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(54) MICROCHANNEL HEAT EXCHANGER AND METHODS OF MANUFACTURE

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Description

Background

[0001] The embodiments described herein relate generally to heat exchanger and methods for the manufacture the same and, more specifically, to micro channel-based heat exchangers for heating compressed gases in turbine engine systems and methods for manufacture of the same.

[0002] Turbine engines (e.g., jet engines, turboshaft engines) typically extract energy from a flow of hot gas produced by the combustion of gas or liquid oil in a stream of compressed air. Irrespective of the exact engine type, most turbine engines operate by initially receiving ambient air at the inlet of a compressor where the ambient air is compressed and discharged at a substantially higher pressure and temperature. The compressed air then typically passes through a combustion chamber, where it is mixed with fuel and burned thereby further increasing the temperature, and by confining the volume, the resultant pressure of the combustion gases. The resultant heated and compressed gases are then passed through a turbine where the heated and compressed gases expand to drive a rotating shaft. Power can be extracted from the turbine via the rotating shaft (also referred to as a torque shaft) that is coupled between the turbine stage and a gearbox or other power extraction mechanism.

[0003] Recently, solar power based heat generation is seen as an attractive and eco-friendly option for heating the compressed gases in gas turbine engines. Current approaches for heating the working fluid in a turbine using solar power employ known heat exchangers, such as shell and tube heat exchangers, that can involve very large and expensive components. Moreover, such known heat exchangers often include tortuous paths through which the heat transfer medium is conveyed, and thus may not be well-suited to certain aspects of alternate methods for providing heat input to a turbine engine (e.g., via a solar input).

[0004] Accordingly, a need exists for systems and methods for compact heat exchangers for heating compressed gases via for use in gas turbine engines. Document FR 962.407 discloses an apparatus (see figure 5), comprising :a first flow panel (1 + 7 + 7) including a base member (1), a first cover (7) and a second cover (7), a first surface of the base member defining a first plurality of channels within which a first portion of a gas can flow in a first direction, a second surface of the base member defining a second plurality of channels, the first cover coupled to the first surface to form a boundary for the first plurality of channels, the second cover coupled to the second surface to form a boundary for the second plurality of channels, the first flow panel coupled to a second flow panel to define a first heat transfer passageway between the first cover of the first flow panel and a cover of the second flow panel, the first flow panel coupled to a third flow panel to define a second heat transfer pas-

sageway between the second cover of the first flow panel and a cover of the second flow panel.

Summary

[0005] According to the present invention there is provided an apparatus, comprising: a first flow panel including a base member, a first cover and a second cover, a first surface of the base member defining a first plurality of microchannels within which a first portion of a gas can flow in a first direction, a second surface of the base member defining a second plurality of microchannels within which a second portion of the gas can flow in a first direction, the first cover coupled to the first surface to form a boundary for the first plurality of microchannels, the second cover coupled to the second surface to form a boundary for the second plurality of microchannels, the first flow panel coupled to a second flow panel to define a first heat transfer passageway between the first cover of the first flow panel and a cover of the second flow panel, within which a heat transfer medium can be conveyed in a second direction, the second direction opposite the first direction, the first flow panel coupled to a third flow panel to define a second heat transfer passageway between the second cover of the first flow panel and a cover of the second flow panel, within which the heat transfer medium can be conveyed in the second direction.

Brief Description of the Drawings

[0006]

FIG. 1 is a cross-sectional schematic view of a portion of a heat exchanger assembly.

FIG. 2 is a perspective view of a heat exchanger assembly.

FIG. 3 is a schematic illustration of a power generation system.

FIG. 4 is a perspective view of a system including one or more heat exchanger assemblies, according to an embodiment of the invention.

FIG. 5 is a perspective view of an air manifold header assembly shown in FIG. 4.

FIG. 6 is a perspective view of a heat exchanger assembly disposed within the system shown in FIG. 4.

FIG. 7 is a top view of the heat exchanger assembly shown in FIG. 6.

FIG. 8 is a zoomed-in view of the top portion of the heat exchanger assembly shown in FIG. 7 and iden-

tified as region Z.

FIG. 9 is a cross sectional view of a flow panel taken along the line X-X in FIG. 8.

FIG. 10 is a zoomed-in view of a portion of the flow panel marked as region Z as shown in FIG. 9.

FIG. 11 is a cross sectional view of the channel portion of the flow panel shown in FIG. 9 taken along the line X-X.

FIG. 12 a cross sectional view of the inlet flow portion of the flow panel shown in FIG. 9 taken along the line Y-Y,

FIG. 13 is a flow chart illustrating a method for fabricating a heat transfer passageway for heating compressed air in microchannels, according to an embodiment.

Detailed Description

[0007] In some embodiments, an apparatus includes a first flow panel, a second flow panel and a third flow panel. The first flow panel includes a base member, a first cover and a second cover, a first surface of the base member defines a first set of microchannels within which a first portion of a gas can flow in a first direction. A second surface of the base member defines a second set of microchannels within which a second portion of the gas can flow in the first direction. The first cover is coupled to the first surface to form a boundary for the first set of microchannels and the second cover is coupled to the second surface to form, a boundary for the second set of microchannels. The first flow panel is coupled to the second flow panel to define a first heat transfer passageway between the first cover of the first flow panel and a cover of the second flow panel, within which, a heat transfer medium can be conveyed in a second direction, where the second direction is opposite the first direction. The first flow panel is coupled to a third flow panel to define a second heat transfer passageway between the second cover of the first flow panel and a cover of the third flow panel, within which the heat transfer medium can be conveyed in the second direction.

[0008] As used in this specification, the singular forms "a," "an" and "the" include plural referents unless the context clearly dictates otherwise. Thus, for example, the term "a flow panel" is intended to mean a single flow panel or a combination of flow panels.

[0009] As used herein, the terms "normal," "perpendicular" and "orthogonal" generally describe a relationship between two directions of flow in which the two directions of flow intersect at substantially 90°. For example, a direction of flow is said to be perpendicular to another direction of flow when the two directions of flow intersect at an angle substantially equal to 90°. Thus, two direc-

tions of flow are considered as "substantially normal" when they are within five degrees of being perpendicular (i.e., within a range of 85 to 95 degrees).

[0010] FIG. 1 is a cross-sectional view of a portion of a heat exchanger assembly 140. The heat exchanger assembly 140 includes a first flow panel 150 and a second flow panel 151 that are coupled together to define a heat transfer passageway 170. The first flow panel 150 includes a first (or an inlet) portion 154 and a second (or a channel) portion 160. The inlet portion 154 defines an inlet flow passageway 155 within which a gas can flow in a first direction as denoted by the arrow AA. The arrow denoted as A_{in} represents the mass and/or direction of gas intake into the heat transfer assembly 140 via an air inlet opening 168. The inlet flow passageway 155 can have a wide variety of cross-sections (i.e., shapes) such as, for example, circular cross-section, elliptical cross-section, rectangular cross-section, and/or the like.

[0011] The channel portion 160 defines a set of microchannels 161 that is in fluid communication with the inlet flow passageway 155 and within which the gas can flow in a second direction as shown by the arrow BB, where the second direction BB is non-parallel to the first direction AA (e.g., where the direction of flow AA and the direction of flow BB are not oriented at substantially 0° or 180° with respect to each other), in this manner, the inlet portion 154 forms an internal manifold for supplying the gas flow to the microchannels 161. Similarly stated, the inlet portion 154 forms an internal manifold the gas within which can be heated via the cross flow of heat transfer medium M_{in} , as described herein.

[0012] Each microchannel in the set of microchannels 161 can be defined to have any suitable cross-sectional shape (e.g., circular cross-section, elliptical cross-section, rectangular cross-section, etc.) and can range in size between, for example, having a hydraulic diameter of about 10 μm and about 200 μm . Although described as being microchannels, in other embodiments, the cross-sectional area of the channels can have a hydraulic diameter of between about 254 μm (0.010 inches) and about 1.5 mm (0.060 inches) (i.e., the channels can be minichannels). In some embodiments, the set of microchannels 161 can include substantially identical microchannels (homogenous set of microchannels 161). In other embodiments, the set of microchannels 161 can include a set of heterogeneous microchannels 161 where the microchannels differ from each other in shape and/or size. In some embodiments, the cross-sectional area and/or shape of each microchannel in the set of microchannels 161 can be selected to maximize the surface area of each microchannel to maximize the heat transfer efficiency. The small features of the microchannels can enable and/or produce large surface areas on the microchannels such that the gas side of the heat exchanger assembly 140 can have an hA product (defined as the heat transfer coefficient of the gas x surface area of the microchannels 161) approximately equivalent to the hA product on the heat transfer medium side (as embodied

in the heat transfer passageway 170) thus maximizing heat transfer efficiency. Although not seen in FIG. 1, the second flow panel 151 can also include substantially similar internal structure as that of the first flow panel 150.

[0013] The first flow panel 150 is coupled to the second flow panel 151 to define a heat transfer passageway 170 within which a heat transfer medium (e.g., heated water, molted salt, molted metal, heated alumina particles, etc.) can be conveyed in a third direction (as denoted by the arrow M_{in}), where the third direction is opposite the direction of gas flow in the channel portion 160 (as denoted by the arrow BB) and orthogonal to the direction of gas flow in the inlet portion 154 (as denoted by the arrow AA). In this manner, the first flow panel 150 provides for a heat exchanger having a counter-flow portion (e.g., between the heat transfer passageway 170 and the microchannels 161 and a cross-flow portion (e.g., between the heat transfer passageway 170 and the inlet passageway 155. The inclusion of both a cross-flow portion and a counter-flow portion can facilitate improved heat transfer efficiency between the heat transfer medium and the compressed air (or gases) as compared to conventional heat exchanger designs. Additionally, the first flow panel 150 is coupled to the second flow panel 151 in such a manner that the heat transfer passageway 170 is fluidically isolated from the inlet flow passageways and the set of microchannels of both the first flow panel 150 and the second flow panel 151 by, for example, a thermally conductive side wall (e.g., a portion of the base member, not identified in FIG. 1, a cover or the like).

[0014] The arrow denoted as M_{out} represents the direction of heat transfer medium exit from the heat transfer assembly 140. Additionally, although the direction of the heat transfer medium M_{in} entering the heat transfer passageway 170 is shown as changing or turning, in other embodiments the heat transfer passageway 170 can be linear and/or devoid of any bends, turns or tortuous regions. For example, in some embodiments, the direction of travel of the heat transfer medium M_{in} to M_{out} can be a straight path for the travel of heat transfer medium through the heat transfer assembly 140. This configuration can facilitate the use of a non-fluidic (e.g., particulates, slurries or the like) heat transfer medium. Similarly stated, in some embodiments, the heat transfer medium (e.g., heated alumina particles) need not travel tortuous (internal) heat transfer pathways where there is a possibility of particles getting clogged within tortuous heat transfer pathway, where the use of high pressure gradients is needed, and the like. The directions of M_{in} and M_{out} shown in FIG. 1 with respect to the microchannels 161 and/or the inlet passageway 155 have been shown as an example only, and not a limitation. In other embodiments, M_{in} and M_{out} can assume a multitude of directions such as, for example, at substantially 60° with to the inlet flow passageway 155. It is to be noted that irrespective of the nature of the heat transfer medium, the heat transfer medium conveys through the heat transfer passageway 170 that is larger in size and structurally simpler than

the set of microchannels 161.

[0015] Although shown as including only two "flow panels", a heat exchanger can include any number of flow panels. For example, FIG. 2 is a perspective view of a heat exchanger assembly 240. The heat exchanger assembly 240 can be composed of a number of individual units or flow panels 250, as shown (only three are identified, for clarity). The heat exchanger assembly 240 is shown in FIG. 2 as having a cuboidal shape with a length "l", a width "w", and a height "h" as denoted. Alternatively, the heat exchanger assembly 240 can be cubical in shape where the length ("l"), the width ("w"), and the height ("h") are substantially identical. Further alternatively, the heat exchanger assembly 240 can be a rectangular prism. The heat exchanger assembly 240 includes a set of input openings 258 for the input of air (or other gases), a set of output openings 268 for the output of air (or other gases), each defined by one of the flow panels 250. The heat exchanger assembly 240 also includes a set of openings 273 defined by and/or between adjacent flow panels 250 for the intake of the heat transfer medium. The arrows denoted as A_{in} represents the direction of air or gas intake into the heat transfer assembly 240, and the arrows denoted as A_{out} represents the direction of air or gas exit from the heat transfer assembly 240. The arrow denoted as M_{in} represents the direction of intake of the heat transfer medium into the heat transfer assembly 240. It is to be noted that M_{in} denotes a direction of heat transfer medium intake that is substantially perpendicular to the top surface of the heat transfer assembly 240. Additionally, although not shown explicitly in FIG. 2, the heat transfer assembly 240 includes a substantially linear heat transfer passageway defined by and/or between adjacent flow panels 250. Thus, the path taken by the heat transfer medium inside the heat transfer assembly 240 can be free of curves, bends and/or tortuous features, thus facilitating a gravity-fed conveyance of the heat transfer medium. The heat exchanger assembly 240 can be constructed by a set of consecutive and substantially parallel flow panels 250 where two adjacent flow panels can define each opening 273 for the intake of the heat transfer medium. Each such flow panel can include an air or gas inlet portion, a microchannel portion and an air or gas outlet portion.

[0016] FIG. 3 is a schematic illustration of a power generation system within which any of the heat exchangers described herein can be used. The power generation system 300 includes a compressor 302, a heat exchanger assembly 340, optionally (as denoted by the dotted line) a combustor 303, and a turbine 304. The compressor 302 is a gas turbine compressor that increases the pressure of an input gas by reducing its volume. The compressor 302 can be, for example, a centrifugal compressor, a diagonal or mixed-flow compressor, an axial-flow compressor, a rotary screw compressor, a rotary vane compressor, and/or the like. Compressed gas can be sent from the compressor 302 to the heat exchanger assembly 340.

[0017] The heat exchanger assembly 340 can be similar to any of the heat exchanger assemblies shown and described herein, and can include a set of microchannels or minichannels that can receive the compressed gas sent by the compressor 302. Additionally, the heat exchanger assembly 340 can also include a set of input openings that can receive a heat transfer medium (e.g., heated water, molted salt, molted metal, heated alumina particles, etc.) in the direction shown by the arrow M_{in} . The heat transfer medium can be heated by, for example, concentrated solar radiation and can transfer heat by thermal conduction, thermal convection and/or thermal radiation to the compressed air or gas via the heat exchanger assembly 340. Upon completion of the heat exchange process, the heat transfer medium can exit the heat exchanger assembly 340 in the direction shown by the arrow M_{out} . The heat exchanger assembly 340 can use heated particles as the heat exchange medium, and the heat exchanger assembly 340 can include and/or be coupled to a particle auger and/or a particle hopper and/or a storage device for heated particles to collect, transfer and/or store the heated particles. The heated and compressed gas is sent from the heat exchanger assembly 340 to the turbine 304.

[0018] The turbine 304 can be a gas turbine, a steam turbine or any other suitable fluid power machine. In the turbine 304, the high-temperature compressed (i.e., high-pressure) gas expands down to the exhaust pressure of the turbine 304, thus producing a shaft work output in the process. The turbine 304 shaft work can be used to drive the compressor 302 and other devices (e.g., an electric generator to generate power) that may be coupled to the shaft of the turbine 304 to produce power. The energy that is not used for shaft work can exit the turbine 304 as exhaust gases that typically have either a high temperature or a high velocity.

[0019] The heated and compressed gas can optionally be sent from the heat exchanger assembly 340 to a combustor 303 for additional heating steps. The combustor 303 can add additional energy (i.e., heat) to the (already) heated gas by injecting fuel (e.g., kerosene, jet fuel, propane, natural gas, etc.) into the heated and compressed gas and igniting the compressed gas so that the combustion generates a high-temperature flow of compressed gas. The new higher temperature of the compressed gas can allow for increased efficiency for power generation. However, temperatures achieved can be limited by the ability of the material of the gas turbine engine (e.g., steel, nickel, ceramic, etc.) to withstand high temperatures and stresses. The combustor 303 can then send the high-temperature high-pressure gas to the turbine 304 where the high-temperature high-pressure gas expands down to the exhaust pressure of the turbine 304 to producing a shaft work output as described above.

[0020] FIG. 4 is a perspective view of a system including one or more heat exchanger assemblies with associated air manifolds and piping, according to an embodiment of the invention. It is to be noted that although not

clearly visible in FIG. 4, the system 400 includes four heat exchanger assemblies (one of which is labeled as 440, see e.g., the dashed line in FIG. 4 and the assembly shown in FIG. 6) contained within the multiple air manifolds, piping and particle feeders. The system 400 includes a heat transfer medium inlet member 416, a heat transfer medium outlet member 417, an air manifold header assembly 420, a housing 422 that contains the heat exchanger assemblies 440, an air inlet pipe 412 (from a compressor), an air outlet pipe 413 (to a turbine), four air inlet members 427 and four air outlet members 428. The arrow denoted as M_{in} represents the direction of heat transfer medium intake into the system 400, and the arrow denoted as M_{out} represents the direction of heat transfer medium exit from the system 400. The arrow denoted as A_{in} represents the direction of air or gas intake into the system 400, and the arrow denoted as A_{out} represents the direction of air or gas exit from the system 400. The manifold header assembly 420 houses the four air inlet members 427 and the four air outlet members 428. Compressed air or gas flows into each of the heat exchanger assemblies 440 (contained in the system 400) from a compressor via the air inlet pipe 412 and corresponding air inlet members 427 that are fluidically coupled to the air inlet pipe 412.

[0021] In some embodiments, the heat transfer medium can be, for example, heated particles such as alumina particles. In such configurations, the heat transfer medium inlet member 416 can be coupled to a particle hopper and/or a particle storage device to obtain and/or store the heated particles. FIG. 4 shows that the heat transfer medium flows through the system 400 in a substantially linear direction with no tortuous paths taken by the heat transfer medium inside the system 400. In this manner, the likelihood of system clogging, flow loss or the like is minimized. This configuration also facilitates a "gravity feed" system for the heat transfer medium. As the heat exchange medium flows through the system 400, it can transfer heat to the compressed air or gas that enters the system 400 from a compressor through the air inlet pipe 412. As described herein, each heat exchanger assembly 440 contained in the system 400 can have a set of microchannels through which the compressed air or gas can travel and thus be heated by the heat exchange medium via either thermal conduction, thermal convection and/or thermal radiation. The heated and compressed air or gas can exit each of the heat exchanger assemblies 440 through their associated air outlet members 428 and can exit the system 400 via the air outlet pipe 413 (which is fluidically coupled to the four air outlet members 428) that can carry the heated and compressed air to a turbine.

[0022] FIG. 5 is a perspective view of the air manifold header assembly shown in FIG. 4. The air manifold header assembly 420 is shown with respect to one heat exchanger assembly (and not four heat exchanger assemblies). The air manifold header assembly 420 includes a housing 422 that can contain a heat exchanger assembly, a first (inlet) opening 423 that can be coupled to the

heated particle inlet member 416, a second (outlet) opening 424 that couples to the heated particle outlet member 417, air inlet members 427 and air outlet members 428. The housing 422 defines an interior volume 425 that can house a heat exchanger assembly with internal microchannels. The arrow denoted as M_{in} represents the direction of heat transfer medium intake into the air manifold header assembly 420, and the arrow denoted as M_{out} represents the direction of heat transfer medium exit from the air manifold header assembly 420. The arrow denoted as A_{in} represents the direction of air or gas intake into the air manifold header assembly 420, and the arrow denoted as A_{out} represents the direction of air or gas exit from the air manifold header assembly 420. Compressed air or gas from a compressor can enter and be distributed in the microchannels of a heat exchanger assembly located in the interior volume 425 from the air inlet members 427 and get heated by the flowing heat exchange medium. Heated air can pass from the heat exchanger assembly via the air outlet members 428 into piping that can deliver the heated compressed air to a gas turbine.

[0023] FIG. 6 is a perspective view of a heat exchanger assembly 240 disposed within the system shown in FIG. 4. The heat exchanger assembly 440 is shown in FIG. 6 without any of the air manifold assembly or particle feeder assembly. The heat exchanger assembly 440 is shown in FIG. 6 as having a cuboidal shape with a length "l", a width "w", and a height "h". In some embodiments, the length l can be approximately 0.61 m (24 inches), the width w can be approximately 0.61 m (24 inches) and the height h can be approximately 0.58 m (22.7 inches). In other embodiments, the heat exchanger assembly 440 can be cubical in shape where the magnitudes of the length ("l"), the width ("w"), and the height ("h") are substantially identical. The heat exchanger assembly 440 includes a set of flow panels 450 (see e.g., FIG. 8, which identifies two panels 450) that are coupled and/or bonded together to provide the performance and/or structure described herein.

[0024] Each of the flow panels 450 defines an inlet opening 458 for the inlet of air and/or other gases, and an outlet opening 468 for the output of air and/or other gases. Thus, the heat exchanger assembly 440 defines a set of inlet openings 458 and a set of outlet openings 468. The heat exchanger assembly further defines a set of openings 473 and heat transfer passageways 470 for the intake and conveyance of the heat transfer medium. The arrow denoted as A_{in} represents the direction of air or gas intake into the heat transfer assembly 440, and the arrow denoted as A_{out} represents the direction of air or gas exit from the heat transfer assembly 440. The arrow denoted as M_{in} represents the direction of intake of the heat transfer medium into the heat transfer assembly 440. It is to be noted that M_{in} denotes a direction of heat transfer medium intake that is substantially perpendicular to the top surface of the heat transfer assembly 440. In other embodiments, the direction of heat transfer medium intake and conveyance can be different than shown in

FIG. 6 and can involve substantially tortuous pathways within the heat exchanger assembly 440.

[0025] As shown in FIG. 7, the heat exchanger assembly 440 can be constructed by coupling together a set of consecutive and substantially parallel flow panels 450 where two adjacent flow panels can define each opening 473 and the heat transfer passageways 470 for the intake and conveyance of the heat transfer medium. Additionally, each opening 473 for the intake of the heat transfer medium leads to a heat transfer passageway 470 that is substantially linear with no tortuous paths taken by the heat transfer medium inside the heat transfer assembly 440. In some embodiments, the cross-sectional shape of heat transfer passageways 470 can be substantially rectangular. In some embodiments, the heat transfer passageways 470 maintain their rectangular cross-section consistently through the height of the heat exchanger assembly 440. In other embodiments, the cross-section of the heat transfer passageways 470 can be heterogeneous through the height ("h") of the heat transfer assembly 440. For example, in such configurations, the heat transfer passageways 470 can have a first cross-sectional profile (e.g., shape, size, etc.) near the entrance of the heat transfer passageways 470 where the heat transfer medium enters the heat transfer assembly 440, and a second cross-sectional profile near the end of the heat transfer passageways 470 where the heat transfer medium exits the heat transfer assembly 440, where the second cross-sectional profile is different from the first cross-sectional profile.

[0026] Moreover, as shown, the flowpath of the heat transfer medium through the heat transfer passageways 470 can be substantially linear through the height of the heat exchanger assembly 440. As described above, this configuration facilitates a "gravity feed" system for the heat transfer medium through the system 400.

[0027] FIG. 8 is an enlarged view of the top portion of the heat exchanger assembly identified as the region Z in FIG. 7, and shows the details of the coupling between adjacent flow panels 450. In some embodiments, the individual flow panels 450 can be coupled together through diffusion bonding. Diffusion bonding operates on the principle of solid-state diffusion, wherein the atoms of the two solid, metallic flow panels intermingle over time under elevated temperature. Diffusion bonding is typically implemented by applying both high pressure and high temperature to the flow panels that are being welded together. In other embodiments, the individual flow panels 450 can be coupled together through other techniques such as, for example, liquid fusion, adhesive bonding, ultraviolet (UV) bonding, and/or the like.

[0028] In particular, the individual heat transfer passageways 470 and/or flow panels 450 are separated from each other by metallic spacers 472 that are solid surfaces that have no internal air passages. The metallic spacers 472 can be coupled to the individual flow panels 450 via diffusion bonding. In some embodiments, the direction of flow of the heat transfer medium in the heat transfer

passageways 470 can be along the same direction of flow of the compressed air or gases in the microchannels. In other embodiments, the direction of flow of the heat transfer medium in the heat transfer passageways 470 can be opposite the direction of flow of the compressed air or gases in the microchannels (counter-flow configuration).

[0029] Referring to FIGS. 9 and 10, which are cross-sectional views of a flow panel 450, each flow panel can include a gas inlet portion 454, a microchannel portion 460 and a gas outlet portion 464. Compressed air or gases can enter the heat transfer assembly 440 via the set of inlet openings 458 and can travel substantially perpendicularly to the inlet direction (i.e., upwards) through a set of microchannels 461 of the microchannel portion 460, where the compressed air or gases are heated by the heat transfer medium. Heated (and compressed) air or gas can flow out of the heat transfer assembly 440 via the set of outlet openings 468. The microchannels 461 can be formed by, for example, electrochemically etching a base member 452 of the flow panels and diffusion bonding to cover the base member (i.e., to form a boundary for the microchannels), as described in greater detail in relation to FIGS. 9-12. The heat transfer passageways 470 defined between adjacent flow panels 450 can be larger and less complex in structure than the microchannels 461 through which the compressed air or gases flow. The heat transfer passageways 470 are fluidically isolated from the air (or gasses) passing through the microchannels 461 by cover sheets 442 and 443 (discussed in greater detail in relation to FIG. 11). In this manner, the heat exchanger assembly 440 can provide an efficient and compact mechanism by which heat from a heat transfer medium (e.g., alumina particles) is transferred to compressed air or other gas that enters the heat exchanger assembly 440 via the set of inlet openings 458.

[0030] Specifically, FIG. 9 is a cross sectional view of a flow panel taken along the line X-X in FIG. 8. The flow panel 450 is fabricated from a base member 452, a first cover 442 (FIG. 11) and a second cover 443 (FIG. 11). The flow panel 450 defines an inlet opening 458 through which a first portion of compressed air or gas can enter the flow panel 450 in a first direction as shown by the arrow marked A_{in} . After entering the flow panel 450, the inlet air or gas passes through the inlet flow portion 454 (or the first flow portion 454) that defines the inlet flow passageway as shown by the arrow labeled 455. The inlet flow portion 454 includes a set of flow structures 456 and 457 within the inlet flow passageway 455 that can produce a spatially uniform air flow within the inlet flow passageway 455. Such flow structures can be, for example, three-dimensional (3D) pedestals or protrusions that are electrochemically etched into the base member 452 and help to create flow restriction orifices to cause uniformity of flow distribution within the inlet flow passageway 455 and/or the microchannels 461. More particularly, as shown in FIG. 10 which is an enlarged view a portion of the flow panel marked as region Z in FIG. 9, the flow

structures 456 can be "staggered" or aligned in offset rows to provide a curved or tortuous path through which the intake air A_{in} flows, which promotes a uniform flow. The flow structures are described in more detail in relation to FIG. 12 which is a cross sectional view of the inlet flow portion 454 of the flow panel 450 taken along the line Y-Y.

[0031] Referring now to FIG. 12, the inlet flow portion 454 includes a base member 452, a first cover 442 and a second cover 443. A first surface 475 of the base member 452 is coupled to the first cover 442, and a second surface 476 of the base member 452 is coupled to the second cover 443. The set of flow structures 456 are fabricated into the base member 452. Thus, the covers 442 and 443 define a boundary of inlet flow passageway 455. Similarly stated, the covers 442 and 443 capture and direct the flow of the compressed air or gases within the inlet flow portion 454. As described above, the set of flow structures 456 within the inlet flow portion 454 can produce a spatially uniform air flow within the inlet flow portion 454. Such flow structures can be, for example, pedestals or protrusions that can cause uniformity of flow distribution in the inlet flow portion 454 and the microchannels 461, and also offer structural rigidity to the inlet flow portion 454. The flow structures have been shown in FIG. 12 as spanning the width of the inlet flow portion of the flow panel (see arrow denoted as "w"). In other embodiments, however, the flow structures 456 may not span the entire width (w) of the inlet flow portion 454 and can be a heterogeneous set of flow structures 456 with a variety of different shapes (cross sections) and sizes. Such flow structures 456 and 457 can be, for example, cuboidal, cubic or cylindrical structures that are electrochemically etched into the base member 452. In some embodiments, the flow structures 456 can be a uniform array of flow structures 456 spread uniformly across the inlet flow portion 454. In other embodiments, the flow structures 456 can be a non-uniform array of flow structures, with larger flow structures (e.g., flow structures labeled as 457 in FIG. 10) being concentrated at the entrance of the inlet opening 458 (as shown in FIG. 10) and/or at the entrance of the channel portion 460 (as shown in FIG. 10) to create flow restriction orifices to cause uniformity of flow distribution to the microchannels 461 (as shown in FIG. 10). In some embodiments, the flow structures 456 and/or 457 can be electrochemically etched in the sheet metal of the base member 452. In other embodiments, the flow structures 456 and/or can be fabricated using methods other than electrochemical etching such as, for example, chemical etching (lithography, molding, and electroplating - LIGA), bulk micromachining, sacrificial etching by surface micromachining, stereolithography, and/or the like.

[0032] The compressed air or gases can then flow through the channel portion 460 (i.e., a second flow portion 460) that defines a set of microchannels 461 in fluid communication with the inlet flow passageway 455. As shown, the gases flow within the microchannels 461 in a second direction (as seen by the arrow 462 in FIGS. 9

and 10), where the second direction is nonparallel to the first direction. In particular, as shown, the second direction is substantially normal to the first direction.

[0033] Each side of the flow panel 450 includes a set of microchannels (that is adjacent a corresponding heat flow passageway). Referring to FIG. 11, which shows a cross sectional view of the channel portion 460 of the flow panel 450 taken along the line X-X, the channel portion of the flow panel 450 includes the base member (e.g., a sheet of metal) 452, the first cover 442, and the second cover 443. The first surface 475 of the base member 452 defines a first set of microchannels 461a within which a first portion of compressed air or gas can flow in a first direction. The second surface 476 of the base member defines a second set of microchannels 461b within which a second portion of compressed air or gas can flow in a first direction. The base member 452 can be any suitable material (e.g., a metal sheet) and can have any suitable size (e.g., approximately 200 μm (0.08 inch) thick). The microchannels 461a and 461b can be etched within each side of the base member 452. The covers 442 and 443 are channel cover sheets (approximately 41 μm or 0.016 inch thick) made of, for example, high temperature resistant Co or Ni alloys that are diffusion bonded to the non-etched region of the base member (sheet metal) 452. The covers 442 and 443 cap the microchannels 461 and capture and direct the flow of the compressed air or gases within the microchannels 461 and also separates the compressed air or gas flowing in the microchannels 461 from the heat transfer medium (e.g., alumina particles) flowing through the heat transfer passageway 470. The first cover 442 is coupled to the first surface 475 via diffusion bonding to form a first boundary for the first set of microchannels 461a, and the second cover 443 is coupled to the second surface 476 via diffusion bonding to form a boundary for the second set of microchannels 461b.

[0034] The microchannels 461 are shown in FIG. 11 to have uniform cross-sectional profile and periodicity. However, in other embodiments, the microchannels 461 may not have uniform cross-sectional profiles (e.g., a first set of microchannels can have a rectangular cross-section and a second set of microchannels can have a circular cross-section) and can also have non-uniform periodicity (e.g., having progressively higher periodicity from the left towards the right in reference to FIG. 11). In yet other embodiments, fabrication methods other than electrochemical etching may be employed to fabricate the set of microchannels 461 (e.g., chemical etching (lithography, molding, and electroplating - LIGA)), bulk micromachining, sacrificial etching by surface micromachining, stereolithography, etc.). The compressed air or gases flowing in the set of microchannels 461 is heated by the heat transfer medium flowing through the heat transfer passageway 470 via thermal conduction, convection and/or radiation.

[0035] Following heating of the compressed air or gases in the microchannels 461 of the channel portion 460,

the heated and compressed air (or gases) passes into the outlet flow portion 464 that defines an outlet flow passageway as denoted by the arrow 465. The outlet flow passageway 465 defines a third direction of flow, where the third direction of flow is opposite the first direction of flow (i.e., the direction of flow in the inlet flow passageway 455). The outlet flow portion 464 also includes a set of flow structures 466 and 467 within the outlet flow passageway 465 that produces a spatially uniform air flow within the outlet flow passageway 465. As in the case of the input passageway flow structures 456 and 457, in some embodiments, the flow structures 466 and 467 can be a uniform array of flow structures 466 and 467. In other embodiments, the flow structures 466 and 467 can be a non-uniform array of flow structures 466 and 467. The flow structures 466 and 467 can also offer structural rigidity to the outlet flow portion 464 and the channel flow portion 460. The heated and compressed air (or gases) can exit the flow panel 450 via the outlet opening 468 along the direction shown by the arrow A_{out} and pass on to a turbine where the heated and compressed air can cool and expand to generate power.

[0036] The heat transfer medium flows into the flow panel 450 in the direction denoted by the arrow M_{in} . It is to be noted that M_{in} denotes a direction of heat transfer medium intake that is substantially perpendicular to the inlet flow passageway 455 and/or the outlet flow passageway 465. The direction of travel of the heat transfer medium M_{in} to M_{out} (see FIG. 6) can be a straight path for the travel of heat transfer medium through the flow panel 450. This configuration can facilitate the use of a non-fluidic (e.g., particulates, slurries or the like) heat transfer medium. Similarly stated, in some embodiments, the heat transfer medium (e.g., heated alumina particles) need not travel tortuous (internal) heat transfer pathways where there is a greater likelihood of particles getting clogged within tortuous heat transfer pathways. The heat transfer medium can also be, for example, high temperature capable liquids such as molten salts. As the heat transfer medium is conveyed through the heat transfer passageways (e.g., via heat transfer passageways 470 shown in FIG. 8) that are in close proximity to the microchannels 461, the compressed air or gases are heated by the heat transfer medium via conduction, convection and/or radiation. The speed of the flow of the heat transfer medium in the heat transfer passageways and/or the speed of the flow of the compressed air or gases in the set of microchannels 461 can be adjusted to obtain the desired efficiency and/or characteristics of heat transfer from the heat transfer medium to the compressed air or gases.

[0037] In other embodiments, the direction of heat transfer medium intake into the flow panel 450 can be oriented in other non-perpendicular angles with respect to the inlet flow passageway 455. The small feature size of the each microchannel in the set of microchannels 461 enable large surface areas on the microchannels 461 that can increase heat transfer efficiency, as discussed

above. Hence, the air (or gas) side hA product (where the hA product is defined as the product of the heat transfer co-efficient of the air (or gas) $\times$ by the surface area of each microchannel) can be approximately equal to the hA product on the heat transfer medium side to allow for maximum heat transfer efficiency from the heat transfer medium to the compressed air or gas.

[0038] In some embodiments, the heat transfer assembly 440 can be used for solar thermal power generation. In such configurations, the inlet compressed air or gases can enter the heat transfer assembly 440 along the path showed by the arrow marked A_{in} from a compressor, can be heated by the heat transfer assembly 440 (e.g., by using solar thermal power heated heat transfer medium), exit the heat transfer assembly 440 along the path showed by the arrow marked A_{out} , and be expanded in a gas turbine to generate power that can drive, for example, an electrical generator.

[0039] In other embodiments, the heat transfer assembly 440 can also be used to create synthetic gas (e.g., syngas that is a mixture of hydrogen and carbon monoxide) for synthetic fuel generation (i.e., fuels generated via a Fischer-Tropsch based process). In such configurations, where synthetic fuel is produced via solar power heated heat exchange medium, the internal microchannel passages (e.g., microchannels 461) and/or the internal heat exchanger passageways 470 can be coated with a suitable catalyst (e.g., platinum), in such embodiments, the heat transfer assembly 440 typically operates at temperatures of approximately greater than 1000°C and thus is fabricated with high temperature capable superalloys such as, for example, Haynes® 230 alloy. The heat transfer assembly 440 shown in FIG. 6 typically has a 97% thermal efficiency and a 2% pressure loss.

[0040] FIG. 13 is a flow chart illustrating a method for fabricating a heat transfer flow panel, according to an embodiment. The method 500 includes producing a first flow passageway in a first portion of a first base member, where the flow passageway defines a first direction of flow, at 502. As described the above, the first base member can be associated with a heat exchanger assembly, and the first flow passageway can be fabricated by electrochemically etching selected regions of the first portion of the first base member. As described above, the first flow passageway can include a set of flow structures that are fabricated into the first portion of the base member via electrochemical etching or other means.

[0041] At 504, a set of microchannels is produced in a second portion of the first base member such that each of the microchannels in the set of microchannels is in fluid communication with the flow passageway. The set of microchannels defines a second direction of flow being nonparallel to the first direction of flow. As described above, in some embodiments, the set of microchannels can be produced or fabricated in the base member of the flow panel via electrochemical etching. In other embodiments, the set of microchannels can be produced or fabricated in the base member of the flow panel via other

microfabrication techniques such as, for example, chemical etching (lithography, molding, and electroplating - LIGA), bulk micromachining, sacrificial etching by surface micromachining, stereolithography, and/or the like.

As described above, in some embodiments, the set of microchannels can have uniform cross-sectional size, shape and periodicity. However, in other embodiments, the microchannels 461 may not have uniform cross-sectional shapes, sizes and can also have non-uniform periodicity.

[0042] At 506, a cover is coupled to the first base member to form a first flow panel. As described above, the first base member can be a metal sheet that is etched with microchannels. The cover can be made of high temperature resistant Co or Ni alloys that are diffusion bonded to the non-etched region of the first base member. These cover sheet can cap the microchannels and capture and direct the flow of the compressed air or gases within the microchannels. Additionally, the cover also separates the compressed air or gas flowing in the microchannels from the heat transfer medium (e.g., alumina particles) that is flowing through the heat transfer passageway. Optionally, at 508 as denoted by the dashed box, the steps 502-506 can be repeated with a second base member to produce a second flow panel.

[0043] At 510, the first flow panel is coupled to a second flow panel to define a heat transfer passageway within which a heat transfer medium can be conveyed in a third direction, where the third direction is opposite the first direction of flow, and the heat transfer passageway is fluidically isolated from the flow passageway and the set of microchannels by the cover. As described above, in some instances, the direction of flow of heat transfer medium in the heat transfer passageways will be along the same direction as the flow of compressed air or gases within the microchannels. In other instances, the direction of flow of heat transfer medium in the heat transfer passageways will be opposite to the direction of flow of compressed air or gases within the microchannels (counter-flow configuration). As described above, in some embodiments, the individual flow panels can be coupled together through diffusion bonding that is typically implemented by applying both high pressure and high temperature to the two flow panels that are being welded together. In other embodiments, the individual flow panels can be coupled together through other techniques such as, for example, liquid fusion, adhesive bonding, ultra-violet (UV) bonding, and/or the like. As described above, the heat transfer medium flows through the heat transfer passageways that are typically larger and less complex in structure than the microchannels through which the compresses air or gases flow.

[0044] The embodiments (e.g., the microchannel based heat exchanger (MCHX)) discussed in herein allows the fabrication of a solar thermal based heat exchanger that is approximately one tenth the volume of a shell and tube heat exchanger with equivalent heat exchanger performance parameters (e.g., compressed gas

pressure loss, thermal efficiency, etc.). It is determined that for a specific gas turbine, a shell and tube heat exchanger would have a volume of 10.5 m³ (370 ft³) with a specified pressure drop and thermal efficiency. For the same gas turbine, a microchannel heat exchanger as discussed in FIGS. 1-13 would occupy a volume of 0.91 m³ (32 ft³) for a comparable pressure drop and thermal efficiency. Hence, it is anticipated that a microchannel heat exchanger would cost significantly less than a traditional shell and tube heat exchanger due to the significant size differences. A further advantage is that the height of any of the heat exchangers described herein can be about 0.61 m (two feet) while the height of a traditional shell and tube heat exchanger is about 10.4 m (34 ft). Because the heat transfer medium (e.g., alumina particles) are often fed from a storage tank, the smaller height of the MCHX allows the heated particle storage tank to be significantly closer to the ground which significantly reduces cost and complexity relative to the shell and tube heat exchanger.

[0045] While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not of limitation. Likewise, the various diagrams may depict an example architectural or other configuration for the invention, which is done to aid in understanding the features and functionality that can be included in the invention. The invention is not restricted to the illustrated example architectures or configurations, but can be implemented using a variety of alternative architectures and configurations. Additionally, although the invention is described above in terms of various embodiments and implementations, it should be understood that the various features and functionality described in one or more of the individual embodiments are not limited in their applicability to the particular embodiment with which they are described, but instead can be applied, alone or in some combination, to one or more of the other embodiments of the invention, whether or not such embodiments are described and whether or not such features are presented as being a part of a described embodiment. Thus the breadth and scope of the present invention should not be limited by any of the above-described embodiments.

[0046] While various embodiments have been described above, it should be understood that they have been presented by way of example only, and not limitation. Where methods described above indicate certain events occurring in certain order, the ordering of certain events may be modified. Additionally, certain of the events may be performed concurrently in a parallel process when possible, as well as performed sequentially as described above.

Claims

1. An apparatus (440), comprising:

a first flow panel (450) including a base member (452), a first cover (442) and a second cover (443), a first surface (475) of the base member defining a first plurality of microchannels (461a) within which a first portion of a gas can flow in a first direction, a second surface (476) of the base member defining a second plurality of microchannels (461b) within which a second portion of the gas can flow in a first direction, the first cover coupled to the first surface to form a boundary for the first plurality of microchannels, the second cover coupled to the second surface to form a boundary for the second plurality of microchannels, the first flow panel coupled to a second flow panel (450) to define a first heat transfer passageway (470) between the first cover of the first flow panel and a cover of the second flow panel, within which a heat transfer medium can be conveyed in a second direction, the second direction opposite the first direction, the first flow panel coupled to a third flow panel (450) to define a second heat transfer passageway (470) between the second cover of the first flow panel and a cover of the second flow panel, within which the heat transfer medium can be conveyed in the second direction.

2. The apparatus of claim 1, wherein the first flow panel includes a first flow portion (454) and a second flow portion (460), the first flow portion defining a flow passageway (455) within which the first portion of the gas and the second portion of the gas can flow in a third direction, the third direction nonparallel to the first direction, the second flow portion defining the first plurality of microchannels and the second plurality of microchannels.
3. The apparatus of claim 2, wherein the first flow portion includes a plurality of flow structures (456, 457) within the flow passageway, the plurality of flow structures configured to produce a uniform flow between at least one of the first plurality of microchannels or the second plurality of microchannels.
4. The apparatus of claim 2, wherein the third direction is substantially normal to the first direction.
5. The apparatus of claim 1, wherein the first flow panel and the second flow panel are configured such that the first heat transfer passageway is substantially linear.
6. The apparatus of claim 1, wherein the first flow panel is planar such that a cross-sectional shape of the heat transfer passageway is substantially rectangular.

Patentansprüche

1. Vorrichtung (440), die Folgendes umfasst:

eine erste Strömungsplatte (450), die ein Basiselement (452), eine erste Abdeckung (442) und eine zweite Abdeckung (443) einschließt, wobei eine erste Fläche (475) des Basiselements eine erste Mehrzahl von Mikrokanälen (461a) definiert, innerhalb derer ein erster Anteil eines Gases in einer ersten Richtung strömen kann, wobei eine zweite Fläche (476) des Basiselements eine zweite Mehrzahl von Mikrokanälen (461b) definiert, innerhalb derer ein zweiter Anteil des Gases in einer ersten Richtung strömen kann, wobei die erste Abdeckung mit der ersten Fläche gekoppelt ist, um eine Begrenzung für die erste Mehrzahl von Mikrokanälen zu bilden, wobei die zweite Abdeckung mit der zweiten Fläche gekoppelt ist, um eine Begrenzung für die zweite Mehrzahl von Mikrokanälen zu bilden, wobei die erste Strömungsplatte mit einer zweiten Strömungsplatte (450) gekoppelt ist, um einen ersten Wärmeübertragungsdurchgang (470) zwischen der ersten Abdeckung der ersten Strömungsplatte und einer Abdeckung der zweiten Strömungsplatte zu definieren, innerhalb dessen ein Wärmeübertragungsmittel in einer zweiten Richtung befördert werden kann, wobei die zweite Richtung entgegengesetzt zu der ersten Richtung ist, wobei die erste Strömungsplatte mit einer dritten Strömungsplatte (450) gekoppelt ist, um einen zweiten Wärmeübertragungsdurchgang (470) zwischen der zweiten Abdeckung der ersten Strömungsplatte und einer Abdeckung der zweiten Strömungsplatte zu definieren, innerhalb dessen das Wärmeübertragungsmittel in der zweiten Richtung befördert werden kann.

2. Vorrichtung nach Anspruch 1, wobei die erste Strömungsplatte einen ersten Strömungsabschnitt (454) und einen zweiten Strömungsabschnitt (460) einschließt, wobei der erste Strömungsabschnitt einen Strömungsdurchgang (455) definiert, innerhalb dessen der erste Anteil des Gases und der zweite Anteil des Gases in einer dritten Richtung strömen können, wobei die dritte Richtung nicht parallel zu der ersten Richtung ist, wobei der zweite Strömungsabschnitt die erste Mehrzahl von Mikrokanälen und die zweite Mehrzahl von Mikrokanälen definiert.

3. Vorrichtung nach Anspruch 2, wobei der erste Strömungsabschnitt eine Mehrzahl von Strömungsstrukturen (456, 457) innerhalb des Strömungsdurchgangs einschließt, wobei die Mehrzahl von Strömungsstrukturen dafür konfiguriert sind, eine gleichförmige Strömung zwischen mindestens einer der

ersten Mehrzahl von Mikrokanälen oder der zweiten Mehrzahl von Mikrokanälen zu erzeugen.

4. Vorrichtung nach Anspruch 2, wobei die dritte Richtung im Wesentlichen senkrecht zu der ersten Richtung ist.

5. Vorrichtung nach Anspruch 1, wobei die erste und die zweite Strömungsplatte derart konfiguriert sind, dass der erste Wärmeübertragungsdurchgang im Wesentlichen linear ist.

6. Vorrichtung nach Anspruch 1, wobei die erste Strömungsplatte eben ist, so dass eine Querschnittsform des Wärmeübertragungsdurchgangs im Wesentlichen rechteckig ist.

Revendications

1. Appareil (440), comprenant :

un premier panneau d'écoulement (450) incluant un élément de base (452), une première couverture (442) et une deuxième couverture (443), une première surface (475) de l'élément de base définissant une première pluralité de micro-canaux (461a) dans lesquels une première partie d'un gaz peut s'écouler dans une première direction, une deuxième surface (476) de l'élément de base définissant une deuxième pluralité de micro-canaux (461b) dans lesquels une deuxième partie du gaz peut s'écouler dans une première direction, la première couverture étant couplée à la première surface pour former une limite pour la première pluralité de micro-canaux, la deuxième couverture étant couplée à la deuxième surface pour former une limite pour la deuxième pluralité de micro-canaux, le premier panneau d'écoulement étant couplé à un deuxième panneau d'écoulement (450) pour définir un premier passage de transfert de chaleur (470) entre la première couverture du premier panneau d'écoulement et une couverture du deuxième panneau d'écoulement, dans lequel un agent de transfert de chaleur peut être amené dans une deuxième direction, la deuxième direction étant opposée à la première direction, le premier panneau d'écoulement étant couplé à un troisième panneau d'écoulement (450) pour définir un deuxième passage de transfert de chaleur (470) entre la deuxième couverture du premier panneau d'écoulement et une couverture du deuxième panneau d'écoulement, dans lequel l'agent de transfert de chaleur peut être amené dans une deuxième direction.

2. Appareil selon la revendication 1, dans lequel le premier panneau d'écoulement inclut une première partie d'écoulement (454) et une deuxième partie d'écoulement (460), la première partie d'écoulement définissant un passage d'écoulement (455) dans lequel la première partie du gaz et la deuxième partie du gaz peuvent s'écouler dans une troisième direction, la troisième direction n'étant pas parallèle à la première direction, la deuxième partie d'écoulement définissant la première pluralité de micro-canaux et la deuxième pluralité de micro-canaux. 5 10
3. Appareil selon la revendication 2, dans lequel la première partie d'écoulement inclut une pluralité de structures d'écoulement (456, 457) à l'intérieur du passage d'écoulement, la pluralité de structures d'écoulement étant configurée pour produire un écoulement uniforme entre au moins l'une de la première pluralité de micro-canaux et de la deuxième pluralité de micro-canaux. 15 20
4. Appareil selon la revendication 2, dans lequel la troisième direction est sensiblement perpendiculaire à la première direction. 25
5. Appareil selon la revendication 1, dans lequel le premier panneau d'écoulement et le deuxième panneau d'écoulement sont configurés de sorte que le premier passage de transfert de chaleur est sensiblement linéaire. 30
6. Appareil selon la revendication 1, dans lequel le premier panneau d'écoulement est plan, de sorte qu'une forme de section transversale du passage de transfert de chaleur est sensiblement rectangulaire. 35

40

45

50

55

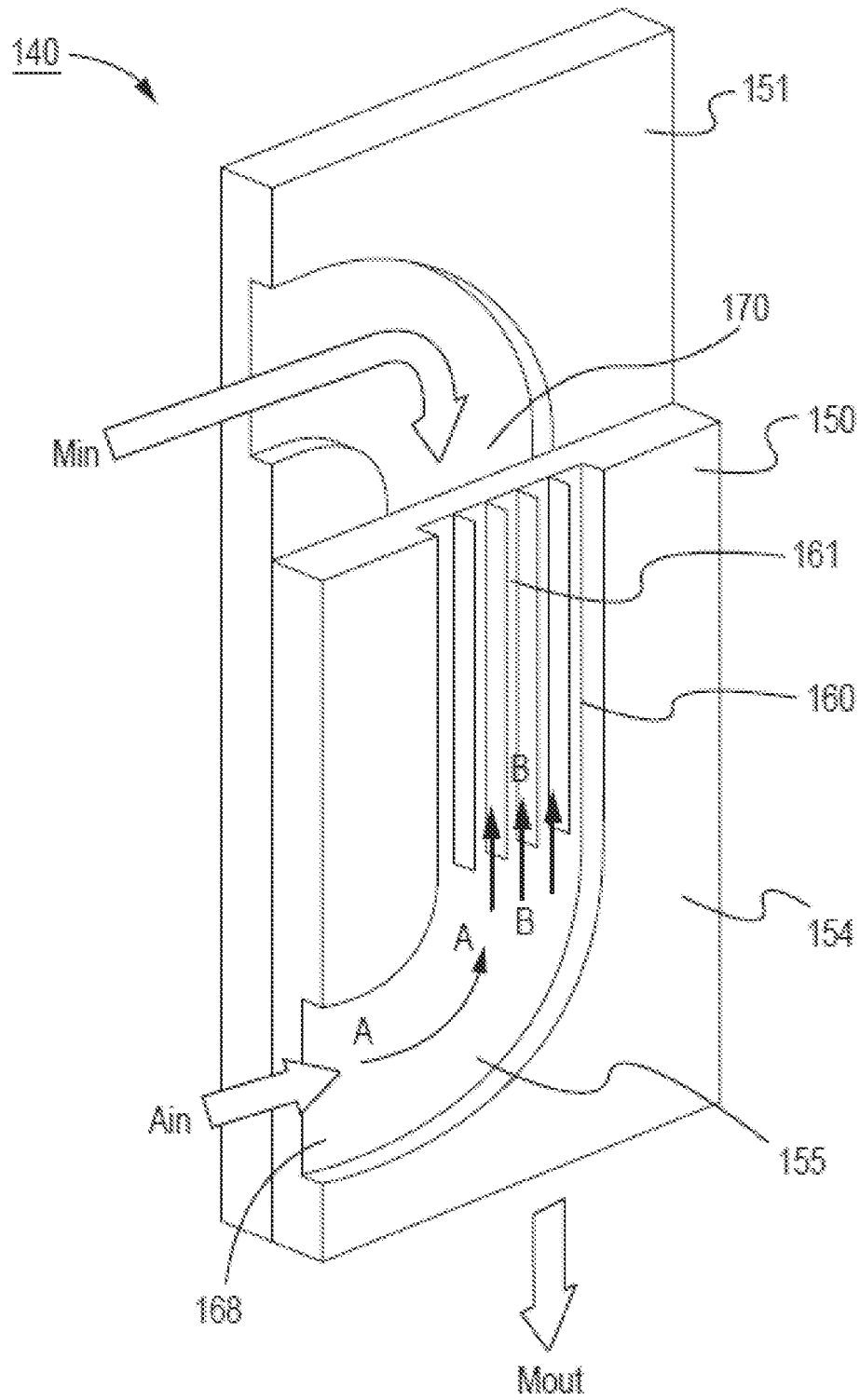


FIG.1

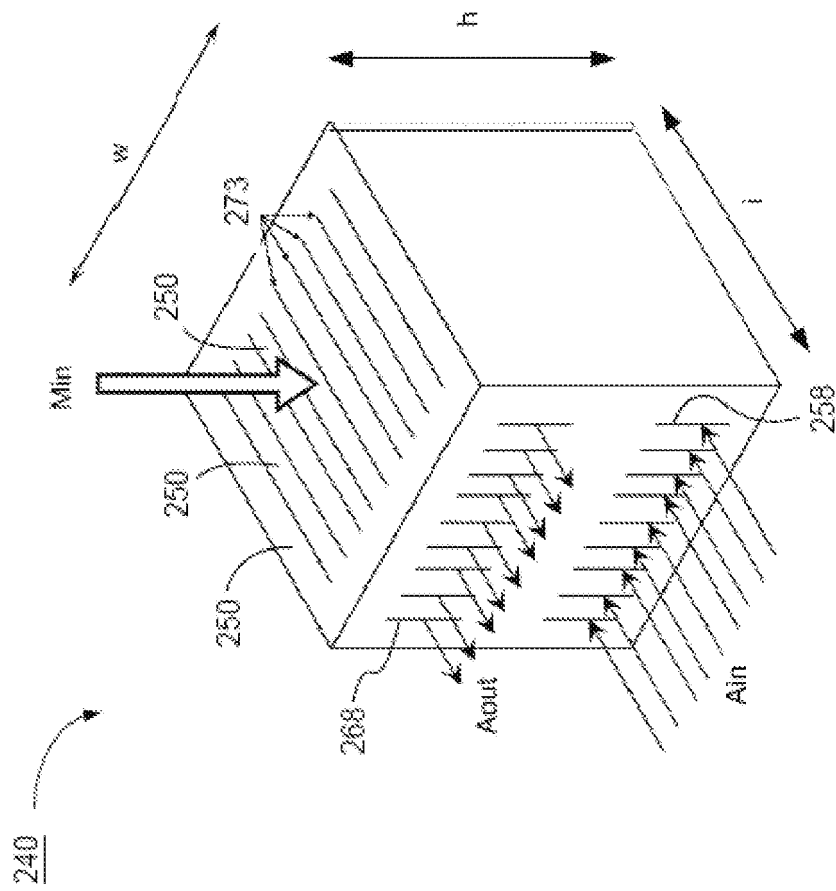


FIG.2

300

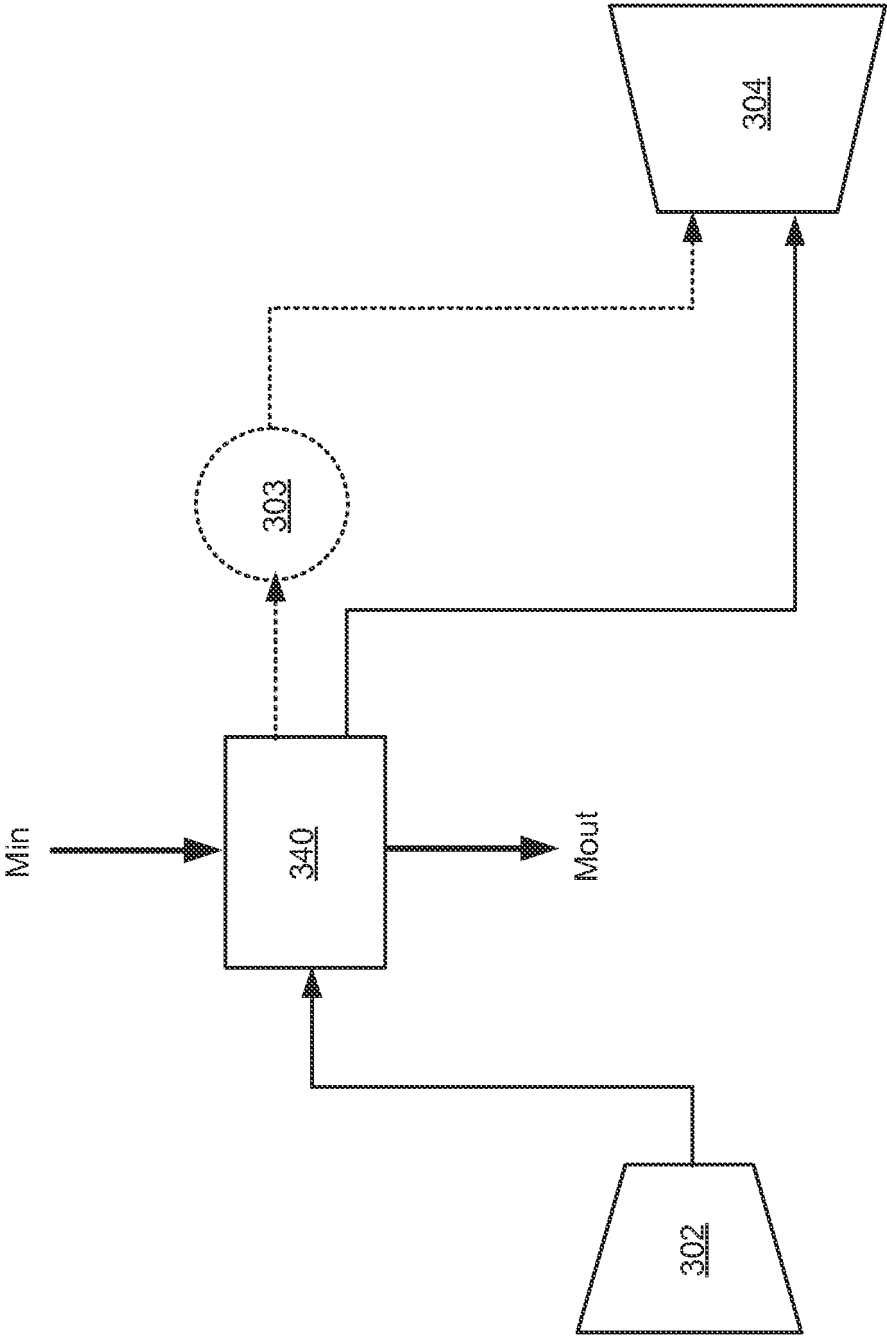
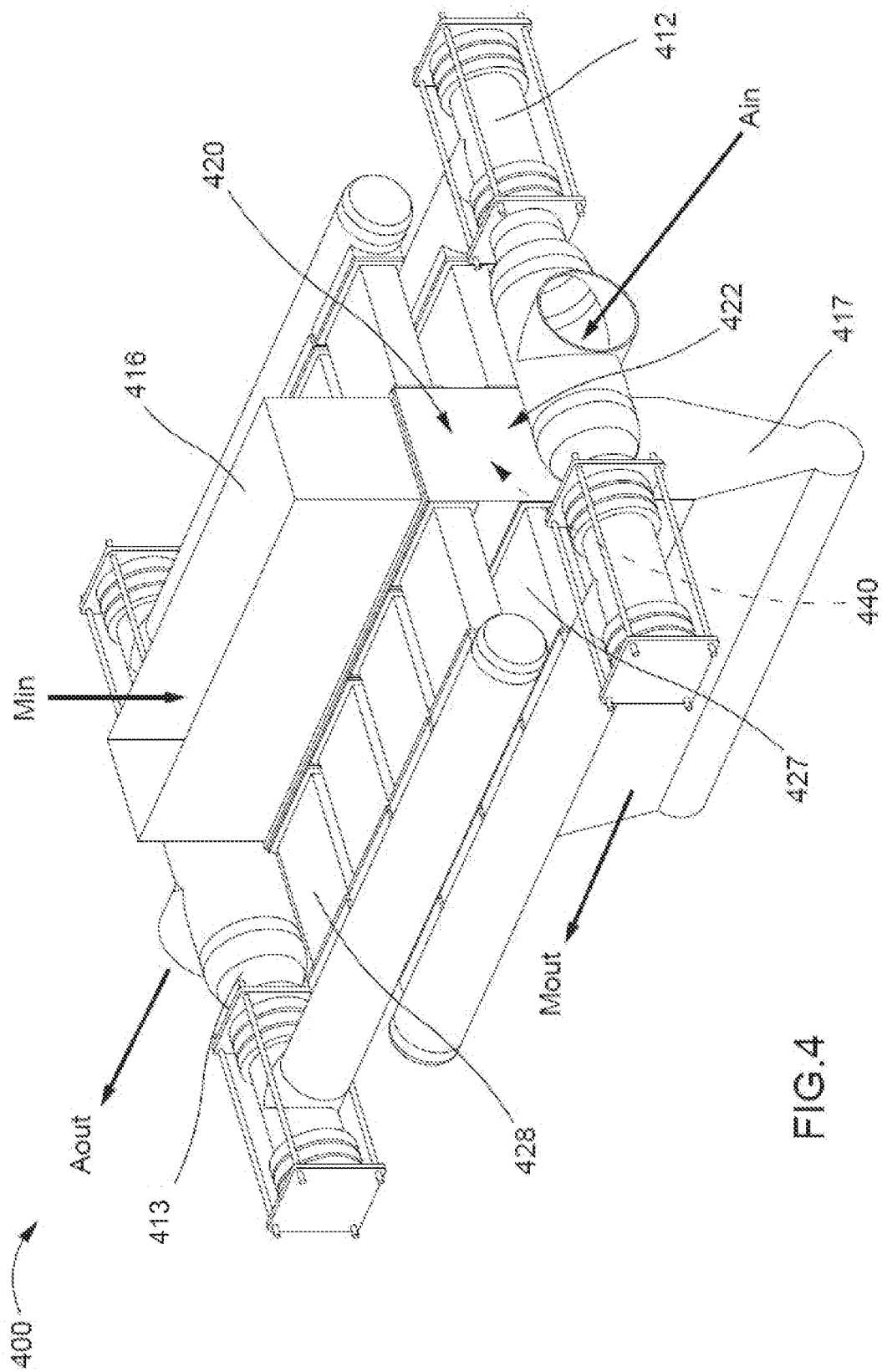


FIG. 3



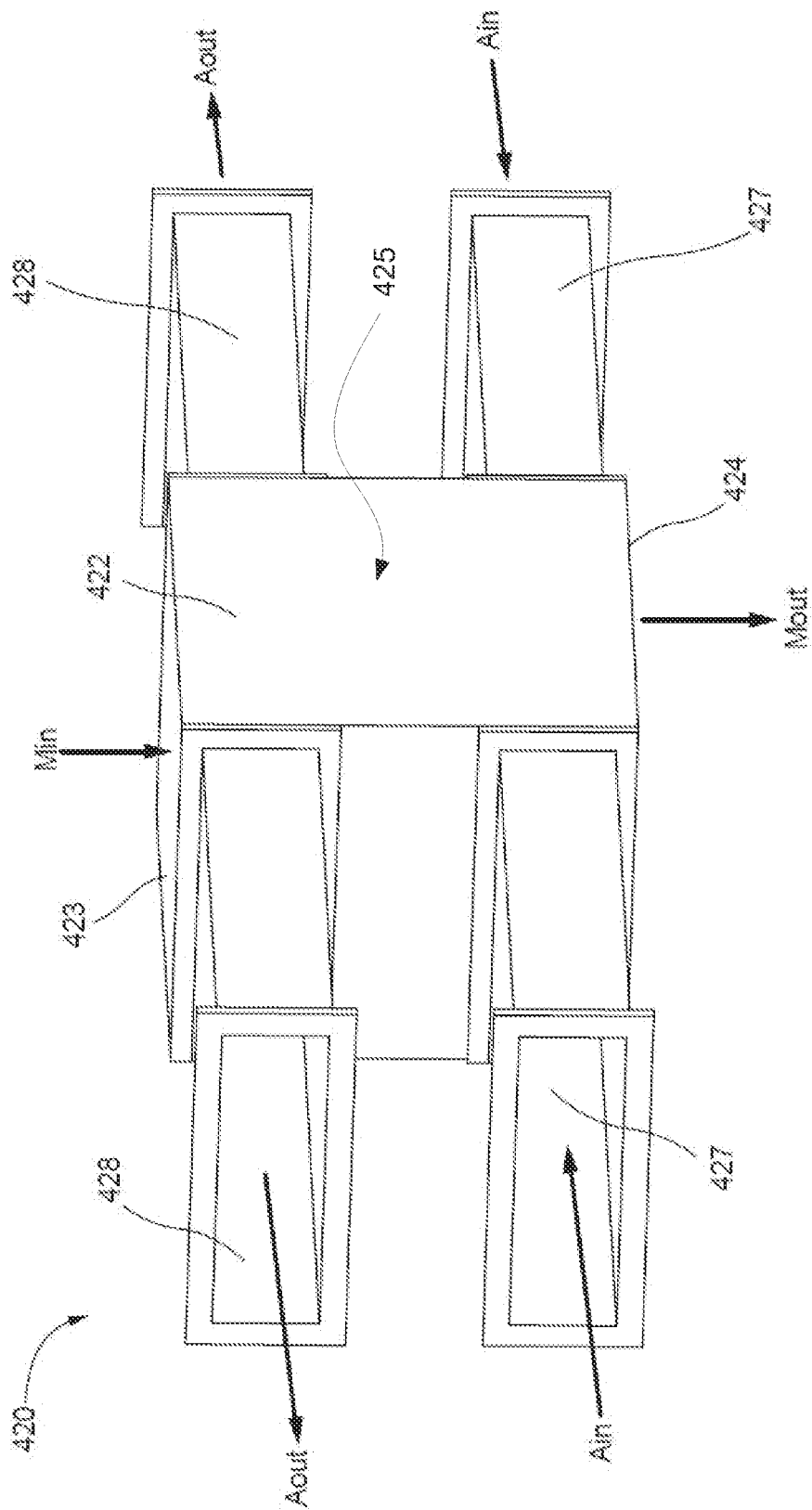


FIG.5

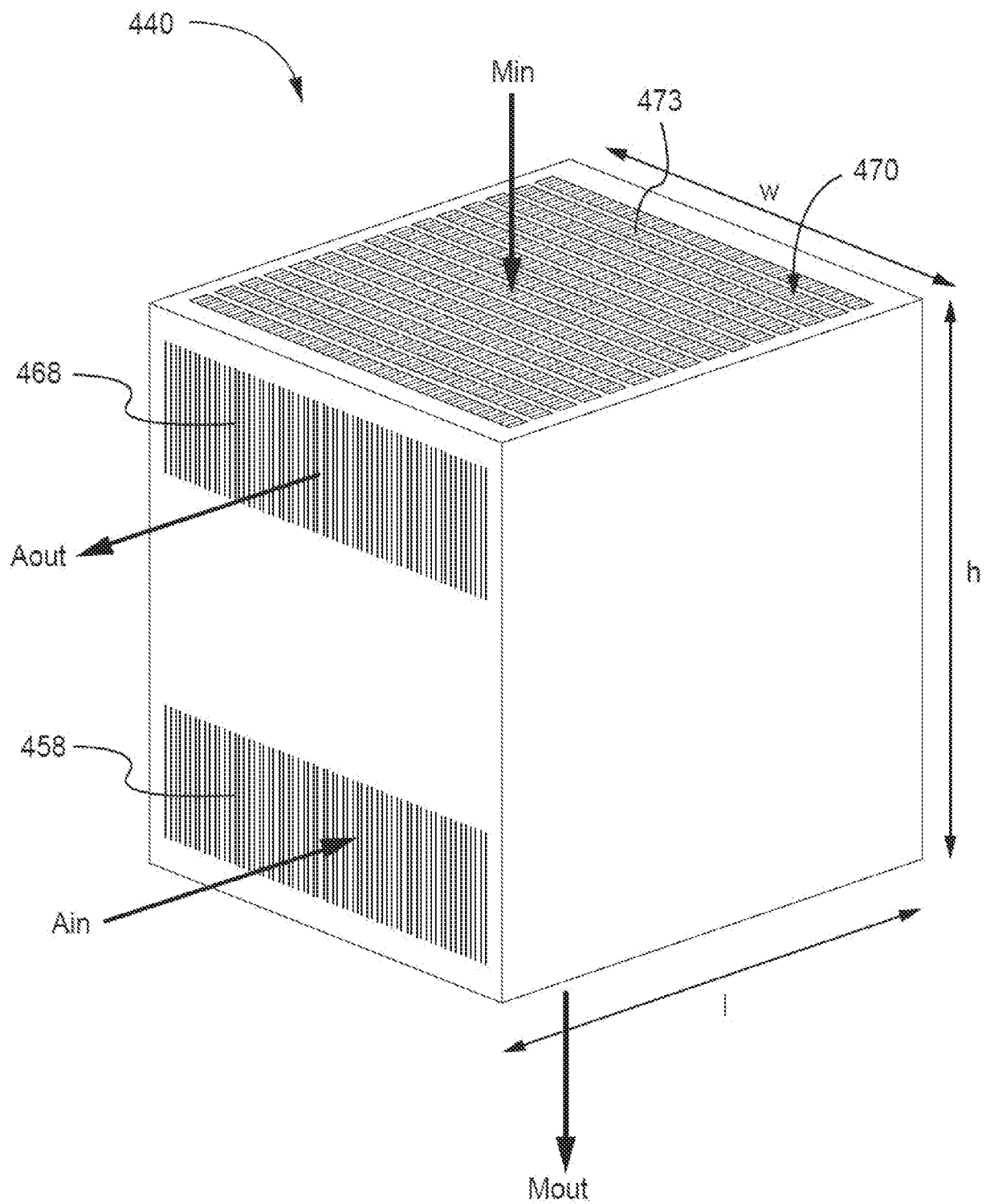


FIG.6

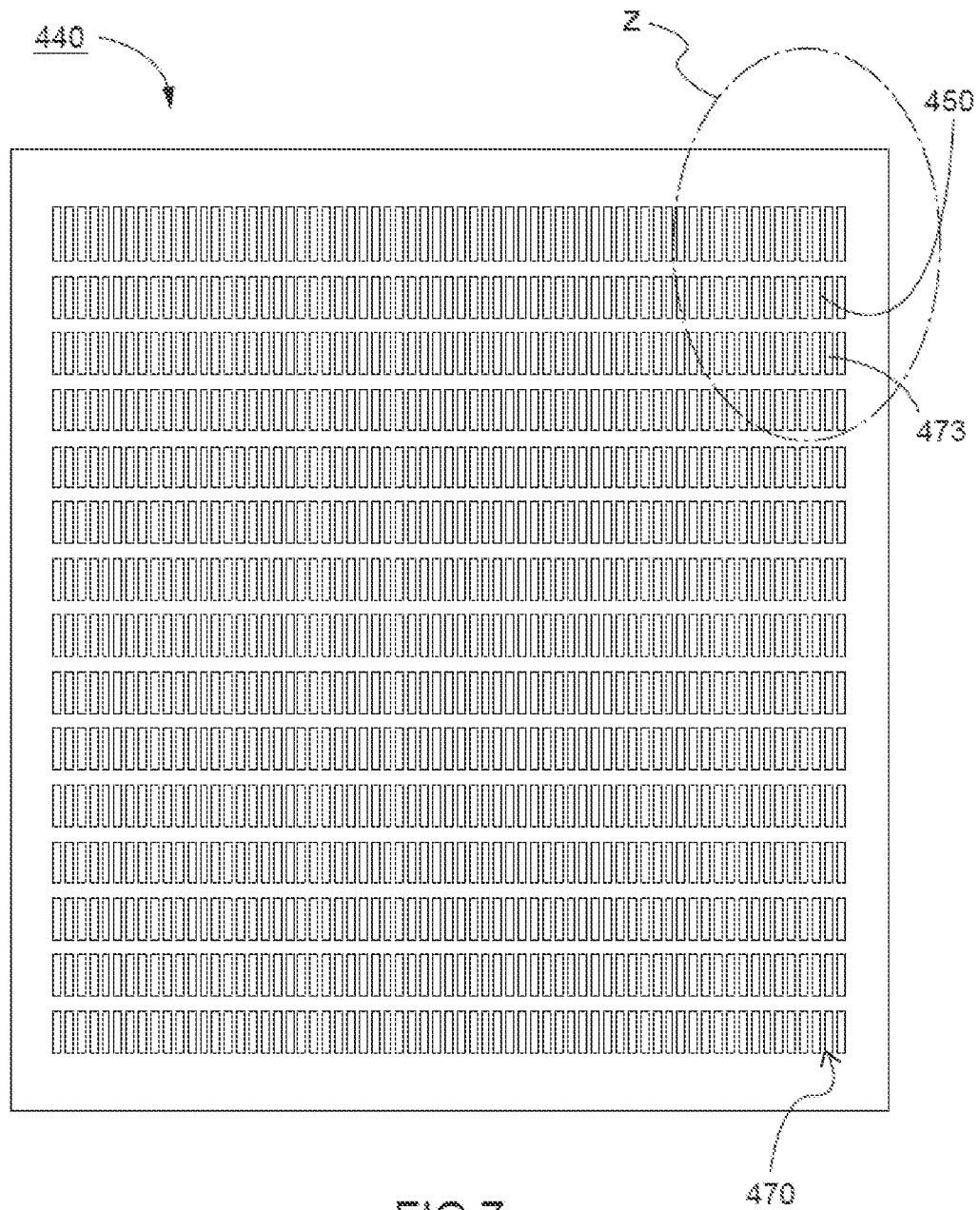


FIG. 7

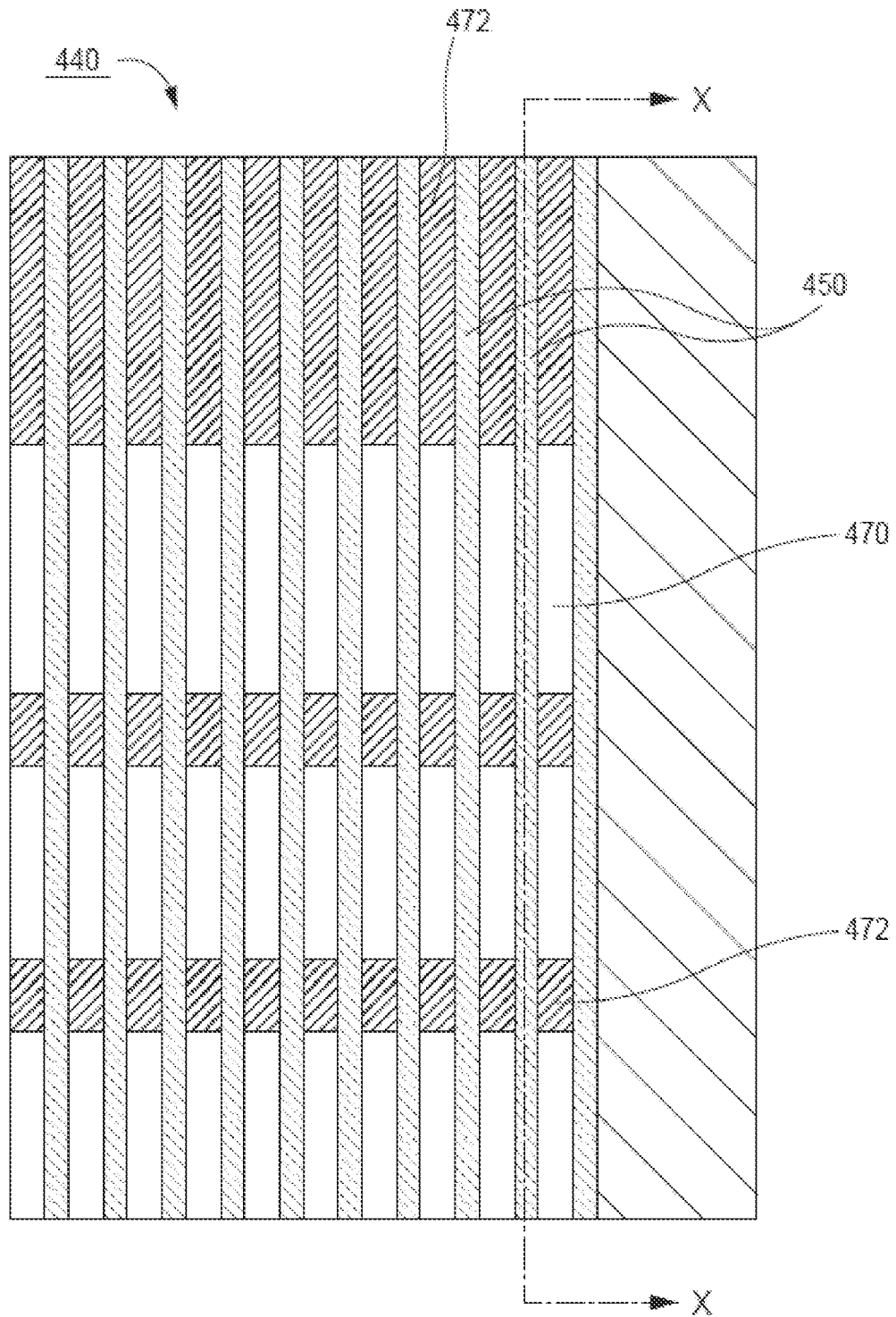


FIG.8

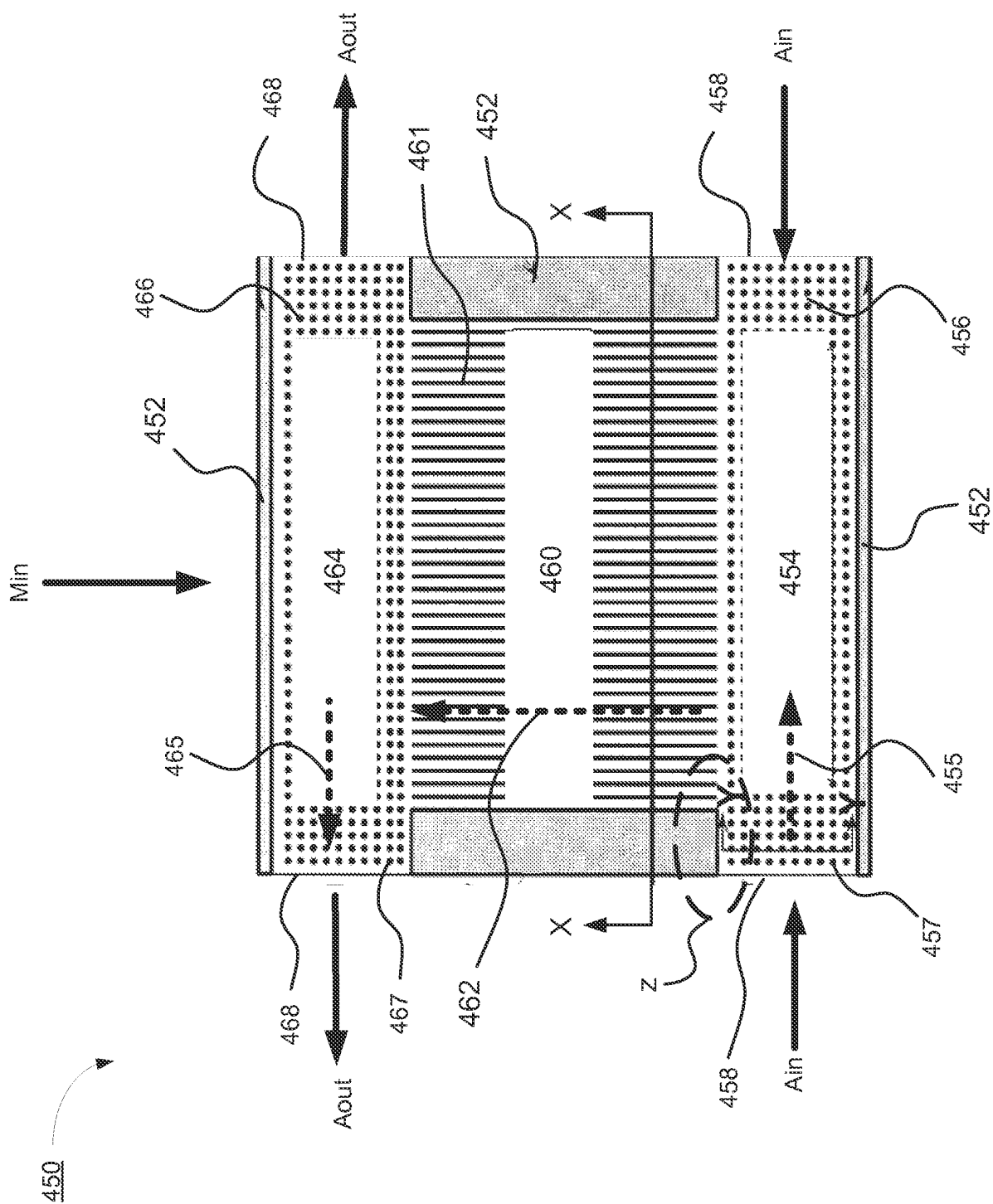
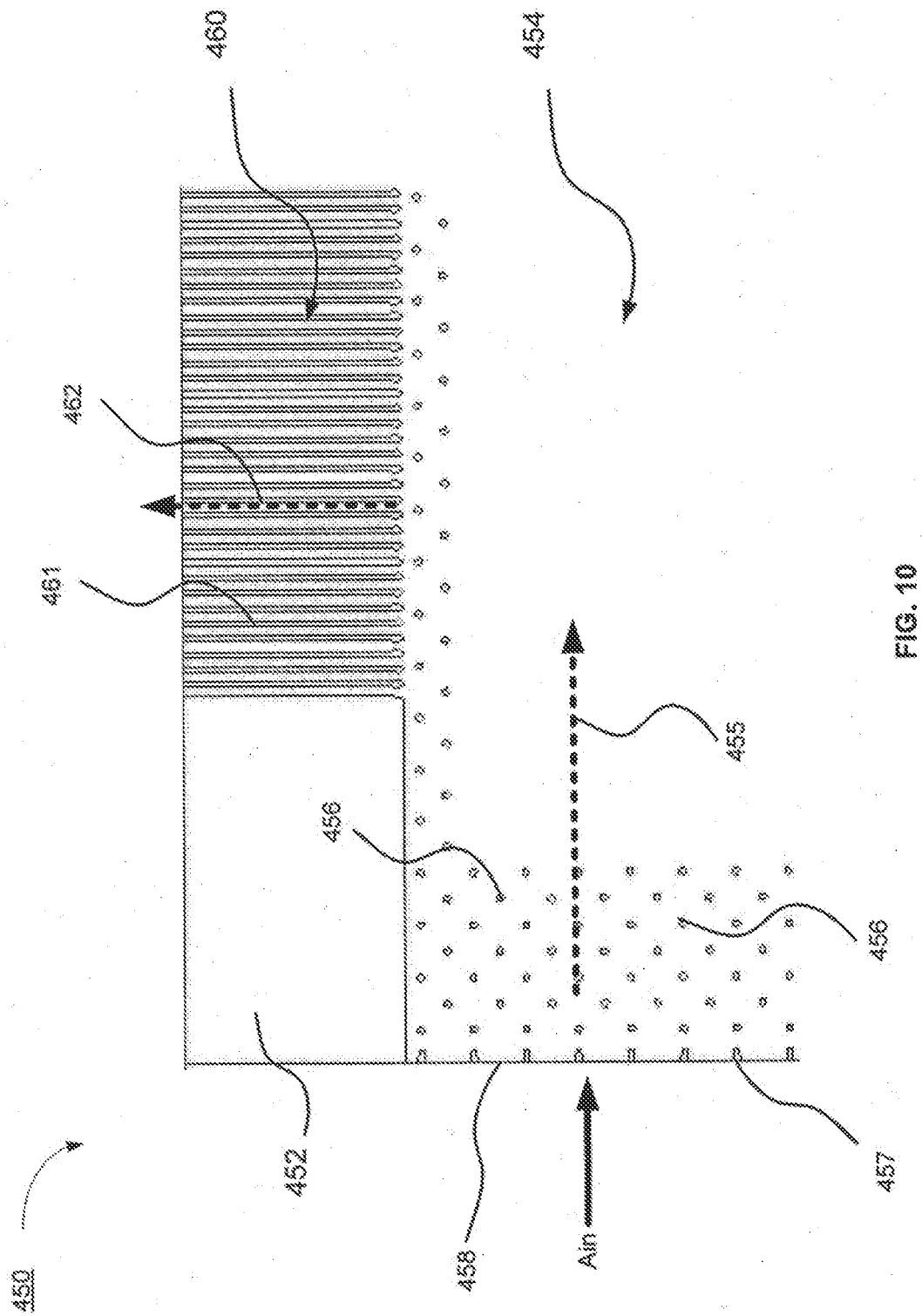


FIG. 9



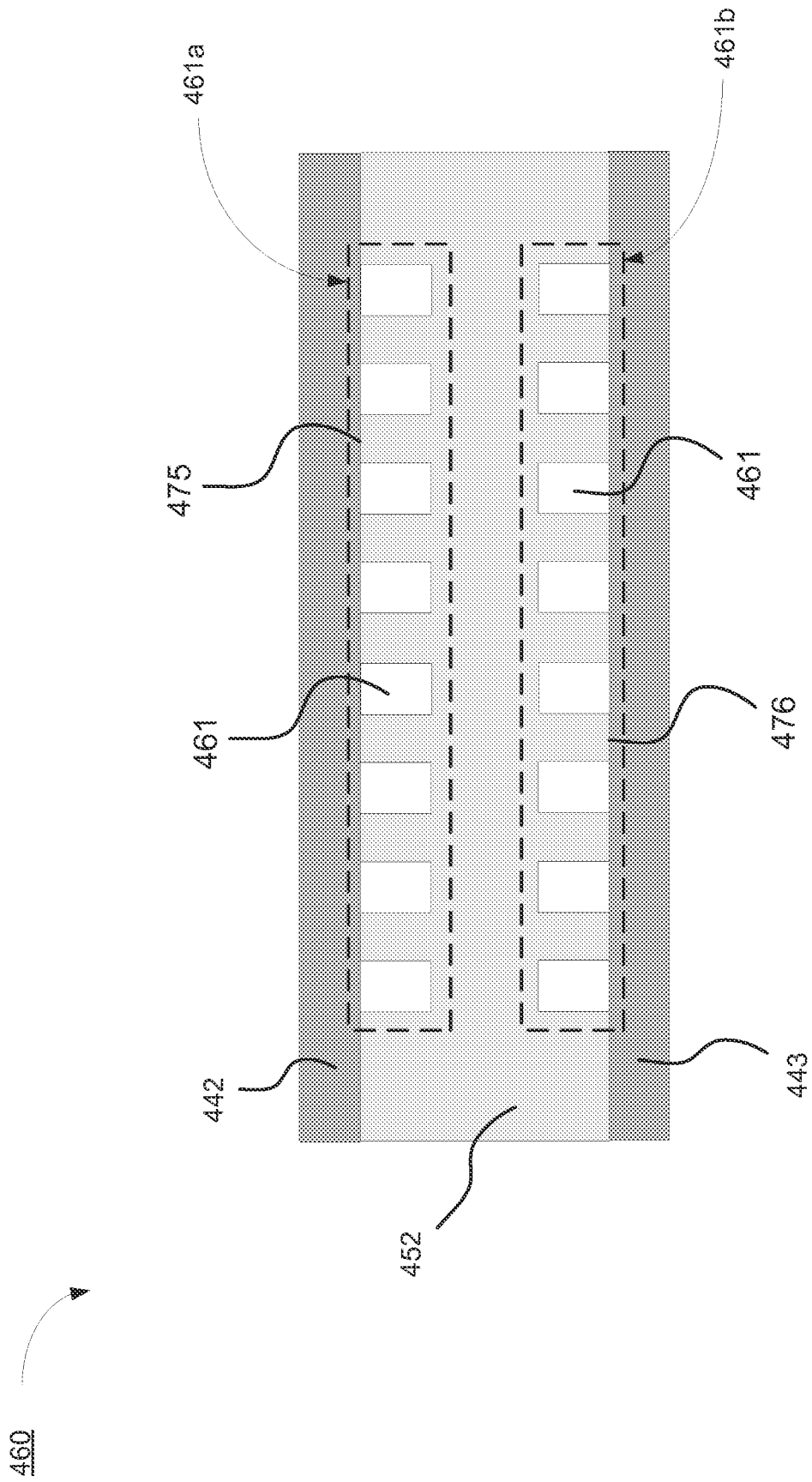


FIG. 11

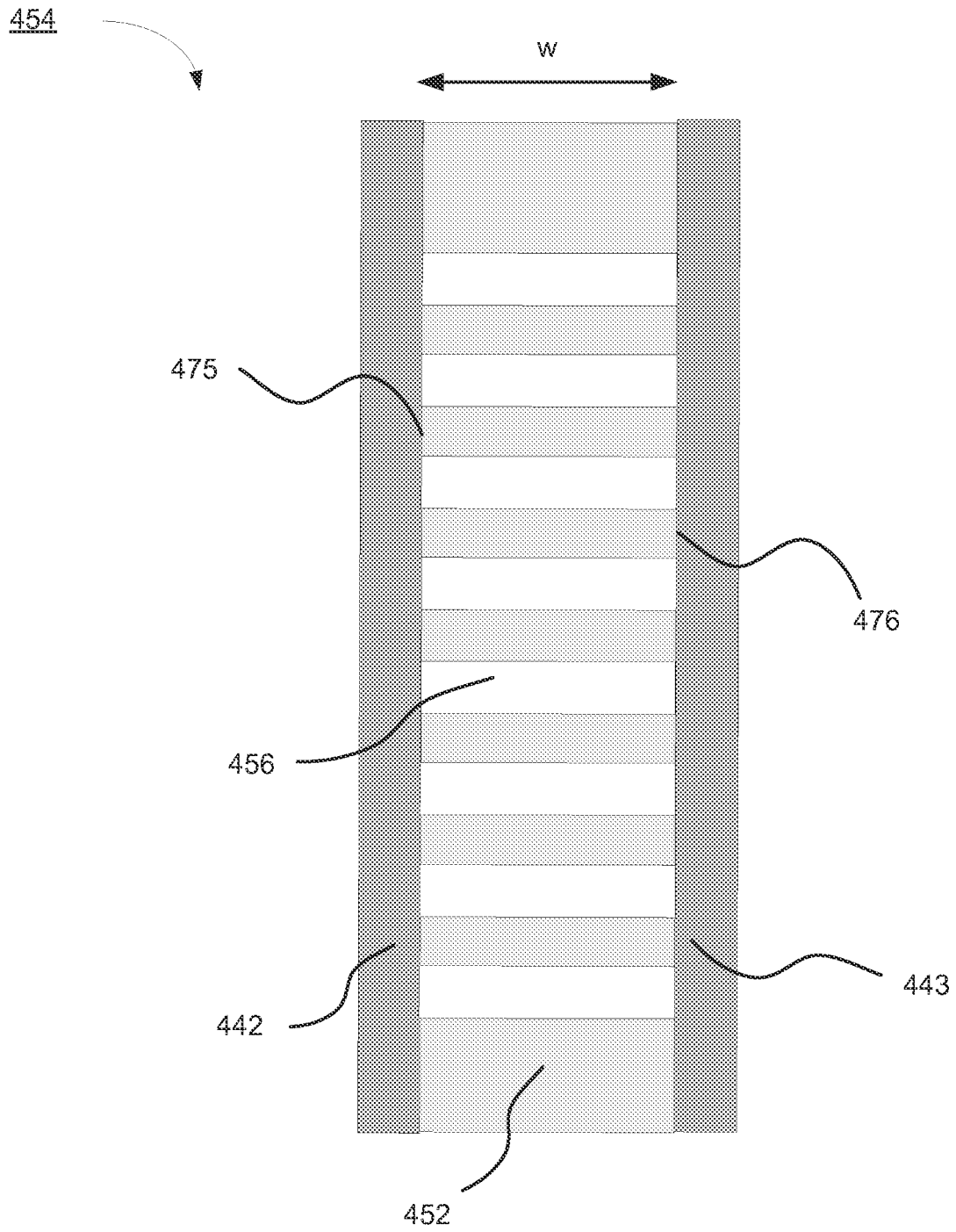


FIG. 12

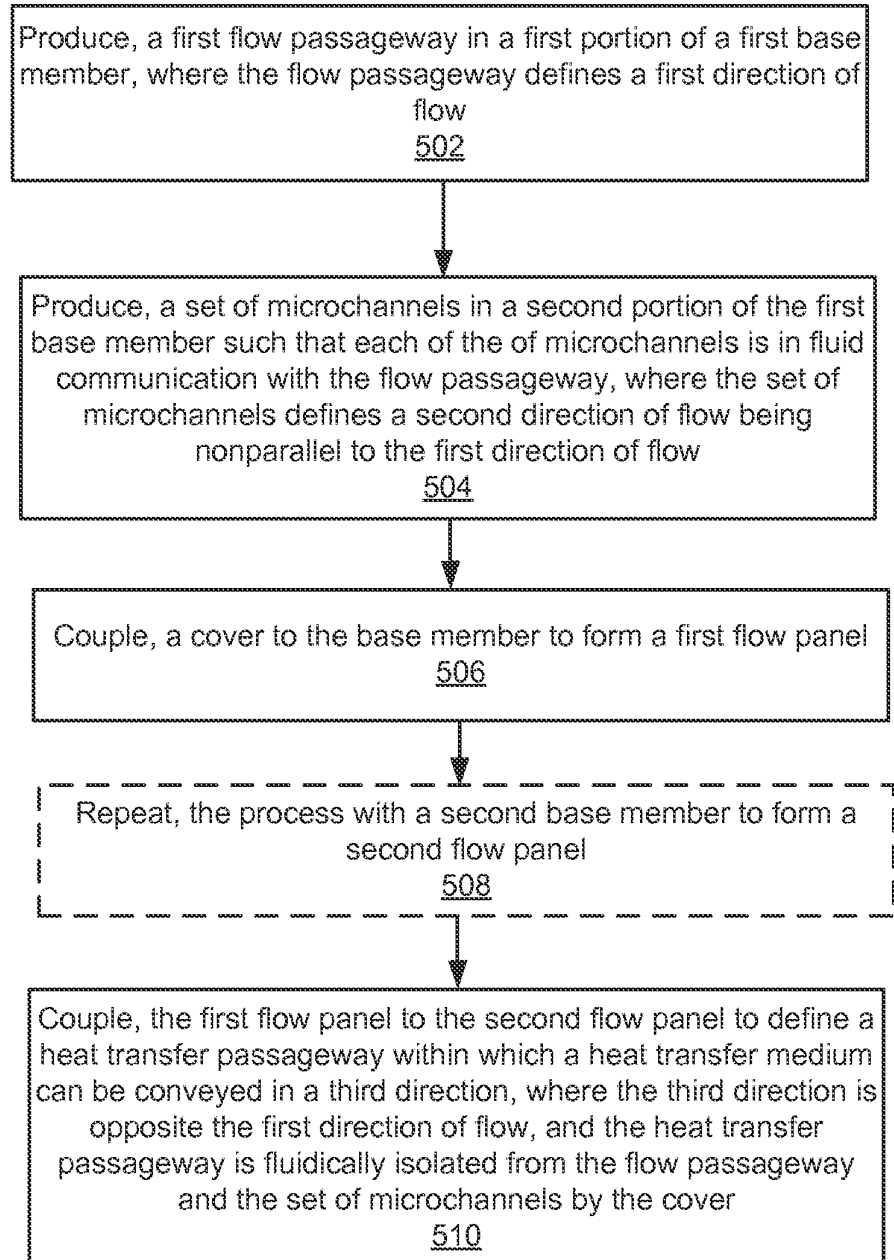
500

FIG. 13

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

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