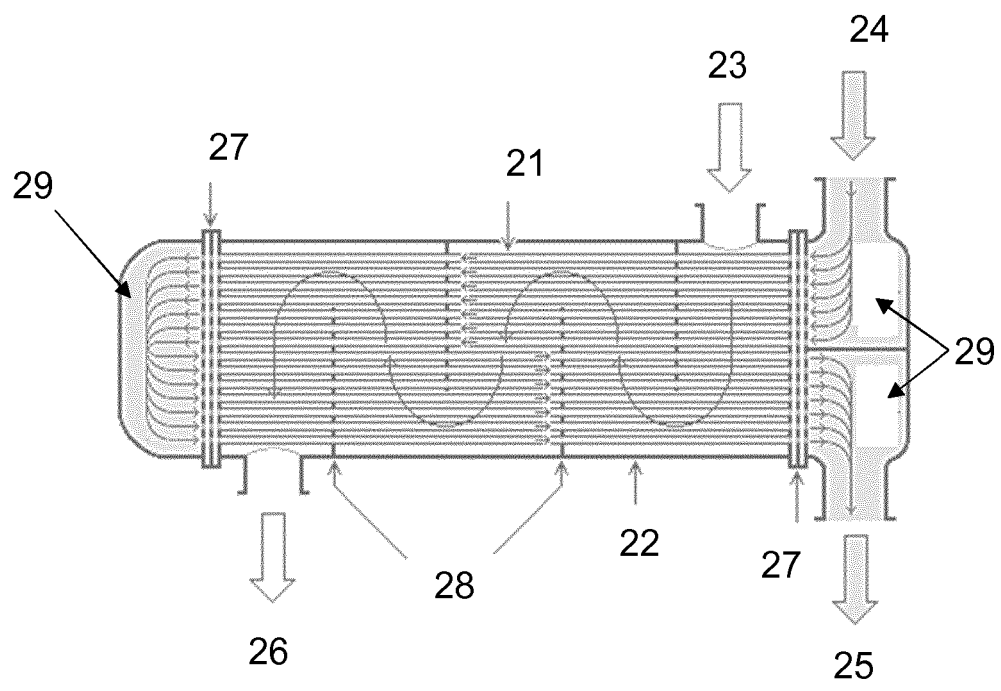


FIG. 2

PRIOR ART

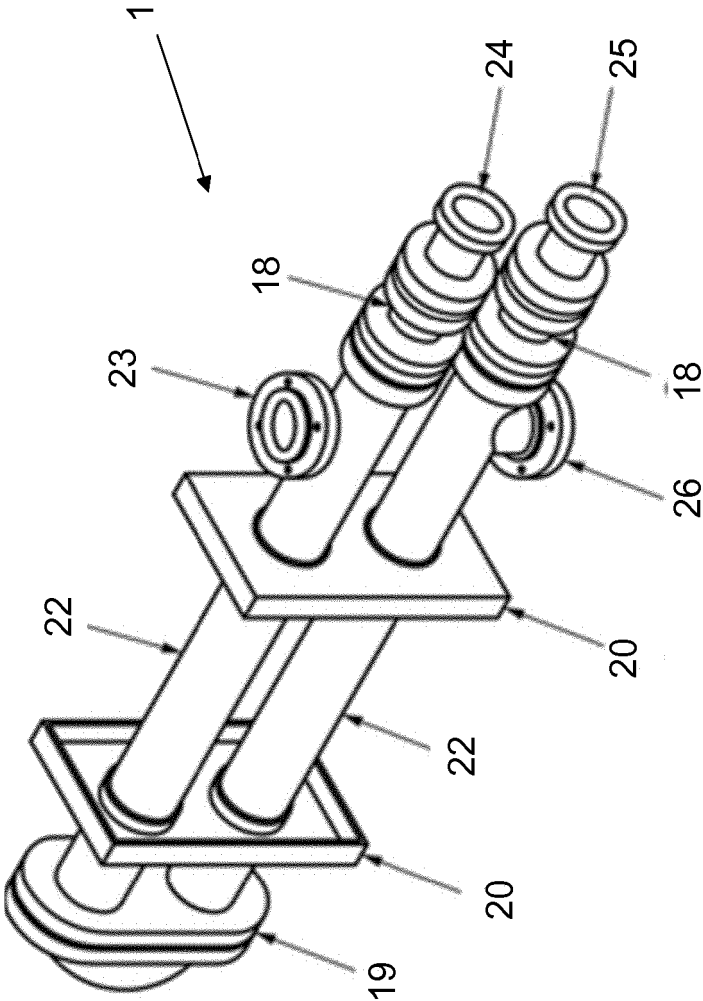


FIG. 3

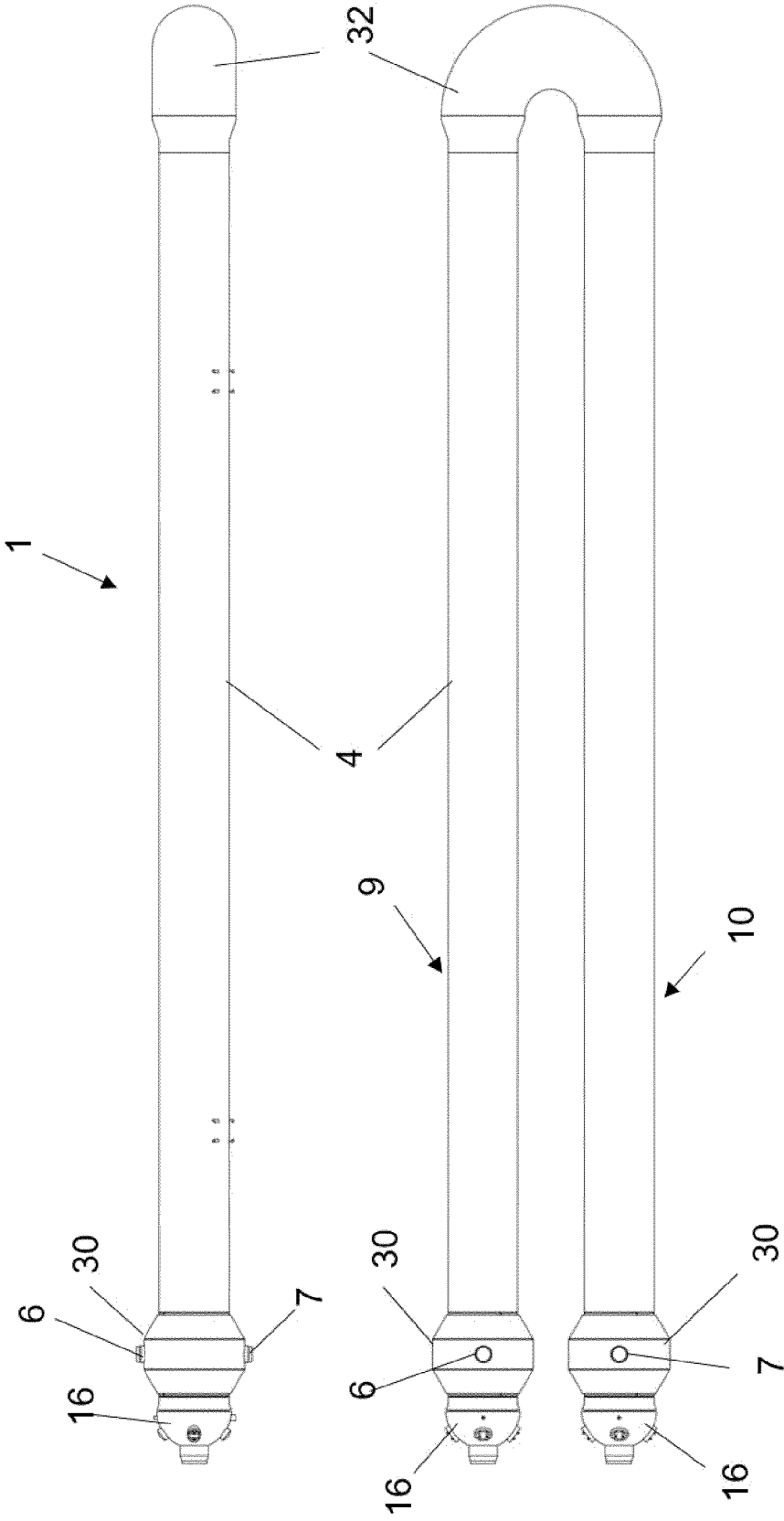


FIG. 4

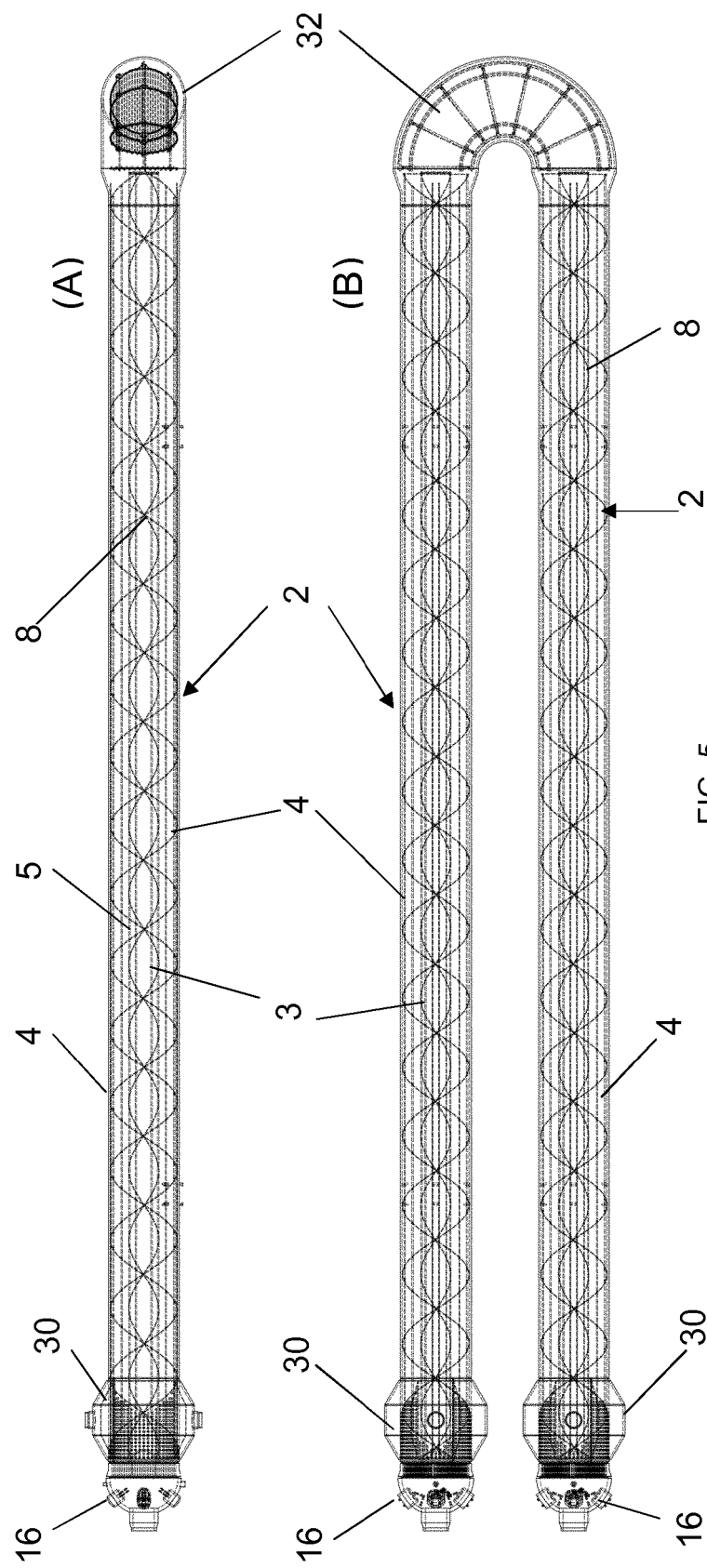


FIG. 5

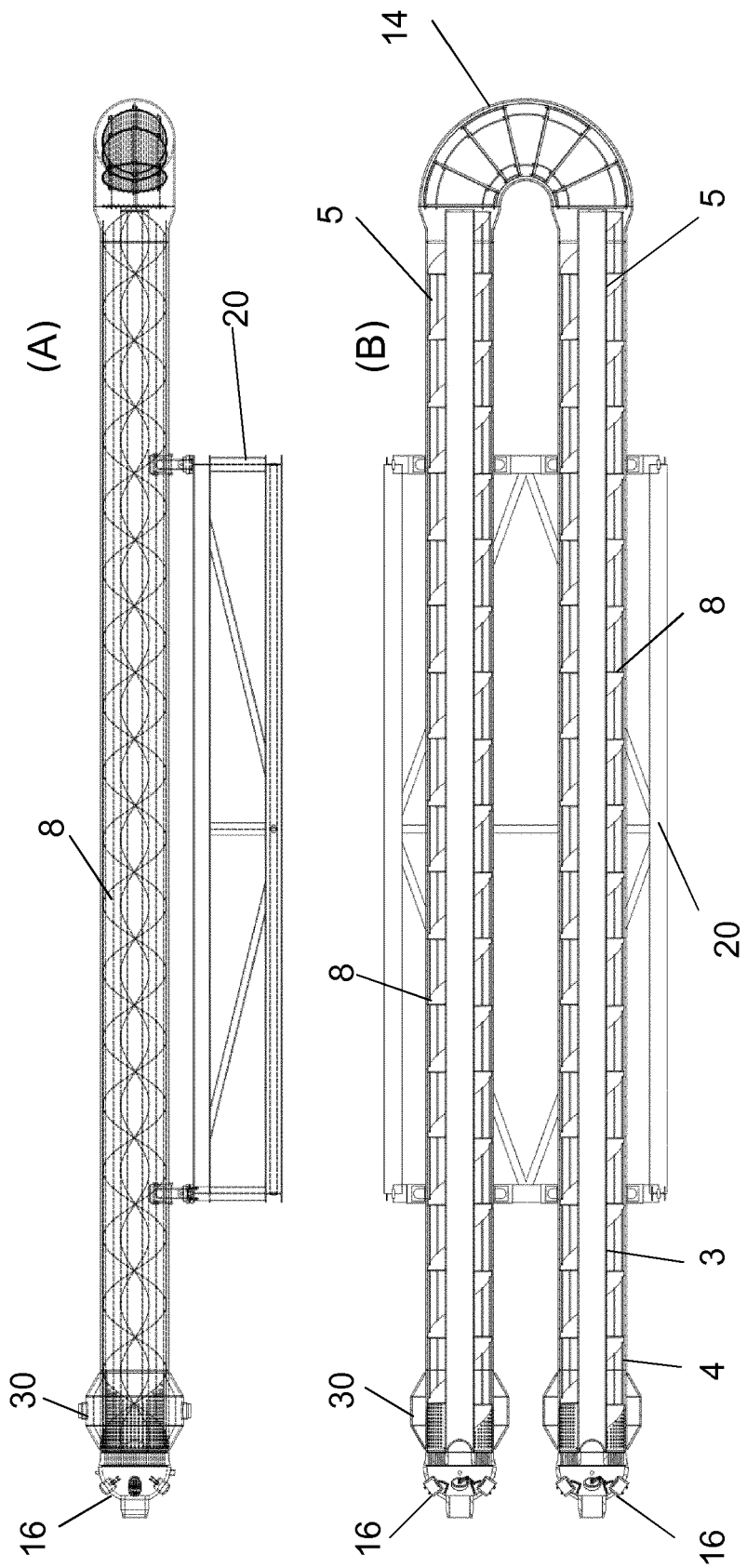
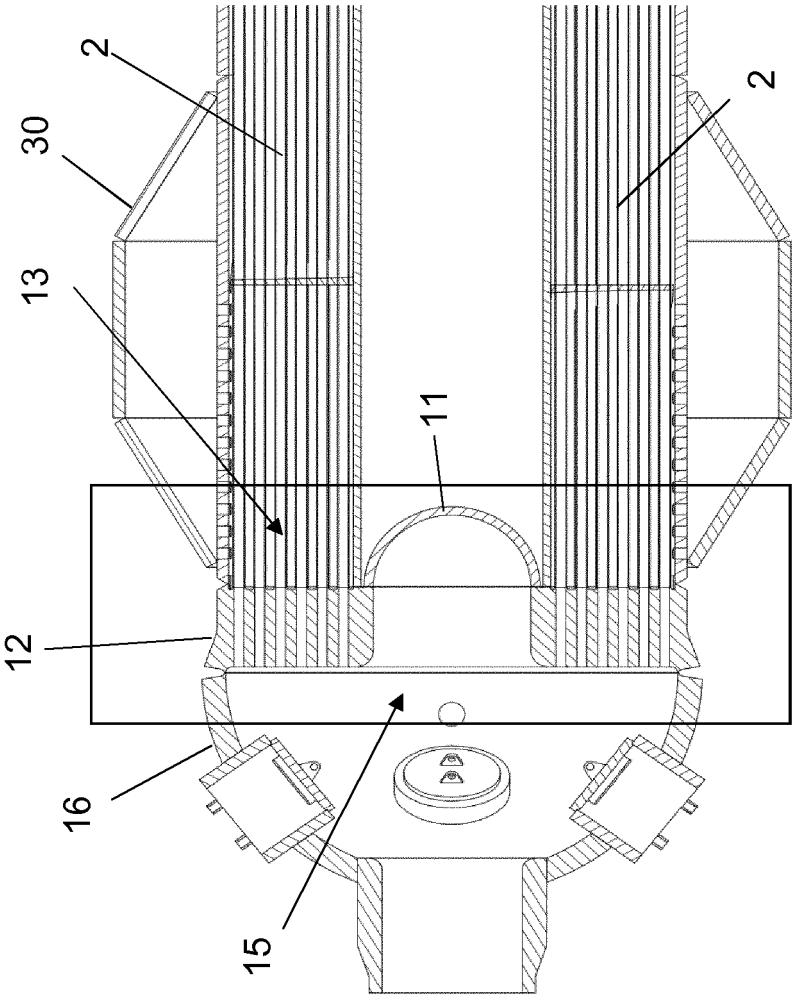


FIG. 6



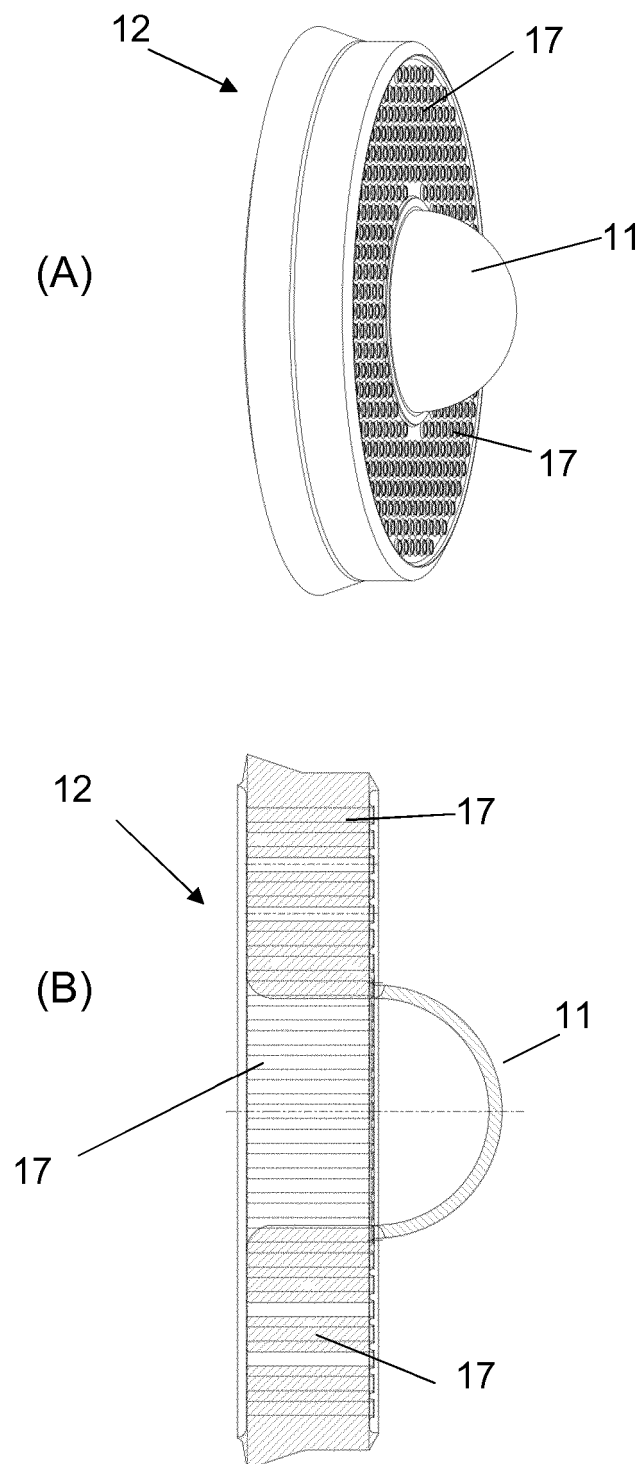


FIG. 8

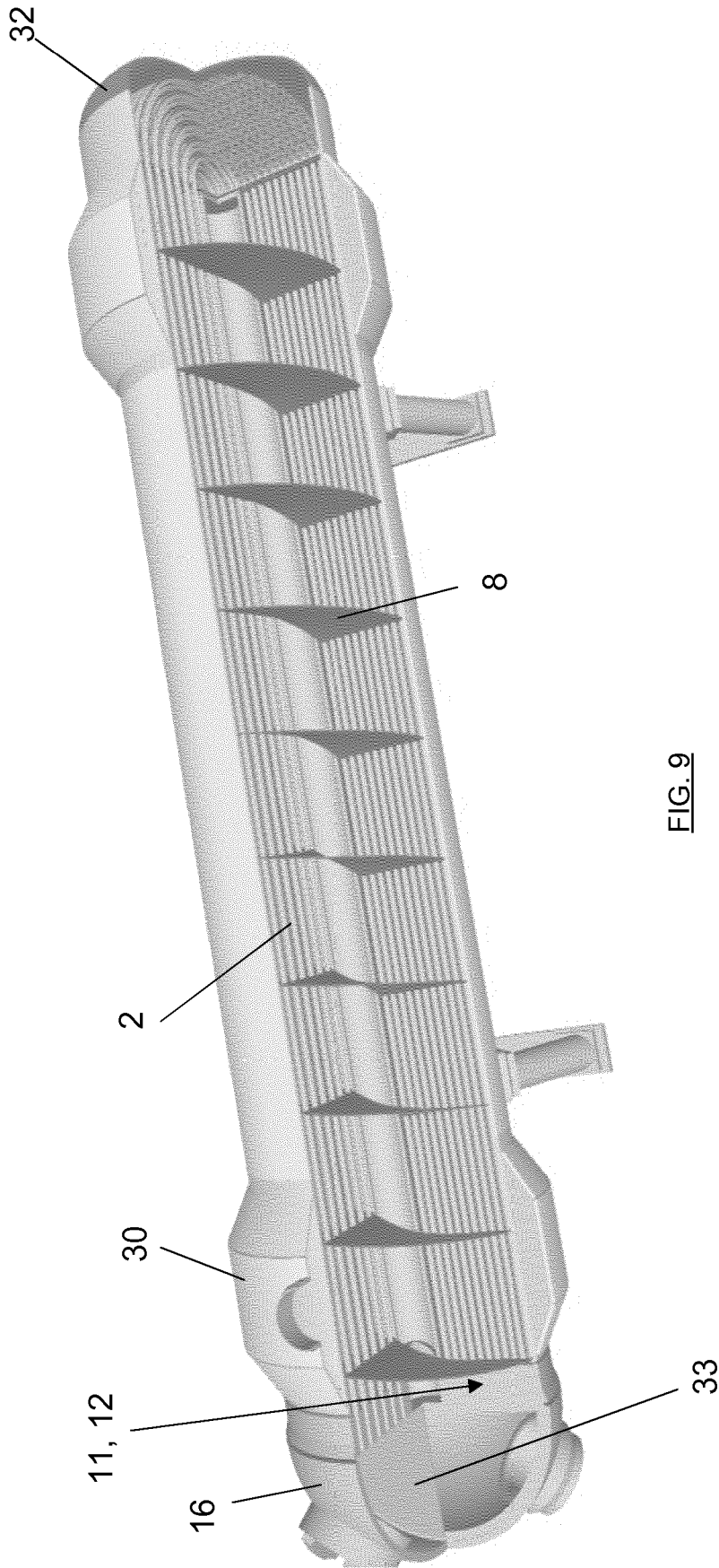


FIG. 9

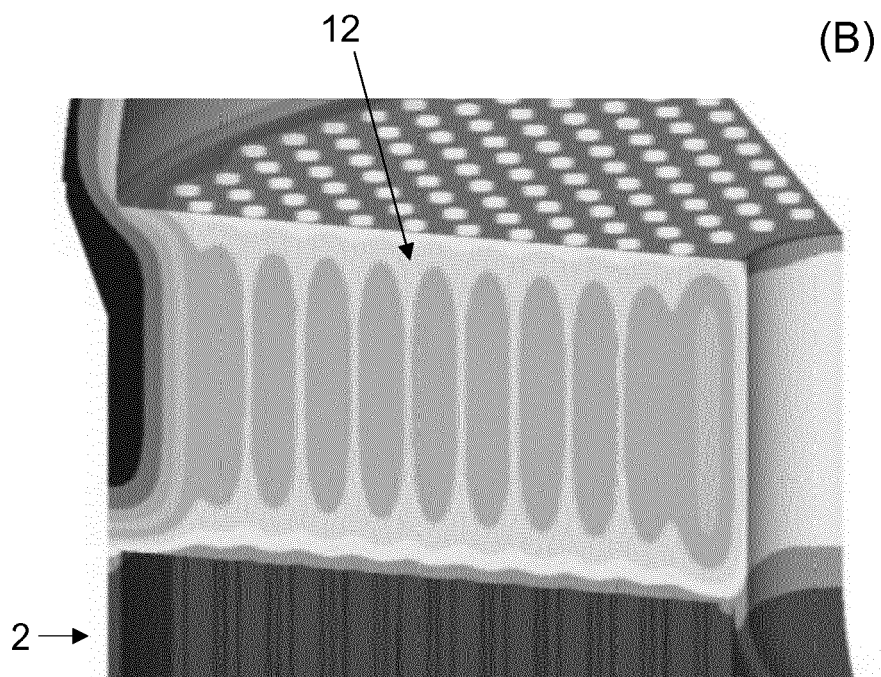
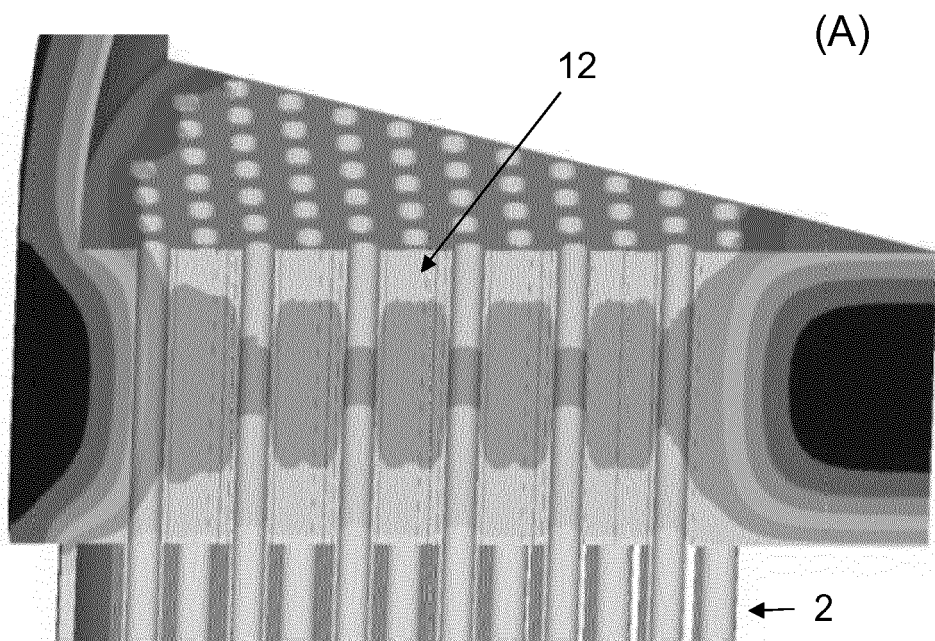


FIG. 10

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- WO 2009148822 A [0011]
- US 2384714 A [0011]
- US 2693942 A [0011]
- US 3400758 A [0011]
- US 4493368 A [0011]
- WO 2005019758 A [0011]
- US 1782409 A [0011]
- GB 2020793 A [0012]
- WO 2008095248 A1 [0013]
- US 5261485 A [0014]

Non-patent literature cited in the description

- *J. Heat Transfer*, 2007, vol. 129 (10), 1425-1431 [0010]
- *J. Heat Transfer*, 2010, vol. 132 (10), 101801 [0010]