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(54) **METHOD TO CONSTRUCT AND SUPPORT TUBE MODULE ASSEMBLIES FOR SOLID PARTICLE SOLAR RECEIVER**

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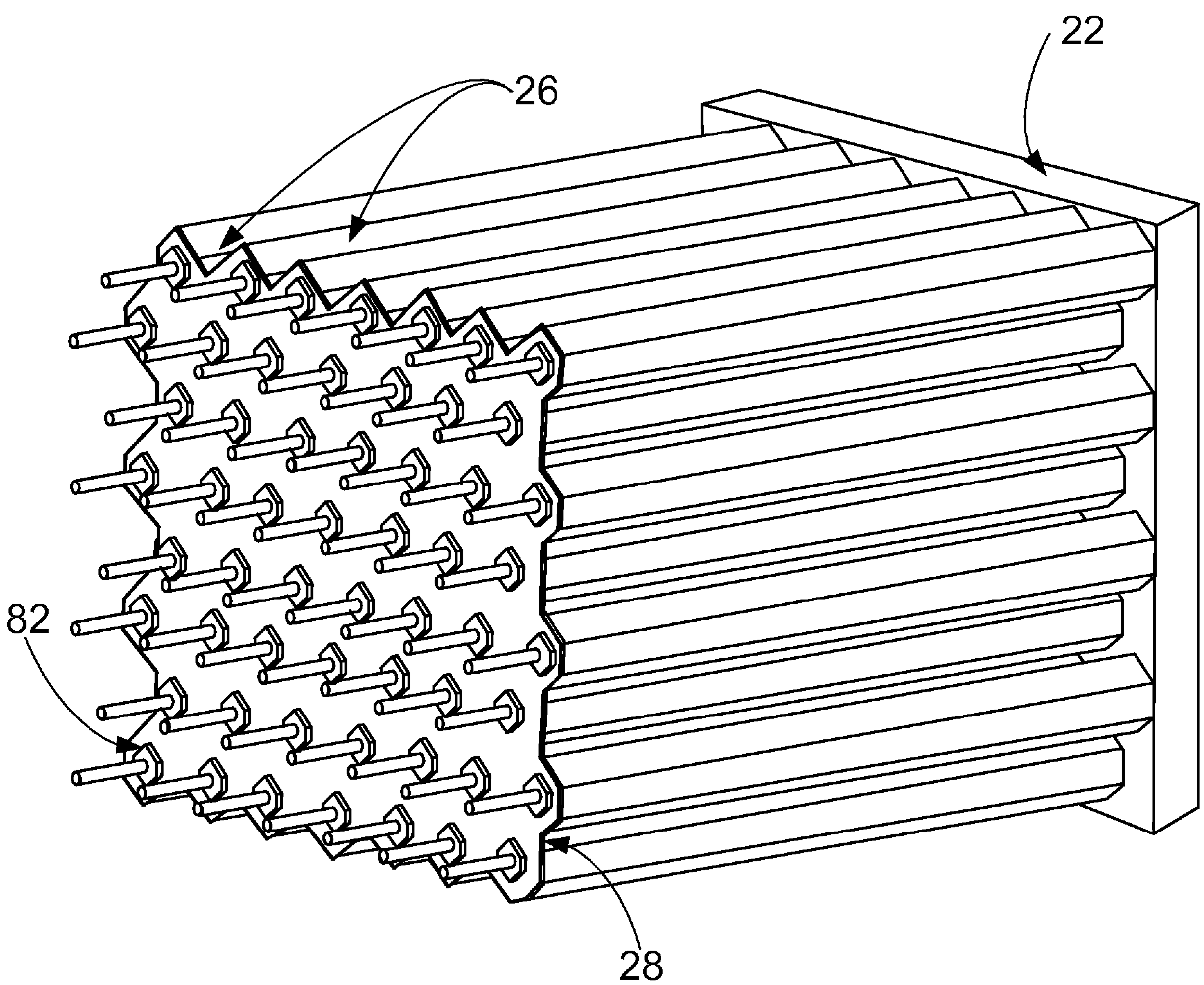
(52) **U.S. Cl.**

CPC .. ***F24J 2/242*** (2013.01); ***F24J 2/26*** (2013.01); ***F24J 2/4607*** (2013.01)

(57) **ABSTRACT**

A solar receiver module includes a front tube sheet with light apertures, a back plate cooperating with the front tube sheet to define a sealed gap, and light channeling tubes optically coupled with the light apertures, extending through the gap and connecting with the back plate. A flowing heat transfer medium flows in the gap over exterior surfaces of the light channeling tubes. Slip joint engagements between light apertures and ends of most or all of the light channeling tubes accommodate thermal expansion. Each slip joint may be defined by an inner or outer perimeter of the light aperture receiving the end of the light channeling tube. A sub-set of the light channeling tubes may be welded to light apertures. A module support post may be secured at a center of the back plate and extend away oppositely from the front tube sheet. A welded or stamped tube sheet provides a seal between tubes at the front face of the tube modules. Thermal expansion provides a seal between adjoining modules at the front face and seal strips provide a seal at the back face.



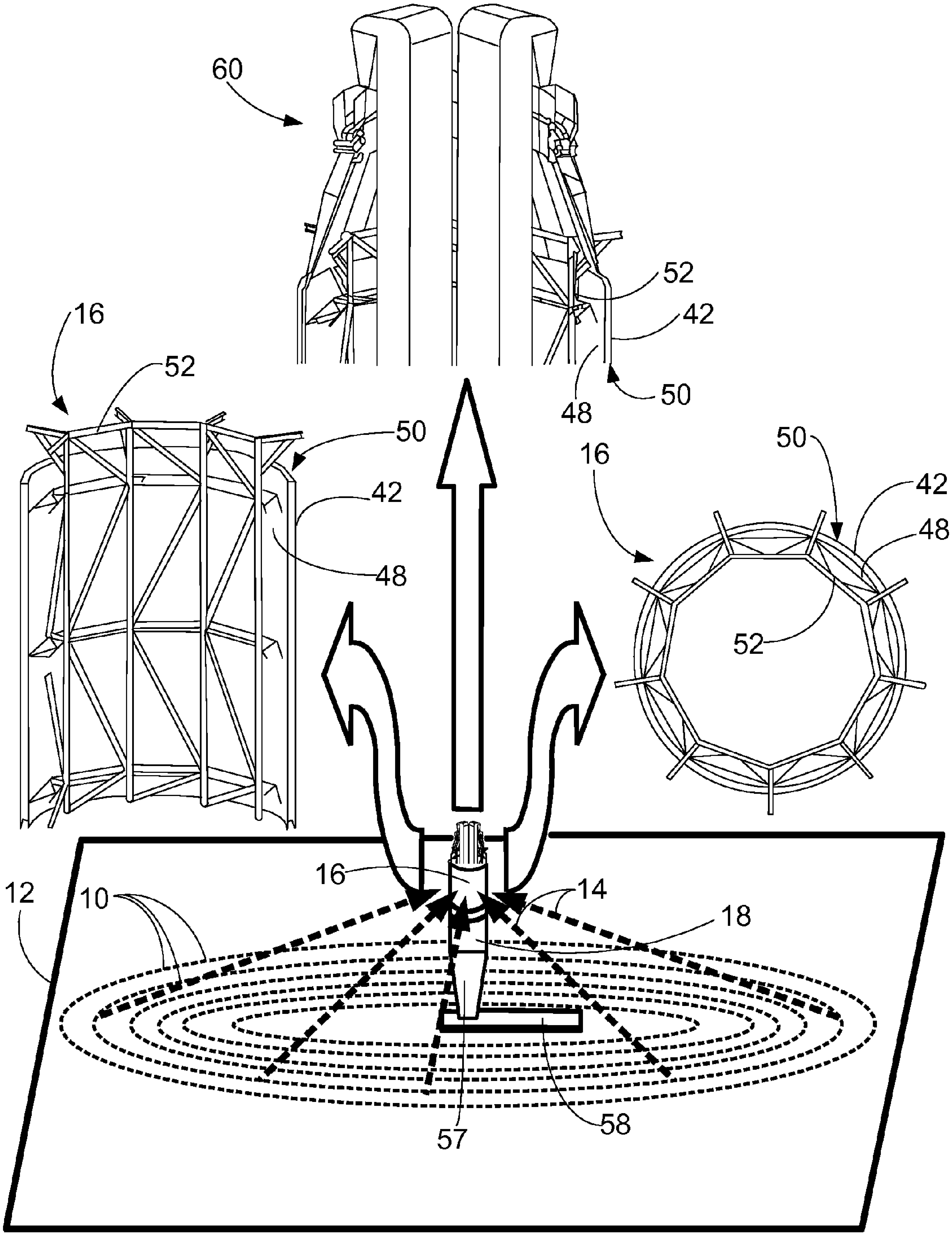


FIG. 1

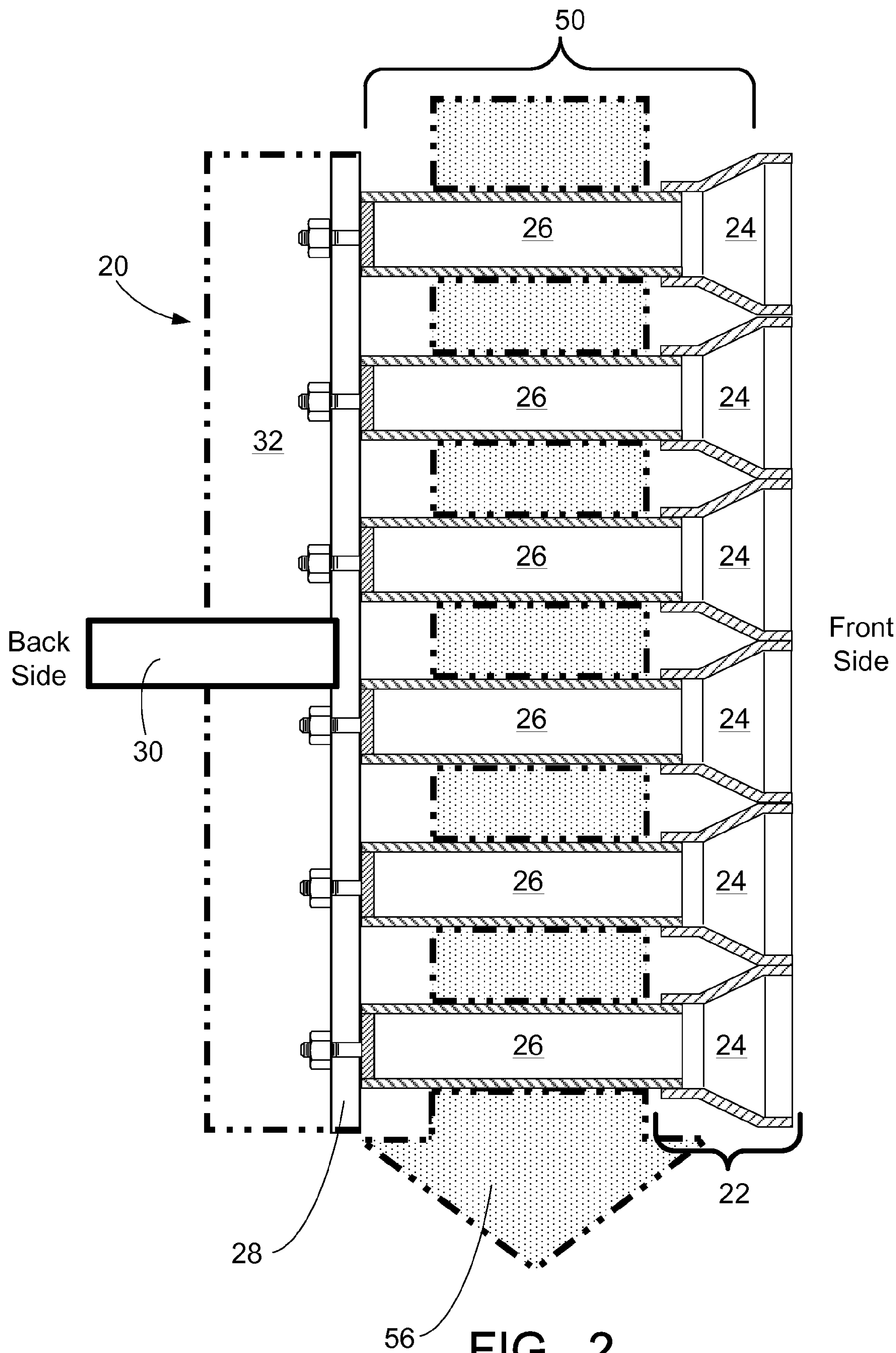
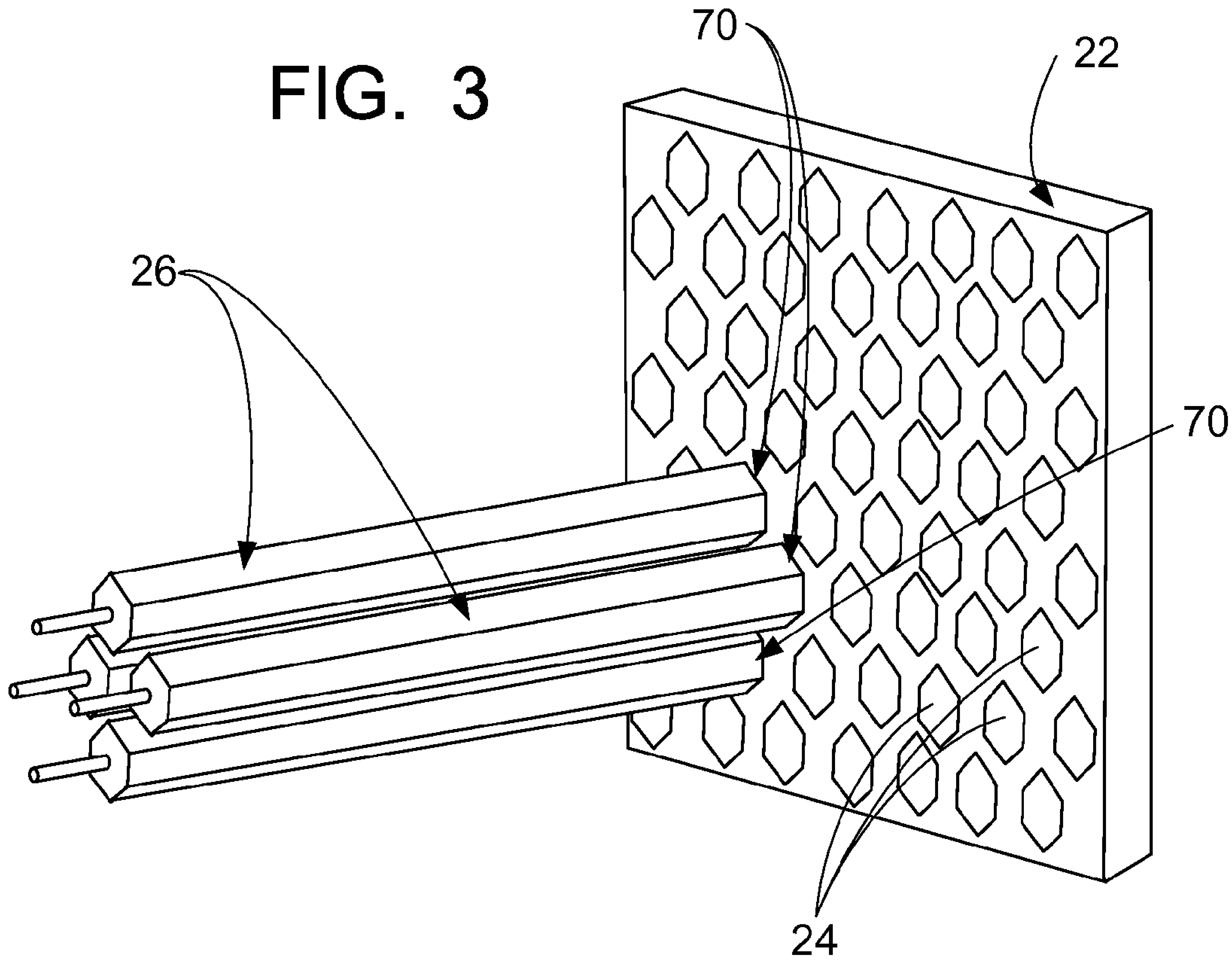


FIG. 2

FIG. 3



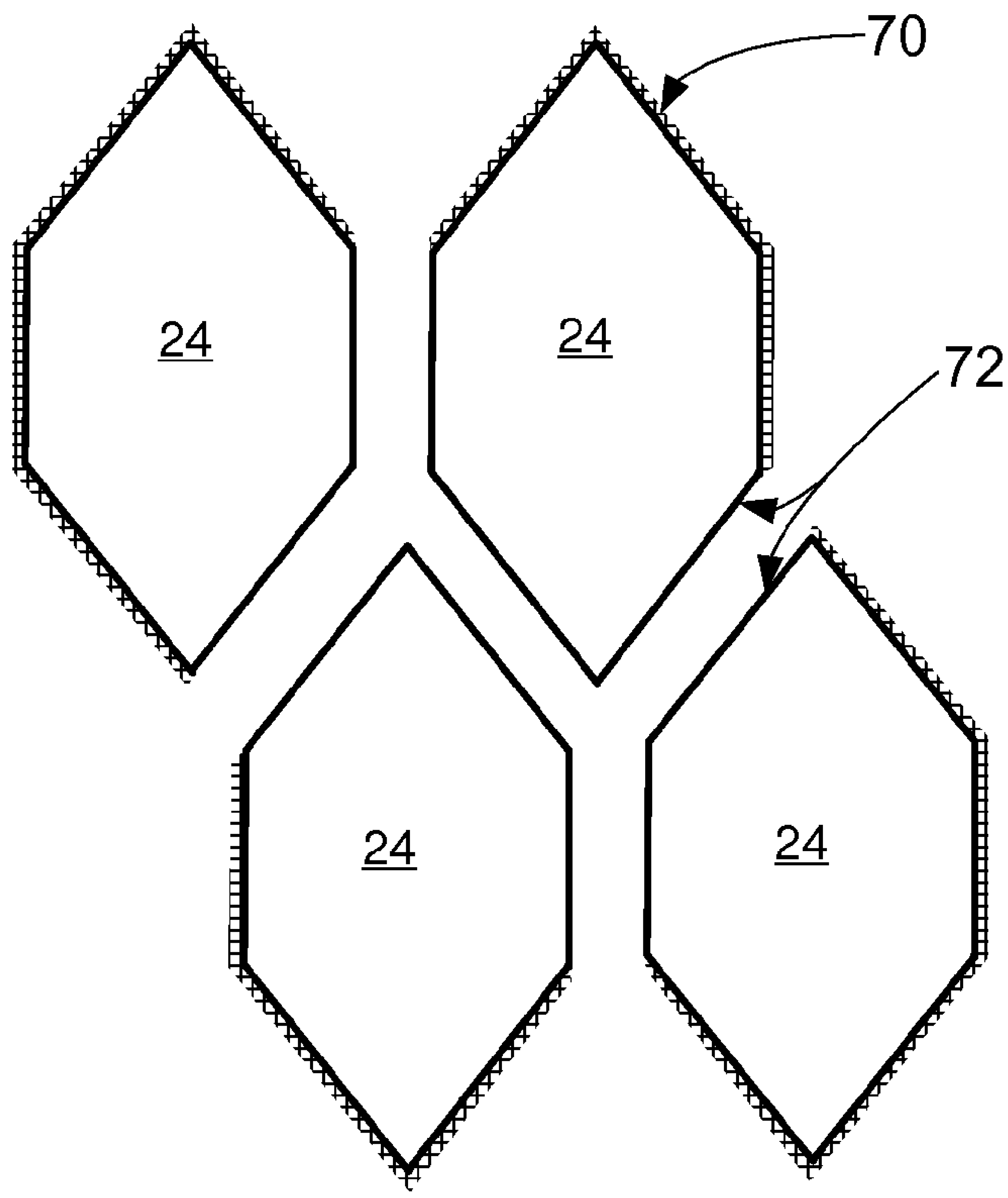


FIG. 4

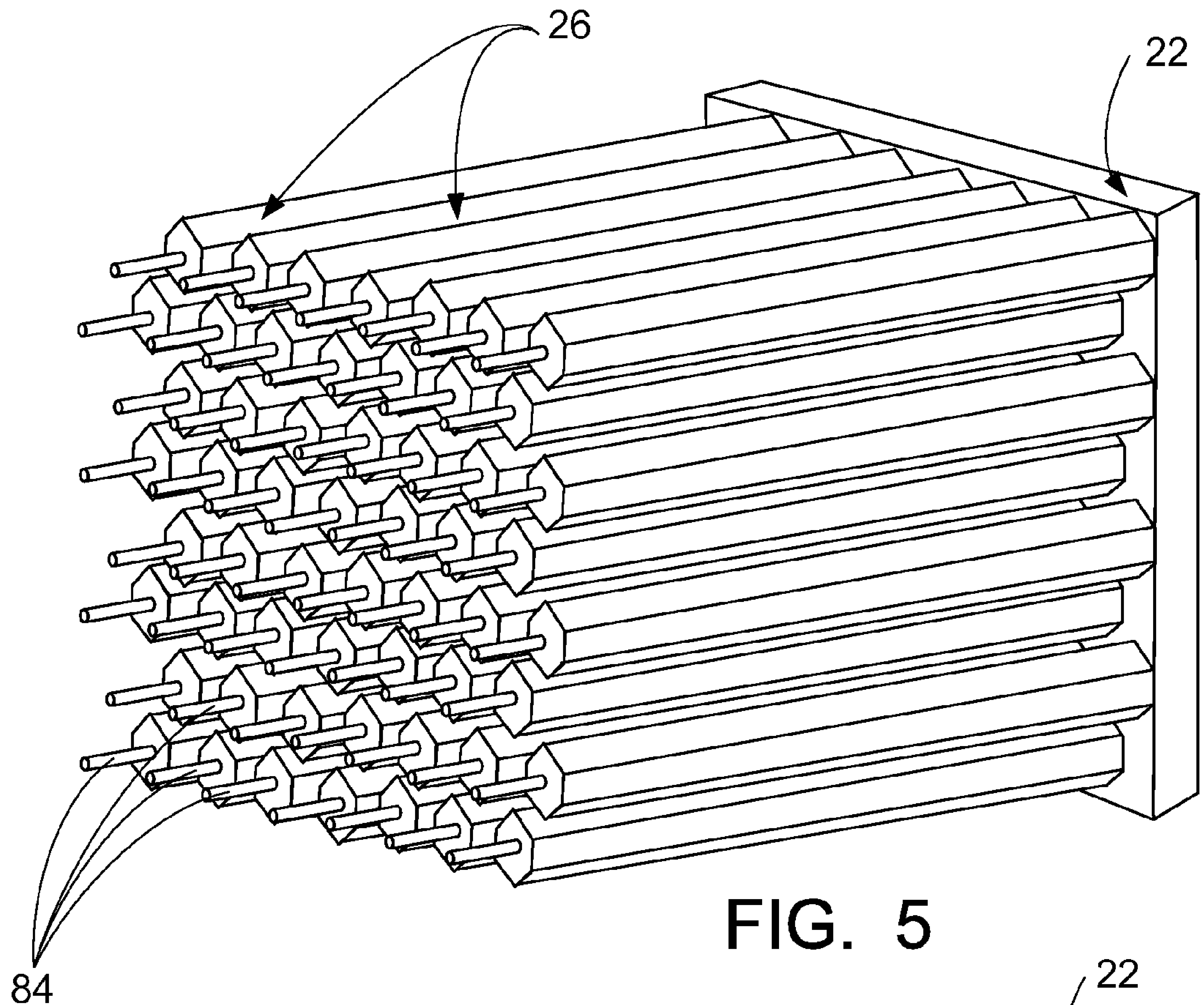


FIG. 5

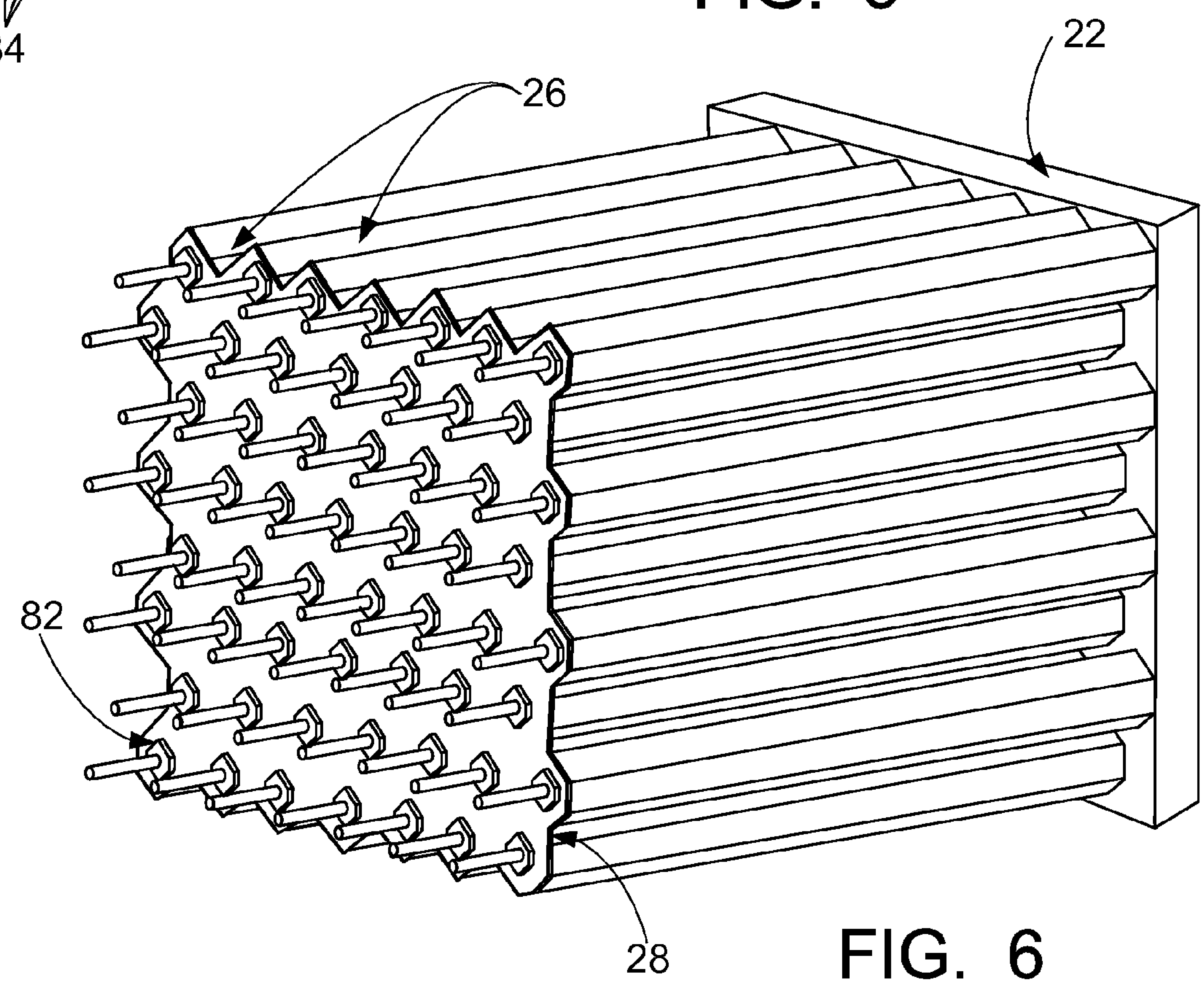


FIG. 6

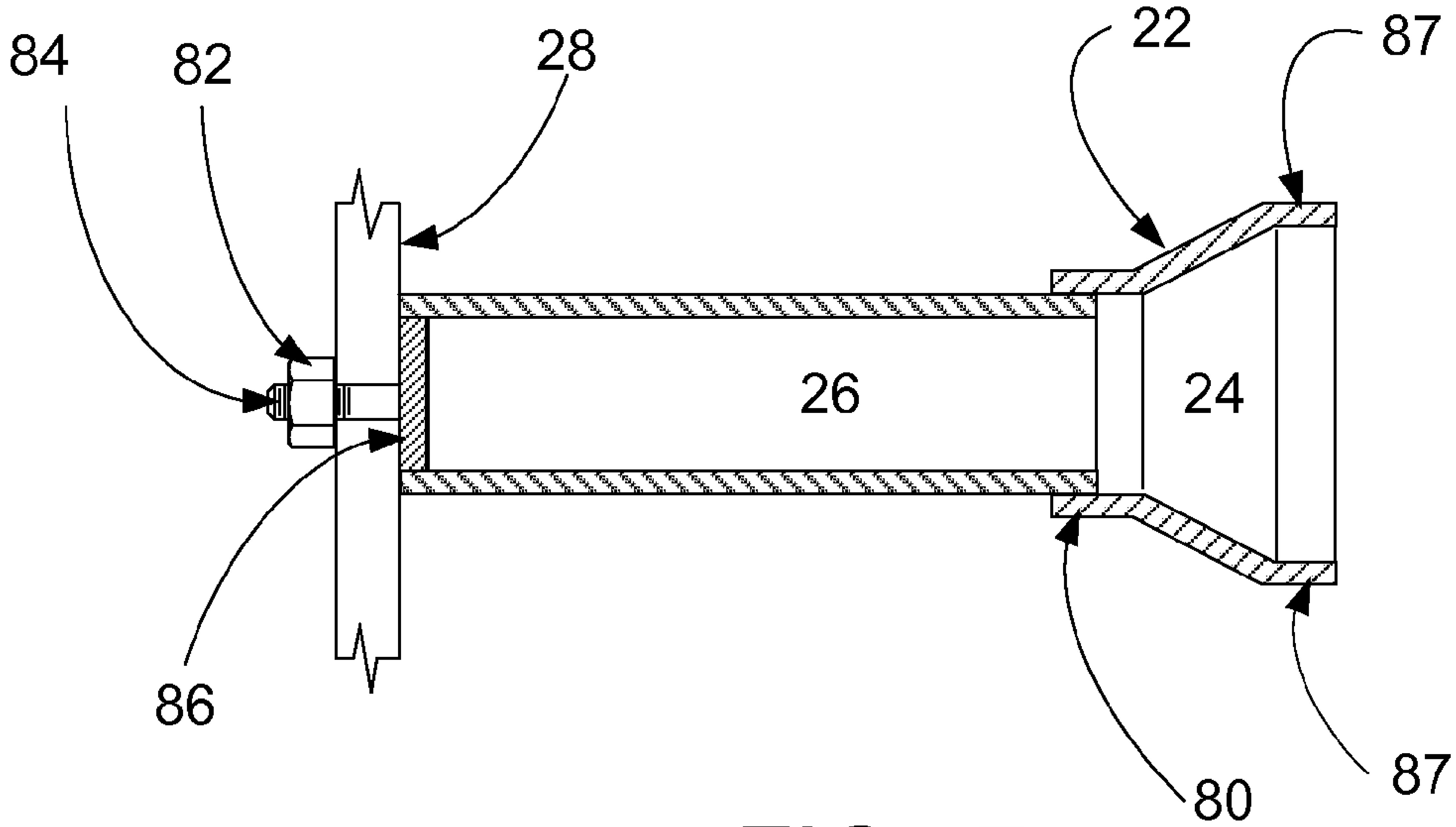


FIG. 7

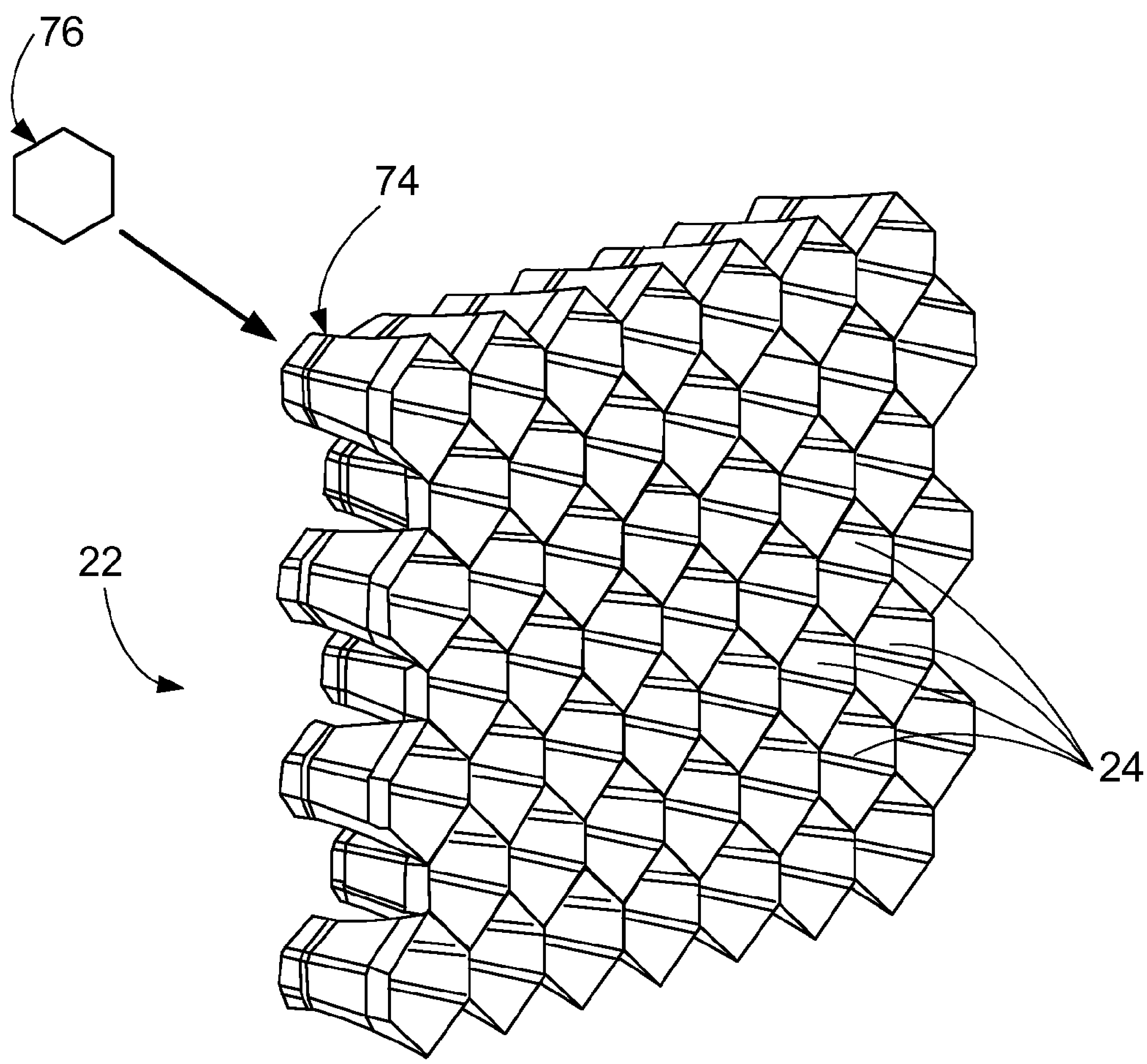


FIG. 8

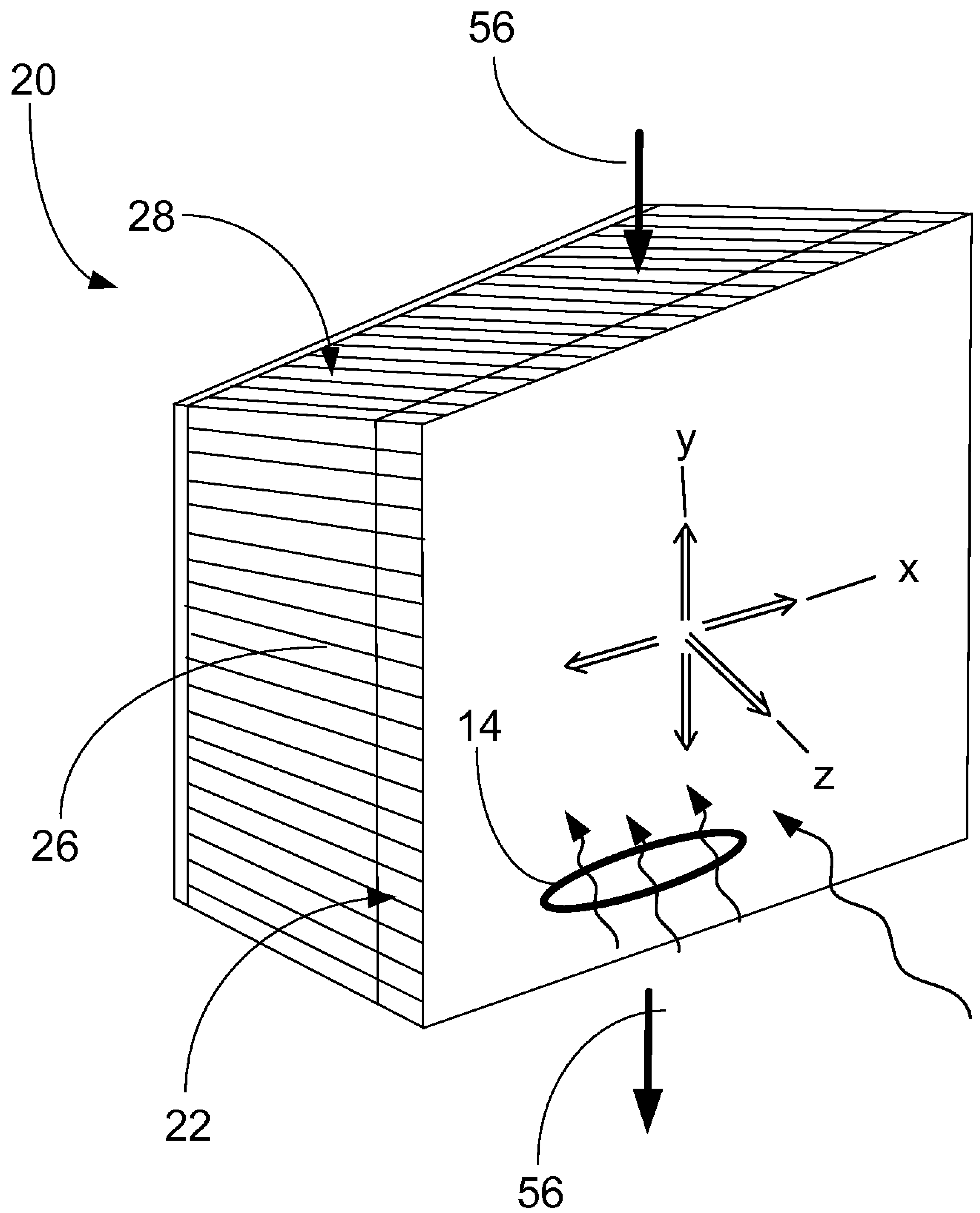


FIG. 9

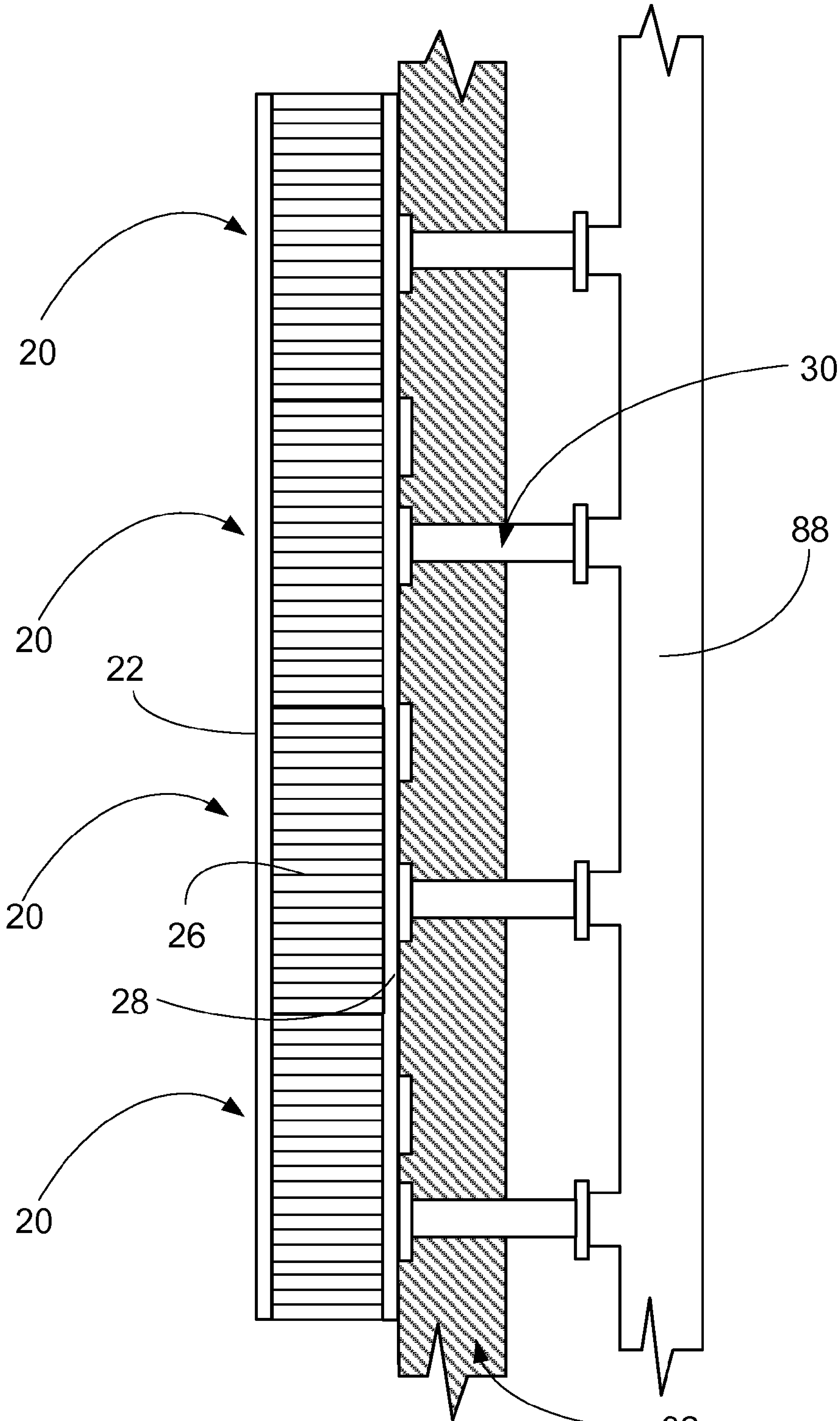


FIG. 10

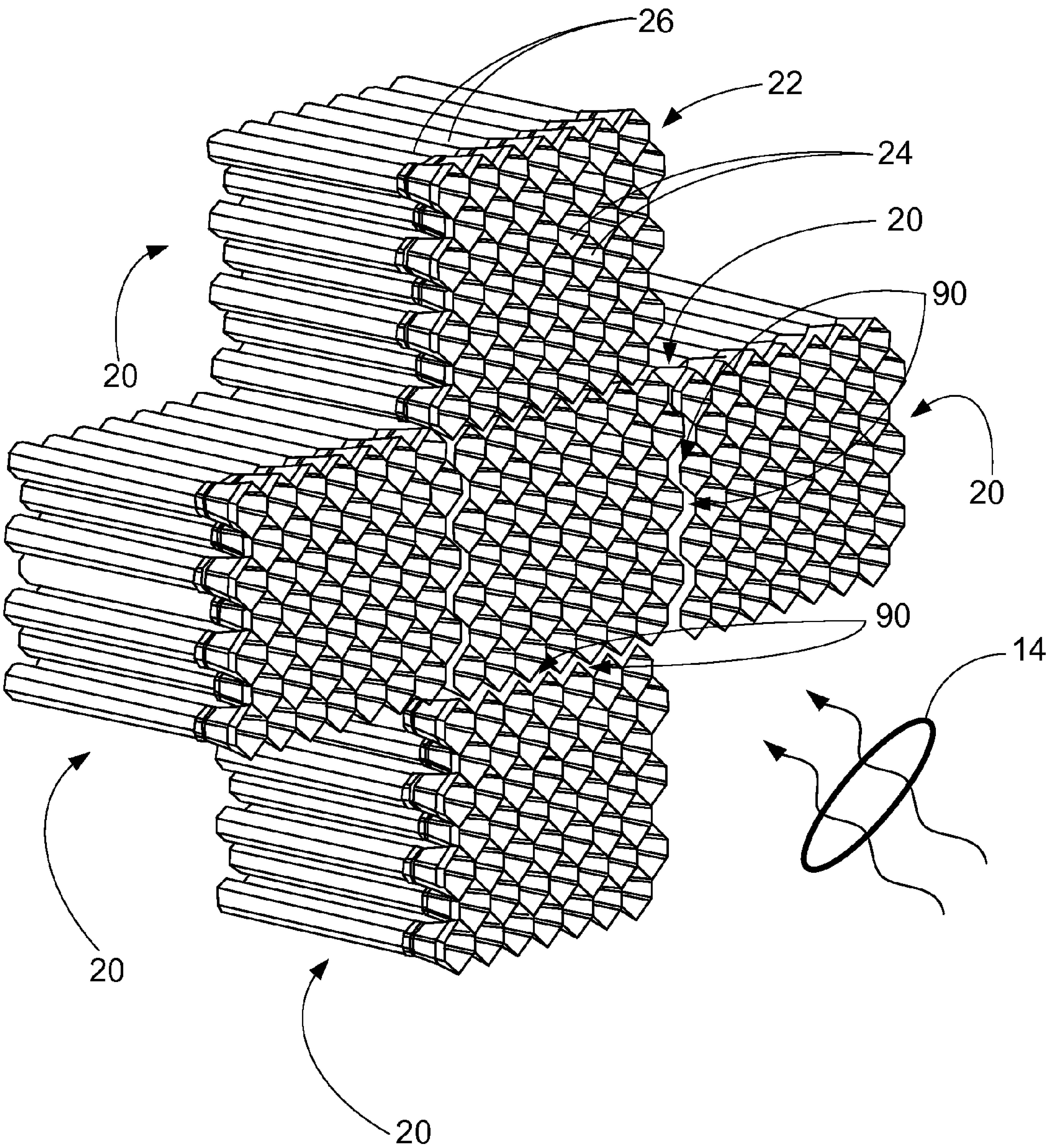


FIG. 11

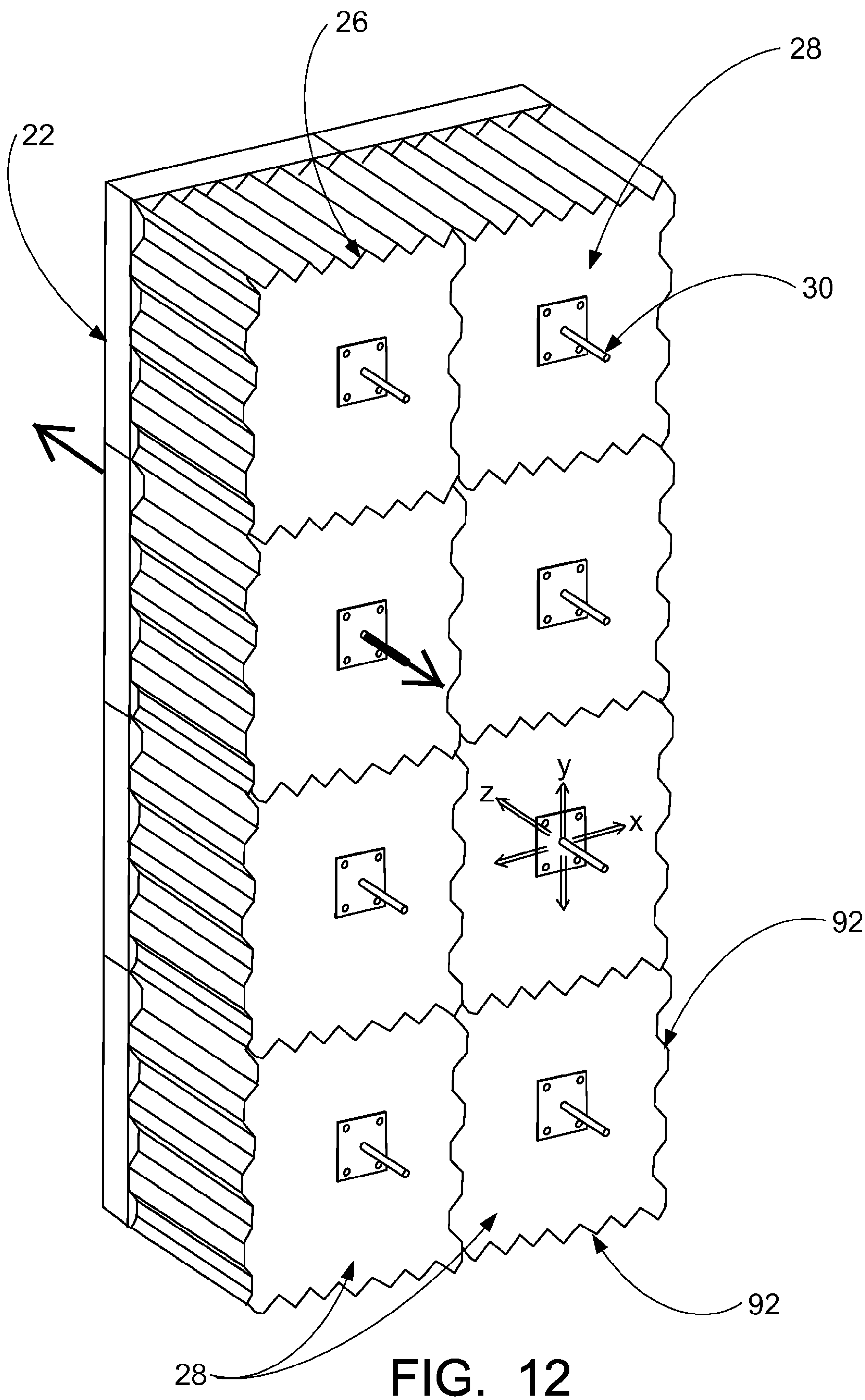


FIG. 12

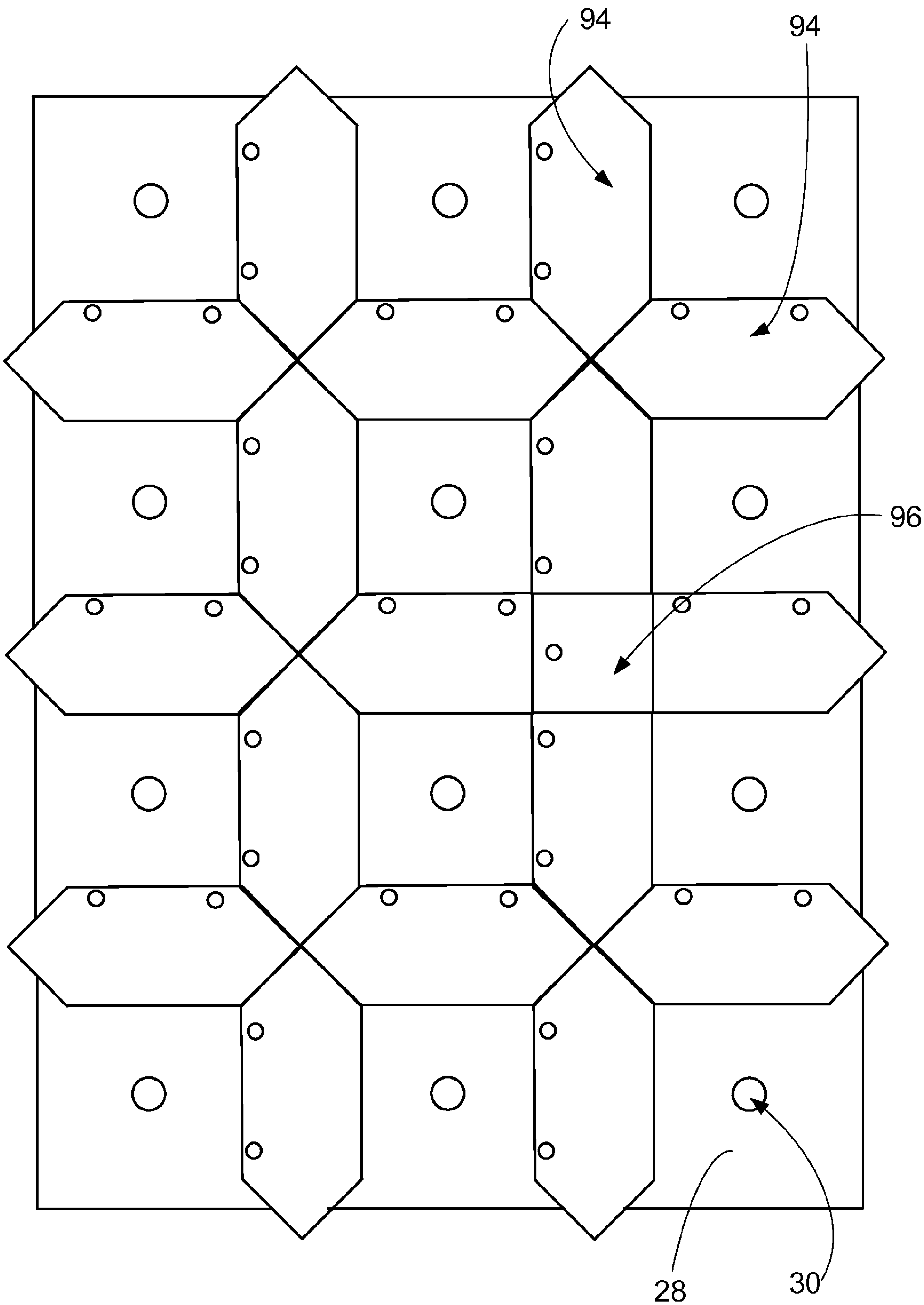


FIG. 13

METHOD TO CONSTRUCT AND SUPPORT TUBE MODULE ASSEMBLIES FOR SOLID PARTICLE SOLAR RECEIVER

RELATED APPLICATION DATA

[0001] This application claims the benefit of U.S. Provisional Application No. 61/981,974 filed Apr. 21, 2014 and titled "Method to Construct and Support Tube Module Assemblies for Solid Particle Solar Receiver". U.S. Provisional Application No. 61/981,974 filed Apr. 21, 2014 is incorporated herein by reference in its entirety.

GOVERNMENT RIGHTS

[0002] The United States Government may have certain rights to this invention pursuant to contract number DE-AC36-08GO28308 between the United States Department of Energy and Alliance For Sustainable Energy, LLC. This invention was developed under subcontract ZGJ-3-23315-01 between Alliance For Sustainable Energy, LLC. and Babcock & Wilcox Power Generation Group, Inc. under contract number DE-AC36-08GO28308.

BACKGROUND

[0003] The following pertains to the solar power generation arts and related arts. In a known solar concentration design, a field of heliostats concentrates solar power onto a (typically tower-mounted) solar receiver. A flowing heat transfer medium flows through the solar receiver. This flowing heat transfer medium absorbs energy from the concentrated light and is thus heated. The hot flowing heat transfer medium may be variously used, for example being fed into a fluidized-bed boiler to generate steam for driving an electrical generator turbine.

[0004] Some such solar concentrators are described, by way of non-limiting illustrative example, in Ma, U.S. Pub. No. 2013/0257056 A1 published Oct. 3, 2013 which is incorporated herein by reference in its entirety, and in Ma et al., U.S. Pub. No. 2013/0255667 A1 published Oct. 3, 2013 which is incorporated herein by reference in its entirety, and in Maryamchik et al., "Concentrated Solar Power Solids-Based System", U.S. Ser. No. 14/250,160 filed Apr. 10, 2014 and published as U.S. Pub. No. 2014/0311479 A1 which is incorporated herein by reference in its entirety.

BRIEF SUMMARY

[0005] In some aspects disclosed herein, a solar receiver module comprises a front tube sheet including light apertures, a back plate cooperating with the front tube sheet to define a sealed gap, and light channeling tubes having first ends optically coupled with the light apertures and extending through the gap and having second ends connected with the back plate. A flowing or fluidized heat transfer medium, for example a flowing particulate medium such as silica sand or calcined flint clay, but not limited thereto, is suitably disposed in the gap over exterior surfaces of the light channeling tubes. In some embodiments the solar receiver module further comprises slip joint engagements between light apertures of the front tube sheet and first ends of most or all of the light channeling tubes. Each slip joint may be defined by an inner perimeter of the light aperture receiving the first end of the light channeling tube. In some such embodiments, each slip joint is defined by the inner perimeter of a necked down portion of the light aperture receiving the first end of the light channeling tube. In some embodiments slip joint engagements are provided between light apertures of the front tube sheet and first ends of all but a sub-set of the light channeling tubes, and welds are provided between light apertures and the first ends of the sub-set of the light channeling tubes. In some such embodiments, the sub-set of the light channeling tubes are immediately neighboring light channeling tubes engaging light apertures that are centrally located on the front tube sheet. In some embodiments the second ends of the light channeling tubes are connected with the back plate by threaded studs extending from the second ends of the light channeling tubes. In some embodiments a module support post extends away from the back plate on the opposite side of the back plate from the front tube sheet, and is secured at a center of the back plate.

[0006] In some aspects disclosed herein, a solar receiver comprises a plurality of solar receiver modules as set forth in the immediately preceding paragraph arranged with adjoining front tube sheets and adjoining back plates to define the solar receiver with an outward facing surface defined by the adjoining front tube sheets and an inward facing surface defined by the adjoining back plates and further having an annular gap between the outward facing surface and the inward facing surface. In some solar receiver embodiments the solar receiver does not include sealing material interposed between the adjoining front tube sheets. In some solar receiver embodiments, the front tube sheets have jagged edges defined by peripheral light apertures and the jagged edges of adjoining front tube sheets mesh together.

[0007] In further aspects disclosed herein, a solar power generation system includes a solar receiver as set forth in the immediately preceding paragraph, a flowing or fluidized heat transfer medium disposed in the annular gap over exterior surfaces of the light channeling tubes of the solar receiver modules, and a fluidized-bed heat exchanger arranged to receive heated heat transfer medium from the solar receiver. In still further aspects disclosed herein, a method of operating a solar receiver as set forth in the immediately preceding paragraph is disclosed. The method comprises disposing a flowing or fluidized heat transfer medium in the annular gap of the solar receiver over exterior surfaces of the light channeling tubes of the solar receiver modules, and operating heliostats to concentrate solar energy onto the solar receiver wherein the concentrated solar energy is effective to induce thermal expansion of the solar receiver modules. In such a method, slip joint engagements between light apertures of the front tube sheet and first ends of most or all of the light channeling tubes suitably accommodates thermal expansion of the solar receiver modules. Additionally, the central rear support of the tube modules allows the modules to thermally expand into one another creating sealing at the front face between adjoining tube modules.

[0008] These and other non-limiting aspects and/or objects of the disclosure are more particularly described below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The invention may take form in various components and arrangements of components, and in various process operations and arrangements of process operations. The drawings are only for purposes of illustrating preferred embodiments and are not to be construed as limiting the invention. This disclosure includes the following drawings.

[0010] FIG. **1** diagrammatically shows an illustrative solar concentrator system, with enlarged detail drawings of the solar receiver shown in insets identified by block arrows.

[0011] FIG. **2** diagrammatically shows a side view of one solar receiver module of the solar receiver of FIG. **1**, with the flow path of the flowing heat transfer medium indicated diagrammatically by a shaded block arrow.

[0012] FIGS. **3-6** diagrammatically illustrate aspects of a suitable assembly of a solar receiver module of the solar receiver of FIG. **1**.

[0013] FIG. **7** shows an enlarged view of one light channeling tube of the solar receiver of FIG. **1**.

[0014] FIG. **8** shows a perspective view of the front tube sheet of the solar receiver of FIG. **1**, with the inner perimeter of the necked-down portion of an aperture shown in an inset.

[0015] FIG. **9** diagrammatically shows thermal expansion experienced by a solar receiver module as it is brought into operation.

[0016] FIGS. **10-13** diagrammatically illustrate aspects of a suitable assembly of adjacent solar receiver modules to construct the solar receiver of FIG. **1**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0017] A more complete understanding of the processes and apparatuses disclosed herein can be obtained by reference to the accompanying drawings. These figures are merely schematic representations based on convenience and the ease of demonstrating the existing art and/or the present development, and are, therefore, not intended to indicate relative size and dimensions of the assemblies or components thereof.

[0018] Although specific terms are used in the following description for the sake of clarity, these terms are intended to refer only to the particular structure of the embodiments selected for illustration in the drawings, and are not intended to define or limit the scope of the disclosure. In the drawings and the following description below, it is to be understood that like numeric designations refer to components of like function.

[0019] The singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise.

[0020] A value modified by a term or terms, such as "about" and "substantially," may not be limited to the precise value specified.

[0021] It should be noted that many of the terms used herein are relative terms. For example, the terms "interior", "exterior", "inward", and "outward" are relative to a center, and should not be construed as requiring a particular orientation or location of the structure.

[0022] The terms "horizontal" and "vertical" are used to indicate direction relative to an absolute reference, i.e. ground level. However, these terms should not be construed to require structures to be absolutely parallel or absolutely perpendicular to each other. For example, a first vertical structure and a second vertical structure are not necessarily parallel to each other.

[0023] The term "plane" is used herein to refer generally to a common level, and should be construed as referring to a volume, not as a flat surface.

[0024] To the extent that explanations of certain terminology or principles of the solar receiver, boiler and/or steam generator arts may be necessary to understand the present disclosure, the reader is referred to Steam/its generation and use, 40th Edition, Stultz and Kitto, Eds., Copyright 1992, The Babcock & Wilcox Company, and to Steamlits generation and use, 41st Edition, Kitto and Stultz, Eds., Copyright 2005, The Babcock & Wilcox Company, the texts of which are hereby incorporated by reference as though fully set forth herein.

[0025] With reference to FIG. **1**, a solar concentrator power generation plant includes a field of heliostats **10** disposed over an area **12** occupied by the plant. The heliostats **10** are diagrammatically represented in FIG. **1**, and typically include suitable components (not shown) such as beam-forming optics typically comprising mirrors or other reflectors and beam-steering apparatus such as multi-axis motorized system that cooperate to capture solar radiation impinging upon the heliostat and form the light into energy beams **14** that are directed to a solar receiver **16**, with the multi-axis motorized systems of the heliostats **10** operating to track the (apparent) movement of the sun across the sky to keep the light beams **14** directed to the solar receiver **16** over the course of the day. (As used herein, the terms such as "light", "solar radiation", and "solar energy" are used interchangeably, and encompass all energy from the sun that is captured and concentrated by the heliostats **10** and/or other referenced system components whether such solar energy is in the form of visible light, infrared light, or ultraviolet light. In the case of components that are heated by solar radiation, the term "energy" or "solar energy" encompasses energy in the form of heat so generated.) In the illustrated configuration, the solar receiver **16** is mounted in an elevated position on a tower **18** so as to provide an unimpeded direct line-of-sight between each heliostat **10** in the field and the solar receiver **16**. However, other physical arrangements are contemplated—for example, a tower could include a top-mounted mirror system that directs light downward to a solar receiver located at (or even below) ground level (variants not illustrated).

[0026] With continuing reference to FIG. **1** including its insets, and with further reference to FIG. **2**, the solar receiver **16** comprises an assembly of solar receiver tube modules **20**, one of which is shown in side view in FIG. **2**, where it is seen that the solar receiver tube module **20** includes a front tube sheet **22** defined by adjoining light apertures **24**, light channeling tubes **26** connected with respective apertures **24** and extending into the receiver tube module **20**, and a back plate **28** to which "rear" ends of the light channeling tubes **26** are connected. By way of non-limiting illustration, the apertures **24** and light channeling tubes **26** may comprise bent sheet metal (e.g. sheet steel) components, drawn tubes, or so forth, and the back plate **28** may comprise a metal plate (e.g. steel plate). For example, the light channeling tubes can be manufactured by a drawing process or by stamping two halves and welding with two longitudinal seam welds. As used herein, the following orientation terms are used: the "front" side of the solar receiver module **20** is faced by the front tube sheet **22** where light enters, while the "back" side of the solar receiver module **20** is the side faced by the back plate **28**. The light channeling tubes **26** are in an approximately horizontal orientation, although some tilting of the light channeling tubes **26** is contemplated, for example a downward tilt of a few degrees to a few tens of degrees to up to about 45° is contemplated to better align with the upward angle of light beams **14** coming from the heliostats **10**. A module support post **30** (for example, a metal pipe or rod) connects with the back plate **28** and extends rearward. Optionally, insulation and/or lagging

32 is provided on the back side of the module **20**, for example contacting the back plate **28**, to reduce heat loss from the back side of the module **20**.

[0027] With reference back to the insets of FIG. **1**, solar receiver modules **20** are assembled to form the solar receiver **16** as a hollow cylindrical structure having an outward-facing (faceted) cylindrical surface **42** defined by adjoining planar front tube sheets **22** of the adjoining solar receiver modules **20**, and an inward-facing (faceted) cylindrical surface **48** defined by adjoining planar back plates **28** of the adjoining solar receiver modules **20**. The two cylindrical surfaces **42**, **48** define an annular gap **50**, which gap **50** is also indicated for the single solar receiver module **20** depicted in FIG. **2**. It will be appreciated from FIG. **2** that the light channeling tubes **26** of the solar receiver modules extend through the annular gap **50** between the two cylindrical surfaces **42**, **48**, and that the light beams **14** suitably input light into the light channeling tubes **26** through the apertures **24** in the outward-facing cylindrical surface **42**. The solar receiver modules **20** are suitably supported by their respective module support posts **30** on a truss or other support structure **52** secured to the tower **18**.

[0028] With continuing reference to FIGS. **1** and **2**, a flowing heat transfer medium **56** (diagrammatically indicated in FIG. **2** by a downward shaded block arrow) flows generally downward through the gap **50** under force of gravity. Additionally or alternatively, the flowing heat transfer medium can be fluidized with compressed air, which may improve contact between the heat transfer medium and tube surfaces to enhance heat transfer. The flowing heat transfer medium **56** thus flows over the exterior surfaces of the light channeling tubes **26**. These tubes **26** are preferably constructed so as to absorb most of the channeled light, for example by including suitable absorbing coatings on their inside surfaces, optional faceting to cause light to scatter within the light channeling tubes **26** so as to increase the number of opportunities for absorption, or so forth. Thus, the solar energy channeled through the light channeling tubes **26** is transferred into heat absorbed by the tubes **26** and then transferred to the flowing heat transfer medium **56**. In this manner, solar energy contained in the light beams **14** is converted to heat energy contained in the flowing heat transfer medium **56**, and thus the solar energy is contained as heat in the flowing heat transfer medium **66** that exits the bottom of the solar receiver **16**.

[0029] With particular reference back to FIG. **1**, the heated flowing heat transfer medium **56** exiting the bottom of the solar receiver **16** may be variously used. In the illustrative example, the heated flowing heat transfer medium **56** exiting the bottom of the solar receiver **16** feeds into a storage silo **57** and fluidized-bed boiler or heat exchanger **58** shown diagrammatically in FIG. **1**. The storage silo **57** provides thermal storage capability, as hot particles are stored in the silo **57** and may for example be used to provide thermal energy during cloudy days or at night. Thermal storage via the silo **57** decouples energy collection and power production thereby allowing dispatchable, continuous power production. The fluidized-bed boiler or heat exchanger **58** may, for example, comprise a bubbling fluidized bed (BFB) or circulating fluidized bed (CFB) boiler or heat exchanger or so forth, in which the heated flowing heat transfer medium **56** is dispersed on the fluidized bed so as to heat water (to form steam) or other working fluids such as air or supercritical CO_2 to drive a power cycle and turbine-generator (not shown) to produce electrical power or to perform other useful work.

[0030] The flowing heat transfer medium **56** is typically a flowing particulate medium such as silica sand or calcined flint clay (e.g. with average particle size on the order of a few hundred microns), but is not limited thereto (for example, it is contemplated to employ air as the flowing heat transfer medium). In typical embodiments in which the flowing heat transfer medium **56** is a flowing particulate medium, it is to be understood that this flowing particulate medium serves as the hot "fluid" which is dispersed onto the fluidized bed of the fluidized-bed boiler or heat exchanger **58**. Said another way, the term "fluid" as used herein in reference to the flowing heat transfer medium **56** encompasses flowing particulate media.

[0031] With reference to FIG. **1**, the flowing particulate medium is suitably returned to the top of the solar receiver **16** by any suitable elevator structure, for example driven by motors, diesel engines, or so forth. The top inset of FIG. **1** diagrammatically shows a suitable return structure **60** for this purpose comprising receiver bucket elevators and a solids distribution hopper.

[0032] With reference to FIG. **2**, the front tube sheet **22** and the back plate **28** define the gap **50** of the solar receiver module **20** through which the flowing heat transfer medium **56** flows over the exterior surfaces of the light channeling tubes **26**. Thus, the front tube sheet **22** and the back plate **28** should seal against leakage of the flowing heat transfer medium **56** outside of the module **20**. Moreover, the connections of the light channeling tubes **26** to the front tube sheet **22** should also seal against leakage of the flowing heat transfer medium **56** into either the apertures **24** or the light channeling tubes **26**, since any such leakage will introduce blockage into the light channeling tubes **26** and/or result in egress of the flowing heat transfer medium **56** outside of the solar receiver module **20**. Moreover, it will be appreciated that interfaces between adjoining modules **20** should be similarly sealed. That is, the interfaces between adjoining front tube sheets **22** of outward-facing cylindrical surface **42** and the interfaces between adjoining back plates **28** of the inward-facing cylindrical surface **48** should seal against leakage of the flowing heat transfer medium **56**, so as to seal against leakage from the annular gap **50** of the solar receiver **16**.

[0033] Another consideration is that the solar receiver **16** undergoes substantial thermal cycling during startup, shutdown, cloud transients and emergency trips. In some contemplated embodiments intended to operate a fluidized bed boiler or heat exchanger, the flowing heat transfer medium **66** is to be heated to a temperature of order 800° C. (1470° F.). Accordingly, the solar receiver **16** should be robust against thermal cycling over a range of 0° C.-800° C. in some embodiments, and over even larger temperature ranges in other contemplated embodiments.

[0034] With reference to FIGS. **3-8**, a suitable approach for assembling the solar receiver module **20** to address these design factors (provide a low stress thermal expansion) is described. FIGS. **3**, **5**, and **6** illustrate diagrammatic perspective views of assembly operations. FIG. **4** diagrammatically shows suitable welds used in the operation depicted in FIG. **3**. FIG. **7** shows an enlarged a diagrammatic side sectional view of one light channeling tube **26** of the assembled solar receiver module. FIG. **8** shows a diagrammatic perspective view of the front tube sheet **22**, with the inner perimeter of the necked-down portion of an aperture shown in an inset.

[0035] FIG. **3** shows a diagrammatic perspective view of a first assembly operation in which a small number (illustrative four) light channeling tubes **26** are welded to their respective corresponding apertures **24** of the front tube sheet **22**. The welded light channeling tubes **26** are optionally chosen to be centrally and adjacently located so as to minimize differential thermal expansion amongst the welded light channeling tubes **26**, although other selections of the light channeling tubes **26** to be welded are also suitable. FIG. **4** illustrates a suitable welding approach for the operation depicted in FIG. **3**. In this approach, each tube to be welded is force-fitted onto or into the mating opening of the front tube sheet **22**, and fillet welds **70** are formed by a suitable welding process. Some interior surfaces **72** may not be accessible for welding in the case of immediately neighboring welded tubes as shown in FIGS. **3** and **4** (although some of these surfaces could be accessible for welding if welding is performed before inserting adjacent tubes). In an alternative approach, the welded tubes are chosen to be spaced apart in the array, so that symmetrical and/or additional welds can be made on each tube in order to provide additional support/rigidity of the front tube sheet to resist wind loads for example.

[0036] FIG. **5** depicts a diagrammatic perspective view of a next operation in which the remaining light channeling tubes **26** are inserted into their corresponding apertures **24**, but are not welded. To this end, as seen in FIGS. **7** and **8** the back side of each aperture **24** of the front tube sheet **22** includes a necked-down portion **74** that defines an inside perimeter **76** facing the end of the light channeling tube **26**. As seen in FIG. **7**, the outer perimeter of the light channeling tube **26** is sized slightly smaller than the matching inside perimeter **76** of a necked-down portion **74** of the aperture **24**, and the insertion of the tube end into the necked-down portion **74** of the aperture **24** forms a slip joint **80** (labeled in FIG. **7**) between the end of the tube **26** and the aperture **24**. Other slip joint configurations are contemplated. For example, the tube can have a larger diameter than the necked-down portion of the aperture, in which case the necked down portion of the aperture fits inside the tube end. It is noted here that the light channeling tubes **26** may have various perimeter shapes, such as triangular, circular, square or diamond, regular or flared hexagonal, or so forth. In the illustrative example of FIGS. **3-8**, the light channeling tubes **26** have regular hexagonal perimeters and accordingly the inner perimeter **76** of the necked-down portion **74** of the aperture **24** is correspondingly hexagonal, as seen in the inset of FIG. **8**.

[0037] In the illustrative example of FIG. **8**, the apertures **24** also have hexagonal perimeters at the front side of the front tube sheet **22**, with the necking of each aperture **24** leading to the light input (i.e. front) side of the aperture **24** being flared outward or approximately conically expanding. This enhances light collection efficiency by the aperture **24**. Additionally, by making the apertures **24** with hexagonal perimeters at the front side of the front tube sheet **22**, they can form a honeycomb structure as seen in FIG. **8**, which maximizes the collection area of the front tube sheet **22** that collects light into the light channeling tubes **26**. Other geometries can be used, such as circular apertures, but such geometries will result in added "dead area" between the circular apertures that does not lead into the light channeling tubes thus reducing the efficiency of the receiver.

[0038] FIG. **6** depicts a next operation in which the back plate **28** is attached to the back ends of the light channeling tubes **26** by fasteners **82**, which may by way of illustrative example be washer/nut fasteners that connect with threaded studs **84** extending from the back ends of the light channeling tubes **26** (see FIG. **5**). With particular reference to FIG. **7**, in one configuration an end cap **86** including the threaded stub **84** is welded to the back end of the light channeling tubes **26**.

[0039] In the solar receiver module **20** fabricated in accord with the process described with reference to FIGS. **3-8**, each light channeling tube **26** is supported in cantilevered fashion from the back plate **28** by way of the fastener **82**, **84**. The front end of the light channeling tube **26** is laterally restrained by the slip joint **80**, but is free to expand or contract in the axial direction (that is, in the direction of the tube axis). This allows independent thermal expansion due to tubes operating at different temperatures and thus expanding to different lengths. In the case of the welded light channeling tubes **26** (those of FIGS. **3-4**), the thermal expansion of the tubes is not accommodated by a slip joint but rather has the effect of moving the front tube sheet **22** outward (during thermal expansion) or inward (during thermal contraction) in response to heating or cooling, respectively, of the solar receiver module **20**. The slip joints of the remaining (large majority) of light channeling tubes accommodates any differences in thermal expansion amongst the array of light channeling tubes **26**. The front tube sheet **22** is supported by all the light channeling tubes **26**, but is secured in the tube-axial direction only by the welded tubes of FIGS. **3-4**.

[0040] In an alternative embodiment, it is contemplated to employ separate designated tie rods (not shown) welded between the back plate **28** and the front tube sheet **22** to provide the tube-axial direction support, rather than obtaining this axial support by welding designated light channeling tubes **26** as in the operation of FIGS. **3-4**. This alternative approach employing tie rods has the advantage of employing the slip joints **74** for all of the light channeling tubes **26** (as none are welded to the front tube sheet **22** in this alternative embodiment), but perhaps at the cost that some light receiving area is lost (i.e. select tubes removed to make room for tie rods) to accommodate the designated tie rods. Additionally, the impact of the tie rods on the flow paths of the flowing heat transfer medium **56** should be taken into account in performing numerical thermal analyses.

[0041] With particular reference to FIGS. **7** and **8**, the front tube sheet **22** provides the front seal between tubes within a module for the gap **50** (see FIG. **2**). To this end, the hexagonal aperture perimeters at the front side of the front tube sheet **22** which form the honeycomb structure seen in FIG. **8** are joined to create the seal. In one contemplated approach, the front tube sheet **22** is formed by punching hexagonal openings corresponding to the apertures **24** into a single metal sheet (e.g. single steel sheet) and then working the openings using sheet metal forming tooling to define the necked-down portion **74**.

[0042] With reference to FIG. **7**, in another contemplated approach, each hexagonal aperture **24** is separately formed from sheet metal, with the six sides of the hexagonal perimeter being flat sides **87**. The flat sides **87** of each pair of adjoining apertures are then welded together to assemble the front tube sheet **22**. Other approaches are contemplated. For example, in a variant approach the sides are flat on one to four of the segments of the hexagonal perimeter around the perimeter of the module and straight on the remaining segments where two apertures adjoin. In this case, only the edges of each adjoining apertures are welded together to assemble the front tube sheet **22**. As yet another variant, it is contemplated to employ separate or integral tube cap pieces that are welded to the back end of the tube or formed as part of the tube to facilitate making good seals.

[0043] The illustrative solar receiver module assembly approach described with reference to FIGS. **3-8** addresses both flow sealing and thermal expansion design considerations within the module.

[0044] With reference to FIGS. **9-13**, approaches are described for assembling the solar receiver modules **20** to form the overall solar receiver **16** while addressing both flow sealing and thermal expansion design considerations between adjoining modules. FIG. **9** illustrates a diagrammatic perspective view of a solar receiver module **20** in isolation, with thermal expansion directions indicated diagrammatically by arrows. (Note that in FIG. **9** the apertures are omitted in depicting the front tube sheet **22**). FIG. **10** illustrates a diagrammatic side sectional view of a portion of the solar receiver **16** including four solar receiver modules **20** mounted by their respective module support posts **30** to a support column **88**, for example using bolted connections or other fastening methods. The support column **88** may, for example be a vertical column of the truss or other support structure **62** (see FIG. **1**). Because each module is mounted via the module support post **30** which is centrally located (see FIGS. **2** and **10**), the thermal expansion of the module in the height and width direction is reduced compared to a top, bottom, or side supported module during heating of the solar receiver module **20** (FIG. **9**), which makes it easier to seal between adjoining modules because they thermally expand from their central support point. Individual module support posts also eliminate the need for a buckstay system of the type employed with top supported modules to resist wind and earthquake loads.

[0045] In addition, this approach enables the use of smaller tube modules, which results in smaller solar heat flux gradients across the face of the module, more uniform operating metal temperatures, lower thermal stresses and reduced potential for thermal distortion compared to larger modules with larger face areas.

[0046] With reference to FIG. **11** which shows a diagrammatic perspective view of the front tube sheet **22** and light channeling tubes **26** of five modules **20**, the hexagonal apertures **24** of neighboring modules are arranged so that jagged edges **90** of adjoining solar receiver modules **20** mesh together, that is, with "slots" of one jagged edge receiving "bumps" of the other jagged edge. The adjoining modules **20** are designed to fit snugly together at non-operational temperature (typically room temperature) to form a seal without employing a sealant material. When brought up to operating temperature, the isotropic thermal expansion of the modules **20** about their respective centrally located module support posts **30** causes the snug fit to become tighter at operational temperature. The aperture perimeters at the jagged edges **90** include the flat sides to increase contact area to create a seal.

[0047] While using the foregoing approaches is expected to provide suitable sealing between adjoining modules **20** at their front sides, it is additionally or alternatively contemplated to employ a high temperature sealant material. However, interposing sealing material between the modules reduces the active area and thus efficiency of the solar receiver **16** for collecting and channeling light.

[0048] With reference to FIGS. **12** and **13** which show diagrammatic perspective and diagrammatic back views, respectively, of a portion of the solar receiver **16** including a 4×2 array of modules **20**, the sealing between adjoining modules **20** at the back side is also required. In illustrative FIGS. **12** and **13** the back plates **28** include contoured edges **92** (e.g. sawtooth at top and bottom and pumpkin tooth edges at sides to match the contour of the tubes) that mesh together but with clearance in the non-operating condition to allow thermal expansion and prevent interference of back plates **28** between adjoining modules in the operating condition. As shown in FIG. **13**, the gap between back plates **28** along the edges and corners are then sealed with seal strips **94** and corner seal plates **96** respectively that are bolted to one but not both adjoining modules as shown to allow free thermal expansion of the back plates **28**. Unlike the case for the front side, however, there is no concern about additional sealing features blocking light at the back side.

[0049] An advantage of the disclosed solar receiver modules **20** is that individual modules are readily removed for repair or replacement. At non-operating temperature the modules **20** have thermally contracted to their smallest configuration, and an individual module can be removed by disconnecting its module support post **30** from the column **88** (see FIG. **10**, or more generally by disconnecting the support post from the module back plate) and pulling the module out. This is facilitated if no sealing material is employed at interfaces between adjoining modules. To facilitate such removal, in the embodiment of FIG. **13** each sealing strip **94** is removable and is attached by fasteners to only one of the two adjoining modules **20**, and at meeting corners a removable corner cover sealing plate **96** is attached to one of the sealing strips **94**. This reduces the number of sealing strips that must be removed to pull out an individual module. Additionally, by securing each sealing element **94**, **96** to only one module, a slip joint is effectively formed so that thermal expansion is accommodated. Repair and replacement of individual light channeling tubes **26** is similarly simplified by the disclosed assembly. To replace a light channeling tube **26**, the center support tubes are unbolted from the back plate. These are the light channeling tubes that are welded to the front tube sheet **22** as described with reference to FIGS. **3** and **4**. (In alternative embodiments in which separate tie rods are employed, these are unbolted from the back plate). The front tube sheet **22** is thereby released so that the slip fitted tubes **26** can unbolted and removed and replaced. To replace one of the support tubes which is welded to the front tube sheet **22**, some of the surrounding support tubes may need to be removed to gain access to break the welds to the tube sheet.

[0050] In similar fashion, it is contemplated to modularize the insulation and/or lagging **32** (FIG. **10**) on the back side of the module **20**, for example by employing a piece of insulation/lagging for each module, or for each set of four neighboring modules, or so forth. The insulation/lagging **32** does not perform any sealing function, and may for example be blanket-type insulation with ship lapped edges to reduce heat loss.

[0051] Illustrative embodiments including the preferred embodiments have been described. While specific embodiments have been shown and described in detail to illustrate the application and principles of the invention and methods, it will be understood that it is not intended that the present invention be limited thereto and that the invention may be embodied otherwise without departing from such principles. In some embodiments of the invention, certain features of the invention may sometimes be used to advantage without a corresponding use of the other features. Accordingly, all such changes and embodiments properly fall within the scope of the following claims. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the present disclosure be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

We claim:

1. A solar receiver module comprising:

a front tube sheet including light apertures;

a back plate cooperating with the front tube sheet to define a sealed gap; and

light channeling tubes having first ends optically coupled with the light apertures and extending through the gap and having second ends connected with the back plate.

2. The solar receiver module of claim **1** further comprising a flowing or fluidized heat transfer medium disposed in the gap over exterior surfaces of the light channeling tubes.

3. The solar receiver module of claim **2** wherein the flowing or fluidized heat transfer medium comprises a flowing particulate medium such as silica sand or calcined flint clay.

4. The solar receiver module of claim **1** further comprising slip joint engagements between light apertures of the front tube sheet and first ends of most or all of the light channeling tubes.

5. The solar receiver module of claim **4** wherein each slip joint is defined by an inner or outer perimeter of the light aperture receiving the first end of the light channeling tube.

6. The solar receiver module of claim **4** wherein each slip joint is defined by the inner or outer perimeter of a necked down portion of the light aperture receiving the first end of the light channeling tube.

7. The solar receiver module of claim **4** comprising slip joint engagements between light apertures of the front tube sheet and first ends of all but a sub-set of the light channeling tubes, the solar receiver further comprising:

welds between light apertures and the first ends of the sub-set of the light channeling tubes.

8. The solar receiver module of claim **7** wherein the sub-set of the light channeling tubes consists of one or more light channeling tubes.

9. The solar receiver module of claim **4** wherein there are slip joint engagements between light apertures of the front tube sheet and first ends of all of the light channeling tubes and the solar receiver module further comprises:

tie rods welded between the back plate and the front tube sheet.

10. The solar receiver module of claim **4** wherein the light channeling tubes are cantilever-supported by the second ends connected with the back plate.

11. The solar receiver module of claim **4** wherein the second ends of the light channeling tubes are connected with the back plate by threaded studs extending from the second ends of the light channeling tubes.

12. The solar receiver module of claim **1** wherein the front tube sheet comprises said light apertures formed from bent sheet metal and having outer perimeters that are welded together.

13. The solar receiver module of claim **1** wherein the front tube sheet comprises single-piece sheet metal having said light apertures punched into the single-piece sheet metal.

14. The solar receiver module of claim **1** wherein the light apertures have triangular, circular, square or diamond, regular or flared hexagonal cross-sections.

15. The solar receiver module of claim **1** wherein the back plate comprises a metal plate.

16. The solar receiver module of claim **1** wherein the light channeling tubes comprise drawn tubes, extruded tubes, or bent sheet metal welded tubes.

17. The solar receiver module of claim **1** further comprising:

a module support post extending away from the back plate on the opposite side of the back plate from the front tube sheet;

wherein the module support post is secured at a center of the back plate.

18. A solar receiver comprising a plurality of solar receiver modules as set forth in claim **1** arranged with adjoining front tube sheets and adjoining back plates to define the solar receiver with an outward facing surface defined by the adjoining front tube sheets and an inward facing surface defined by the adjoining back plates and further having an annular gap between the outward facing surface and the inward facing surface.

19. The solar receiver of claim **18** wherein the solar receiver does not include sealing material interposed between the adjoining front tube sheets.

20. The solar receiver of claim **18** wherein the front tube sheets have jagged edges defined by peripheral light apertures with flat sides, and the jagged edges with flat sides of adjoining front tube sheets mesh together.

21. The solar receiver of claim **18** further comprising:

sealing strips disposed at interfaces between adjoining back plates.

22. The solar receiver of claim **21** wherein each sealing strip is attached to only one of any two adjoining solar receiver modules.

23. A solar power generation system comprising:

a solar receiver as set forth in claim **18**;

a flowing or fluidized heat transfer medium disposed in the annular gap over exterior surfaces of the light channeling tubes of the solar receiver modules; and

a fluidized-bed boiler or heat exchanger arranged to receive heated heat transfer medium from the solar receiver.

24. A method of operating a solar receiver as set forth in claim **18**, the method comprising:

disposing a flowing or fluidized heat transfer medium in the annular gap of the solar receiver over exterior surfaces of the light channeling tubes of the solar receiver modules; and

operating heliostats to concentrate solar energy onto the solar receiver wherein the concentrated solar energy is effective to induce thermal expansion of the solar receiver modules.

25. The method of claim **24** wherein the solar receiver modules have slip joint engagements between light apertures of the front tube sheet and first ends of most or all of the light channeling tubes that accommodates thermal expansion of the solar receiver modules.

26. The method of claim **24** wherein each solar receiver module further comprises a module support post secured at a center of the back plate and extending inward from the inward facing surface defined by the adjoining back plates whereby thermal expansion of the solar receiver modules increases sealing force between adjoining front tube sheets.

27. A method of performing maintenance on the solar receiver of claim **18**, the method comprising:

disconnecting a solar receiver module support post from the back plate or a support column; and pulling the disconnected solar receiver module out of the solar receiver.

28. A method of performing maintenance on the solar receiver module of claim **1**, the method comprising:

removing a connection between the light channeling tubes and the back plate of the solar receiver module;

removing the front tube sheet of the solar receiver module by operations including disengaging slip joint engagements between light apertures of the front tube sheet and first ends of light channeling tubes wherein after removal of the front tube sheet the light channeling tubes remain cantilever-supported by the connections of their second ends with the back plate; and

removing a selected light channeling tube by disconnecting the second end of the selected light channeling tube from the back plate.

29. The method of claim **28** wherein removing the front tube sheet of the solar receiver module further comprises:

breaking welds between axial support light channeling tubes and the front tube sheet.

30. The method of claim **28** wherein removing the front tube sheet of the solar receiver module comprises:

disconnecting tie rods connecting the back plate and the front tube sheet.

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