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(54) **Title**: HEAT STORAGE DEVICES AND CIRCUITS FOR SOLAR STEAM GENERATION, AND ASSOCIATED SYSTEMS AND METHODS

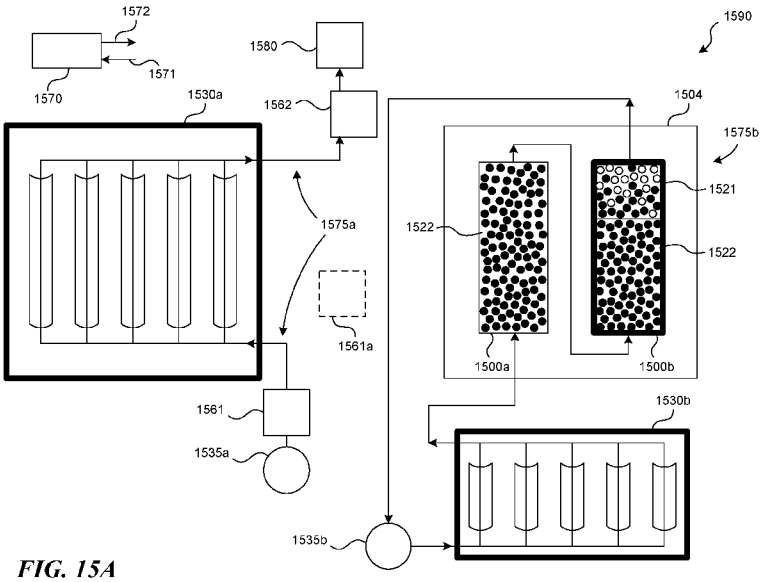


FIG. 15A

(57) **Abstract**: Heat storage devices and circuits suitable for storing solar energy, and associated systems and methods are disclosed. Representative systems can include a solar energy collection system having a first solar field coupled between a first working fluid source and a target heat user via first fluid network, at least one heat storage device, and a second solar field coupled to the at least one heat storage device via a second fluid network. The second fluid network carries a second working fluid and is isolated from fluid communication with the first fluid network. At least one heat exchanger is coupled to the first and second fluid networks to provide thermal communication between the first and second fluid networks.

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HEAT STORAGE DEVICES AND CIRCUITS FOR SOLAR STEAM GENERATION, AND ASSOCIATED SYSTEMS AND METHODS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present application claims priority to pending U.S. Provisional Application No. 62/298,409, filed on February 22, 2016 and incorporated herein by reference.

TECHNICAL FIELD

[0002] The present technology is directed generally to techniques for storing the energy produced by solar concentrators, including methods and devices for economical and robust heat storage, and associated systems.

BACKGROUND

[0003] As fossil fuels become more scarce, the energy industry has developed more sophisticated techniques for extracting fuels that were previously too difficult or expensive to extract. One such technique includes injecting steam into an oil-bearing formation to free up the oil. For example, steam can be injected into an oil well and/or in the vicinity of the oil well. The high temperature of the steam heats up the adjacent formation and oil within the formation, thereby decreasing the viscosity of the oil and enabling the oil to more easily flow to the surface of the oil field. To make the process of oil extraction more economical, steam can be generated from solar power using, for example, solar power systems with concentrators (e.g., mirrors) that direct solar energy to a receiver (e.g., piping that contains a working fluid). The concentrators focus solar energy from a relatively large area (e.g., the insolated area of the mirror) to a relatively small area of the receiver (e.g., axial cross-sectional area of a pipe), thereby producing a relatively high energy flux at the receiver. As a result, the working fluid changes its phase (e.g., from water to steam) while flowing through the receiver that is subjected to a high energy flux. Generally, a steady supply of steam is preferred at an oil field for a steady production of oil. However, the production of steam by solar concentrators is a function of solar insolation, which is intrinsically cyclical (e.g., day/night, sunny/cloudy, winter/summer, etc.). Therefore, in

some field applications, the solar power systems include solar heat storage devices that can store excess energy when the insolation is high and release energy when the insolation is small or nonexistent. An example of such a system is described below.

[0004] Figure 1 is a schematic view of a system for generating steam in accordance with the prior art. In the illustrated system, the sun 13 emits solar radiation 14 toward a curved concentrator (e.g., a mirror) 11 that has a line focus corresponding to the location of a receiver 12. As a result, the solar radiation 14 from a relatively large curved concentrator 11 is focused on a relatively small area of the receiver 12. As water W flows through the receiver 12, the highly concentrated solar energy causes a phase change from water W to steam S. A first portion of the steam (S1) is directed to an oil well 18 or its vicinity and a second portion of the steam (S2) is directed to a heat exchanger 15. A valve V maintains a suitable balance between the flows of steam S1 and S2. For example, the valve V can be fully closed when the steam production is relatively low, and all available steam is directed to the oil well 18. When there is excess steam available (e.g., during a period of high insolation), the second portion of steam S2 enters the heat exchanger 15, exchanges thermal energy E with a working fluid WF, which can be, for example, steam or thermal oil, and returns to the entrance of the receiver 12. Depending on the exchange of energy E in the heat exchanger 15, the temperature of the second portion of steam (S2) may still be higher than that of the water W, thereby decreasing the amount of solar energy that the water W would otherwise require to change its phase to steam.

[0005] As explained above, when the insolation is relatively high, the temperature of the second portion of steam (S2) is sufficiently high to transfer thermal energy to the working fluid WF in the heat exchanger 15. The working fluid WF then transfers thermal energy to a heat storage unit 16. Conversely, when the insolation is relatively low, the temperature of the second portion of steam (S2) is also relatively low, and the second portion of steam (S2) receives thermal energy from the working fluid WF in the heat exchanger 15. Overall, thermal energy that is stored in the heat storage device 16 when the insolation is relatively high is transferred back to steam when the insolation is relatively low. This transfer of thermal energy to and from the heat storage device 16 promotes a

more even flow of the first portion of steam S1 at the oil well 18. Some examples of the prior art heat storage devices are described in the following paragraphs.

[0006] Figure 2 illustrates a portion 20 of a heat storage device in accordance with the prior art. In the portion 20 of the heat storage device (e.g., the heat storage device 16 of Figure 1), concrete blocks 22 surround pipes 21. When the temperature of the working fluid WF is relatively high, the flow of the working fluid WF through the pipes 21 heats up the adjacent concrete blocks 22. This part of the thermal cycle generally occurs during a period of high insolation. Conversely, when the insolation is low, the concrete blocks 22 heat the working fluid WF, which then transfers energy back to the water/steam in the heat exchanger 15 (Figure 1). Accordingly, the heat storage device 16 recovers some thermal energy to smooth the distribution of the thermal energy. However, the illustrated system has some drawbacks. For example, the pipes 21 are relatively expensive, making the overall heat storage device 16 expensive. Due to a relatively dense distribution of the pipes 21, the amount of working fluid WF contained in the heat storage device 16 can be relatively high which further increases cost of the heat storage device 16. Furthermore, the rate of heat transfer can be poor at the junction between the pipes 21 and the concrete blocks 22, therefore reducing the efficiency of the heat storage process.

[0007] Figure 3 is a partially schematic cross-sectional view of another heat storage device 30 in accordance with the prior art. A first working fluid WF1 (e.g., steam or oil) flows through a piping system 33 and exchanges thermal energy with a second working fluid WF2 (e.g., oil) contained in the heat storage device 30. The second working fluid WF2 can be heated by the first working fluid WF1 during periods of high insolation and the first working fluid WF1 can be heated by the second working fluid WF2 during periods of low insolation. In general, the second working fluid WF2 can absorb relatively large amount of heat without having to be pressurized due to its relatively high heat capacity and boiling point. Because the second working fluid WF2 is generally expensive, relatively inexpensive concrete plates 31 can be inserted in the heat storage device 30 to reduce the required volume of the second working fluid WF2 inside the heat storage device 30. To improve the heat transfer to/from the concrete plates 31, pumps 32 circulate the second working fluid WF2 within the heat storage device 30. However, the flow of the second

working fluid WF2 around the concrete plates 31 can still vary significantly, resulting in thermal non-uniformities when heating/cooling the concrete plates 31, thereby reducing the thermal capacity of the system. Furthermore, the pumps 32 are potential points of failure within the overall system. Accordingly, there remains a need for inexpensive and thermally efficient heat storage devices that can facilitate solar heat storage and recovery.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Figure 1 is a schematic view of a system for generating steam in accordance with the prior art.

[0009] Figure 2 illustrates portion of a heat storage device in accordance with the prior art.

[0010] Figure 3 is a partially schematic cross-sectional view of a heat storage device in accordance with the prior art.

[0011] Figures 4A-4C are partially schematic cross-sectional views of a heat storage device in accordance with an embodiment of the presently disclosed technology.

[0012] Figures 5A and 5B are partially schematic views of an arrangement of plates for a heat storage device in accordance with an embodiment of the presently disclosed technology.

[0013] Figures 6A-6C are schematic views of a mold for manufacturing a heat storage device in accordance with embodiments of the presently disclosed technology.

[0014] Figures 7A and 7B are partially schematic isometric views of sacrificial sheets used to manufacture heat storage devices in accordance with embodiments of the presently disclosed technology.

[0015] Figures 8A and 8B are partially schematic isometric views of a heat storage device in accordance with an embodiment of the presently disclosed technology.

[0016] Figure 9 is a schematic illustration of an arrangement of heat storage devices in accordance with an embodiment of the presently disclosed technology.

[0017] Figure 10A is a partially schematic, isometric illustration of a heat storage device configured in accordance with an embodiment of the present technology.

[0018] Figure 10B is a partially schematic, isometric illustration of a plurality of composite heat storage devices, each of which can include one or more heat storage devices, and together can form a heat storage facility in accordance with an embodiment of the present technology.

[0019] Figure 10C is a partially schematic illustration of a representative composite heat storage device illustrating temperature zones in accordance with an embodiment of the present technology.

[0020] Figure 10D is a flow diagram illustrating a process for collecting solar energy in accordance with an embodiment of the present technology.

[0021] Figures 11A-11K are schematic diagrams of a system that includes a heat storage device operating in accordance with embodiments of the present technology.

[0022] Figure 12 is a graph illustrating the effect of storing and releasing heat in accordance with embodiments of the present technology.

[0023] Figure 13 is a schematic illustration of a solar collection and storage system that includes multiple solar fields configured in accordance with an embodiment of the present technology.

[0024] Figures 14A-14B illustrate processes for storing and releasing heat via a system of the type shown in Figure 13, in accordance with embodiments of the present technology.

[0025] Figures 15A-15O are schematic illustrations of a solar collection and storage system that includes multiple solar fields configured in accordance with further embodiments of the present technology.

DETAILED DESCRIPTION

1.0 Introduction

[0026] Specific details of several embodiments of representative heat storage technologies and associated systems and methods for manufacture and use are described below. Heat storage technology can be used in conjunction with solar energy systems in oil fields, electrical power generation, residential or industrial heating, and other uses. Embodiments of the present technology can be used to store excess energy at, for example, periods of high insolation, and also for supplementing production of steam at, for example, periods of low insolation. A person skilled in the relevant art will also understand that the technology may have additional embodiments, and that the technology may be practiced without several of the details of the embodiments described below with reference to Figures 4A-14B.

[0027] Briefly described, methods and systems for storing thermal energy (heat) are disclosed. The disclosed methods and systems enable cost effective and robust storage/recovery of heat energy. In contrast with the conventional heat storage devices described above, the present technology uses thin members (e.g., thin plates) that are spaced closely together. The relatively thin members (e.g., thin concrete plates) have a more uniform temperature distribution in the thickness direction than do thicker plates. As a result, the thin plates can store larger amounts of heat per unit weight, with the entire cross-section of the plates being at or close to isothermal conditions. Such plates can store and release heat faster because the final temperature gradient is established faster for a thin plate than for a thick plate made of the same material. Additionally, the relatively thin, closely spaced plates have a relatively large area for heat exchange, resulting in a faster heat storage/release process. Furthermore, the disclosed methods and systems control the flow of the working fluid (e.g., a thermal oil) to be within a generally laminar flow regime, which is beneficial because the pressure drops in the laminar flow regime are smaller than those associated with turbulent flow regimes. In contrast with the present technology, conventional technologies rely on turbulent flows that result in higher coefficients of heat transfer (generally a desirable outcome), but at the cost of significantly higher pressure drops in the system. With the present technology, the laminar flow is facilitated by generally small distances between the adjacent plates and, at least in some embodiments, by controllers that limit the flow rate of the working fluid in the spaces between the adjacent plates. In several embodiments, the potential downside of the lower

heat transfer coefficient of the laminar flow is more than offset by the benefit of the lower pressure drops in the system.

[0028] In some embodiments of the present technology, the thin plates can be manufactured at the installation site. For example, a sacrificial material (e.g., wax sheets) can be spaced apart within a mold and then concrete can be added into the mold. After the concrete in the mold solidifies (e.g., to form concrete plates), the sacrificial material can be removed (e.g., by melting). Manufacturing at the installation site reduces the transportation costs for the generally large and heavy heat storage devices. In at least some embodiments, the sacrificial material can have apertures that enable interconnections between the concrete plates in the mold. After the concrete poured in the mold solidifies and the sacrificial material is removed, the interconnected concrete plates can have (1) improved crack resistance due to additional structural strength of the connections between the plates, and/or (2) improved heat transfer due to the additional heat transfer area that the connections create in the flow of working fluid.

[0029] In the following discussion, Section 2.0 describes representative heat storage devices, generally with reference to Figures 4A-9. Section 3.0 describes representative systems that incorporate heat storage devices, generally with reference to Figures 10A-14B.

[0030] Many embodiments of the technology described below may take the form of computer- or controller-executable instructions, including routines executed by a programmable computer or controller. Those skilled in the relevant art will appreciate that the technology can be practiced on computer/controller systems other than those shown and described below. The technology can be embodied in a special-purpose computer, controller or data processor that is specifically programmed, configured or constructed to perform one or more of the computer-executable instructions described below. Accordingly, the terms "computer" and “controller” as generally used herein refer to any data processor and can include Internet appliances and hand-held devices (including palm-top computers, wearable computers, cellular or mobile phones, multi-processor systems, processor-based or programmable consumer electronics, network computers,

mini computers and the like). Information handled by these computers can be presented at any suitable display medium, including a CRT display or LCD.

[0031] The technology can also be practiced in distributed environments, where tasks or modules are performed by remote processing devices that are linked through a communications network. In a distributed computing environment, program modules or subroutines may be located in local and remote memory storage devices. Aspects of the technology described below may be stored or distributed on computer-readable media, including magnetic or optically readable or removable computer disks, as well as distributed electronically over networks. Data structures and transmissions of data particular to aspects of the technology are also encompassed within the scope of the embodiments of the technology.

2.0 Representative Heat Storage Devices

[0032] Figure 4A is a partially schematic cross-sectional view of a heat storage device 400 configured in accordance with an embodiment of the presently disclosed technology. The heat storage device 400 can include plates 431 (e.g., concrete plates) spaced apart and arranged in a housing 410, an inlet pipe 413 connected to an inlet manifold 414, and an outlet pipe 423 connected to an outlet manifold 424. In some embodiments, the plates 431 can be generally parallel and equidistant. In operation, a flow (indicated by a flow arrow 411) of the working fluid WF (e.g., thermal oil) can enter the heat storage device 400 through the inlet pipe 413. In some embodiments, the inlet manifold 414 has a larger cross section than that of the inlet pipe 413. Therefore, as the working fluid WF enters the inlet manifold 414, the velocity of the working fluid WF decreases and the pressure increases, resulting in a more uniform discharge of the working fluid through openings 412 spaced along the manifold 414. As a result, the flow of the working fluid leaving the manifold 414 and approaching the plates 431 can also be more uniform.

[0033] Channels 441 between the adjacent plates 431 can be sized to facilitate a predominantly laminar flow in the channels. For example, in some embodiments the velocity of the working fluid and spacing between the plates 431 can be selected such that the Reynolds number (i.e., [velocity of the fluid] x [characteristic dimension of the flow

passage] / [kinematic viscosity of the fluid]) is smaller than 2,000 - 5,000. The term "predominantly laminar" in this disclosure encompasses flows that may be turbulent or separated in some regions, e.g., close to the outer edges of the plates 431, but are mostly laminar between the plates 431. In some embodiments of the present technology, the spacing between the adjacent plates 431 (i.e., the width of the channels 441) can be 1-2 mm. Such a spacing between the plates can also prevent an excessively low Reynolds number (e.g., less than about 3), where the viscous forces would dominate the flow and the flow between the plates 431 would be too slow.

[0034] The predominantly laminar flow in the flow channels 441 can result in relatively low pressure drops within the heat storage device 400. As a result of the relatively low pressure drops, the thermal performance of the heat storage device 400 can be less sensitive to imperfections and nonuniformities in the size/shape of the channels 441. That is, the velocity of the working fluid varies with the nonuniformities in the size/shape of the channels 441, but these variations are generally less pronounced for laminar flow than for turbulent flow. Since the heat transfer to/from the plates 431 is a function of the velocity of the working fluid, the variations in in the heat transfer to/from the plates 441 will also be smaller as a result of the laminar flow in the channels 441.

[0035] After flowing through the channels 441, the working fluid WF can enter the outlet manifold 424 through openings 422. As explained in relation to the inlet manifold 414, a relatively large diameter of the outlet manifold 424 reduces the velocity of the working fluid therefore increasing the uniformity of the flow across the heat storage device 400. The working fluid WF can leave the heat storage 400 through the outlet pipe 423 as indicated by a flow arrow 421, and can flow back to the solar heating system.

[0036] As described above, the plates 431 can be relatively thin. For example, in some embodiments, the thickness of an individual plate 431 can be 10-20 or 20-30 mm. The relatively thin plates 431 produce a relatively large overall plate surface area for a given volume of the heat storage device 400. Since heat is transferred between the working fluid WF and the plates 431 through the surface area of the plates 431, a large total surface area of the plates 431 (relative to their volume) improves the transfer of heat into and out of the plates. This improved heat transfer can, for example, reduce the time to

fully warm up or cool down plates 431, thereby increasing the thermal efficiency of the heat storage device 400. Furthermore, the temperature gradients in the thickness direction of the plates 431 are expected to be more uniform from one plate to another than for thick plates. For an individual plate, the temperature gradients are expected to be shallower, allowing the thin plates to reach equilibrium more quickly than would the thick plates. In at least some embodiments, the plates may be designed to have temperature distribution in the direction of the thickness of the plate within +/- 5% or +/- 1% of the average temperature in the direction of thickness at a given height of the plate (i.e., the temperature being within 5% or 1% of the isothermal condition in the direction of the thickness). In other embodiments the temperature distributions can be different, for example, the temperature distribution can be within +/- 10% of the average temperature in the direction of the thickness of the plate. With the thick plates used in the conventional technology, such a narrow temperature distribution across the thickness of the plates is generally not achievable within the typical daily insolation cycles.

[0037] In at least some embodiments, the working fluid WF can withstand relatively high temperatures (e.g., 300ºC or higher) without being pressurized, so as to transfer a large amount of energy to the plates 431. In some embodiments, the working fluid WF can be a molten salt capable of operating at even higher temperatures (e.g., 500ºC or higher). An optional coating, cladding or other encapsulant or enclosure can provide insulation around all or a portion of the heat storage device 400. For example, the insulation can include an air barrier, woven insulation, blown insulation, a ceramic barrier, and/or another suitable configurations.

[0038] Figures 4B and 4C are partially schematic views of the plates of a heat storage device 400 configured in accordance with an embodiment of the presently disclosed technology. Collectively, Figures 4B and 4C illustrate balancing the flow of the working fluid through the channels 441. In at least some embodiments, the direction of the flow of the working fluid can be downward when the working fluid transfers heat to the plates 431 (e.g., when the insolation is relatively high), and upward when the plates 431 transfer heat to the working fluid (e.g., when the insolation is relatively low). For example, the direction of the flow in Figure 4B is from the top to the bottom, which can be

representative of the plates 431 being heated by the working fluid (e.g., the working fluid is warmer than the plates 431). The direction of the flow in Figure 4C is from the bottom to the top, that is the plates 431 can be cooled down by the working fluid (e.g., the working fluid is colder than the plates 431.) The direction of the gravitational force is from the top to the bottom in both Figures 4B and 4C. The channels 441 can have a non-uniform width due to, for example, manufacturing errors or tolerances. For example, in Figures 4B and 4C the leftmost channels have width W_1 that is larger than the width W_2 of the rightmost channels. Generally, relatively wide channels having width W_1 would result in a relatively larger working fluid velocity U_1 due to smaller pressure drops associated with the wider channels. Conversely, relatively narrow channels having width W_2 would result in a relatively smaller working fluid velocity U_2. Such a non-uniformity in the working fluid velocity may be undesirable because, for example, some plates 431 would be heated/cooled too fast or too slow in comparison with the other plates 431. For example, during a heating cycle, a plate 431 that is adjacent to a wide channel, may be heated faster than the rest of the plates in the thermal storage 400, leading to a flow of the warm working fluid through the wide channel that, at least for a part of the cycle, does not transfer heat from the working fluid to the plate (e.g., after the plate is fully warmed up). The undesirable non-uniformities in the working fluid flow/plate temperature can be at least partially offset as explained below.

[0039] As explained above, a channel with a larger width W_1 generally promotes a relatively larger working fluid velocity U_1, and a narrower channel width W_2 generally promotes a relatively smaller working fluid velocity U_2. In at least some embodiments, for the relatively thin plates 431 the heat transfer from the working fluid to the plates can be relatively fast, i.e., the plates reach the temperature of the working fluid relatively fast. For example, in Figure 4B the higher fluid velocity U_1 heats the vertical length of the plates in the channel (e.g., the leftmost plate) faster than the lower fluid velocity U_2 (e.g., the rightmost plate). As a result, the portion of the vertical length of the plates 431 at a relatively high temperature T_H is larger for the plates of the wider channel W_1 than the corresponding portion T_H for the plates of the narrower channel W_2. The working fluid at a higher temperature also has a lower viscosity and lower density than the working fluid at a lower temperature. Therefore, an overall relatively warmer fluid in the channel W_1 has

overall relatively smaller viscosity v_1 and smaller density ρ_1 in comparison to the (overall) relatively colder fluid in the channel W_2. The lower viscosity v_1 corresponding to the working fluid in the channel W_1 further promotes faster velocity of the working fluid in comparison to the working fluid in the channel W_1. However, the overall warmer fluid in the channel W_1 also experiences a higher buoyancy, which can at least partially counteract the higher velocity of the working fluid in the channel W_1. Namely, the flow direction that the buoyancy promotes is from the bottom to the top, i.e., in the direction opposite from the direction of the gravitational force. Due to a relatively smaller density ρ_1 in the channel W_1, the buoyancy effect will be more pronounced in the channel W_1 than in the channel W_2. Therefore, in at least some embodiments of the present technology, the buoyancy of the working fluid in the channels 431 can make the flow in the channels having different widths (e.g., W_1 and W_2) at least substantially uniform.

[0040] In Figure 4C, the flow of the working fluid in the two channels having different widths (W_1 and W_2) is from the bottom of the page to the top of the page, and is opposite from the direction of the gravitational force. As explained above, the pressure drop coefficient for a wider channel is generally smaller than the pressure drop coefficient for a corresponding narrow channel, thus generally promoting a higher working flow velocity in the wider channel. In some embodiments, the working fluid entering the channels can be colder than the plates 431, therefore heat is transferred from the plates 431 to the working fluid. As explained above, cooling the plates 431 with a relatively faster flow velocity U_1 in the wide channel W_1 generally results in a longer vertical length of the plates 431 being at a relatively cold temperature T_C. Conversely, a relatively slower flow velocity U_2 in the narrow channel W_2 results in a shorter length of the plates 431 being at a relatively cold temperature T_C. Since the density of the working fluid in the channels 441 is proportional to the (overall) temperature of the working fluid in the channel, an average density ρ_1 of the working fluid in the wider channel W_1 is higher (due to the overall lower temperature of the working fluid) than the corresponding average density ρ_2 of the working fluid in the more narrow channel W_2 (due to the overall higher temperature of the working fluid). For a vertical column of the working fluid, the relatively higher density ρ_1 results in a relatively higher pressure head in the wider channel W_1, and the relatively lower density ρ_2 results in a relatively lower pressure head in the narrower channel W_2. As a result, the higher

pressure head in the wider channel W_1 tends to reduce the working fluid velocity U_1 in the wider channel, and the lower pressure head in the narrower channel W_2 tends to promote (increase) the working fluid velocity U_2 in the narrower channel. As a consequence, the differences in the pressure heads of the wider channel W_1 and narrow channel W_2 promote a generally uniform flow (or at least a more uniform flow) within the channels having different widths.

[0041] Figures 5A and 5B are partially schematic views of an arrangement of plates for a heat storage unit in accordance with an embodiment of the presently disclosed technology. Figure 5A illustrates the plates 431, e.g., concrete plates. Figure 5B schematically illustrates the expected thermal expansion of a plate 431 as it undergoes heating during normal use. In a particular embodiment, the individual concrete plates 431 are 0.5-1.5 m deep (D), 2.5-5 m high (H) and 10-30 mm thick (d), and the plates can have other suitable dimensions in other embodiments. In operation, the working fluid WF enters the channels 441 between the adjacent plates 431 as indicated by the flow arrow 411, and leaves as indicated by the flow arrows 421. Therefore, in the illustrated embodiment the working fluid WF flows inside the channels 441 primarily in the direction of the height H. In some embodiments, due to a generally steady flow in the individual channels 441, the temperature of the plates 431 changes uniformly from T_1 to T_2 in the direction of the flow (with T_1 generally higher than T_2). In at least some embodiments, it is desirable that the velocity and temperature of the working fluid do not vary from one channel to another, or at least do not vary significantly, and for the individual plates 431 to have the same or comparable temperature profiles (e.g., the same or comparable temperature gradient from T_1 to T_2). Therefore, in at least some embodiments, a distance between the adjacent plates 431 (i.e., the width W of the channels 441) is generally same (aside from, e.g., manufacturing errors and tolerances) to promote the same flow rates in the channels 441 and the same temperature profiles in the plates 431.

[0042] Figure 5B schematically illustrates an expected thermal expansion of a plate 431 in accordance with an embodiment of the presently disclosed technology. As explained above, the widths of the channels 441 between neighboring plates 431 can be designed and formed to be generally constant. However, cracks that develop in the plate

431 (e.g., due to thermal stresses or vibrations) may change the channel widths. With some cracks, a section of the plate 431 may become offset from the principal plane of the plate therefore changing the effective width of the channel 441. For example, a crack 512 may separate a section of the plate 431 from the rest of the plate. Under some conditions, the separated section of the plate can move out of the principal plane of the plate (e.g., out of the plane of page in Figure 5B) to create a wider channel on one side of the plate 431 and a narrower channel on the opposite side of the plate 431, thereby affecting the uniformity of the flow in the channels. To counteract this problem, the present technology can include one or more preferred direction(s) for crack development, as explained below.

[0043] In Figure 5B, an initial outline 520 of the unheated plate 431 is illustrated with a solid line. As the working fluid travels downwardly in the channels 441 (in the direction of the height H), the working fluid heats the plate 431. The upper portion of the plate achieves a higher temperature (T_1) than the temperature T_2 of the lower portion of the plate. The resulting outline of the plate 431 is illustrated (in an exaggerated manner for purposes of illustration) with a dashed line 521, and indicates that the upper portion of the plate 431 has a depth D_H that is larger than a depth D_C at the lower portion of the plate. The difference between the depths D_H and D_C can promote diagonal cracks 511 that extend diagonally across the plate. Such diagonally extending cracks 511 in general do not promote separation of the sections of the plate out of the principal plane of the plate. In some embodiments, the plate 431 may be purposely weakened (e.g., thinned), to create a preferred direction for a crack 510 to propagate (e.g., by shaping the wax sheet described below with reference to Figures 6A-6C). The cracks 510 and 511 do not (or at least do not significantly) promote separation of the sections of the plate that could change the width of the channels for the working fluid. Therefore, even when the plate 431 includes cracks 510 and/or 511, the channel width remains generally constant and the flow of the working fluid remains generally the same in the individual channels.

[0044] Figure 6A is a schematic view of a mold 600a for manufacturing a heat storage device in accordance with an embodiment of the presently disclosed technology. Figure 6B is a detailed view of a portion of the mold 600a. Figures 6A and 6B are discussed together below. The mold 600 can include a mold housing 610 that contains

sacrificial sheets 641 (e.g., formed from a meltable wax) arranged at a spacing or pitch P. In some embodiments of the present technology, an arrangement of supporting structures, for example grooves 611, can maintain the sacrificial sheets 641 at a required spacing. In other embodiments, clips or holders or other suitable devices may be used to hold the sacrificial sheets in place. After arranging the sacrificial sheets 641 inside the mold housing 610, a molding material 631 (e.g., concrete) can be poured into the mold 600a (e.g., into the plane of page). In some embodiments of the present technology, the molding material 631 can be poured between the sacrificial sheets 641 such that an approximately similar amount of the molding material 631 flows into the spaces between the sacrificial sheets 641. As a result, a pressure of the concrete on the two opposing sides of the sacrificial sheets 641 is similar, and the sacrificial sheets 641 generally maintain their initial position and shape during the molding process. In other embodiments, the mold 600a can be turned on its side such that the sacrificial sheets 641 are horizontal. The molding process can start by adding an amount of the molding material 631 to cast one plate 431. Next, a sacrificial sheet 641 can be placed over the already added molding material, followed by adding an amount of the molding material that is sufficient to cast another plate 431. The process can then be repeated for the number of required plates 431.

[0045] When the molding material 631 solidifies, the sacrificial sheets 641 can be removed by, for example, melting them at a sufficiently high temperature (e.g. when the sacrificial sheets are made of a meltable wax or other material. In some embodiments, the sacrificial sheets may be removable by a chemical reaction that, for example, dissolves or gasifies the sacrificial sheets 641. A depth D of the sacrificial sheets 641 generally corresponds to a depth D of the channels 441. In any of the above embodiments, after the molding material 631 solidifies, the plates 431 can be removed by, for example, disassembling the mold housing 610. An advantage of embodiments of the present technology is that relatively thin plates 431 can be created without having to machine the concrete. Furthermore, in at least some embodiments of the present technology, the illustrated molding process can be performed at the site, resulting in reduced transportation costs and delays.

[0046] Figure 6C is a schematic view of a mold 600b for manufacturing a heat storage device in accordance with an embodiment of the presently disclosed technology. The mold 600b can include a mold housing 610 that contains sacrificial sheets 641 (e.g., formed from meltable wax or plastic). The sacrificial sheets 641 can be arranged generally horizontally, but do not need to be necessarily horizontal and can be generally wavy. In an embodiment of the present technology, the process for manufacturing the plates 631 can start with pouring concrete at the bottom of the mold housing 610, followed by placing down a sacrificial sheet 641 (or pouring the material of the sacrificial sheet 641) over the concrete. Next, an additional layer of concrete (or other plate material) can be poured, followed by an additional sacrificial sheet 641, and the process continues. After the concrete (or other material of the plates 631) solidifies, the sacrificial sheets 641 are removed by, for example, melting or chemical reaction. The resulting channels (where the sacrificial sheets 641 used to be) can have a generally constant width W. Therefore, for a flow of the working fluid in and out of the page, even though the channel may be wavy, the width W of the channel is essentially constant (other than for manufacturing or tolerance variations). In at least some embodiments, not having to produce flat plates may simplify the manufacturing process and/or make it more robust.

[0047] Figures 7A-B are partially schematic isometric views of sacrificial sheets configured in accordance with embodiments of the presently disclosed technology. Figures 7A, 7B illustrate sacrificial sheets 712a, 712b, respectively, having a depth D_S and a height H_S that generally determine the depth/height of the corresponding channels of the heat storage device. In an embodiment shown in Figure 7A, the sacrificial sheet 712a is generally solid. As a result, the molded plates have side surfaces that are generally flat and are not connected to the adjacent plates. In an embodiment shown in Figure 7B, the sacrificial sheet 712b includes openings 710 that, during the molding process, allow a flow of the molding material through the openings 710 from a space occupied by one plate to a space occupied by an adjacent plate. As a result, the side surfaces of the adjacent plates in the mold can be connected by the mold material in the openings 710. After the sacrificial material is removed (e.g., by melting), the connections between the adjacent plates remain in place. Generally, the connections can add structural strength and can reduce cracking of the otherwise relatively slender plates. Additionally, in operation, when

the working fluid flows in the channel, the fluid also flows around the connections between the adjacent plates. Therefore, the connections can provide an additional area for the heat exchange between the working fluid and the plates, and will reduce the amount of working fluid within the heat storage device. Furthermore, the connections can maintain the designed spacing between plates, and therefore the widths of the flow channels between plates. The illustrated openings 710 are generally oval, but can have other shapes (e.g., slits oriented in the direction of flow) in other embodiments.

[0048] Figure 8A is a partially schematic isometric view of a heat storage device 800 configured in accordance with an embodiment of the presently disclosed technology. Figure 8B is a detailed view of a portion of the heat storage device 800. The illustrated heat storage device 800 includes several plates 431 arranged along a length L. The plates 431 have a thickness t, a depth D and a height H. The spaces between the adjacent plates corresponds to the width W of the channels 441. A distance between the consecutive channels 441 is a pitch P. Flow arrows 411, 421 indicate the direction of flow of the working fluid WF. In operation, the working fluid WF can flow through the channels 441 from the top to the bottom of the heat storage device 800 to transfer heat to the plates 431. The working fluid WF leaves the heat storage device 800 at the bottom, as illustrated by the flow arrow 421.

[0049] Figure 8B illustrates a portion of an arrangement of the plates 431. In the illustrated embodiment, a base plate 811 supports the plates 431 inside corresponding base grooves 812. A width of the base grooves 812 is generally the same as the thickness of the plates 431. In other embodiments, the width of the base grooves can be larger than the thickness of the plates 431. In some embodiments, additional base plates 811 can support the plates 431 at, for example, corners of the plates 431 to maintain a generally vertical position of the plates 431. A distance between the adjacent base grooves 812 can at least in part determine the width W of the channels 441. In some embodiments of the present technology, the base plate 811 can be manufactured from the same material as the plates 431 (e.g., from concrete) for lower cost and shorter lead times. Depending on a required amount of steam at the oil field or in other field use, a single heat

storage device 800 may not have sufficient capacity and, therefore, multiple heat storage devices 800 may be arranged together, as explained below with reference to Figure 9.

[0050] Figure 9 is a schematic illustration of an arrangement 900 of multiple heat storage devices in accordance with an embodiment of the presently disclosed technology. The illustrated embodiment includes three heat storage devices (indicated as first-third devices 900a-900c), and in other embodiments, the arrangement can include other numbers of heat storage devices, depending (for example) on the overall heat storage capacity needs of a particular application. In any of these embodiments, when the solar insolation is relatively high, the working fluid generally (e.g., for most of the time) transfers heat to the plates inside the heat storage. Conversely, when the solar insolation is relatively low, the plates generally transfer heat to the working fluid.

[0051] In the illustrated arrangement 900, the working fluid WF can enter the first heat storage 900a as indicated by flow arrow 411a at the top of the unit, and leave as indicated by flow arrow 421a at the bottom of the unit when the working fluid WF transfers heat to the plates of the heat storage 900a. The heat storage devices 900a-900c are arranged in series, e.g., the working fluid WF flows from the outlet of the first heat storage device 900a to the inlet of the second heat storage device 900b, and, after exiting the second heat storage device 900b, further to the inlet of the third heat storage device 900c. Such an arrangement of the flow of the working fluid WF through the heat storage devices 900a-900c can correspond to a relatively high insolation. Conversely, when the insolation is relatively low, the flow of the working fluid WF can enter the first heat storage device 900a at the bottom, flow through the first heat storage device 900a while receiving heat from the plates in the first heat storage device 900a, exit the first heat storage device 900a at the top, and enter at the bottom of the second heat storage device 900b, and go on to the third heat storage device 900c.

[0052] The arrangement 900 is a sample arrangement of heat storage devices, and other field-specific serial/parallel arrangements can be used in other embodiments. Furthermore, the three heat storage devices are illustrated as having generally the same shape and size, but the heat storage devices can have different shapes and/or sizes in other embodiments.

[0053] The arrangement 900 can include valves positioned to regulate amount of the working fluid flowing through any one or combination of heat storage devices. In some embodiments, the valves can be controlled by a controller 901 to limit or stop the flow of the working fluid to some of the heat storage devices, depending on, for example, insolation and required production of the steam in the field. In other embodiments, the controller 901 can control valves 910-913 to maintain a laminar or generally laminar flow through the heat storage devices of the arrangement 900, or at least through some heat storage devices. In other embodiments, the arrangement can include other numbers and/or locations of the valves. The controller 901 may include a computer-readable medium (e.g., hard drive, programmable memory, optical disk, non-volatile memory drive, etc.) that carries computer-based instructions for directing the operation of the valves 910-913 and/or other components of the assembly and/or larger system.

3.0 Representative Systems Incorporating Heat Storage Devices

[0054] Figures 10A-14B illustrate representative systems that, in at least some embodiments, incorporate any of the heat storage devices of the type described above with reference to Figures 4A-9. In other embodiments, the systems described below can incorporate heat storage devices other than those described above, and in still further embodiments, the heat storage devices described above can be incorporated into systems other than those specifically described below.

[0055] Figure 10A illustrates a representative heat storage device 1000 that includes internal heat storage elements generally similar to those discussed above, and that receives heat and discharges heat by passing a heat transfer fluid through the device along a generally vertical axis V. Figure 10B is a schematic illustration of a heat storage facility 1004, that can include multiple composite heat storage devices 1002, each of which can include multiple heat storage devices 1000 (Figure 10A). Accordingly, the heat storage device 1000 represents a building block or unit element that can operate alone or can be coupled with other devices in the overall facility 1004.

[0056] Figure 10C illustrates a representative composite heat storage device 1002 formed from multiple heat storage devices 1000. Figure 10C also illustrates representative temperature contours 1023 for one such heat storage device 1000. As discussed above,

the composite heat storage device 1002 generally receives a heat transfer fluid from the top or from the bottom, which, during operation, creates generally vertical thermal gradients. For example, Figure 10C illustrates a point in time for which the composite heat storage device 1000 has a cold zone 1020 toward the bottom of the device, a hot zone 1022 toward the top of the device, and an intermediate zone 1021 between the cold zone 1020 and the hot zone 1022. As will be discussed further below, one aspect of the technology disclosed herein is to cycle the heat storage device 1000 between a state in which the hot zone 1022 extends over the entire device, and a state in which the cold zone 1020 extends over the entire device. In particular, the effect of the intermediate zone 1021 (which can represent an efficiency loss due to incomplete heating or incomplete cooling) can be mitigated to improve the overall efficiency of the system in which the heat storage device 1000 operates.

[0057] Figure 10D is a flow diagram illustrating a method 1060 for collecting solar energy in accordance with an embodiment of the present technology. Schematic diagrams illustrating the changes in a corresponding system as the method is performed are described later with reference to Figures 11A-11K. The method 1060 can include collecting solar energy at a solar field (block 1061) and directing at least a portion of the solar energy to a target heat user during a first process (block 1062). The target heat user can include a solar EOR field, an electrical power generation facility, and/or other industrial facilities for which solar-generated heat provides a useful input.

[0058] Block 1063 includes directing heat from the solar field to first and second heat storage devices during a second process. Accordingly, the second process includes storing heat generated at the solar field in the heat storage devices. This process can continue at least until the first and second heat storage devices are generally at a first thermal equilibrium. As used herein, the term "thermal equilibrium" refers to a state at which the amount of energy contained by the heat storage device has stabilized, whether during a heat addition process or a heat removal process. When at thermal equilibrium, the heat storage device may well include internal thermal gradients, but the gradients remain generally static if more heat is added (during a heat addition process), or more heat is withdrawn (during a heat removal process). Put another way, "thermal equilibrium"

corresponds to a state at which the total thermal energy in the heat storage devices is constant or at least approximately constant.

[0059] Block 1064 includes directing heat from the first and second heat storage devices to the target heat user during a third process. Accordingly, the third process can be performed during night-time hours, when energy is not available directly from the solar field, but is available from the heat storage devices. In representative operations, the thermal equilibrium is maintained for a period of time that may depend on the capacities of the heat storage devices relative to the capacity of the solar field and the demand by the target heat user. Representative times range from several minutes to several hours. For example, the thermal equilibrium may be maintained for a few minutes during transitions, e.g., transitions between receiving heat and giving up heat. The capacity of the heat storage devices may be considerably longer, e.g., 8-16 hours, to provide heat to the target user throughout the night and (at least in some embodiments) also during solar field start-up and shut-down.

[0060] In block 1065, heat is directed from the first and second storage devices to the solar field during a fourth process, at least until the first and second heat storage devices are generally at a second thermal equilibrium. The second thermal equilibrium corresponds to a lower stored thermal energy level (and a lower temperature) than the first thermal equilibrium. Accordingly, the fourth process corresponds to cooling the heat storage devices. The heat removed from the heat storage devices during the fourth process can be directed to the solar field, for example, to add to the heat provided by the solar field as the solar field initiates operation the following day and/or as the solar field reduces output in the evening.

[0061] In particular embodiments, multiple processes shown in Figure 10D can be performed simultaneously. For example, at least portions of the first and second processes can be performed simultaneously to direct heat to both the target heat user and the heat storage device. In addition to or in lieu of the foregoing simultaneous processes, at least portions of the first and fourth processes can be performed simultaneously to direct heat from the solar field to the target heat user, and from the heat storage device to the

solar field. Further details of the foregoing processes are described below with reference to Figures 11A-11K.

[0062] Figure 11A is a partially schematic illustration of a system 1190 that includes a solar field 1130, a heat storage facility 1104 and (optionally) a supplemental heat source 1140. The solar field 1130 can include an inlet 1133 at which water or another working fluid is delivered from a working fluid source 1135. For purposes of explanation, the working fluid is described as water in much of the following discussion, but can have other compositions in other embodiments. The water passes from the inlet 1133 to a series of receivers 1131, which are positioned adjacent to a corresponding series of solar concentrators 1132. The concentrators 1132 concentrate or otherwise focus solar energy on the receivers 1131, to produce a hot working fluid (e.g., steam) at an outlet 1134 of the solar field 1130. A fluid flow network 1175 directs the working fluid from the source 1135, through the solar field 1130, and to a target heat user 1180. Accordingly, the working fluid can operate in an open loop or "once through" manner. In a particular embodiment, the working fluid includes water, and can be provided directly to the target heat user as steam. In another embodiment, the working fluid can include another material (e.g., a non-aqueous heat transfer fluid, such as a molten salt) which is either used directly at the target heat user 1180, or transfers heat to another fluid (e.g., water) for use at the target heat user 1180.

[0063] The heat storage facility 1104 can include multiple heat storage devices 1100, two of which are illustrated in Figure 11A as a first heat storage device 1100a and a second heat storage device 1100b. The heat storage devices 1100 exchange heat with the solar field 1130 and the target heat user 1180, under the direction of a controller 1170. Accordingly, the controller 1170 can receive inputs 1171 (e.g., temperature, pressure, steam quality, time, and/or other data) and issue outputs 1172 (e.g., directions for opening and closing valves, moving the solar concentrators 1132 and/or taking other actions). The controller 1170 can accordingly include computer-readable media programmed with instructions that execute tasks or directions described herein. The fluid flow network 1175 is coupled among the solar field 1130, the working fluid source 1135, the heat storage facility 1104, the supplemental heat source 1140, and the target heat user 1180.

[0064] For purposes of illustration, only those portions of the fluid flow network 1175 that are active during the illustrated portion of the overall operation are shown in the associated Figure.

[0065] In the configuration shown in Figure 11A, the solar field 1130 directs heat to the target heat user 1180, in accordance with the first process 1062 described above with reference to Figure 10D. Both the heat storage devices 1100a, 1100b have been fully heated (e.g., to an upper thermal equilibrium temperature) and accordingly contain only hot zones 1122, indicated by filled dots. For example, the first and second heat storage devices 1100a, 1100b have been heated by the solar field 1130 in accordance with the second process 1063 described above with reference to Figure 10D. The heat storage devices 1100a, 1100b are therefore available to discharge heat as the output from the solar field 1130 falls e.g., toward the end of the day and into the night.

[0066] Figure 11B illustrates the system 1190 executing the third process 1064 described above with reference to Figure 10D, in particular, directing heat from the first and second heat storage devices 1100a, 1100b to the target heat user 1180. Accordingly, the controller 1170 directs working fluid from the solar field 1130 into the first heat storage device 1100a (e.g., at the bottom of the first heat storage device 1100a). The working fluid exits the first heat storage device 1100a at the top, and is directed to the bottom of the second heat storage device 1100b. The working fluid exiting the top of the second heat storage device 1100b is directed to the target heat user 1180. Accordingly, the components of the heat storage devices 1100 are selected to store heat at a temperature high enough to elevate the working fluid to a temperature suitable for use by the target heat user 1180. In a representative embodiment, the temperature can be about 300°C, e.g., for a target heat user 1180 that includes an EOR facility.

[0067] In some embodiments, the working fluid is water, which is pressurized to about 100 bar so as to be in a vapor state at 300°C. However, using water at such pressures will require the heat storage devices 1100a, 1100b to also withstand such pressures, which can increase the cost of manufacturing and maintaining the system. Accordingly, other embodiments use a higher temperature fluid (e.g., a fluid such as a molten salt having a higher vaporization temperature) in the heat storage devices 1100a, 1100b, together with

heat exchangers that transfer heat to/from water or another working fluid. The heat exchangers can include a heat exchanger that transfers heat from the steam exiting the solar field to the working fluid flowing through the heat storage devices, and also transfers heat from the heat storage devices to the steam delivered to the target user 1180. Several embodiments that include such heat exchangers are described below with reference to Figures 11F and 13-15O.

[0068] Because the heat provided by the solar field 1130 decreases toward the end of the day and into the night, the incoming working fluid forms an intermediate zone 1121 (indicated by a mixture of open dots and filled dots) and a cold zone 1120 (indicated by open dots) as the hot fluid is forced out of the heat storage facility 1104. Internal thermal gradients may also contribute to the formation of the intermediate zone 1121. As more working fluid is directed through the first heat storage device 1100a and the second heat storage device 1100b, the cold zone 1120 and intermediate zone 1121 advance through the heat storage facility 1104, forcing more hot working fluid out of the heat storage facility 1104 and reducing the size of the hot zones 1122. Figure 11C illustrates the system 1190 after the first heat storage device 1100a has been completely cooled (e.g., reached a lower thermal equilibrium temperature) and the second heat storage device 1100b is partially cooled. The second heat storage device 1100b accordingly includes an enlarging cold zone 1120, a shrinking hot zone 1122, and an intermediate zone 1121.

[0069] Figure 11D illustrates the system 1190 after the hot zone 1122 has been eliminated because heat at the upper thermal equilibrium temperature has all been transferred to the target heat user 1180. Because transferring additional heat from the second heat transfer heat device 1100b to the target heat user 1180 would necessarily be performed at a lower temperature, the heat transfer process from the heat storage facility 1104 to the target heat user 1180 is halted in this embodiment.

[0070] If, at this point in the process, the solar field 1130 is ready to resume operation (e.g., if the sun has risen), then the process continues by delivering heat from the intermediate zone 1021, not to the target heat user 1180, but to the solar field 1130, as will be discussed further below with reference to Figures 11E-11F. If the solar field 1130 is not ready to resume operation (e.g., if the capacity of the heat storage facility 1104 is not

sufficient to provide heat through the entire night), then the supplemental heat source 1140 (e.g., a gas fired boiler) can be activated to provide heat to the target heat user 1180, in a fifth process. Once the solar field 1130 is ready to resume operation, the heat transfer process from the heat storage facility 1104 continues, as shown in Figure 11E.

[0071] In Figure 11E, the controller 1170 has redirected the fluid flow network 1175 to direct flow to the second heat storage device 1100b to force out the intermediate-temperature working fluid at the intermediate zone 1121. The heat from this working fluid is then directed into the solar field 1130. If the initial temperature of the working fluid at the outlet 1134 of the solar field 1130 is too low, it can be directed from the outlet 1134 through the supplemental heat source 1140 before passing to the target heat user 1180. Accordingly, the process shown in Figure 11E corresponds to the fourth process 1065 (directing heat from the heat storage devices to the solar field) and the first process 1062 (directing solar energy to the target heat user) shown in Figure 10D, as well as the fifth process (providing heat form the supplemental heat source 1140).

[0072] In one aspect of the embodiment shown in Figure 11E, heat from the second heat storage device 1100b is provided directly to the solar field 1130. In another embodiment, this fluid can be used to heat water entering the solar field 1130 via a heat exchanger, as discussed above. For example, referring now to Figure 11F, the system 1190 can include a pre-heater 1150, and the controller 1170 can configure the fluid flow network 1175 to include a pre-heater loop 1176. The pre-heater loop 1176 can route fluid from the second heat storage device 1100b through the pre-heater 1150 (where it heats water entering the solar field 1130), and then back to the second heat storage device 1100b.

[0073] Whether the fourth process is conducted using the configuration shown in Figure 11E, or the configuration shown in Figure 11F, the fourth process is completed when both the first and second heat storage devices 1100a, 1100b have been completely cooled and are at the lower thermal equilibrium temperature. Figure 11G illustrates this state. Because both the first and second heat storage devices 1100a, 1100b are completely occupied by the cold zone 1120, they provide no further heat to either the target heat user 1180 or the solar field 1130. Instead, the solar field 1130 directs heated

working fluid (e.g., steam) to the target heat user 1180, in accordance with the first process 1062 described above with reference to Figure 10D.

[0074] As the solar field 1130 generates more and more heat, it eventually exceeds the capacity of the target heat user 1180. At this point, as shown in Figure 11H, at least a portion of the heat generated by the solar field 1130 is used to re-heat the heat storage facility 1104. Accordingly, the controller 1170 can open or partially open a valve 1110 to direct some of the working fluid (exiting the solar field 1130) into the first heat storage device 1100a. As the hot working fluid enters the first heat storage device 1100a, an intermediate zone 1121 forms at the interface between the existing cold zone 1120 and a newly formed hot zone 1122. The working fluid is directed from the bottom of the first heat storage device 1100a to the top of the second heat storage device 1100b, and then into the inlet 1133 of the solar field 1130. In one aspect of the illustrated embodiment, the temperature of the cold zone 1120 is no lower than the temperature of the working fluid at the source 1135, so directing cold working fluid from the heat storage devices 1100 into the solar field 1130 is no less efficient than directing cold working fluid from the source 1135 into the solar field 1130.

[0075] In Figure 11I, the first heat storage device 1100a has been completely heated and is accordingly occupied by only a hot zone 1122. The second heat storage device 1100b is partially heated. The cold zone 1120 in the second storage device 1100b has been eliminated and only the intermediate zone 1121 remains. Because the temperature of the intermediate zone 1121 is no less than (and is typically higher than) the temperature of the water from the source 1135, the water from the second heat storage device 1100b continues to pass to the inlet 1133 of the solar field 1130. This in turn adds to the heat provided by the solar field 1130, which would otherwise begin reducing output toward the end of the day.

[0076] Figure 11J illustrates the system 1190 with both the first and second heat storage devices 1100a, 1100b fully heated. Accordingly, the heat storage devices 1100 have achieved the upper thermal equilibrium temperature, with both devices entirely occupied by hot zones 1122. The second process (directing heat from the solar field to the heat storage devices) is now complete, and the configuration generally duplicates that

shown in Figure 11A, with the heat storage facility 1104 ready to provide heat to the target heat user 1180 as the solar field 1130 shuts down for the day.

[0077] Figure 11K illustrates the heat storage facility 1104 providing heat to the target heat user 1180. This process is generally similar to the process described above with reference to Figure 11B, except that (in at least some embodiments) heat is initially extracted from the first heat storage device 1100a and then the second heat storage device 1100b. This re-ordering can be significant when one of the heat storage devices is not completely heated, as described further below with reference to Figures 15A-O. The heat extraction process continues until the lower thermal equilibrium temperature is reached in both heat storage devices 1100. The foregoing processes are then repeated, and with each cycle, the heat storage device 1100 from which heat is initially extracted, and into which heat is initially supplied, is alternated.

[0078] Figure 12 shows a graph 1200 illustrating the expected result of operating a solar collection system in the manner described above with reference to Figures 11A-11K. The graph 1200 illustrates temperature and fluid flow rate of fluid exiting the solar field as a function of time over the course of a representative day. The effect of heat provided by the heat storage devices at night is not shown in Figure 12 because that heat is provided directly to the target heat user, not the solar field. Line 1201 indicates the flow rate and temperature of fluid provided to the target heat user without the use of the heat storage devices described above. Accordingly, the solar field provides a peak flow rate at a peak temperature at about noon, and produces a lower temperature and flow rate both before and after noon. Line 1202 illustrates the flow rate and temperature with the use of the heat storage device arrangement described above with reference to Figures 11A-11K. As indicated by arrows A and B, the heat storage device supplements the heat provided by the solar field alone to "flatten" the solar output. It is estimated that in a particular embodiment, this arrangement can deliver 35% more energy to the target heat user than if the heat storage devices are not used. In addition, this arrangement allows for more efficient use of structures that are sized to handle peak conditions because more time is spent at those conditions.

[0079] Figure 12 also illustrates the feed water inlet temperature to the solar field (line 1203). As shown in Figure 12, the inlet water temperature is high at the beginning of the day, as the heat from the intermediate zone of the heat storage facility is transferred to the solar field inlet. As that remaining heat is exhausted, the temperature falls and reaches a steady state when all the heat from the heat storage devices has been transferred to the solar field. The temperature begins to rise again as the heat storage devices near the end of the charging cycle, with water at the intermediate zone 1121 (shown in Figure 11I) providing heat to the solar field inlet.

[0080] One feature of embodiments of the system described above with reference to Figures 10A-12 is a controller that is operatively coupled to paired heat storage devices and programmed with instructions that, when executed, direct heat to and from the heat storage devices in different manners, depending upon the available output of the solar field. An advantage of this feature, as illustrated in Figure 12, is that stored heat can supplement the heat provided by the solar field (during off-peak hours of the day) and can provide heat directly to the target heat user (e.g., at night). Accordingly, this arrangement can address a fundamental issue associated with solar energy, in particular, the cyclic nature of the output provided by such facilities. Accordingly, embodiments of the foregoing arrangements can significantly improve the efficiency with which energy is provided to the target heat user by the solar field.

[0081] Another advantage of embodiments of the foregoing systems is that the thermal mixing created at the intermediate zones of the heat storage devices does not create a significant amount of waste heat. Instead, the heat from these zones is used to provide additional heat to the solar field at appropriate times, (e.g., as the solar field is started up and before it is shut down), thereby increasing the overall efficiency of the system.

[0082] Figure 13 illustrates a system 1390 configured in accordance with another embodiment of the present technology. The system 1390 includes one or more first solar fields 1330a that receive a first working fluid (e.g., water) from a source 1335, heats the first working fluid (e.g., to steam), and direct the first working fluid to a target heat user 1380 via a first fluid network 1375a, e.g., in an open loop or "once-through" manner. The

system 1390 further includes a one or more second solar fields 1330b coupled to a heat storage facility 1304 via a second fluid network 1375b that can operate in a closed loop manner. The second fluid network 1375b can carry a second working fluid that has a composition the same as or different than the composition of the first working fluid. For example, the second working fluid can include a high-temperature molten salt, and the first working fluid can include water. Each of the solar fields 1330a, 1330b can include an arrangement of concentrators and receivers, e.g., generally similar to that described above with reference to Figure 11A. The heat storage facility 1304 can include at least one, and typically one or more pairs of heat storage devices 1300, illustrated as a first heat storage device 1300a and a second heat storage device 1300b. The second fluid flow network 1375b can include a first circuit 1376a and a second circuit 1376b. The first circuit 1376a directs fluid from the second solar field 1330b to the heat storage devices and then to a first heat exchanger 1350. At the first heat exchanger 1350, heat from the heat storage facility 1304 is transferred to the first working fluid entering the first solar field 1330a. The second circuit 1376b is coupled between the heat storage facility 1304 and a second heat exchanger 1360. At the second heat exchanger 1360, heat from the heat storage facility 1304 is transferred to a flow of the first working fluid that proceeds directly to the target end user 1380. The first and second heat exchangers 1350, 1360 can accordingly be connected in parallel between the working fluid source 1335 and the target heat user 1380.

[0083] In operation, a controller 1370 receives inputs 1371 and produces outputs 1372 to direct the operation of the overall system 1390, in a manner generally similar to that discussed above with reference to Figures 11A-11K. Accordingly, the controller 1370 can direct the working fluid from the source 1335 to the first solar field 1330a and then to the target heat user 1380. In addition, the controller 1370 can direct operation of the first and second circuits 1376a, 1376b to heat the heat storage facility 1304, and direct heat to the heat exchangers 1350, 1360. In general, the first network 1375a and the first circuit 1376a operate during daylight hours, during which both the first solar field 1330a and the second solar field 1330b produce heat. Heat from the first solar field 1330a is directed to the target heat user 1380, and heat from the second solar field 1330b is directed to the heat storage facility 1304. Because the first circuit 1376a passes through the first heat exchanger 1350, at least some of the heat from the second solar field 1330b is also

directed to the target heat user 1380 via the first heat exchanger 1350 and the first solar field 1330a.

[0084] At night, the first network 1375a and the first circuit 1376a of the second network 1375b may be shut down, while the second circuit 1376b directs heat from the heat storage facility 1304 to the second heat exchanger 1360, which in turn heats the first working fluid from the source 1335 and directs it to the target heat user 1380.

[0085] In a particular aspect of an embodiment shown in Figure 13, the heat storage facility 1304 can include pairs of heat storage devices, 1300a, 1300b that operate together in the manner described above with reference to Figures 11A-11K. Accordingly, heat directed into the heat storage facility 1304 by the second solar field 1330b can be used to pre-heat working fluid entering the first solar field 1330a via the first heat exchanger 1350, and can be used to provide heat to the first target heat source 1380 via the second heat exchanger 1360. In other embodiments, the system can include a single, common heat exchanger that performs the same functions as both the first and second heat exchangers by routing different flows through the heat exchanger. In still further embodiments, one or the other of the first and second heat exchangers can be eliminated.

[0086] Figures 14A illustrates a representative method in accordance with embodiments of the present technology for operating a solar collection system having some or all of the characteristics described above with reference to Figure 13. Figure 14A illustrates a process 1400 that includes collecting first thermal energy at a first solar field (e.g., the first solar field 1330a shown in Figure 13) and directing at least a portion of the first thermal energy to a target heat user (block 1402). The process can further include collecting second thermal energy at a second solar field (e.g., the second solar field 1330b shown in Figure 13) and directing at least a portion of the second thermal energy to at least one heat storage device, e.g., the heat storage facility 1304 described above with reference to Figure 13 (block 1404). In block 1408, an inter-field discharge process is used to direct heat from the at least one heat storage device to a working fluid that enters the first solar field. For example, a representative process includes directing heat from the heat storage facility 1304 to the first heat exchanger 1350 described above with reference to Figure 13. Accordingly, heat provided by the second solar field is directed to the first

solar field. At block 1406, an extra-field discharge process is used to direct heat from the at least one heat storage device to the target heat user. For example, block 1406 can include directing heat from the heat storage facility 1304 to the second heat exchanger 1360, from which heat is conveyed to the target heat user 1380, as discussed above with reference to Figure 13.

[0087] Figure 14B illustrates another process 1420 in which elements of the processes described above with reference to Figures 11A-11K are combined with the elements described above with reference to Figures 13 and 14A. In particular, block 1402 (described above with reference to Figure 14A) can include directing heat from the second solar field to the first and second heat storage devices during a first process at least until the first and second heat storage devices are generally at a first (e.g., high-temperature) thermal equilibrium (block 1422). This process corresponds to the process described above with reference to Figures 11G-11J. Block 1406 (directing heat from at least one storage device to the target heat user in an extra-field discharge process) can include directing heat from first and second storage devices to the target heat user during a second process (block 1426). This process can correspond generally to the process discussed above with reference to Figures 11B-11C.

[0088] Block 1408 (directing heat from the at least one heat storage device to a working fluid that enters the first solar field, during an inter-field discharge process) can include directing heat from the first and second heat storage devices to the first solar field during a third process, at least until the first and second heat storage devices are generally at a second (e.g., low-temperature) thermal equilibrium (block 1428). This process can correspond generally to the process described above with reference to Figures 11E-11G.

[0089] Figures 15A-15O illustrate a system 1590 having multiple solar fields configured to operate in accordance with still further embodiments of the present technology. The system 1590 can include multiple solar fields 1530, illustrated as a first solar field 1530a and a second solar field 1530b. The first solar field 1530a is coupled to a first fluid flow network 1575a, receives a first working fluid from a first working fluid source 1535a, and delivers the heated working fluid to a target user 1580. In a particular

embodiment, the first working fluid includes water, and the system delivers steam to the target user 1580.

[0090] The second solar field 1530b is coupled to a second fluid flow network 1575b through which a second working fluid passes. The second working fluid can be stored at a second working fluid source 1535b. The second fluid flow network 1575b can also be coupled to a heat storage facility 1504 that includes multiple heat storage devices 1500, illustrated as a first heat storage device 1500a and a second heat storage device 1500b. In a particular embodiment, the second working fluid is different than the first working fluid (e.g., the second working fluid can be a molten salt), and is therefore contained in a separate network that is not in fluid communication with the first network. However, the two working fluids can be in thermal communication with each other via a first heat exchanger 1561 and/or a second heat exchanger 1562. The first heat exchanger 1561 can be positioned between the first solar field 1530a and the first working fluid source 1535a to preheat the first working fluid entering the first solar field 1530a. The second heat exchanger 1562 can be positioned between the first solar field 1530a and the target user 1580 to further heat the first working fluid exiting the first solar field 1530a.

[0091] In addition to operating with different working fluids, the two solar fields can operate at different temperatures. For example, a solar field that uses molten salt as the working fluid will typically operate at a higher temperature than a solar field operating with water as the working fluid.

[0092] In a manner generally similar to that discussed above with reference to Figure 13, the two heat exchangers 1561, 1562 can be replaced with a single heat exchanger 1561a (shown in dashed lines in Figure 15A). The single heat exchanger 1561a can exchange heat between the heat storage device 1504 and the first working fluid before or after the first working fluid enters the first solar field 1530, depending on how the first working fluid is routed through the single heat exchanger 1561a. Accordingly, while two heat exchangers 1561, 1562 are shown in Figures 15A-15O for purposes of illustration, the functions performed by the two heat exchangers can also be performed by the single heat exchanger 1561a.

[0093] In still further embodiments, one or the other of the first and second heat exchangers 1561, 1562 can be eliminated. For example, the second heat exchanger 1562 can be eliminated, and heat from the heat storage device 1504 can be directed only to the first working fluid entering the first solar field 1530a, and not to the first working fluid exiting the first solar field 1530a.

[0094] A controller 1570 receives inputs 1571 and provides outputs 1572 to control the operation of the system 1590. Further details of the operation are described below with reference to Figures 15A-15O. For purposes of illustration, components that are actively receiving heat or giving up heat are illustrated with a thick outline.

[0095] Figure 15A illustrates the system 1590 during the day after a significant amount of energy has been generated by the second solar field 1530b. Accordingly, the first heat storage device 1500a contains only a hot zone 1522, and the second heat storage device 1500b includes a hot zone 1522 and an intermediate zone 1521. The first solar field 1530a provides heat directly to the target user 1580.

[0096] In Figure 15B, the heat provided by the second solar field 1530b has exceeded the capacity of the heat storage facility 1504. Accordingly, both the first and second heat storage devices 1500a, 1500b contain only a hot zone 1522 and no longer absorb additional heat. Instead, the excess heat passes through the storage devices 1500a, 1500b to the second heat exchanger 1562 where the heat is transferred to the first working fluid passing to the target user 1580. Accordingly, the excess heat generated by the second solar field 1530b can supplement heat provided by the first solar field 1530a.

[0097] Figure 15C illustrates the system 1590 as the outputs of both the first and second solar fields 1530a, 1530b begin to wane. Accordingly, the first heat storage device 1500a develops an intermediate zone 1521 as a result of a reduced heat output from the second solar field 1530b. The output of the heat storage facility 1504 is directed to the second heat exchanger 1562, where it adds further heat to the first working fluid exiting the first solar field 1530a. Accordingly, the stored energy from the second heat storage device 1500b supplements the waning output of the first solar field 1530a.

[0098] In Figure 15D, both the first and second solar fields 1530a, 1530b have shut down for the night, and the heat storage facility 1504 continues to direct heat to the second heat exchanger 1562 to heat the first working fluid, which is provided directly from the first working fluid source 1535a. The second working fluid is directed from the second heat storage device 1500b through the second heat exchanger 1562 and back to the first heat storage device 1500a. Accordingly, the first heat storage device 1500a further cools, as indicated by the initiation of a cold zone 1520.

[0099] In Figure 15E, the hot zones of both the first and second heat storage devices 1500a, 1500b have been exhausted, leaving only an intermediate zone 1521 at the second heat storage device 1500b. At this point, if the sun has not yet risen, the second fluid flow network 1575b is shut down, and heat is provided to a gas-fired boiler 1540 or other suitable heat source, as is shown in Figure 15F.

[00100] Figure 15G illustrates the system 1590 after the sun has risen. Both the first solar field 1530a and the second solar field 1530b are actively heating the respective first and second working fluids. The second working fluid network 1575b has been divided into two circuits: a first circuit 1576a, and a second circuit 1576b. The first circuit 1576a directs heat from the second solar field 1530b to the first heat storage device 1500a, as indicated by the presence of an intermediate zone 1521 in the first heat storage device 1500a. The second circuit 1576b directs the remaining heat from the second heat storage device 1500b to the first heat exchanger 1561 to preheat the first working fluid entering the first solar field 1530a. This portion of the operation allows even the relatively low-grade heat from the intermediate zone 1521 to be used to heat the target 1580 because, while low-grade, this heat can be at a higher temperature than that of the first working fluid source 1535. Another feature of this operation is that the heat storage facility 1504 can simultaneously receive heat from the second solar field 1530b and deliver heat to the first solar field 1530a. Accordingly, the intermediate zone 1521 at the first heat storage device 1500a increases in size, while the intermediate zone 1521 at the second heat storage device 1500b decreases in size.

[00101] Figure 15H illustrates the system after the heat from the second heat storage device 1500b has been depleted. The first heat storage device 1500a continues to receive

heat from the second solar field 1530b. Before the intermediate zone 1521 reaches the top of the first heat storage device 1500a, the first heat storage device 1500a is coupled to the second heat storage device 1500b, as shown in Figure 15I.

[00102] Figure 15J illustrates the system 1590 after the first heat storage device 1500a has been fully heated, and the second heat storage device 1500b has been partially heated. In at least some embodiments, there may be insufficient heat from the second solar field 1530b to completely heat the second heat storage device 1500b. In such an instance, it would not be thermally efficient to direct heat from the second heat storage device 1500b to the second heat exchanger 1562 during nighttime operation. Instead, as shown in Figure 15K, heat is directed from the hot zone 1522 of the second heat storage device 1500b to the first heat storage device 1500a and then to the second heat exchanger 1562. As shown in Figure 15L, the heat is transferred from the first heat storage device 1500a until the hot zones in both the first and second heat storage devices 1500a, 1500b have been exhausted, and only an intermediate zone 1521 remains at the first heat storage device 1500a. At this point, no more heat is removed from the heat storage facility 1504. If the sun has not yet risen, the system 1590 can provide supplemental heat to the target user 1580 via a supplemental heat source 1540, as described above with reference to Figure 15F.

[00103] Figure 15M illustrates the system 1590 after the sun has risen and both the first solar field 1530a and the second solar field 1530b have been activated. The remaining heat from the first heat storage device 1500a (stored at the intermediate zone 1521) is used to preheat the first working fluid entering the first solar field 1530a, via the first heat exchanger 1561. This operation can be performed using the first circuit 1576a. Simultaneously, the second solar field 1530b can begin heating the second heat storage device 1500b via the second circuit 1576b. An advantage of this arrangement is that, in addition to extracting all or nearly all available heat (even including relatively low-grade heat from the intermediate zone 1521), the second heat storage device 1500b can be heated at the same time the first heat storage device 1500a is being cooled.

[00104] Figure 15N illustrates the system after the remaining heat in the first heat storage device 1500a has been exhausted. Accordingly, the first heat storage device

1500a is connected in series with the second heat storage device 1500b, so that it is in position to receive heat generated by the second solar field 1530b.

[00105] Figure 15O illustrates the system after the second heat storage device 1500b has been fully heated, and the first heat storage device 1500a is approaching a fully heated condition. If the first heat storage device 1500a becomes fully heated before the second solar field 1530b shuts down for the night, then either the first heat storage device 1500a or the second heat storage device 1500b can be used to provide heat to the target user 1580 via the second heat exchanger 1562 at night. If the first heat storage device 1500a is not fully heated, and still includes an intermediate zone 1521 at the end of the day, heat is directed from the bottom of the first heat storage device 1500a to the second heat storage device 1500b and from both heat storage devices to the second heat exchanger 1562, similar to the operation discussed above with reference to Figure 15K, but with the roles of the first and second heat storage devices reversed. In a typical operation, whichever heat storage device is the first to be heated will be first depleted during nighttime operation, to reduce or eliminate the likelihood for inadvertently from an incompletely heated heat storage device.

[00106] One feature of embodiments described above with reference to Figures 13-15O is that the illustrated systems can include two solar fields, each with a different function. In particular, the first solar field can be used primarily to provide heat to the target user, and a second solar field can be used to store heat to supplement the output of the first solar field. An advantage of this arrangement is that it can further smooth the delivery of energy from the inherently cyclical solar fields to the target heat user.

[00107] Another feature of several of the embodiments described above is that individual heat storage devices can be cycled between a first (e.g., high temperature) thermal equilibrium value and a second (e.g., low temperature) thermal equilibrium value. This process can eliminate wasted heat that may result when a heat storage device is only partially heated and/or partially cooled. In operation, this approach can include beginning to cool the heat storage device only after it has reached its first thermal equilibrium value, and/or beginning to heat the heat storage device only after it has reached its second thermal equilibrium value.

[00108] From the foregoing, it will be appreciated that specific embodiments of the present technology have been described herein for purposes of illustration, but that various modifications may be made without deviating from the present technology. For example, in some embodiments, the plates 431 described above can be arranged at a non-uniform pitch and/or may not be parallel. Furthermore, in some embodiments of the present technology, the plates 431 can be made of thermally enhanced concrete that includes materials with high thermal conductivity (e.g., metal shavings, metal particles, etc.). In addition to or instead of concrete, other moldable materials may be used for the plates 431.

[00109] The heat storage devices described above can have a number of suitable configurations. For example, in some embodiments, the heat storage devices can be monolithic structures. In other embodiments, the heat storage devices can be formed from subunits, modules, and/or other separable or initially separated elements. Heat storage devices can be combined to provide larger heat storage capacities.

[00110] In a particular embodiment, the systems described above can include trough-shaped, mirror-based solar concentrators. In other embodiments, the solar collection systems can include other types of solar collectors, including, but not limited to point-source collectors, power-tower arrangements, dish-shaped collectors, and/or Fresnel collectors. Particular embodiments of the systems described above were described in the context of water as a working fluid. In other embodiments, the systems can operate in generally the same manner, using other types of working fluids, or, as discussed above with reference to Figure 13, combinations of different working fluids. For purposes of illustration, the first and second solar fields are shown in Figure 13 as physically separate entities. Depending upon the embodiment, the first and second solar fields can be housed in the same structure while still operating via different fluid flow networks. In still further embodiments, the respective sizes of the two solar fields can be changed, e.g., by selectively coupling particular receivers and associated concentrators to one field or the other, provided that if each field uses a different working fluid, the piping and other hardware can operate with either one. This arrangement can be used to account for variations in solar output, e.g., seasonal variations.

[00111] While various advantages and features associated with certain embodiments have been described above in the context of those embodiments, other embodiments may also exhibit such advantages and/or features, and not all embodiments need necessarily exhibit such advantages and/or features to fall within the scope of the present technology. Accordingly, the disclosure can encompass other embodiments not expressly shown or described herein.

[00112] To the extent any materials incorporated herein by reference conflict with the present disclosure, the present disclosure controls.

CLAIMS

I/we claim:

1. A solar energy collection system, comprising:

a first solar field coupled between a first working fluid source and a target heat user via first fluid network;

at least one heat storage device;

a second solar field coupled to the at least one heat storage device via a second fluid network and carrying a second working fluid, the second fluid network being isolated from fluid communication with the first fluid network; and

at least one heat exchanger coupled to the first and second fluid networks, the at least one heat exchanger providing thermal communication between the first and second fluid networks.

2. The system of claim 1 wherein the at least one heat exchanger includes a first heat exchanger and a second heat exchanger, and wherein the first heat exchanger is coupled to the first fluid network between the first working fluid source and the first solar field, and wherein the second heat exchanger is coupled to the first fluid network between the first solar field and the target heat user.

3. The system of claim 1, further comprising a controller operatively coupled to the second fluid network and programmed with instructions that, when executed:

direct the second fluid through the at least one heat storage device in a first direction to heat the at least one heat storage device; and

direct the second fluid through the at least one heat storage device in a second direction opposite the first direction to cool the at least one heat storage device.

4. The system of claim 1 wherein the at least one heat storage device operates between a first thermal equilibrium temperature and a second thermal equilibrium temperature less than the first thermal equilibrium temperature, and wherein the system further comprises a controller programmed with instructions that when executed:

direct the second working fluid through the at least one heat storage device to heat the at least one heat storage device to the first equilibrium temperature; and

only after the at least one heat storage device is heated to the first equilibrium temperature, direct the second working fluid through the at least one heat storage device to cool the at least one heat storage device to the second equilibrium temperature.

5. The system of claim 1, further comprising a controller coupled to the first and second fluid networks, the controller being programmed with instructions that, when executed:

direct heat from the second solar field to the at least one heat storage device during a first process, at least until the at least one heat storage device is generally at a first thermal equilibrium;

direct heat from the at least one heat storage device to the target heat user during a second process; and

direct heat from the at least one heat storage device to the first solar field during a third process, at least until the at least one heat storage device is generally at a second thermal equilibrium, the second thermal equilibrium corresponding to a lower average temperature than the first thermal equilibrium.

6. The system of claim 1 wherein the at least one heat storage device includes a first heat storage device and a second heat storage device, and wherein the system further comprises a controller programmed with instructions that when executed:

direct the second working fluid through the first and second heat storage devices in series.

7. The system of claim 1 wherein the at least one heat storage device includes a first heat storage device and a second heat storage device, and wherein the system further comprises a controller programmed with instructions that when executed:

direct the second working fluid through the first and second heat storage devices in parallel.

8. The system of claim 1 wherein first and second working fluids have different compositions.

9. The system of claim 8 wherein the first working fluid has a first vaporization temperature and the second working fluid has a second vaporization temperature higher than the first.

10. The system of claim 9 wherein the first working fluid includes water and wherein the second working fluid includes a molten salt.

11. The system of example 1 wherein each of the first and second solar fields includes:

a fluid inlet;

a fluid outlet;

at least one receiver coupled between the fluid inlet and the fluid outlet; and

at least one solar concentrator positioned to direct incoming solar radiation onto the at least one receiver.

12. A solar energy collection system, comprising:

a solar field, the solar field including:

a fluid inlet;

a fluid outlet;

at least one receiver coupled between the fluid inlet and the fluid outlet; and

at least one solar concentrator positioned to direct incoming solar radiation onto the at least one receiver;

a first heat storage device coupled to the fluid outlet of the solar field;

a second heat storage device coupled to the fluid outlet of the solar field;

a fluid flow network coupled among the solar field, the first and second heat storage devices, and a target heat user; and

a controller coupled to the fluid flow network and programmed with instructions that, when executed:

direct heat from the solar field to the target heat user during a first process;

direct heat from the solar field to the first and second heat storage devices during a second process, at least until the first and second heat storage devices are generally at a first thermal equilibrium;

direct heat from the first and second heat storage devices to the target heat user during a third process; and

direct heat from the first and second heat storage devices to the solar field during a fourth process, at least until the first and second heat storage devices are generally at a second thermal equilibrium, the second thermal equilibrium corresponding to a lower average temperature than the first thermal equilibrium.

13. The system of example 12, further comprising a working fluid carried by the receiver, and wherein the working fluid includes water.

14. The system of example 12, further comprising a working fluid carried by the first and second heat storage devices, and wherein the working fluid includes water.

15. The system of example 12 wherein the controller is programmed with instructions that, when executed:

direct a first quantity of working fluid from the outlet of the solar field to the first heat storage device, and then to the second heat storage device, during the second process; and

direct a second quantity of working fluid from the second heat storage device to the first heat storage device, and then to the inlet of the solar field, during the fourth process.

16. The system of example 12 wherein the first and second processes are performed simultaneously.

17. The system of example 12 wherein the first and fourth processes are performed simultaneously.

18. The system of example 12 wherein the controller is programmed with instructions that, when executed, direct heat from a gas-fired boiler to the target heat user during a fifth process.

19. The system of example 18 wherein the fifth process is performed simultaneously with the fourth process.

20. The system of example 12 wherein the first thermal equilibrium corresponds to a first temperature distribution in the first and second heat storage devices that is generally fixed for a period of time.

21. The system of example 12 wherein the first heat storage device includes a plurality concrete plates spaced apart to form individual flow channels, and wherein the controller is programmed with instructions that, when executed, direct a working fluid through the flow channels at a laminar flow rate.

22. A solar energy collection system, comprising:

a controller coupleable to a fluid flow network that is in turn coupled to a first heat storage device, a second heat storage device, a solar field, and a target heat user, the controller being programmed with instructions that, when executed:

direct heat from the solar field to the target heat user during a first process;

direct heat from the solar field to the first and second heat storage devices during a second process, at least until the first and second heat storage devices are generally at a first thermal equilibrium;

direct heat from the first and second heat storage devices to the target heat user during a third process; and

direct heat from the first and second heat storage devices to the solar field during a fourth process, at least until the first and second heat storage devices are generally at a second thermal equilibrium, the second thermal equilibrium corresponding to a lower average temperature than the first thermal equilibrium.

23. The system of example 22 wherein the controller is programmed with instructions that, when executed:

direct a first quantity of working fluid from the outlet of the solar field to the first heat storage device, and then to the second heat storage device, during the second process; and

direct a second quantity of working fluid from the second heat storage device to the first heat storage device, and then to the inlet of the solar field, during the fourth process.

24. The system of example 22, further comprising:

the first heat storage device;

the second heat storage device;

the solar field; and

the fluid flow network.

25. A method for operating a solar collection system, comprising:

collecting solar energy at a solar field;

directing at least a portion of the solar energy to a target heat user during a first process;

directing heat from the solar field to first and second heat storage devices during a second process at least until the first and second heat storage devices are generally at a first thermal equilibrium;

directing heat from the first and second heat storage devices to the target heat user during a third process; and

directing heat from the first and second heat storage devices to the solar field during a fourth process at least until the first and second heat storage devices are generally at a second thermal equilibrium, the second thermal equilibrium corresponding to a lower average temperature than the first thermal equilibrium.

26. The method of example 25 wherein directing heat from the first and second heat storage devices to the target heat user during the third process includes directing the heat at a first temperature, and wherein the method further comprises halting directing the heat in response to a temperature drop corresponding to a reduction from the first temperature to a second temperature.

27. The method of example 25, further comprising repeating the second process after completing the fourth process.

28. A method for operating a solar collection system, comprising:

collecting first thermal energy at a first solar field and directing at least a portion of the first thermal energy to a target heat user;

collecting second thermal energy at a second solar field and directing at least a portion of the second thermal energy to at least one heat storage device;

during an inter-field discharge process, directing heat from the at least one heat storage device to a working fluid that enters the first solar field; and

during an extra-field discharge process, directing heat from the at least one heat storage device to the target heat user.

29. The method of example 28 wherein at least part of the first process is performed during daylight hours and at least part of the second process is performed during night-time hours.

30. The method of example 28 wherein the working fluid that enters the first solar field is a first working fluid, and wherein heat storage device carries a second working fluid, and wherein directing heat from the heat storage device to the first working fluid includes transferring heat from the second working fluid to the first working fluid at a heat exchanger.

31. The method of example 28 wherein directing heat from the heat storage device to the target heat user incudes transferring heat at a heat exchanger from a second working fluid carried by the heat storage device to a first working fluid directed to the target heat user.

32. The method of example 28 wherein the at least one heat storage device includes a first heat storage device and a second heat storage device, and wherein the method further comprises:

directing heat from the second solar field to the first and second heat storage devices during a first process, at least until the first and second heat storage devices are generally at a first thermal equilibrium;

directing heat from the first and second heat storage devices to the target heat user during a second process; and

directing heat from the first and second heat storage devices to the first solar field during a third process, at least until the first and second heat storage devices are generally at a second thermal equilibrium, the second thermal equilibrium corresponding to a lower average temperature than the first thermal equilibrium.

AMENDED CLAIMS
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1. A solar energy collection system, comprising:

a first solar field coupled between a first working fluid source and a target heat user via first fluid network;

at least one heat storage device;

a second solar field coupled to the at least one heat storage device via a second fluid network and carrying a second working fluid, the second fluid network being isolated from fluid communication with the first fluid network; and

at least one heat exchanger coupled to the first and second fluid networks, the at least one heat exchanger providing thermal communication between the first and second fluid networks.

2. The system of claim 1 wherein the at least one heat exchanger includes a first heat exchanger and a second heat exchanger, and wherein the first heat exchanger is coupled to the first fluid network between the first working fluid source and the first solar field, and wherein the second heat exchanger is coupled to the first fluid network between the first solar field and the target heat user.

3. The system of claim 1, further comprising a controller operatively coupled to the second fluid network and programmed with instructions that, when executed:

direct the second fluid through the at least one heat storage device in a first direction to heat the at least one heat storage device; and

direct the second fluid through the at least one heat storage device in a second direction opposite the first direction to cool the at least one heat storage device.

4. The system of claim 1 wherein the at least one heat storage device operates between a first thermal equilibrium temperature and a second thermal

equilibrium temperature less than the first thermal equilibrium temperature, and wherein the system further comprises a controller programmed with instructions that when executed:

direct the second working fluid through the at least one heat storage device to heat the at least one heat storage device to the first equilibrium temperature; and

only after the at least one heat storage device is heated to the first equilibrium temperature, direct the second working fluid through the at least one heat storage device to cool the at least one heat storage device to the second equilibrium temperature.

5. The system of claim 1, further comprising a controller coupled to the first and second fluid networks, the controller being programmed with instructions that, when executed:

direct heat from the second solar field to the at least one heat storage device during a first process, at least until the at least one heat storage device is generally at a first thermal equilibrium;

direct heat from the at least one heat storage device to the target heat user during a second process; and

direct heat from the at least one heat storage device to the first solar field during a third process, at least until the at least one heat storage device is generally at a second thermal equilibrium, the second thermal equilibrium corresponding to a lower average temperature than the first thermal equilibrium.

6. The system of claim 1 wherein the at least one heat storage device includes a first heat storage device and a second heat storage device, and wherein the system further comprises a controller programmed with instructions that when executed:

direct the second working fluid through the first and second heat storage devices in series.

7. The system of claim 1 wherein the at least one heat storage device includes a first heat storage device and a second heat storage device, and wherein the system further comprises a controller programmed with instructions that when executed:

direct the second working fluid through the first and second heat storage devices in parallel.

8. The system of claim 1 wherein first and second working fluids have different compositions.

9. The system of claim 8 wherein the first working fluid has a first vaporization temperature and the second working fluid has a second vaporization temperature higher than the first.

10. The system of claim 9 wherein the first working fluid includes water and wherein the second working fluid includes a molten salt.

11. The system of claim 1 wherein each of the first and second solar fields includes:

a fluid inlet;

a fluid outlet;

at least one receiver coupled between the fluid inlet and the fluid outlet; and

at least one solar concentrator positioned to direct incoming solar radiation onto the at least one receiver.

12. A solar energy collection system, comprising:

a solar field, the solar field including:

a fluid inlet;

a fluid outlet;

at least one receiver coupled between the fluid inlet and the fluid outlet; and

at least one solar concentrator positioned to direct incoming solar radiation onto the at least one receiver;

a first heat storage device coupled to the fluid outlet of the solar field;

a second heat storage device coupled to the fluid outlet of the solar field;

a fluid flow network coupled among the solar field, the first and second heat storage devices, and a target heat user; and

a controller coupled to the fluid flow network and programmed with instructions that, when executed:

direct heat from the solar field to the target heat user during a first process;

direct heat from the solar field to the first and second heat storage devices during a second process, at least until the first and second heat storage devices are generally at a first thermal equilibrium;

direct heat from the first and second heat storage devices to the target heat user during a third process; and

direct heat from the first and second heat storage devices to the solar field during a fourth process, at least until the first and second heat storage devices are generally at a second thermal equilibrium, the second thermal equilibrium corresponding to a lower average temperature than the first thermal equilibrium.

13. The system of claim 12, further comprising a working fluid carried by the receiver, and wherein the working fluid includes water.

14. The system of claim 12, further comprising a working fluid carried by the first and second heat storage devices, and wherein the working fluid includes water.

15. The system of claim 12 wherein the controller is programmed with instructions that, when executed:

direct a first quantity of working fluid from the outlet of the solar field to the first heat storage device, and then to the second heat storage device, during the second process; and

direct a second quantity of working fluid from the second heat storage device to the first heat storage device, and then to the inlet of the solar field, during the fourth process.

16. The system of claim 12 wherein the first and second processes are performed simultaneously.

17. The system of claim 12 wherein the first and fourth processes are performed simultaneously.

18. The system of claim 12 wherein the controller is programmed with instructions that, when executed, direct heat from a gas-fired boiler to the target heat user during a fifth process.

19. The system of claim 18 wherein the fifth process is performed simultaneously with the fourth process.

20. The system of claim 12 wherein the first thermal equilibrium corresponds to a first temperature distribution in the first and second heat storage devices that is generally fixed for a period of time.

21. The system of claim 12 wherein the first heat storage device includes a plurality concrete plates spaced apart to form individual flow channels, and wherein the controller is programmed with instructions that, when executed, direct a working fluid through the flow channels at a laminar flow rate.

22. A solar energy collection system, comprising:

a controller coupleable to a fluid flow network that is in turn coupled to a first heat storage device, a second heat storage device, a solar field, and a target heat user, the controller being programmed with instructions that, when executed:

direct heat from the solar field to the target heat user during a first process;

direct heat from the solar field to the first and second heat storage devices during a second process, at least until the first and second heat storage devices are generally at a first thermal equilibrium;

direct heat from the first and second heat storage devices to the target heat user during a third process; and

direct heat from the first and second heat storage devices to the solar field during a fourth process, at least until the first and second heat storage devices are generally at a second thermal equilibrium, the second thermal equilibrium corresponding to a lower average temperature than the first thermal equilibrium.

23. The system of claim 22 wherein the controller is programmed with instructions that, when executed:

direct a first quantity of working fluid from the outlet of the solar field to the first heat storage device, and then to the second heat storage device, during the second process; and

direct a second quantity of working fluid from the second heat storage device to the first heat storage device, and then to the inlet of the solar field, during the fourth process.

24. The system of claim 22, further comprising:

the first heat storage device;

the second heat storage device;

the solar field; and

the fluid flow network.

25. A method for operating a solar collection system, comprising:

collecting solar energy at a solar field;

directing at least a portion of the solar energy to a target heat user during a first process;

directing heat from the solar field to first and second heat storage devices during a second process at least until the first and second heat storage devices are generally at a first thermal equilibrium;

directing heat from the first and second heat storage devices to the target heat user during a third process; and

directing heat from the first and second heat storage devices to the solar field during a fourth process at least until the first and second heat storage devices are generally at a second thermal equilibrium, the second thermal equilibrium corresponding to a lower average temperature than the first thermal equilibrium.

26. The method of claim 25 wherein directing heat from the first and second heat storage devices to the target heat user during the third process includes directing the heat at a first temperature, and wherein the method further comprises halting directing the heat in response to a temperature drop corresponding to a reduction from the first temperature to a second temperature.

27. The method of claim 25, further comprising repeating the second process after completing the fourth process.

28. A method for operating a solar collection system, comprising:

collecting first thermal energy at a first solar field and directing at least a portion of the first thermal energy to a target heat user;

collecting second thermal energy at a second solar field and directing at least a portion of the second thermal energy to at least one heat storage device;

during an inter-field discharge process, directing heat from the at least one heat storage device to a working fluid that enters the first solar field; and

during an extra-field discharge process, directing heat from the at least one heat storage device to the target heat user.

29. The method of claim 28 wherein at least part of the first process is performed during daylight hours and at least part of the second process is performed during night-time hours.

30. The method of claim 28 wherein the working fluid that enters the first solar field is a first working fluid, and wherein heat storage device carries a second working fluid, and wherein directing heat from the heat storage device to the first working fluid includes transferring heat from the second working fluid to the first working fluid at a heat exchanger.

31. The method of claim 28 wherein directing heat from the heat storage device to the target heat user incudes transferring heat at a heat exchanger from a second working fluid carried by the heat storage device to a first working fluid directed to the target heat user.

32. The method of claim 28 wherein the at least one heat storage device includes a first heat storage device and a second heat storage device, and wherein the method further comprises:

directing heat from the second solar field to the first and second heat storage devices during a first process, at least until the first and second heat storage devices are generally at a first thermal equilibrium;

directing heat from the first and second heat storage devices to the target heat user during a second process; and

directing heat from the first and second heat storage devices to the first solar field during a third process, at least until the first and second heat storage devices are generally at a second thermal equilibrium, the second thermal equilibrium corresponding to a lower average temperature than the first thermal equilibrium.

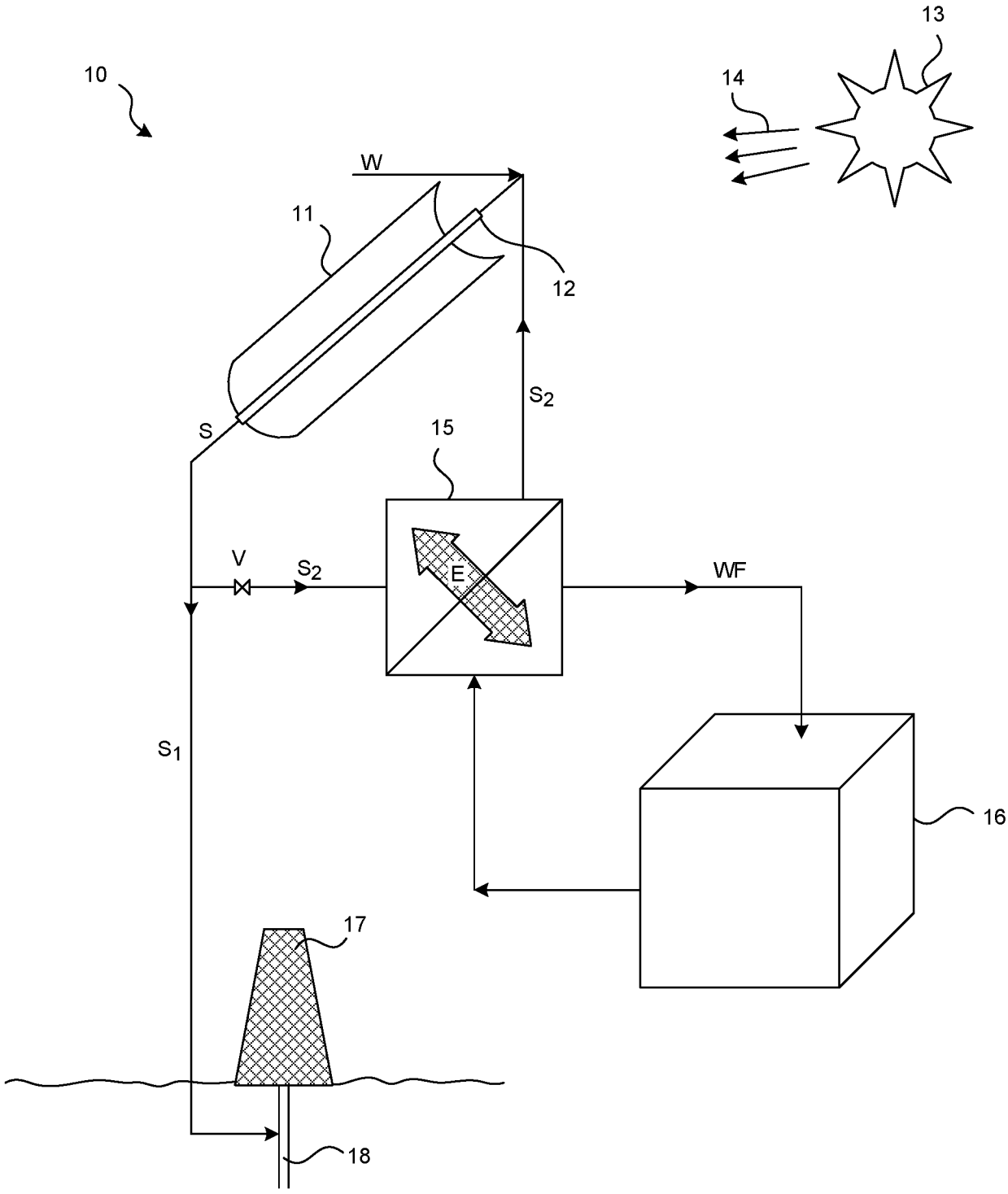


FIG. 1
(Prior Art)

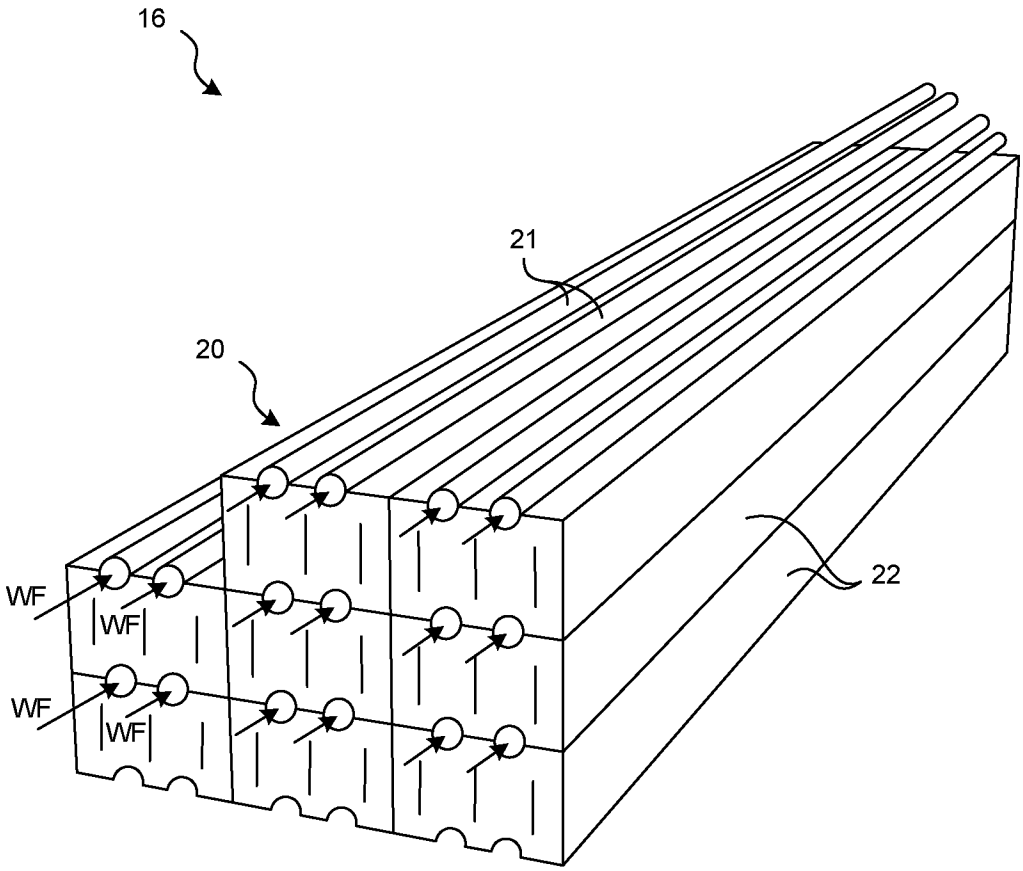


FIG. 2
(Prior Art)

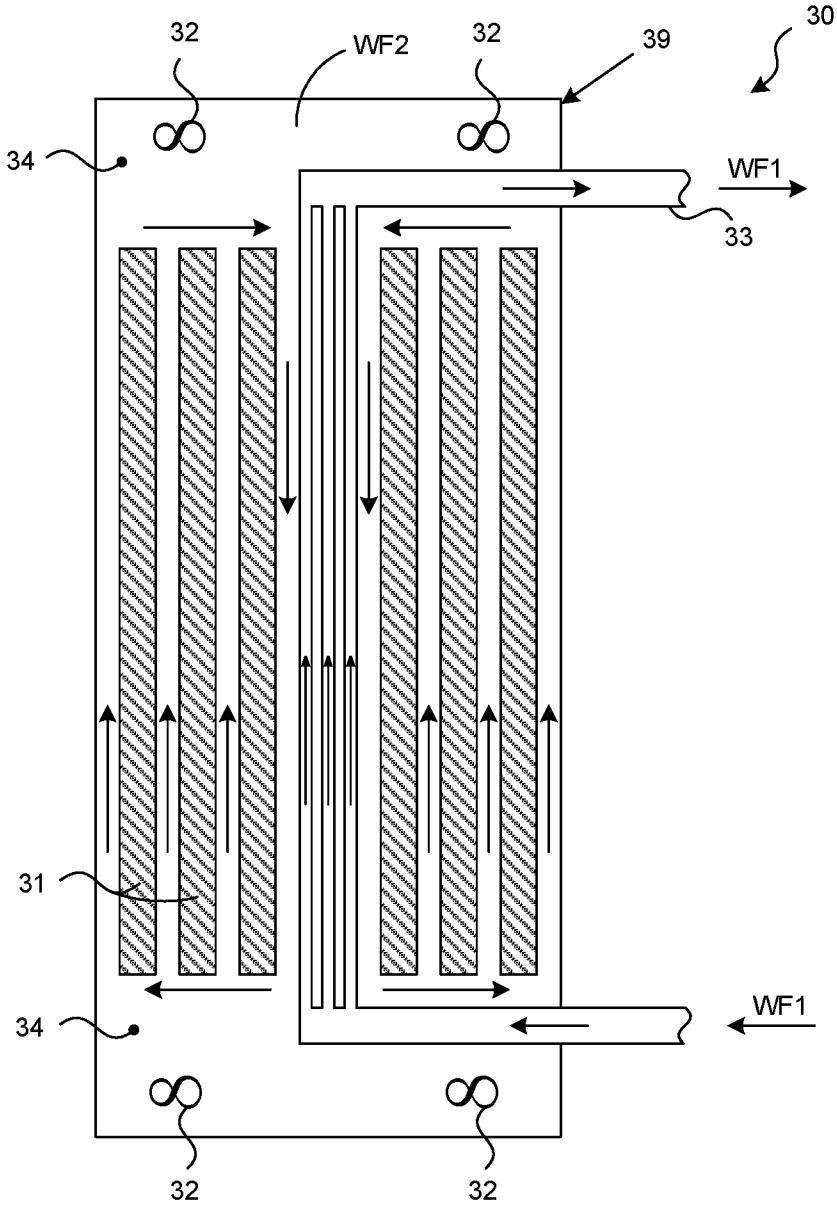


FIG. 3
(Prior Art)

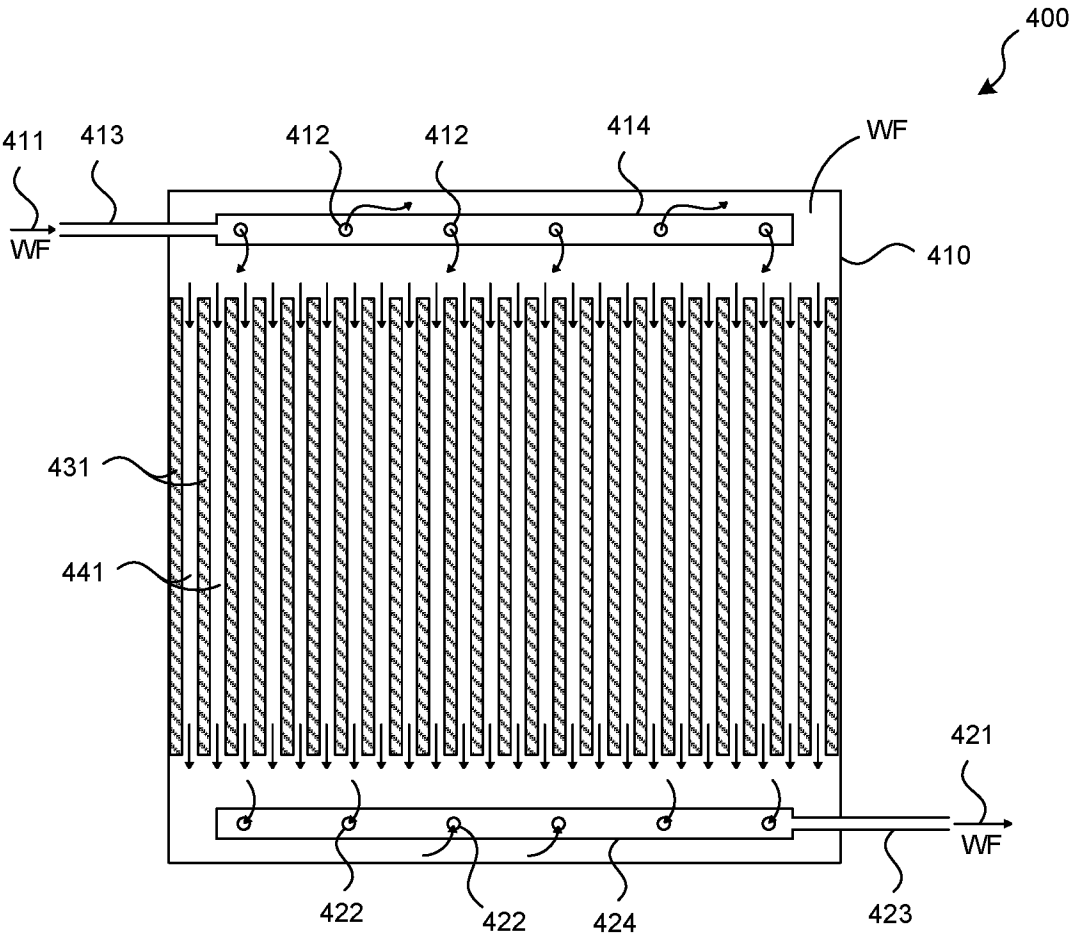


FIG. 4A

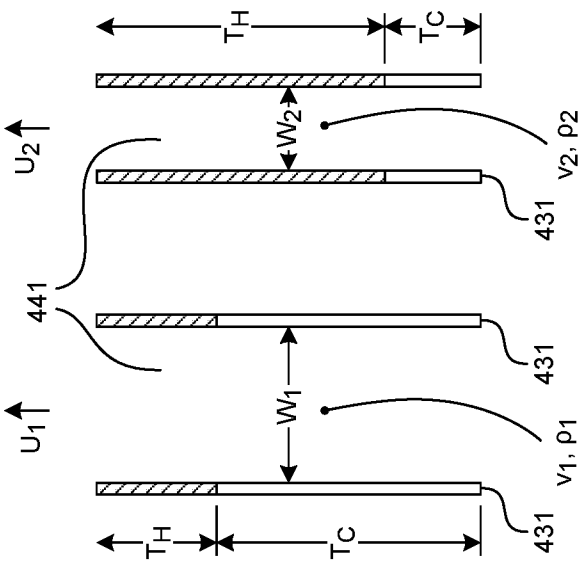

T_H
T_C
W_2
U_2
v_2, ρ_2
431
441
431
W_1
U_1
v_1, ρ_1
431
T_H
T_C

FIG. 4C

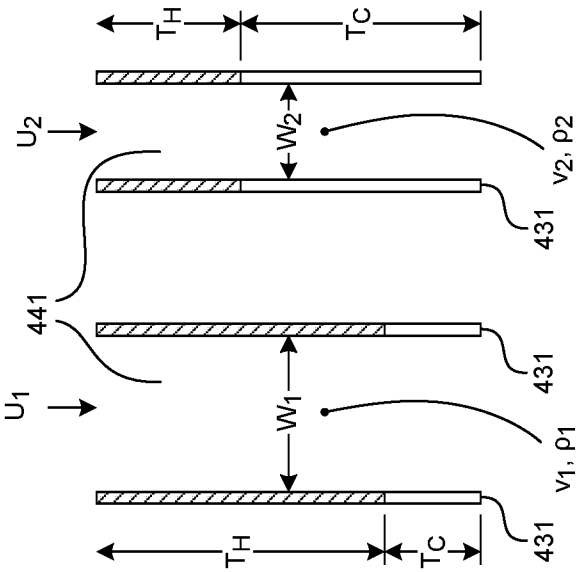

T_H
T_C
U_2
W_2
v_2, ρ_2
431
441
431
U_1
W_1
v_1, ρ_1
431
T_H
T_C

FIG. 4B

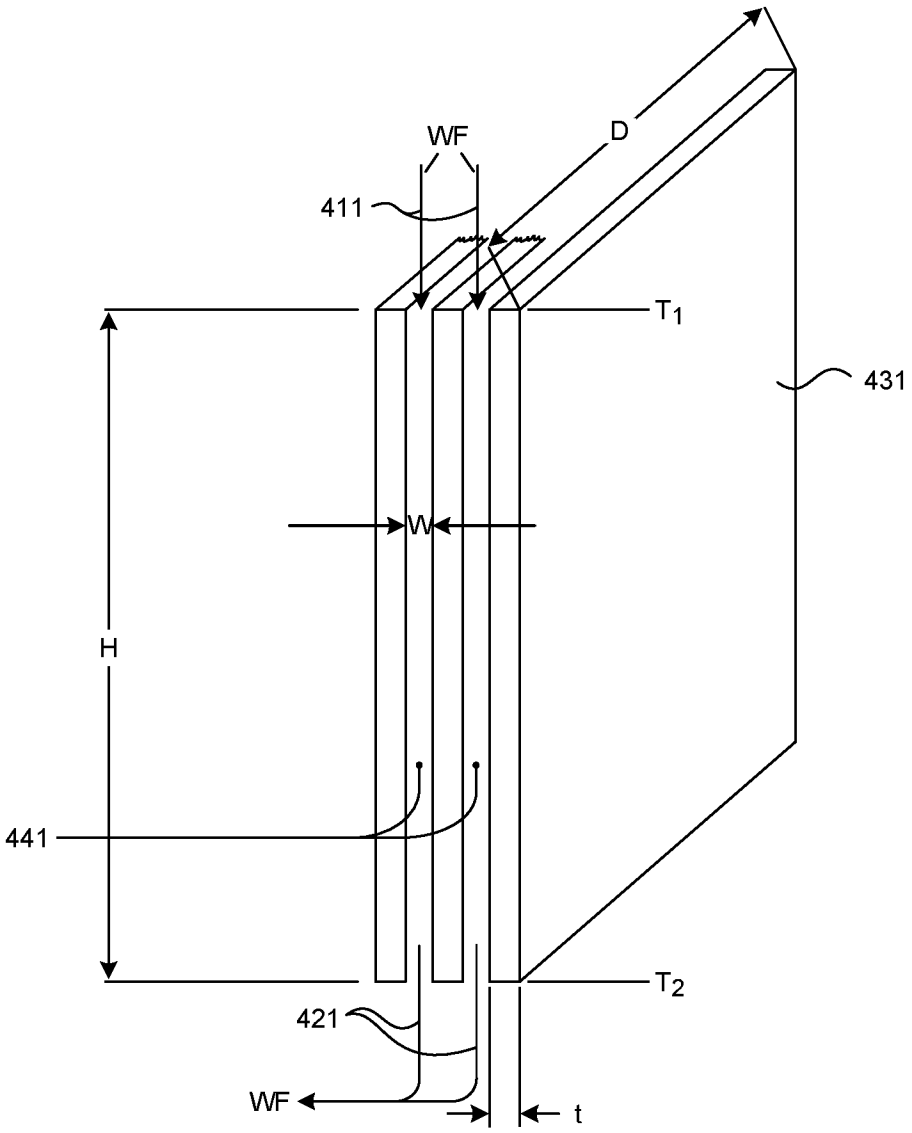


FIG. 5A

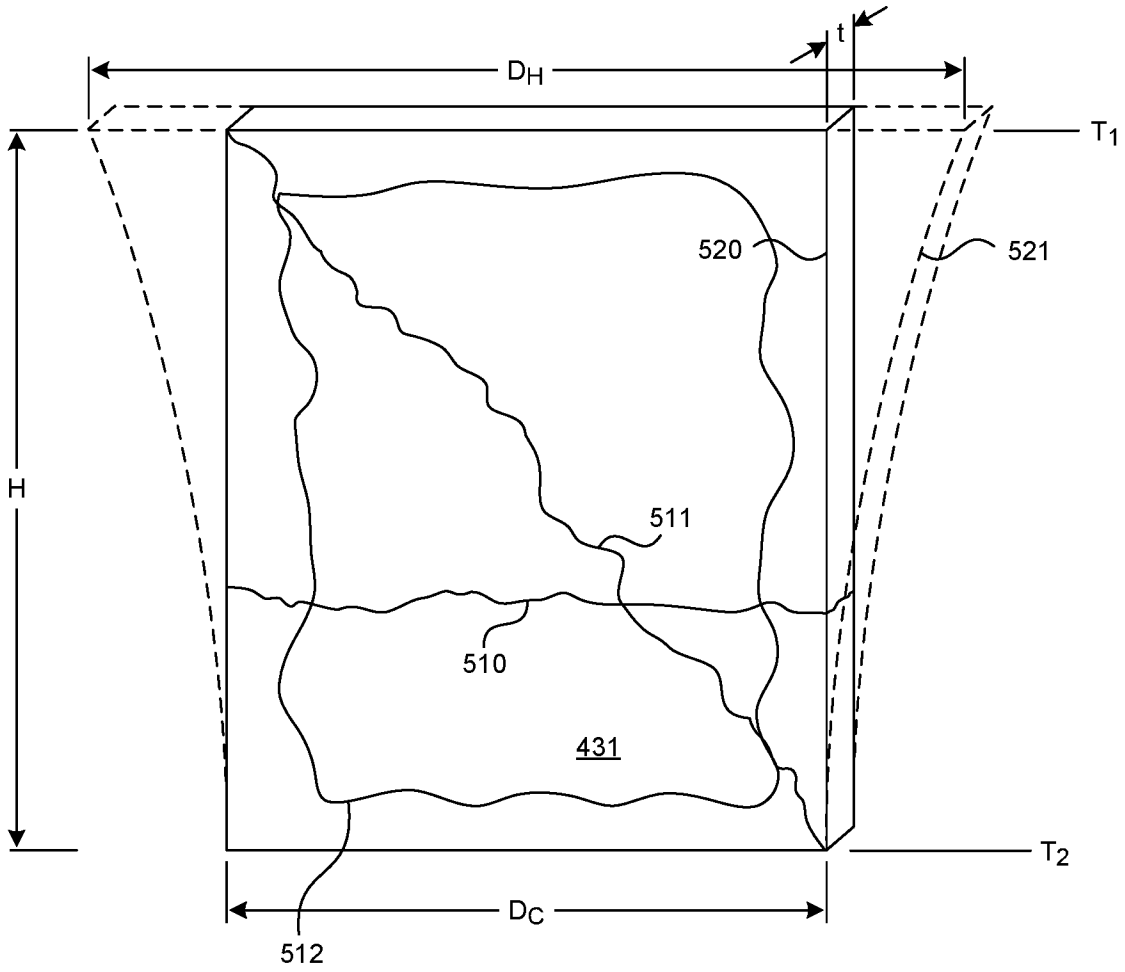


FIG. 5B

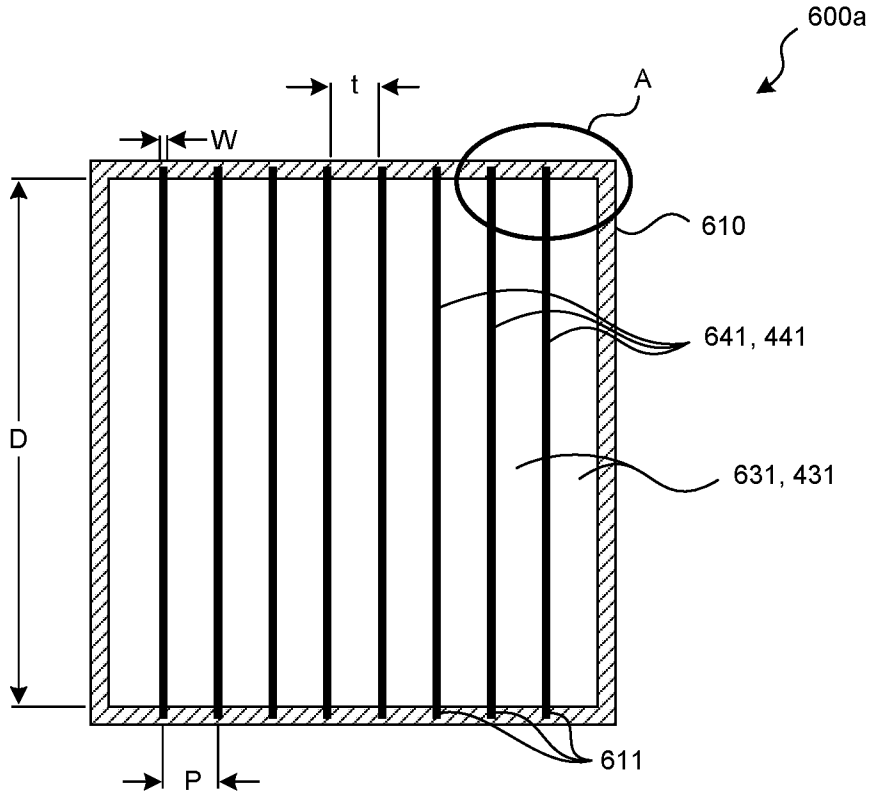

600a
t
A
W
610
641, 441
D
631, 431
611
P

FIG. 6A

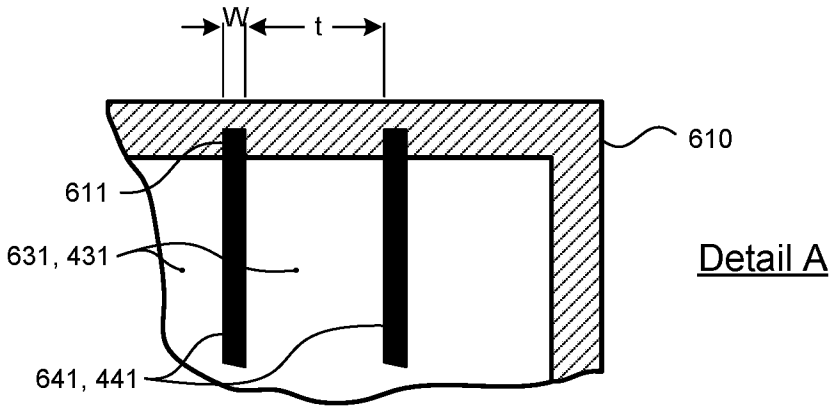

W
t
610
611
631, 431
641, 441
Detail A

FIG. 6B

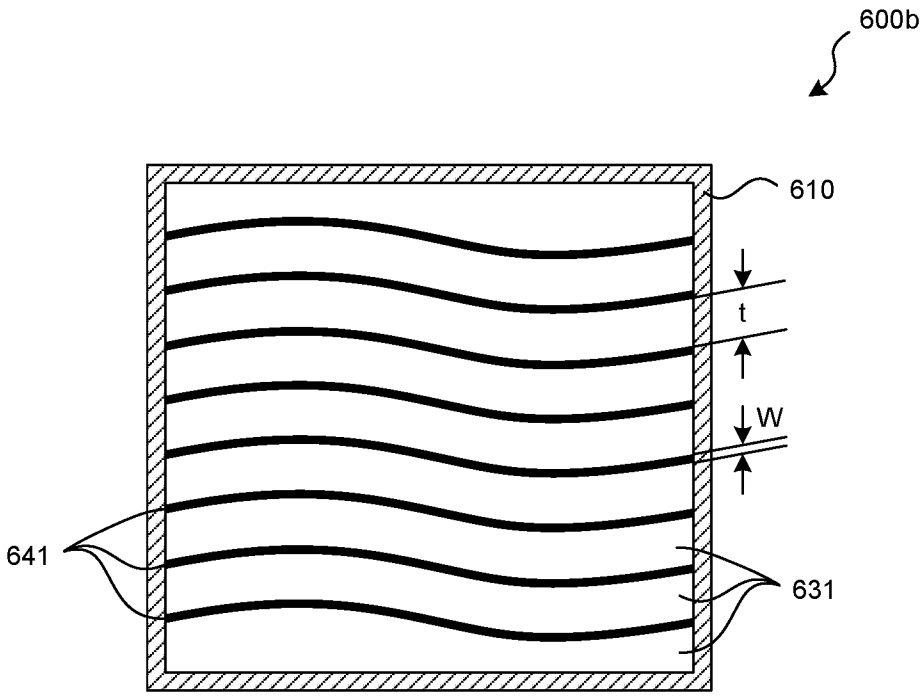


FIG. 6C

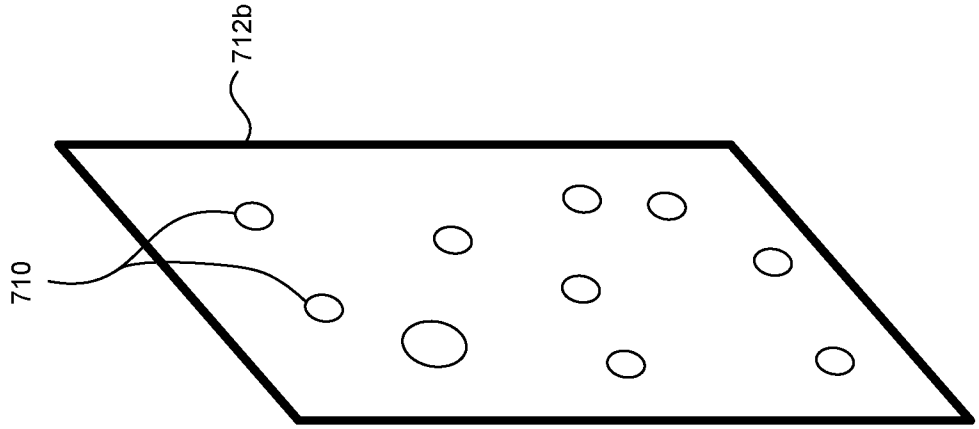


FIG. 7B

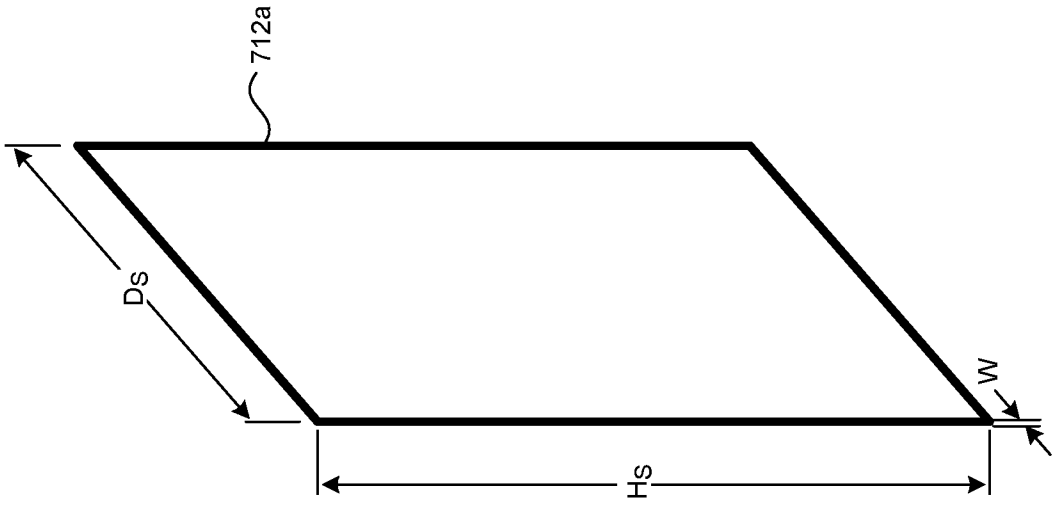


FIG. 7A

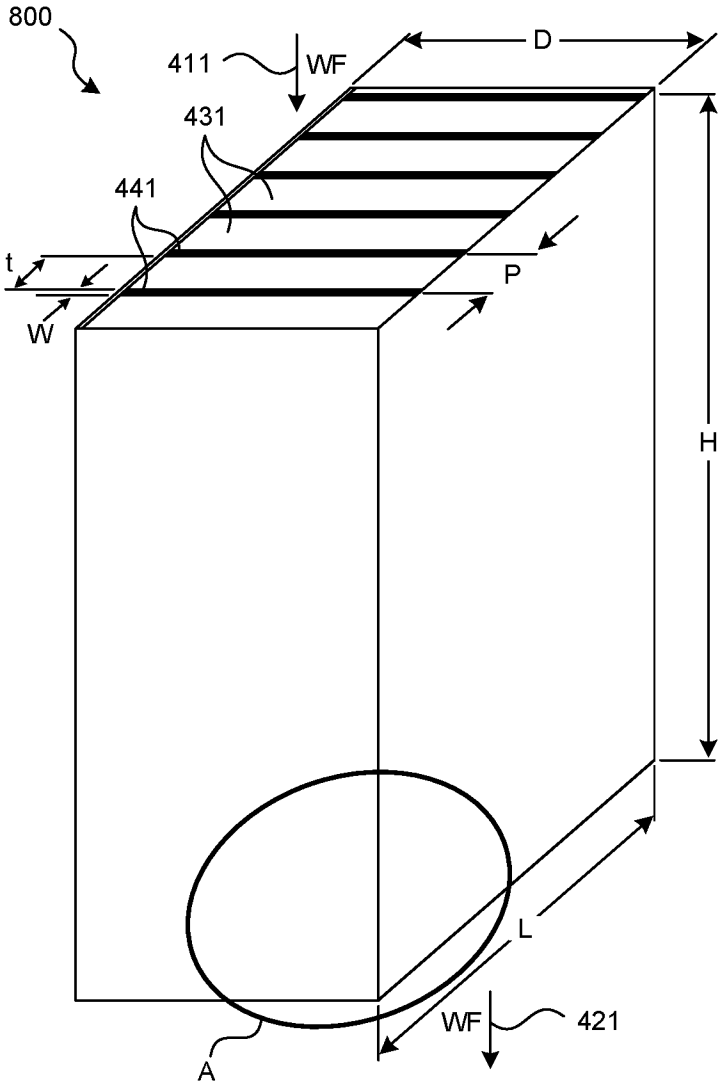


FIG. 8A

Detail A

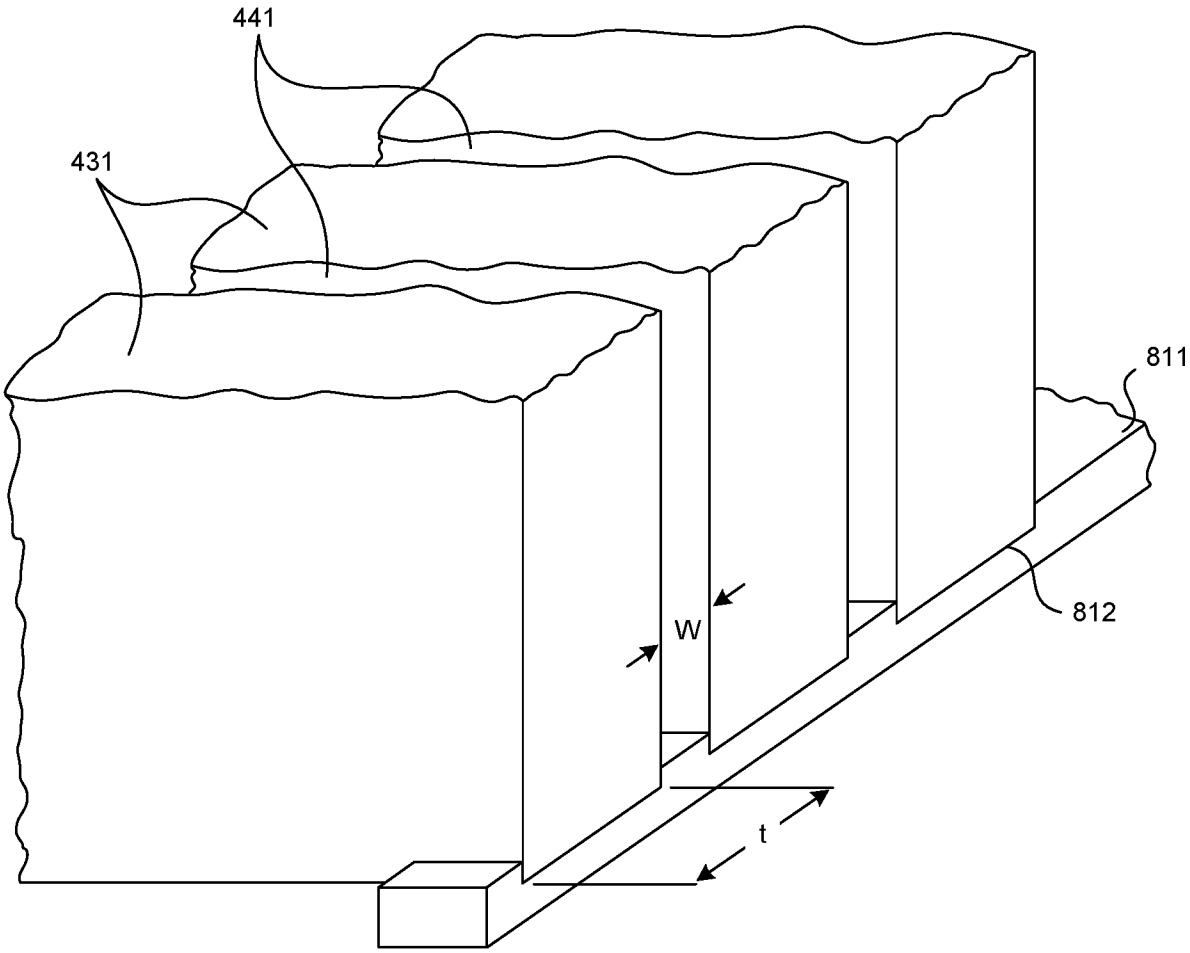


FIG. 8B

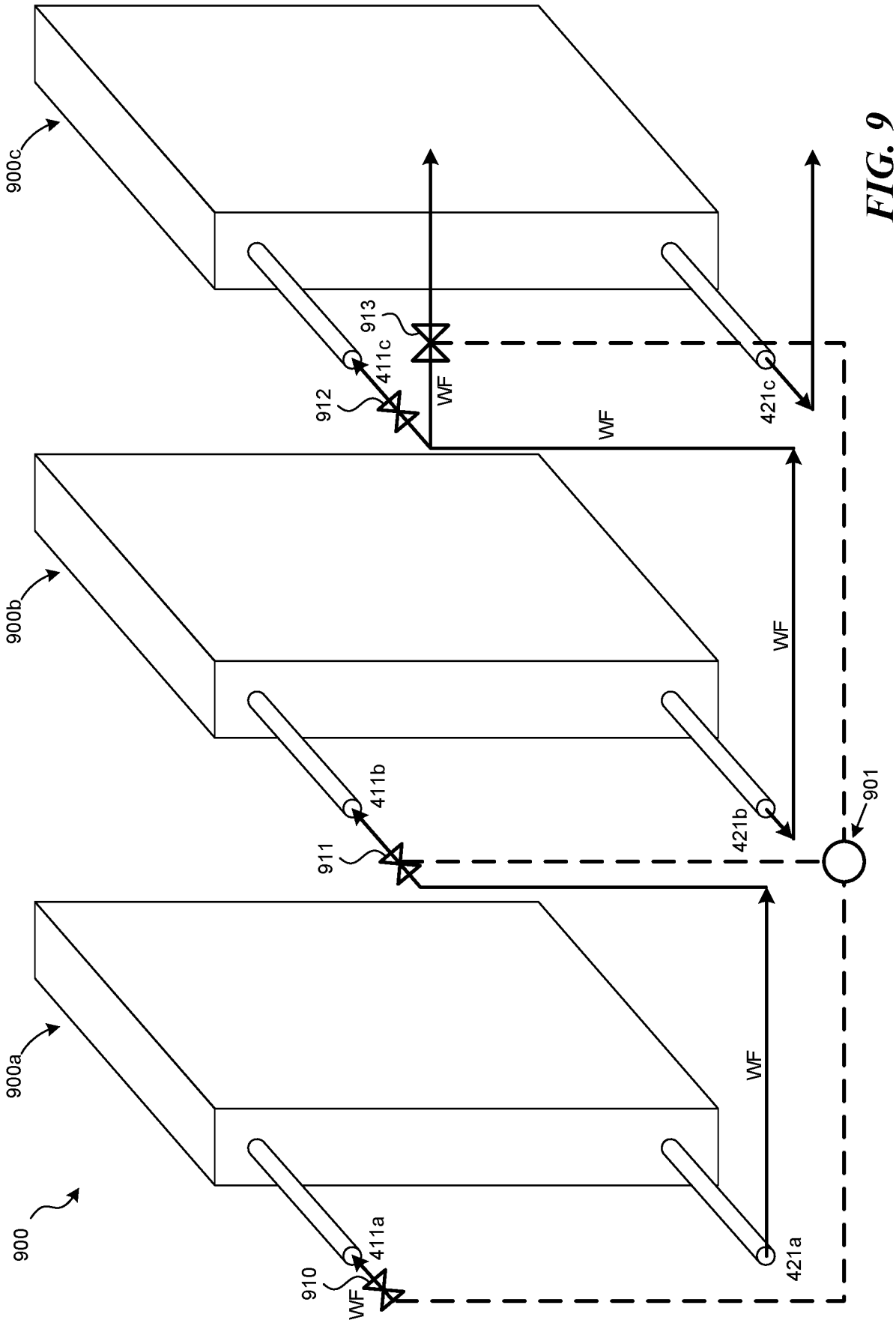

900
900a
900b
900c
901
910
911
912
913
411a
411b
411c
421a
421b
421c
WF

FIG. 9

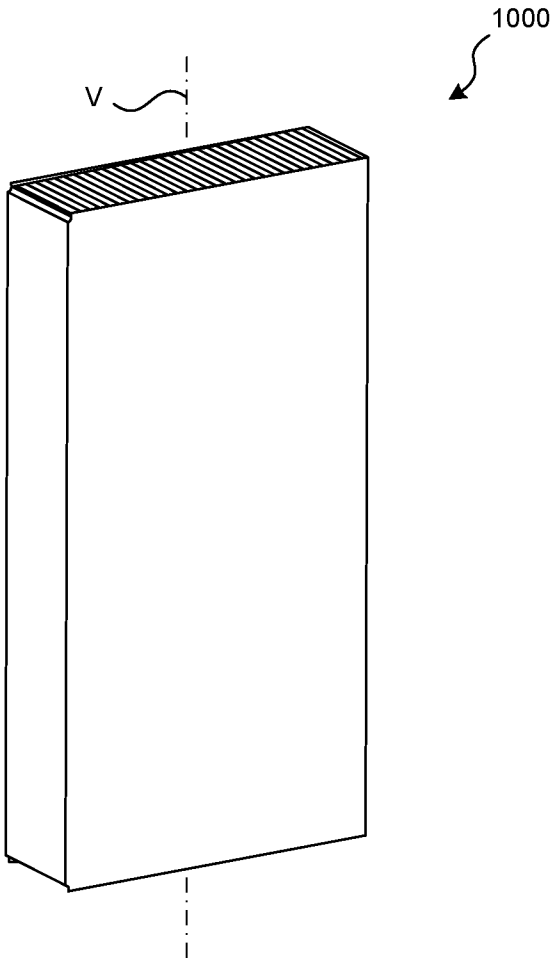


FIG. 10A

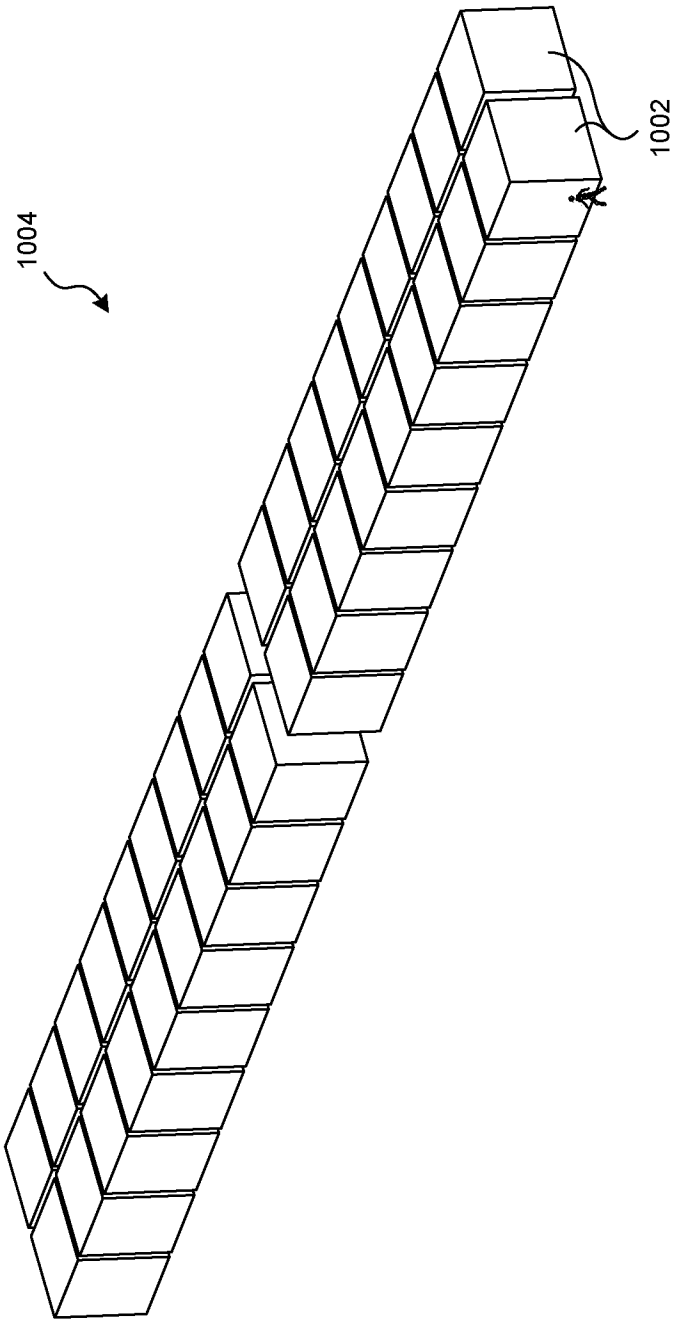


FIG. 10B

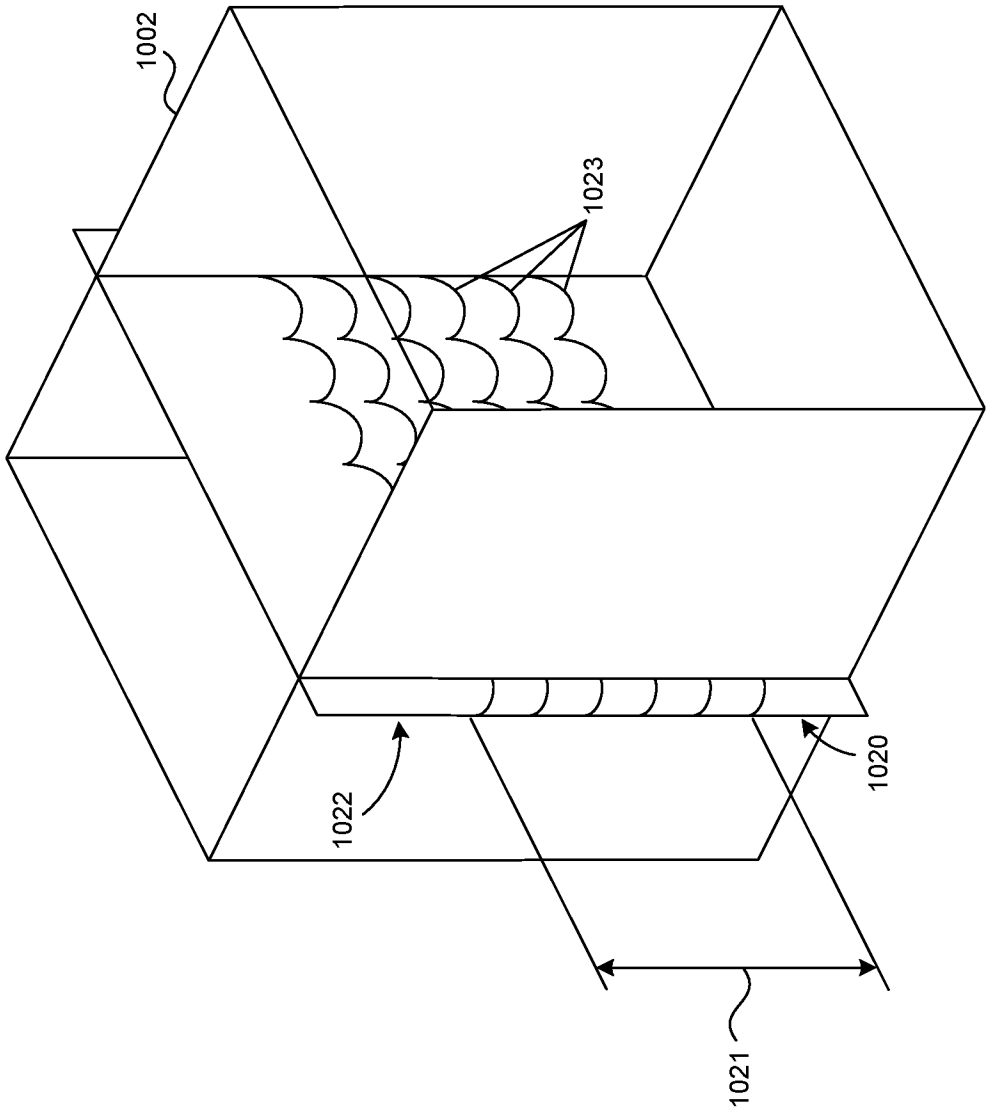


FIG. 10C

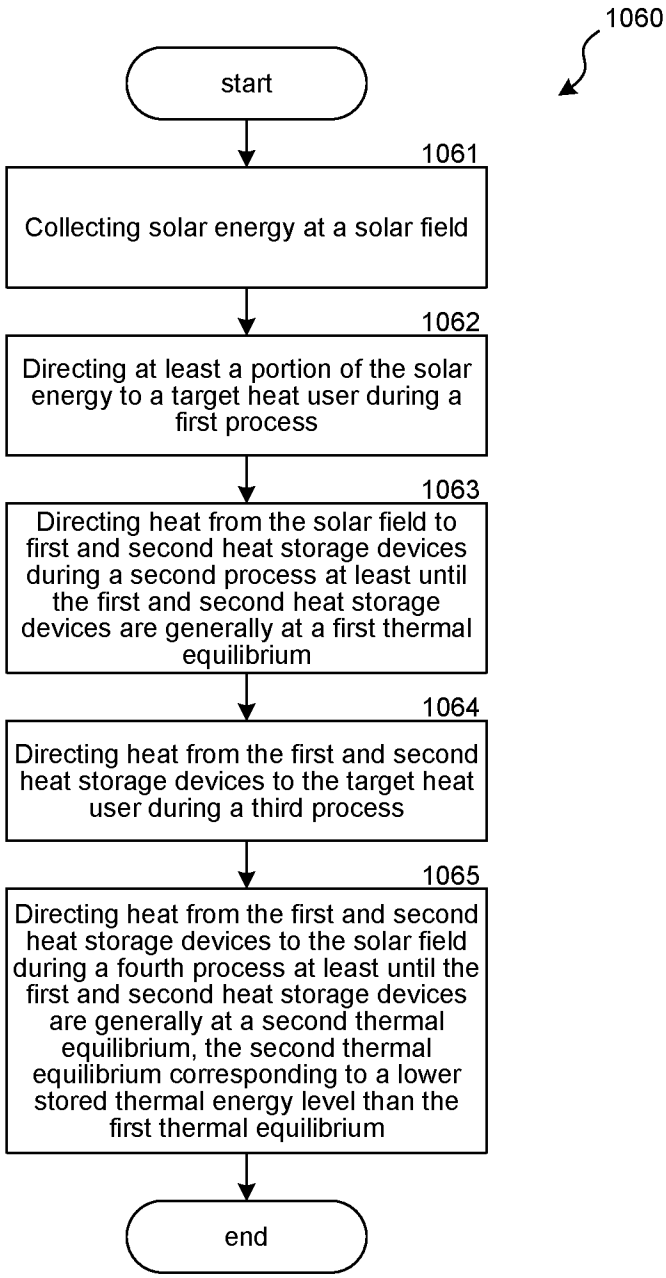

1060
start
1061
Collecting solar energy at a solar field
1062
Directing at least a portion of the solar energy to a target heat user during a first process
1063
Directing heat from the solar field to first and second heat storage devices during a second process at least until the first and second heat storage devices are generally at a first thermal equilibrium
1064
Directing heat from the first and second heat storage devices to the target heat user during a third process
1065
Directing heat from the first and second heat storage devices to the solar field during a fourth process at least until the first and second heat storage devices are generally at a second thermal equilibrium, the second thermal equilibrium corresponding to a lower stored thermal energy level than the first thermal equilibrium
end

FIG. 10D

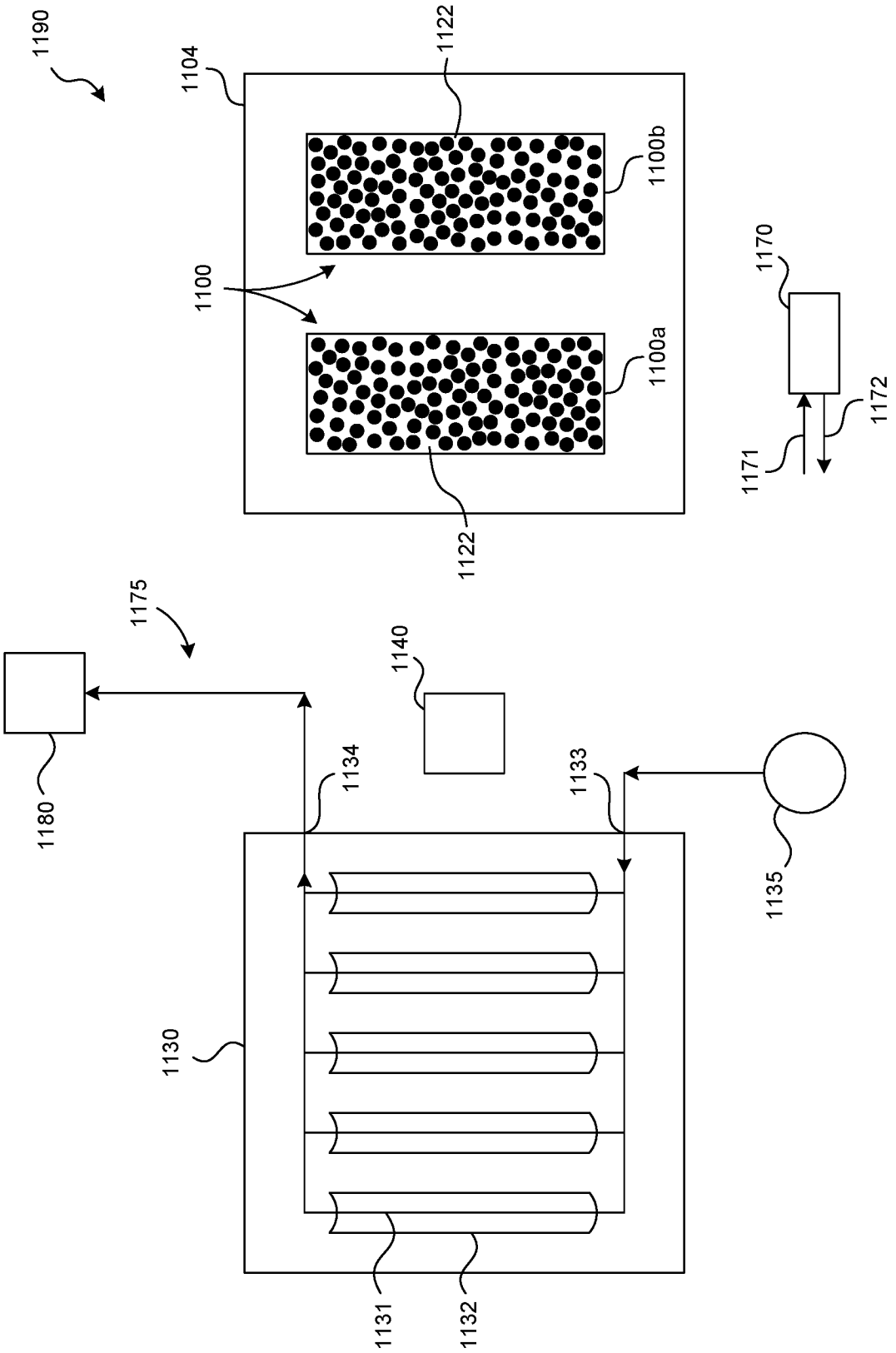

1190
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FIG. 11A

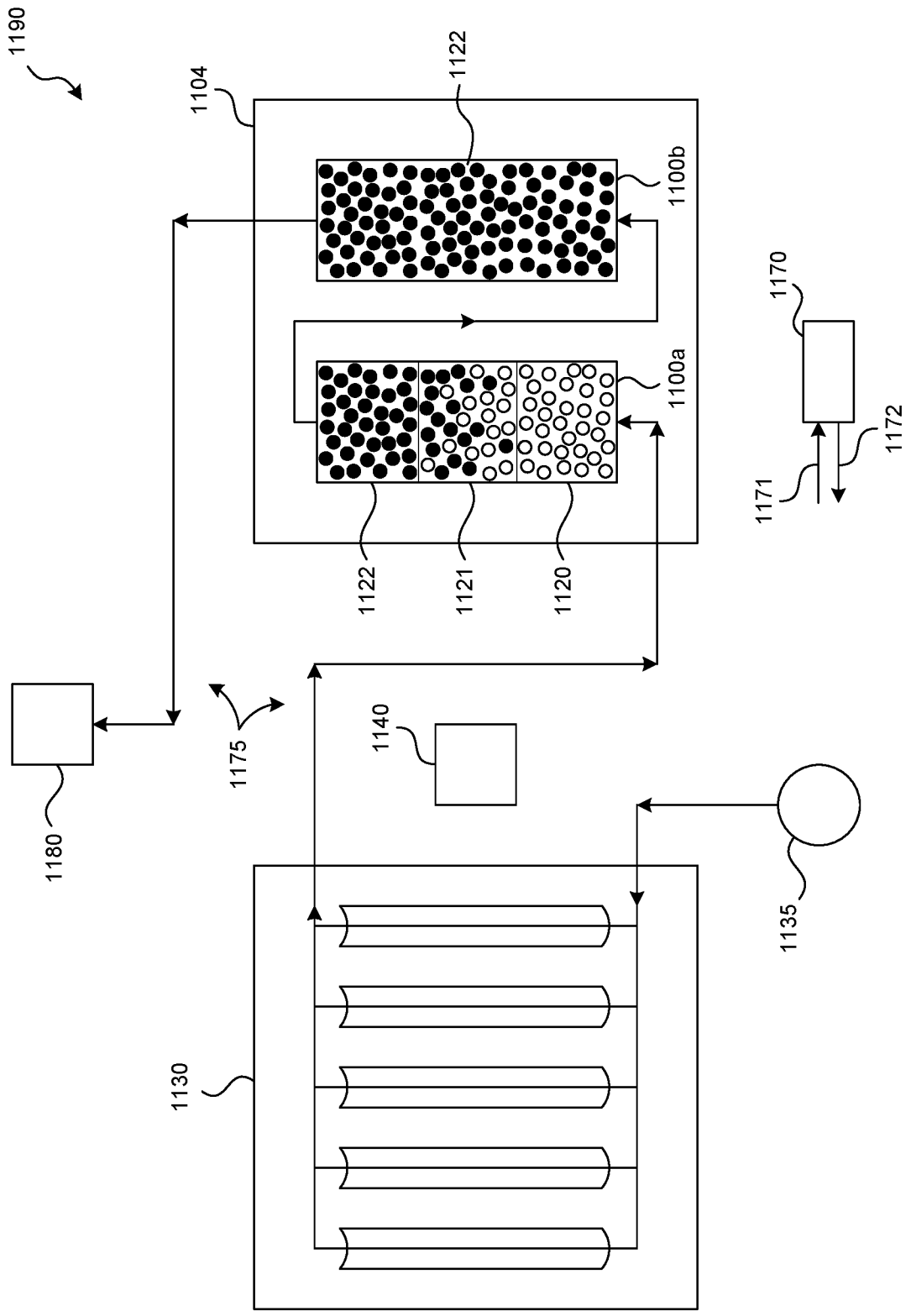

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FIG. 11B

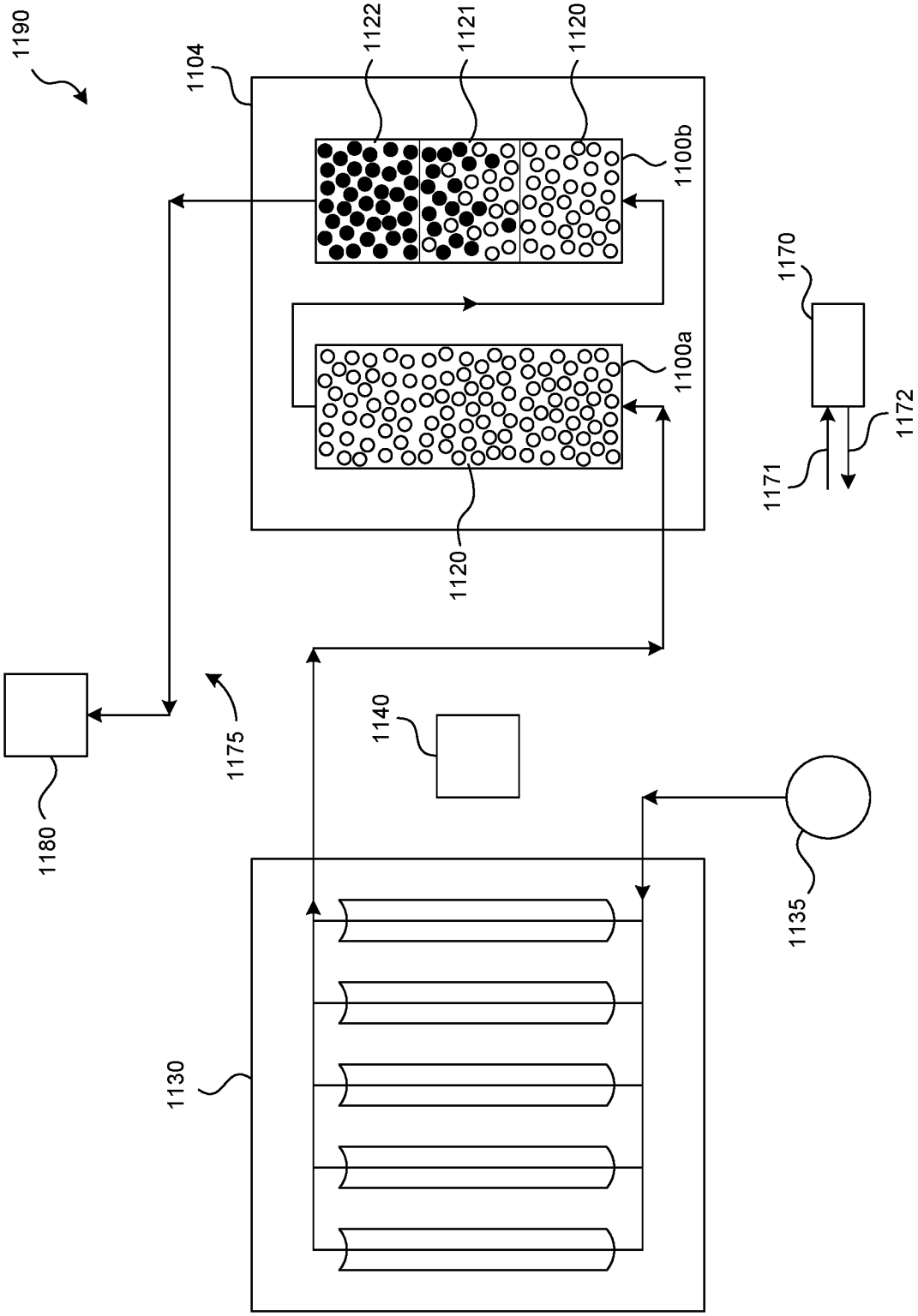

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FIG. 11C

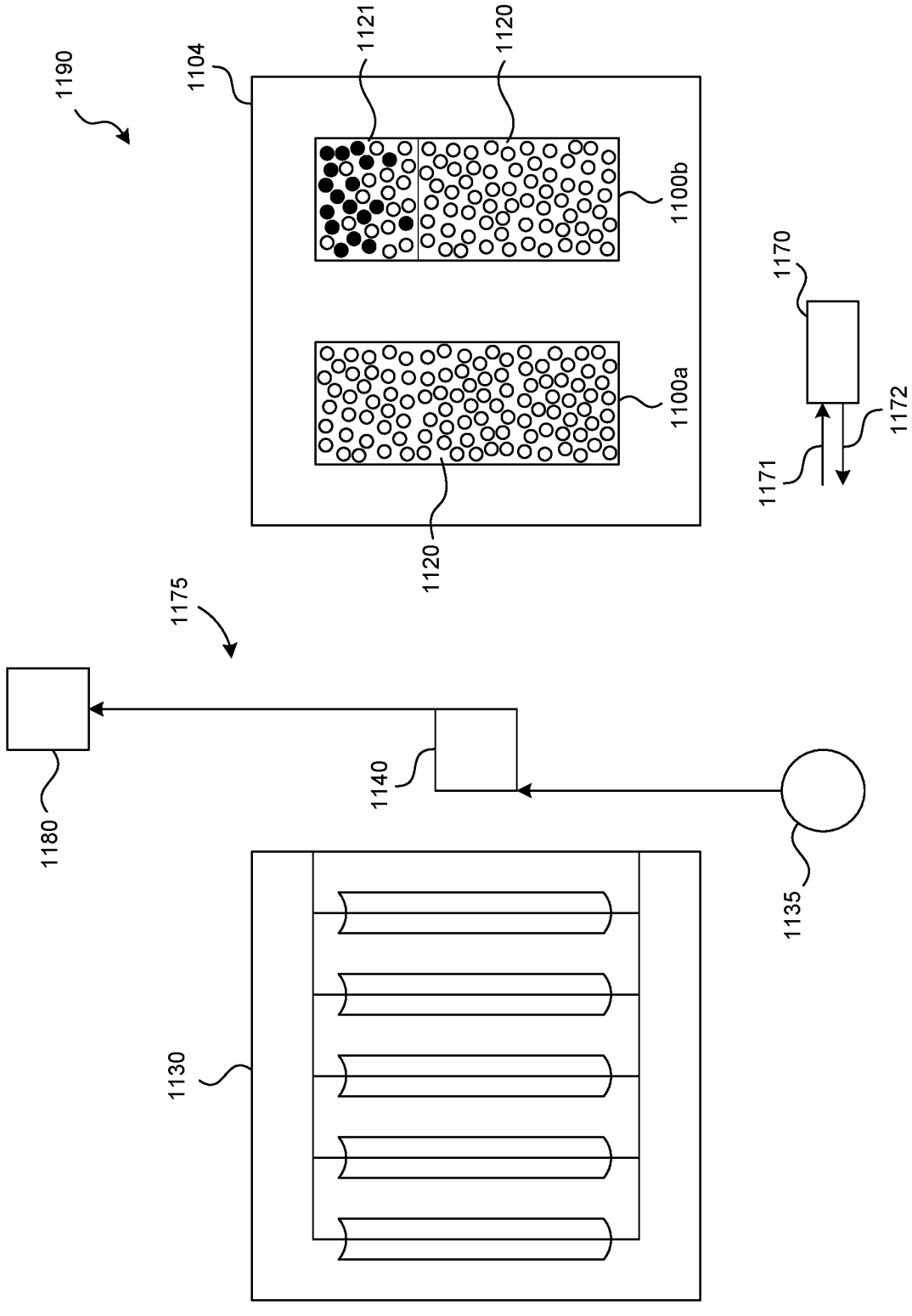

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FIG. 11D

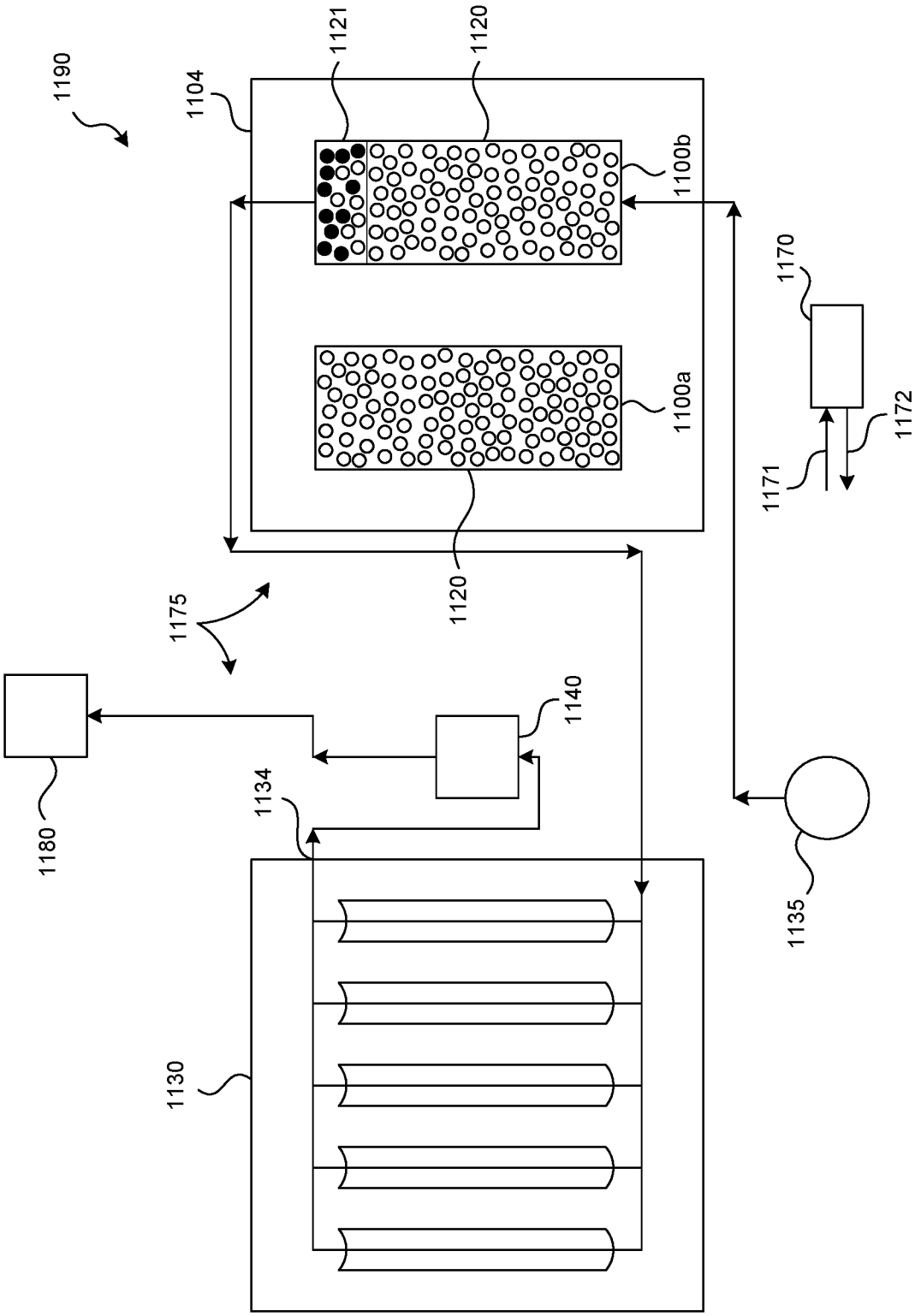

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FIG. 11E

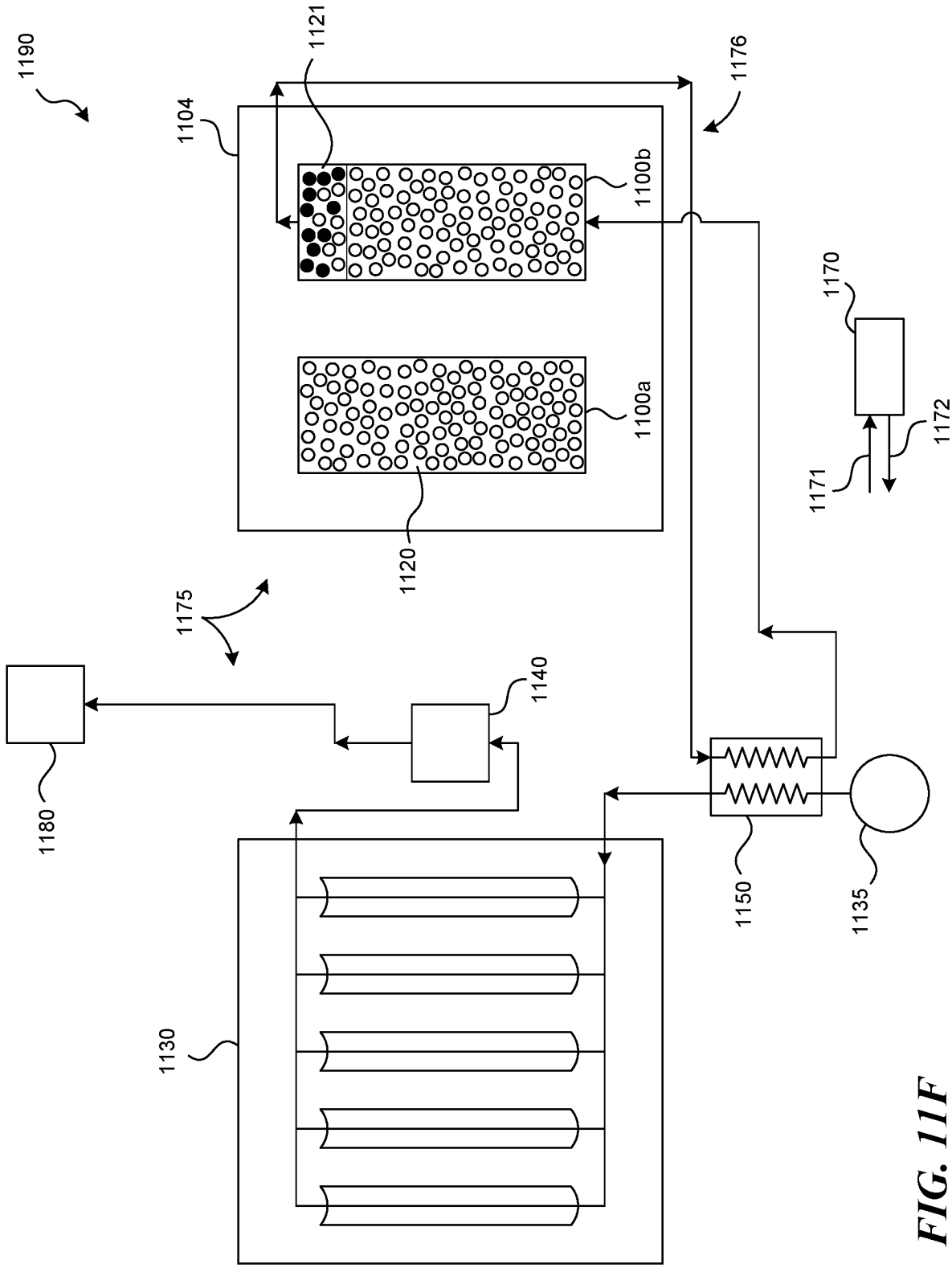

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1180
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FIG. 11F

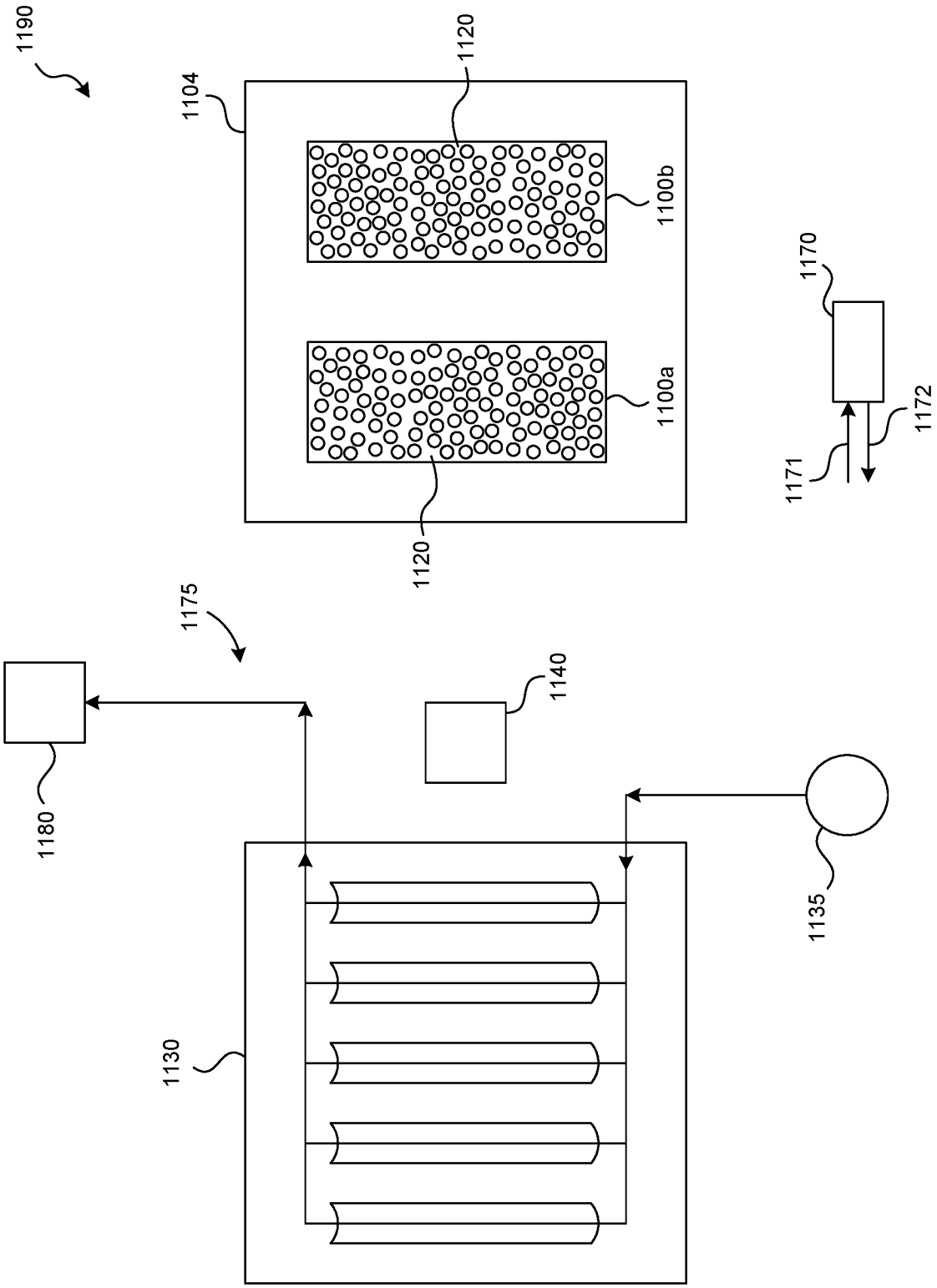

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FIG. 11G

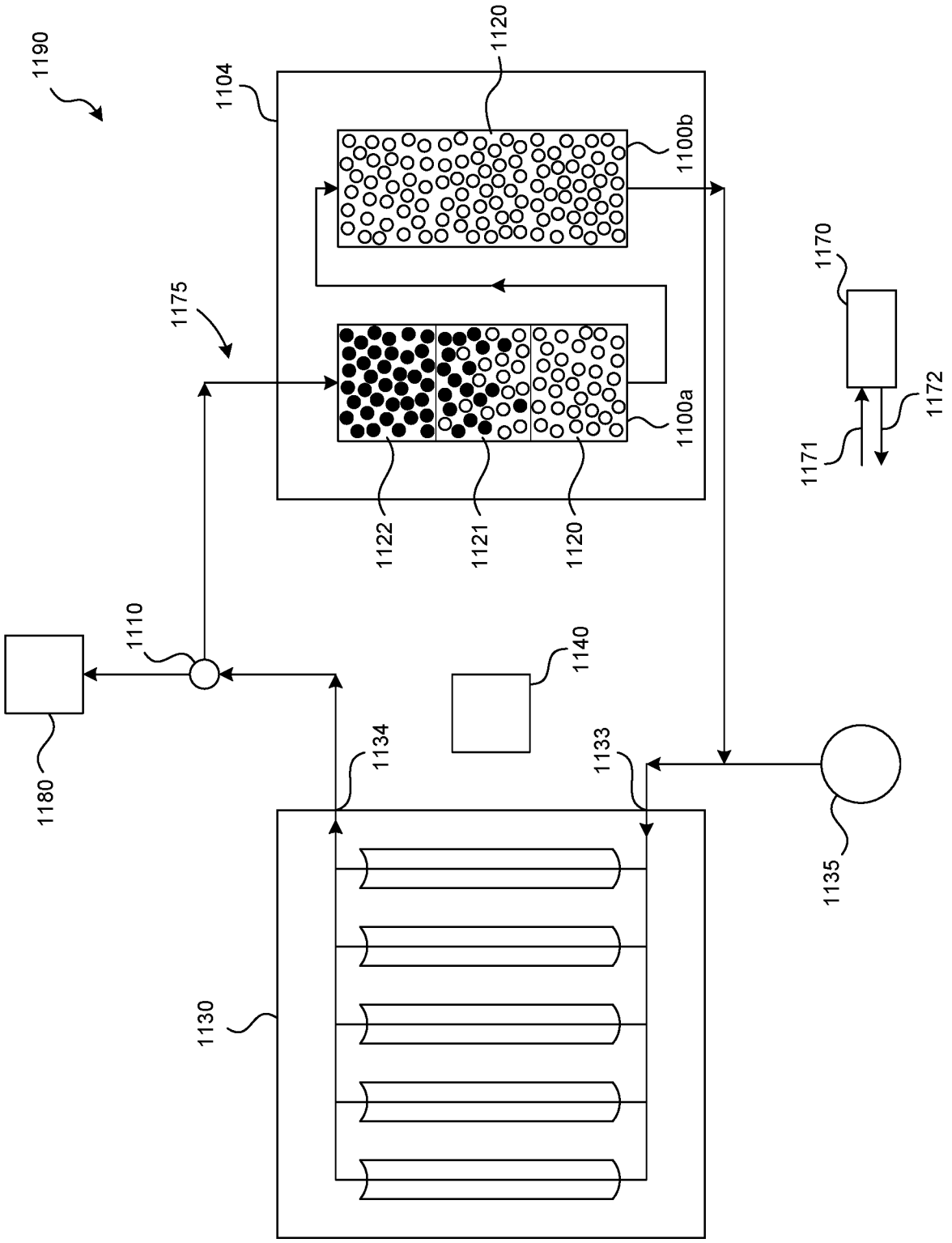

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FIG. 11H

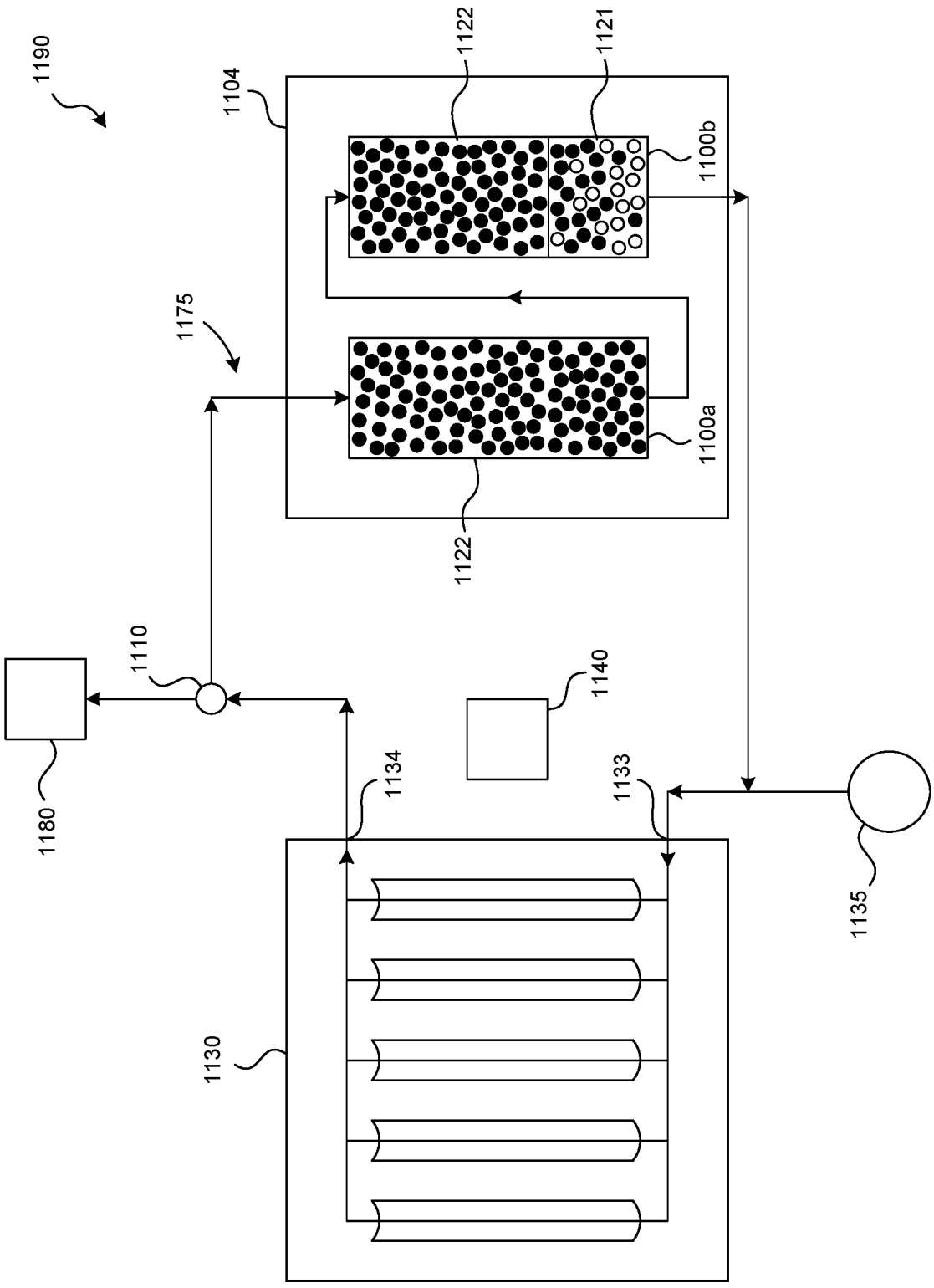

1190
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1140
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1130

FIG. 1I1

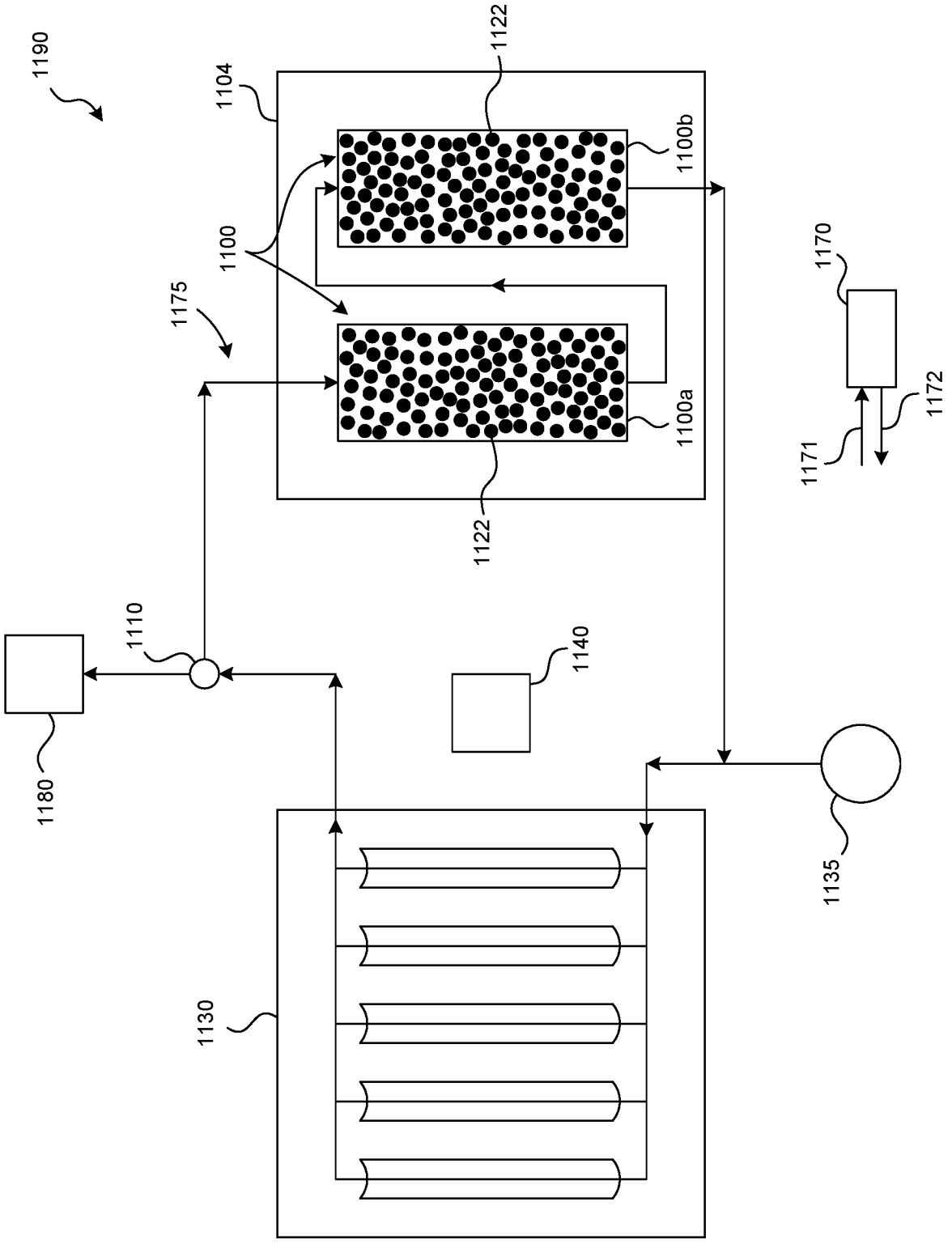

1190
1104
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1171
1100a
1122
1110
1140
1180
1135
1130

FIG. 11J

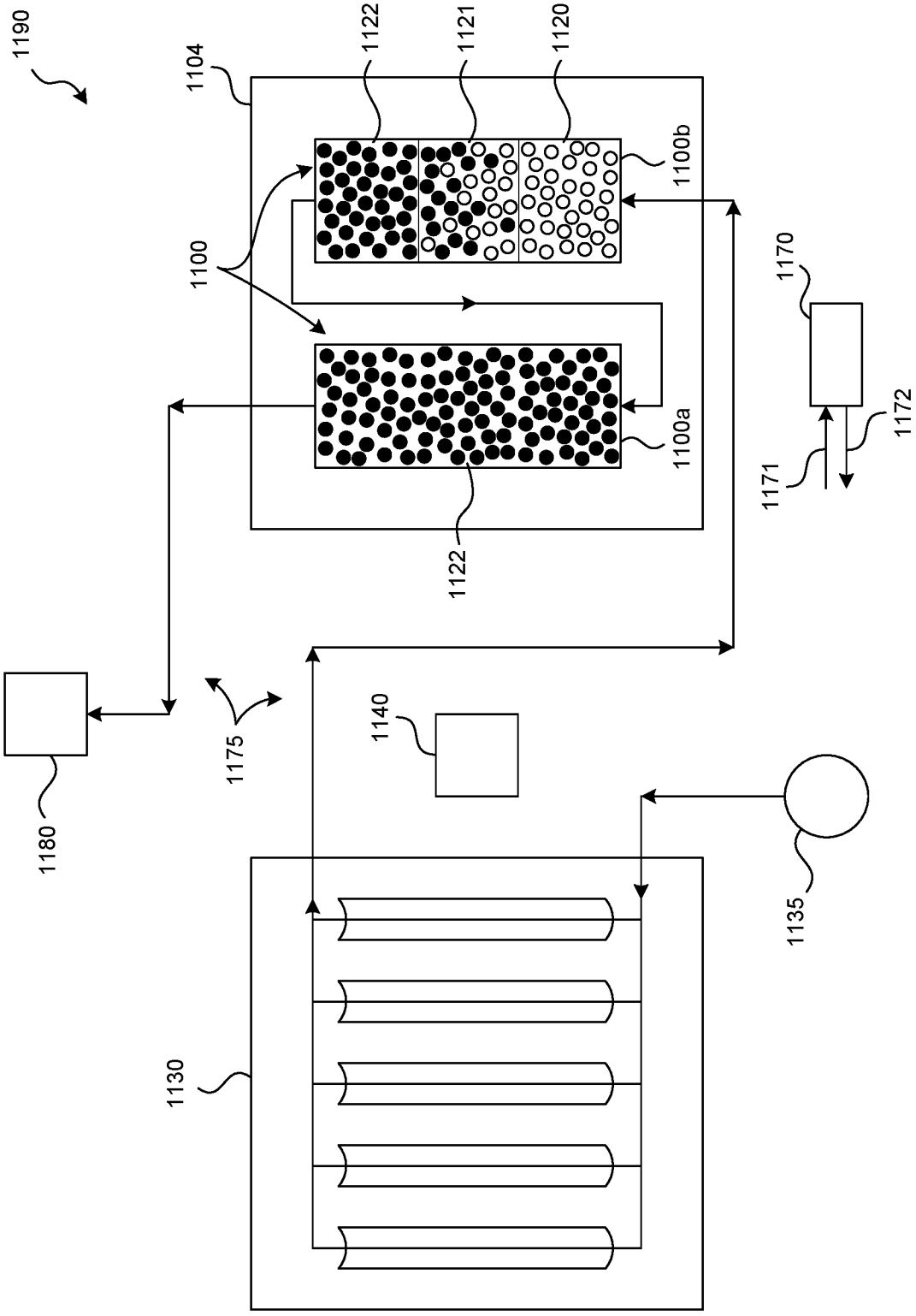

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1100a
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1130

FIG. 11K

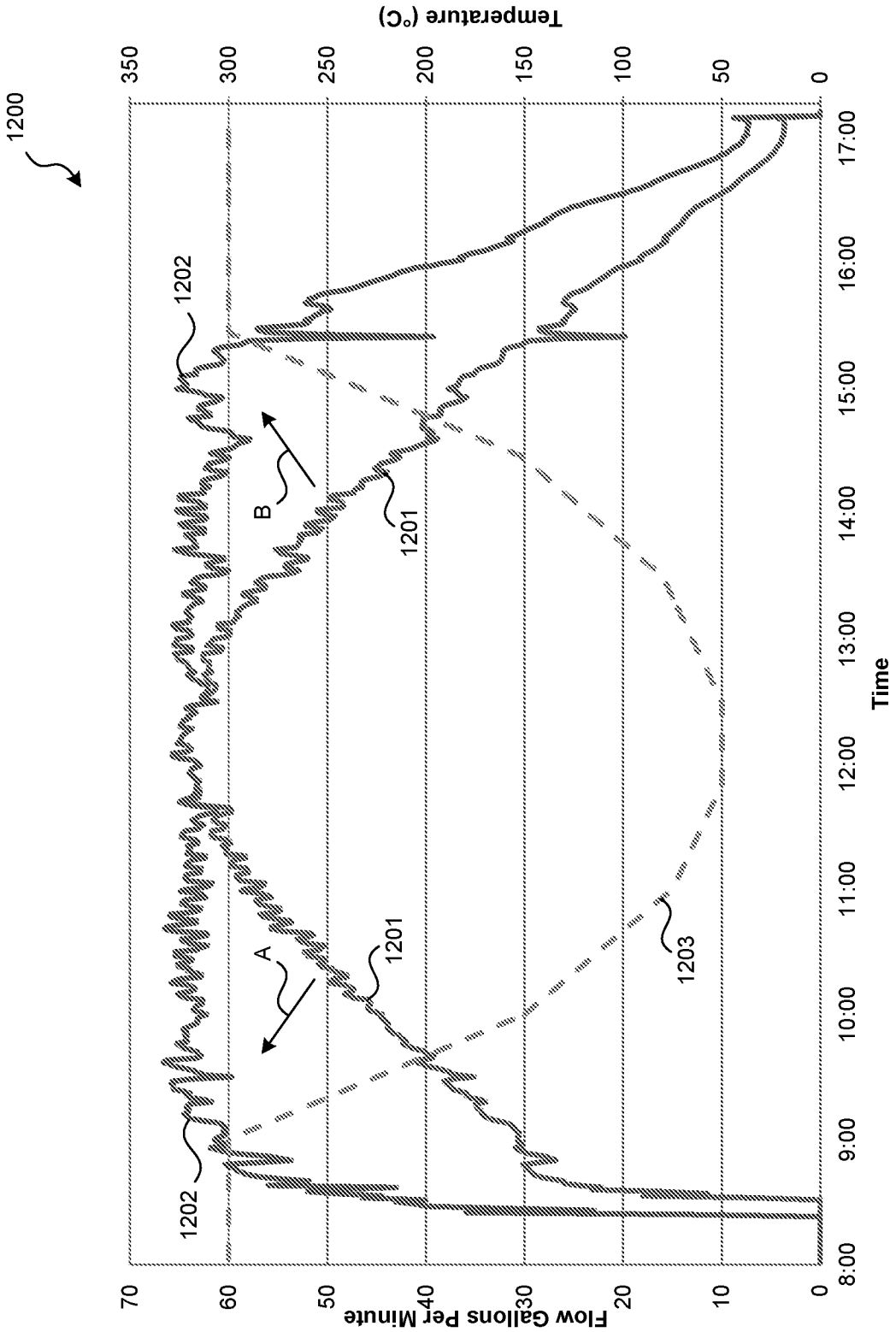

1200
Temperature (°C)
350
300
250
200
150
100
50
0
1202
1201
B
A
1201
1203
1202
70
60
50
40
30
20
10
0
Flow Gallons Per Minute
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
Time

FIG. 12

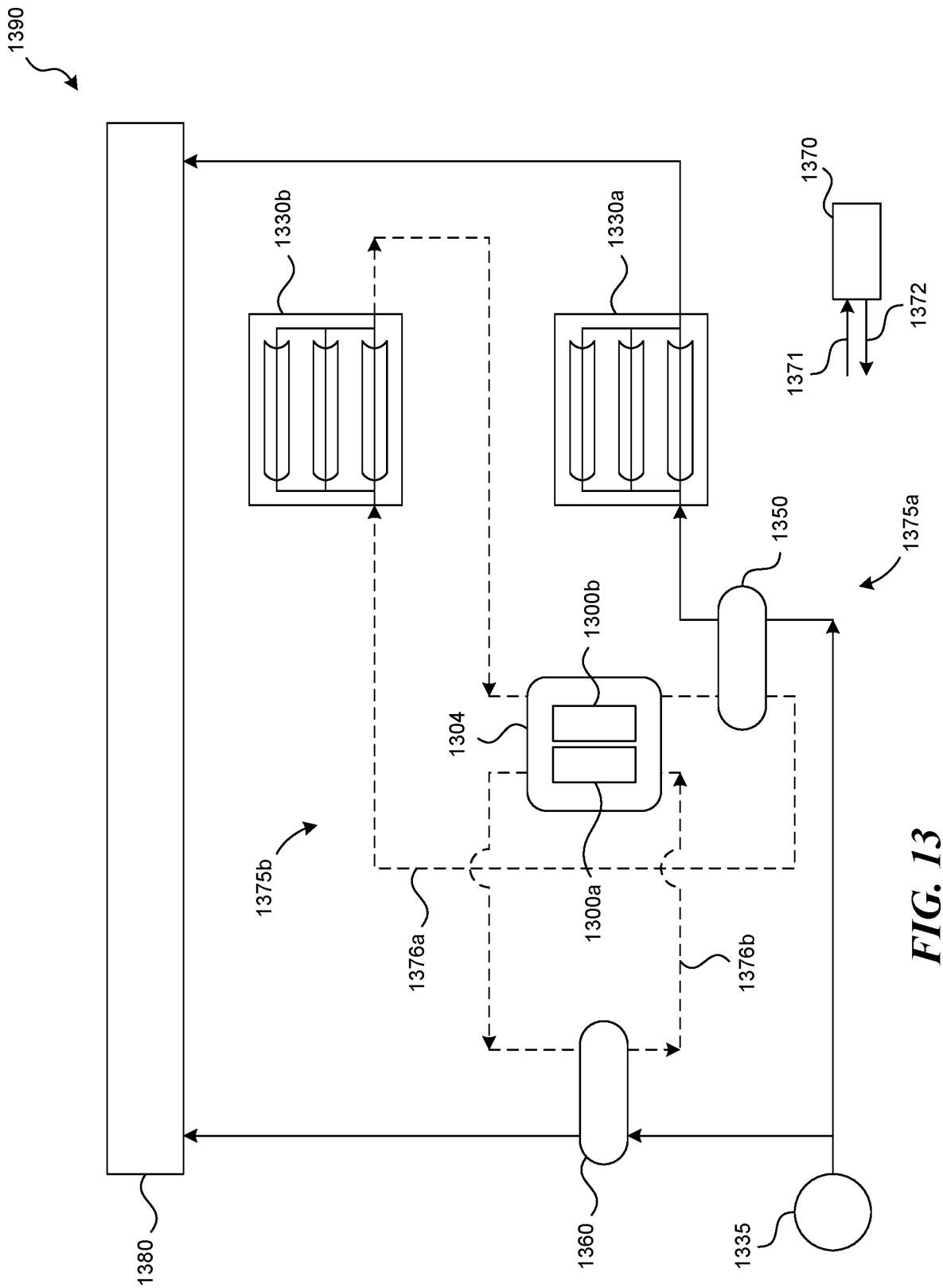

1390
1330b
1330a
1370
1372
1371
1350
1375a
1300b
1304
1375b
1376a
1300a
1376b
1380
1360
1335

FIG. 13

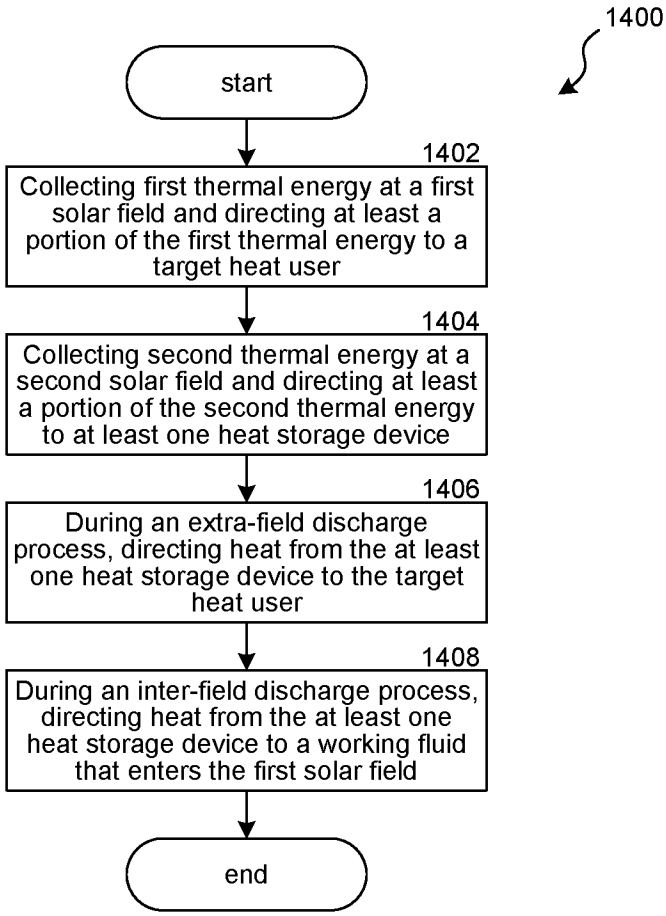

1400
start
1402
Collecting first thermal energy at a first solar field and directing at least a portion of the first thermal energy to a target heat user
1404
Collecting second thermal energy at a second solar field and directing at least a portion of the second thermal energy to at least one heat storage device
1406
During an extra-field discharge process, directing heat from the at least one heat storage device to the target heat user
1408
During an inter-field discharge process, directing heat from the at least one heat storage device to a working fluid that enters the first solar field
end

FIG. 14A

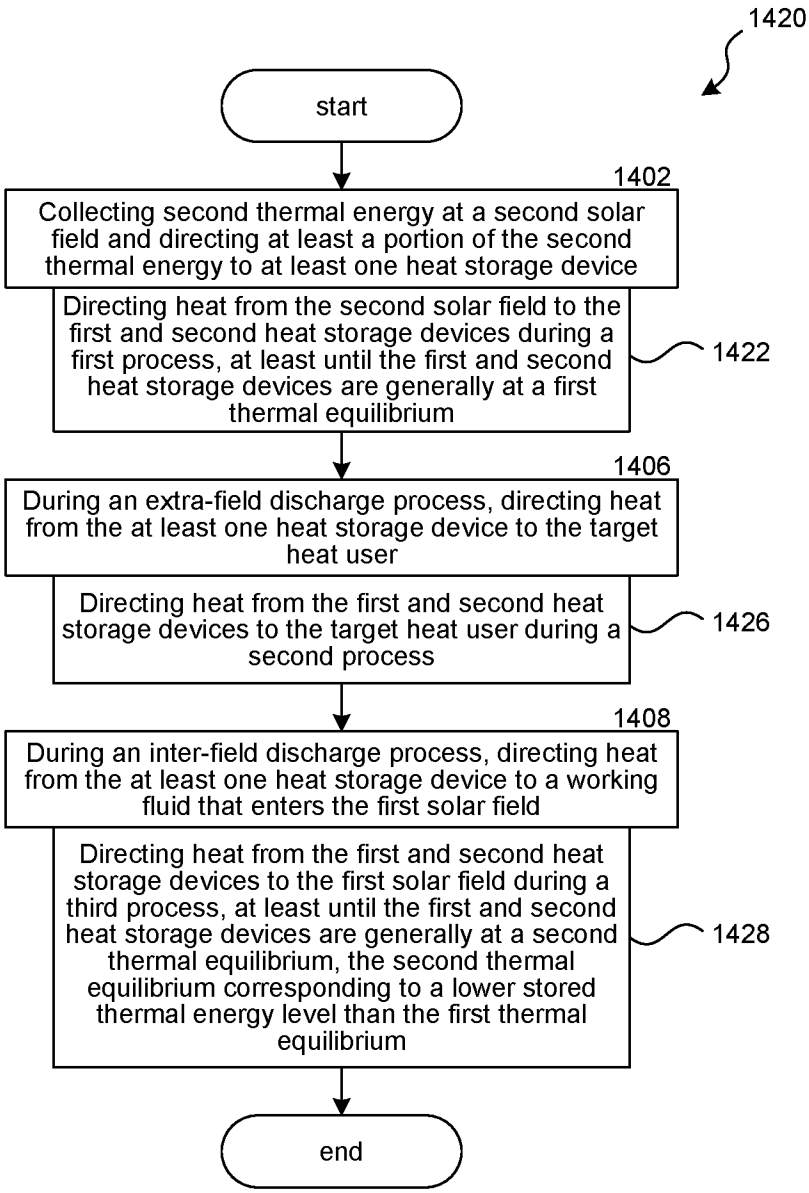

1420
start
1402
Collecting second thermal energy at a second solar field and directing at least a portion of the second thermal energy to at least one heat storage device
Directing heat from the second solar field to the first and second heat storage devices during a first process, at least until the first and second heat storage devices are generally at a first thermal equilibrium
1422
1406
During an extra-field discharge process, directing heat from the at least one heat storage device to the target heat user
Directing heat from the first and second heat storage devices to the target heat user during a second process
1426
1408
During an inter-field discharge process, directing heat from the at least one heat storage device to a working fluid that enters the first solar field
Directing heat from the first and second heat storage devices to the first solar field during a third process, at least until the first and second heat storage devices are generally at a second thermal equilibrium, the second thermal equilibrium corresponding to a lower stored thermal energy level than the first thermal equilibrium
1428
end

FIG. 14B

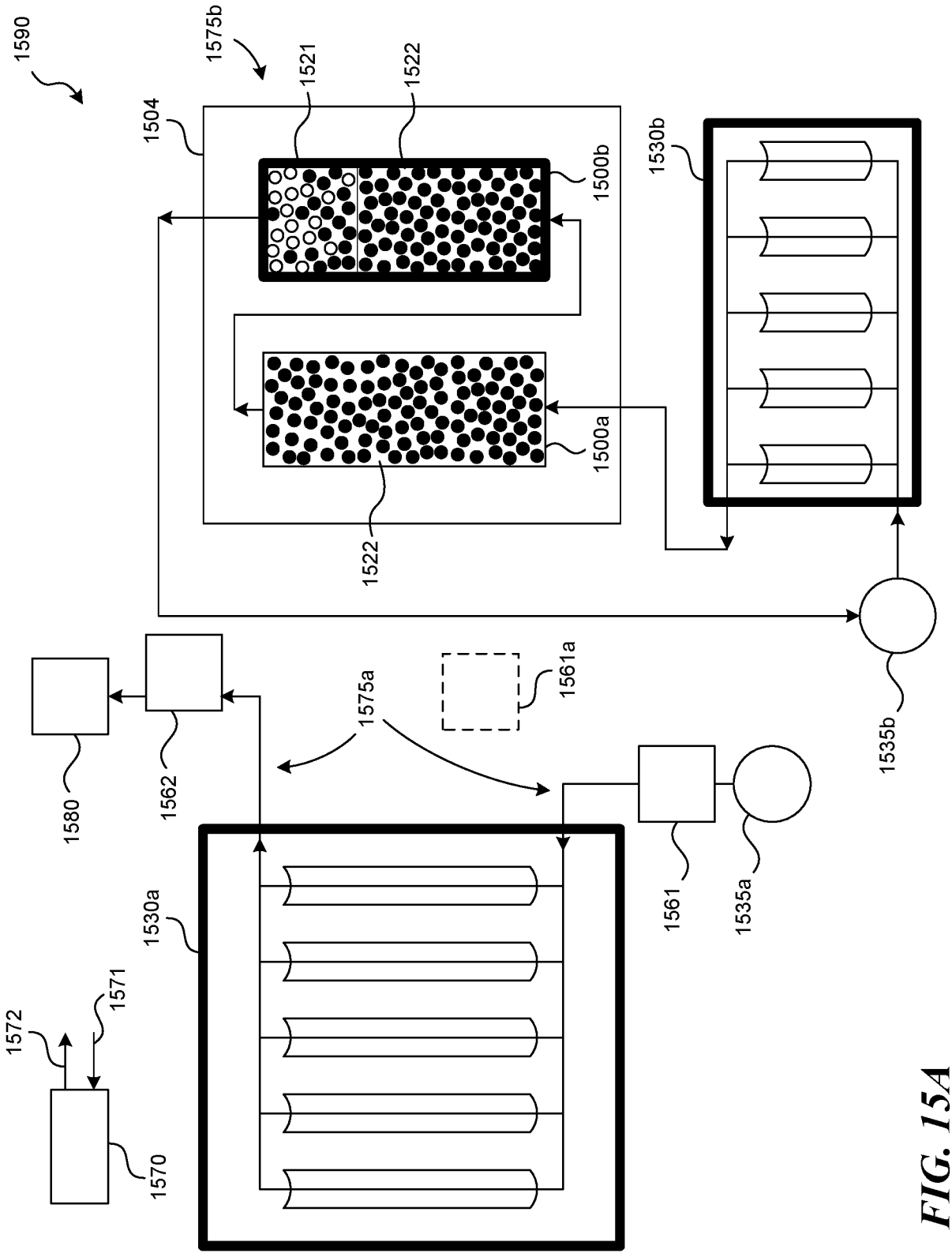

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FIG. 15A

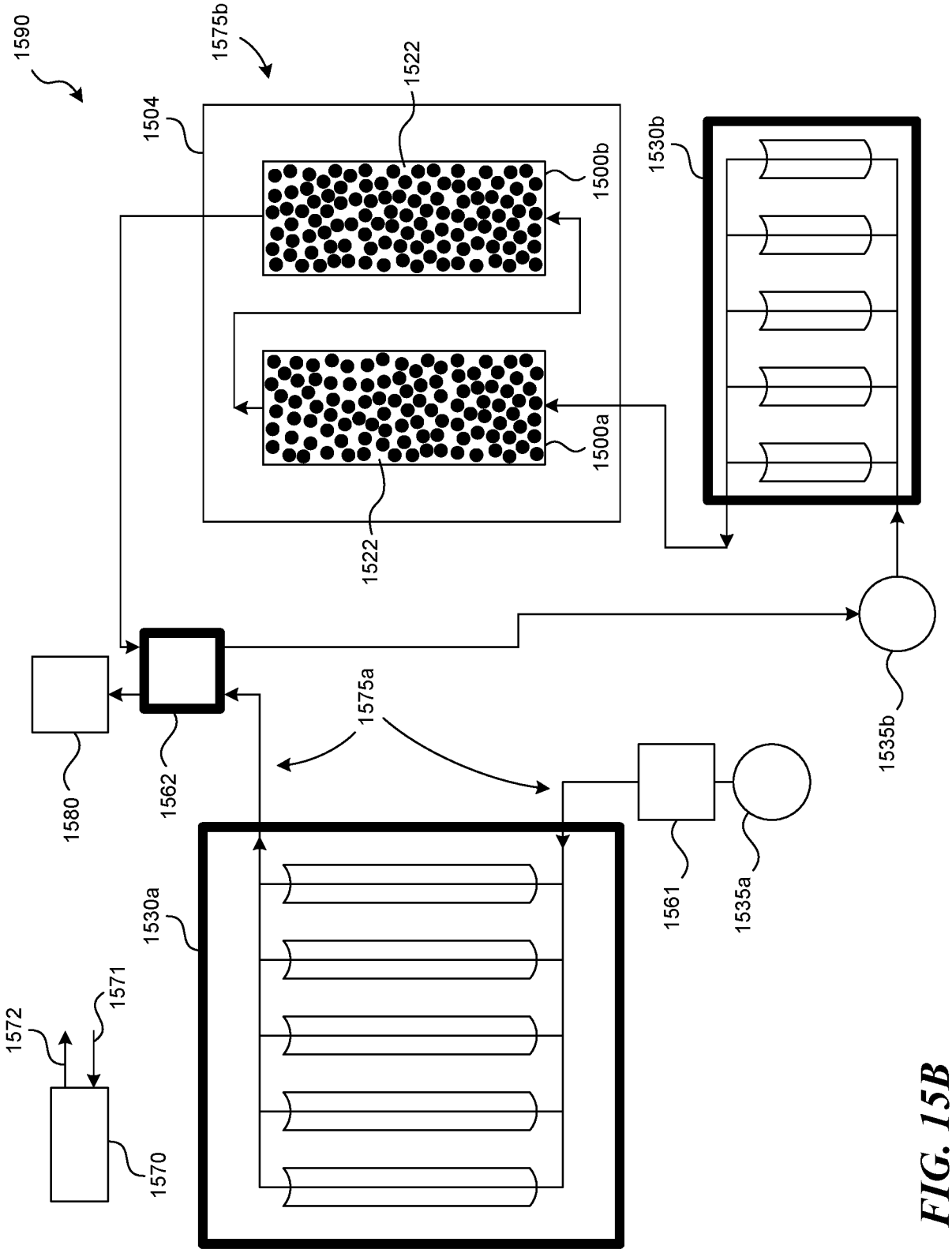

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FIG. 15B

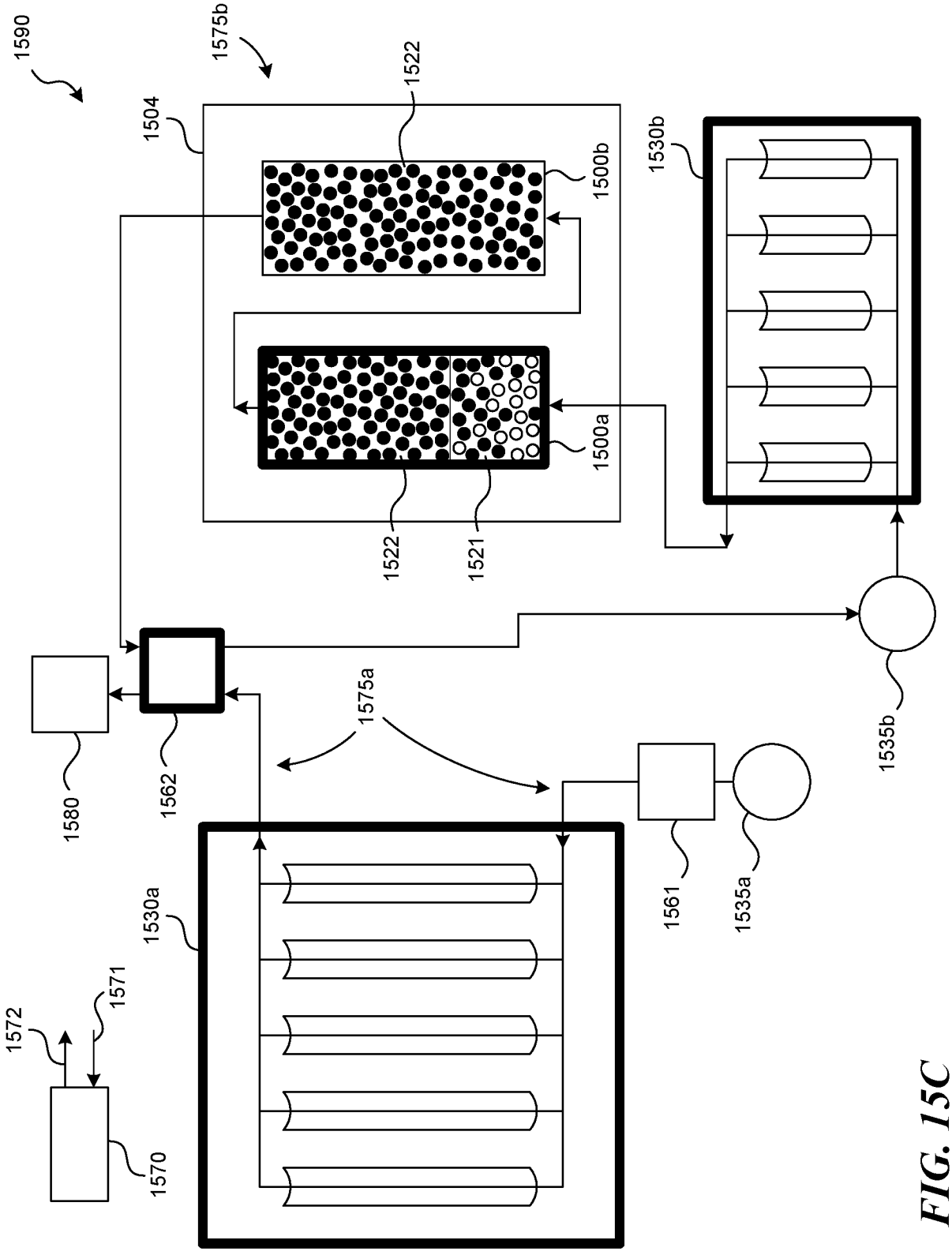

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FIG. 15C

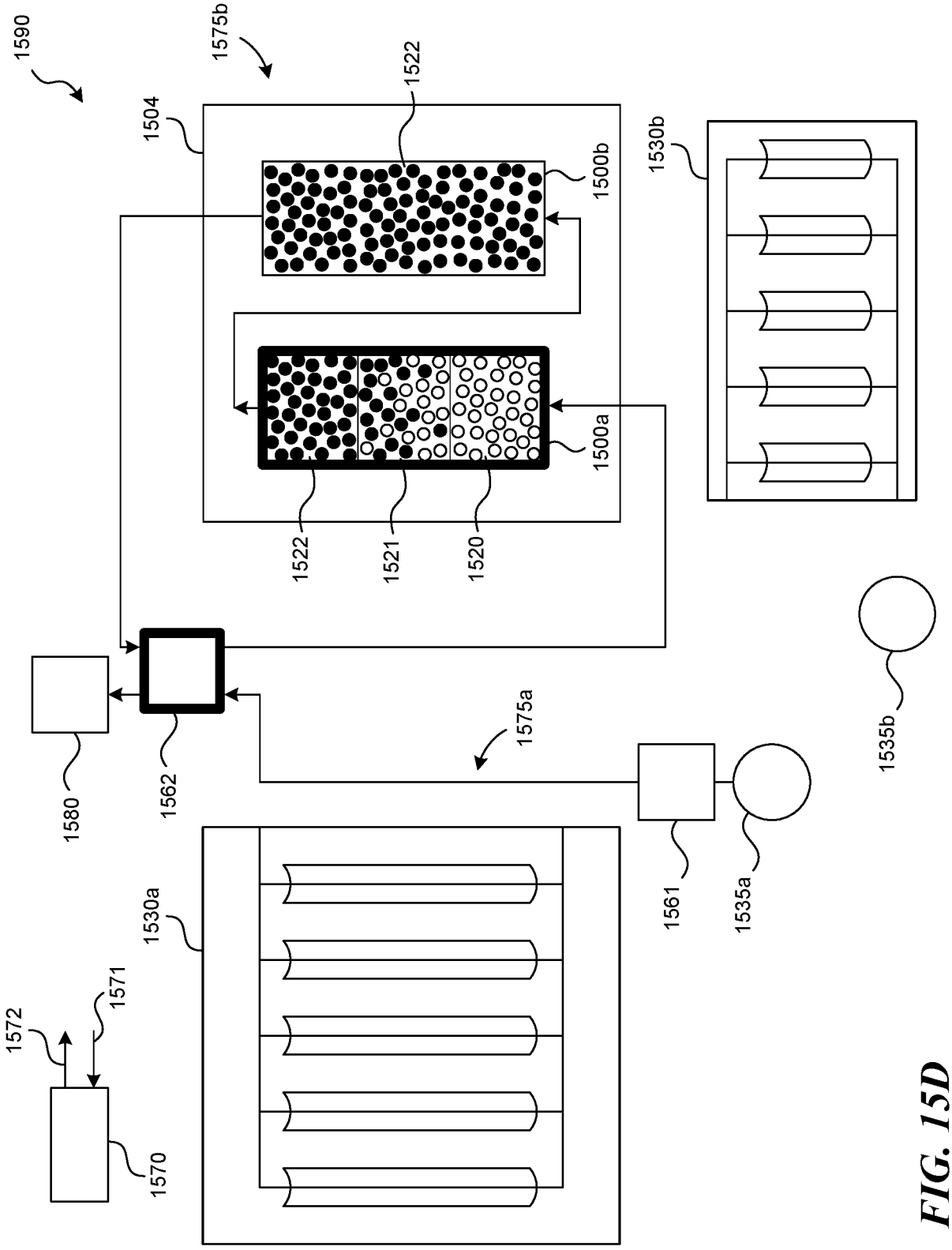

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FIG. 15D

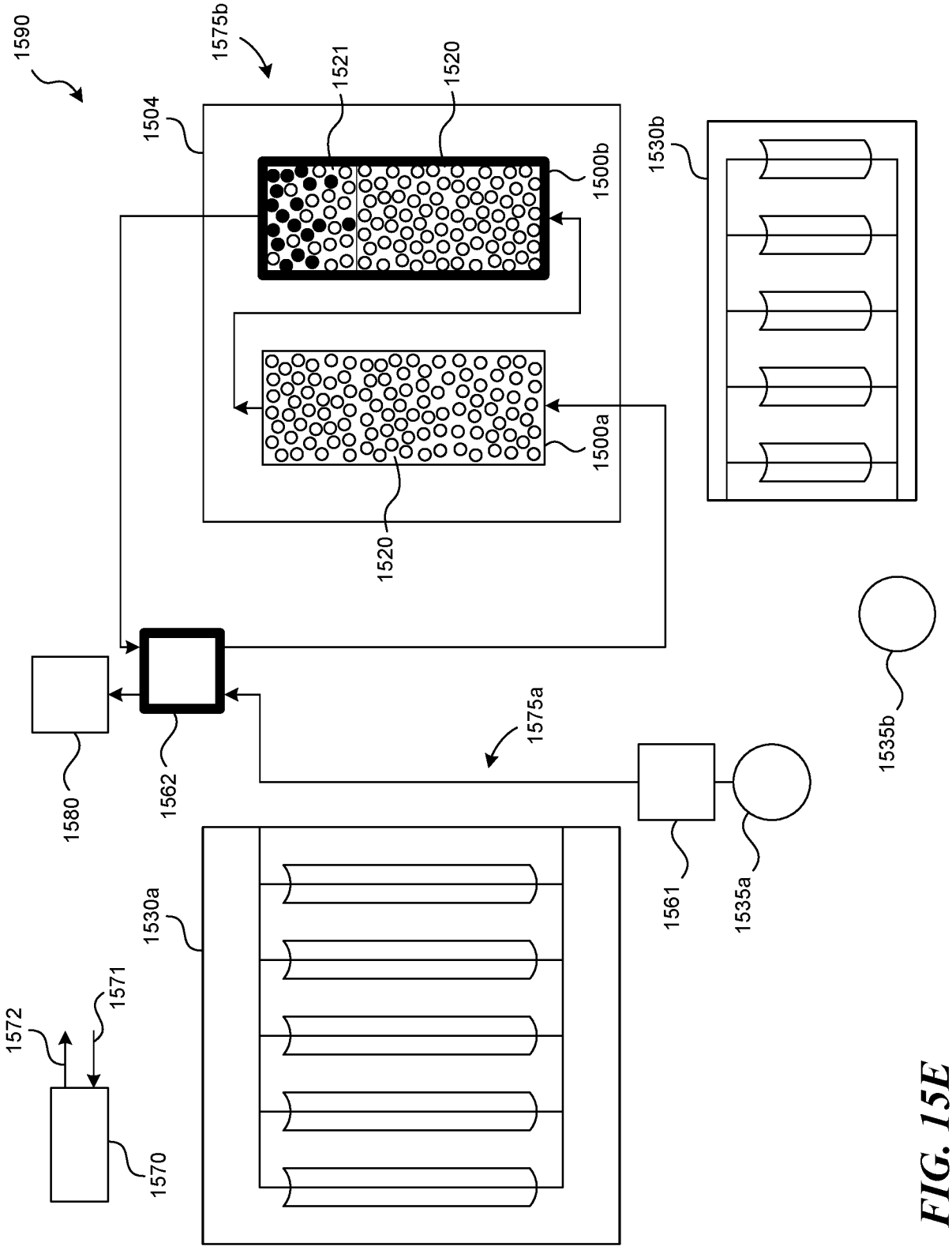

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FIG. 15E

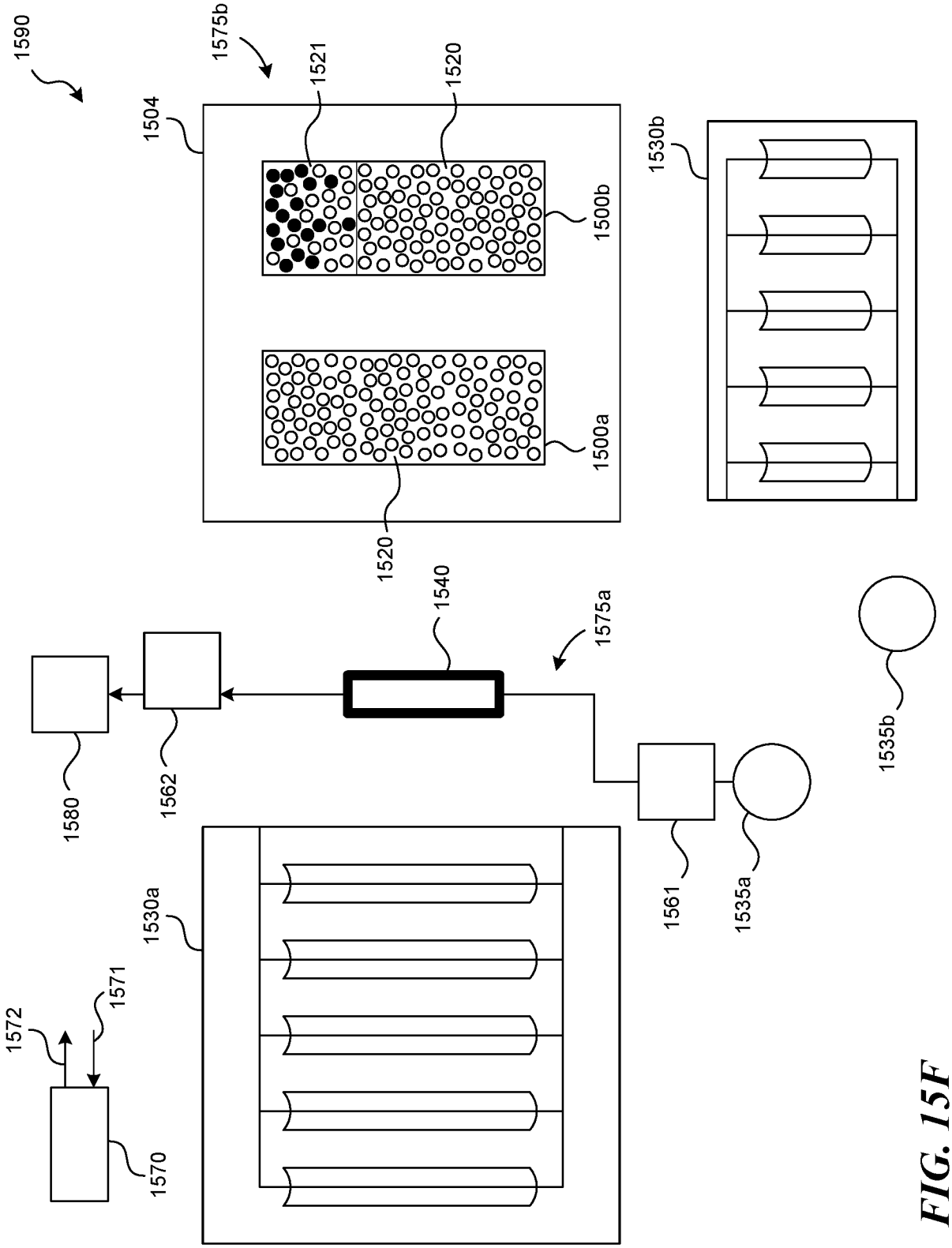

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FIG. 15F

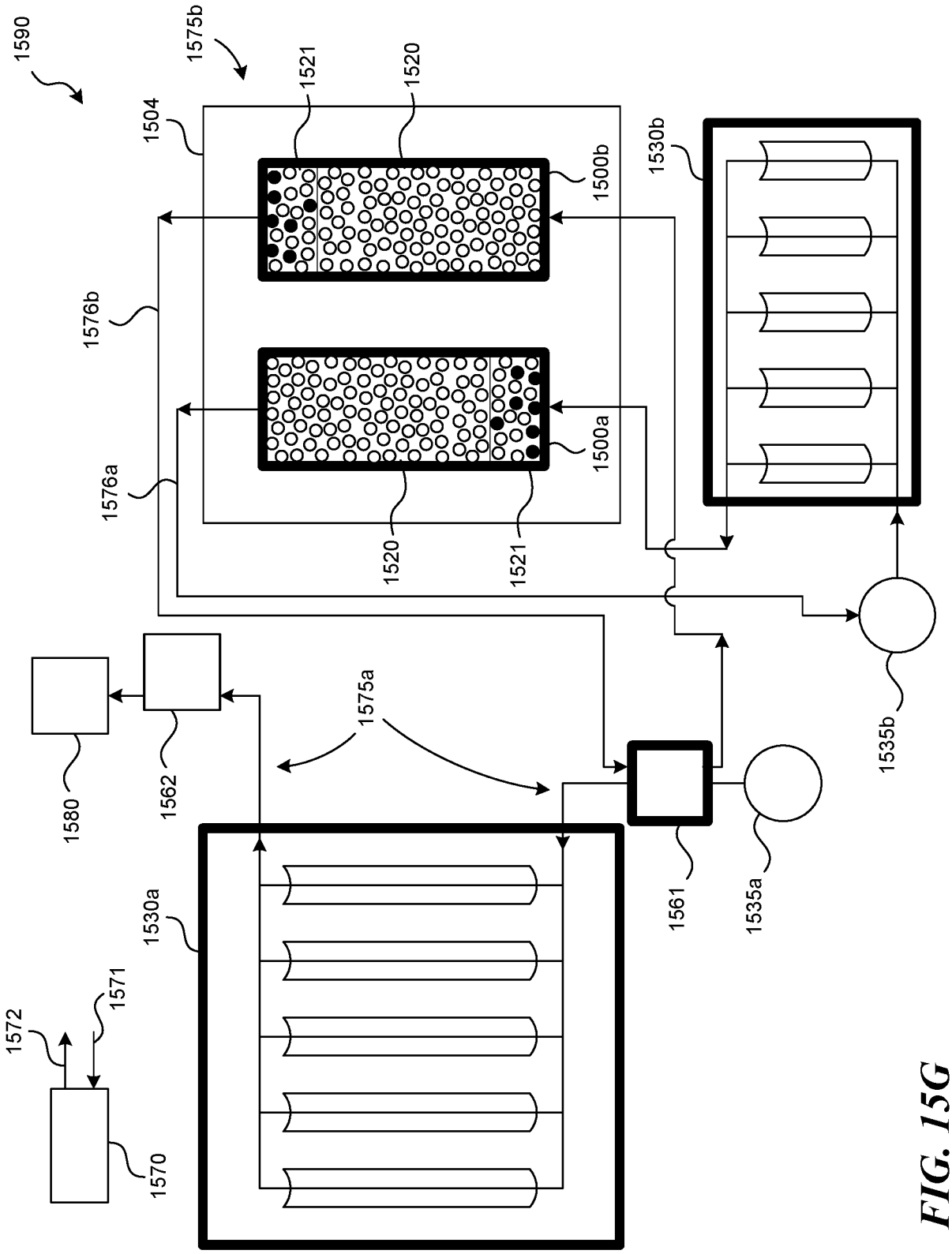

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FIG. 15G

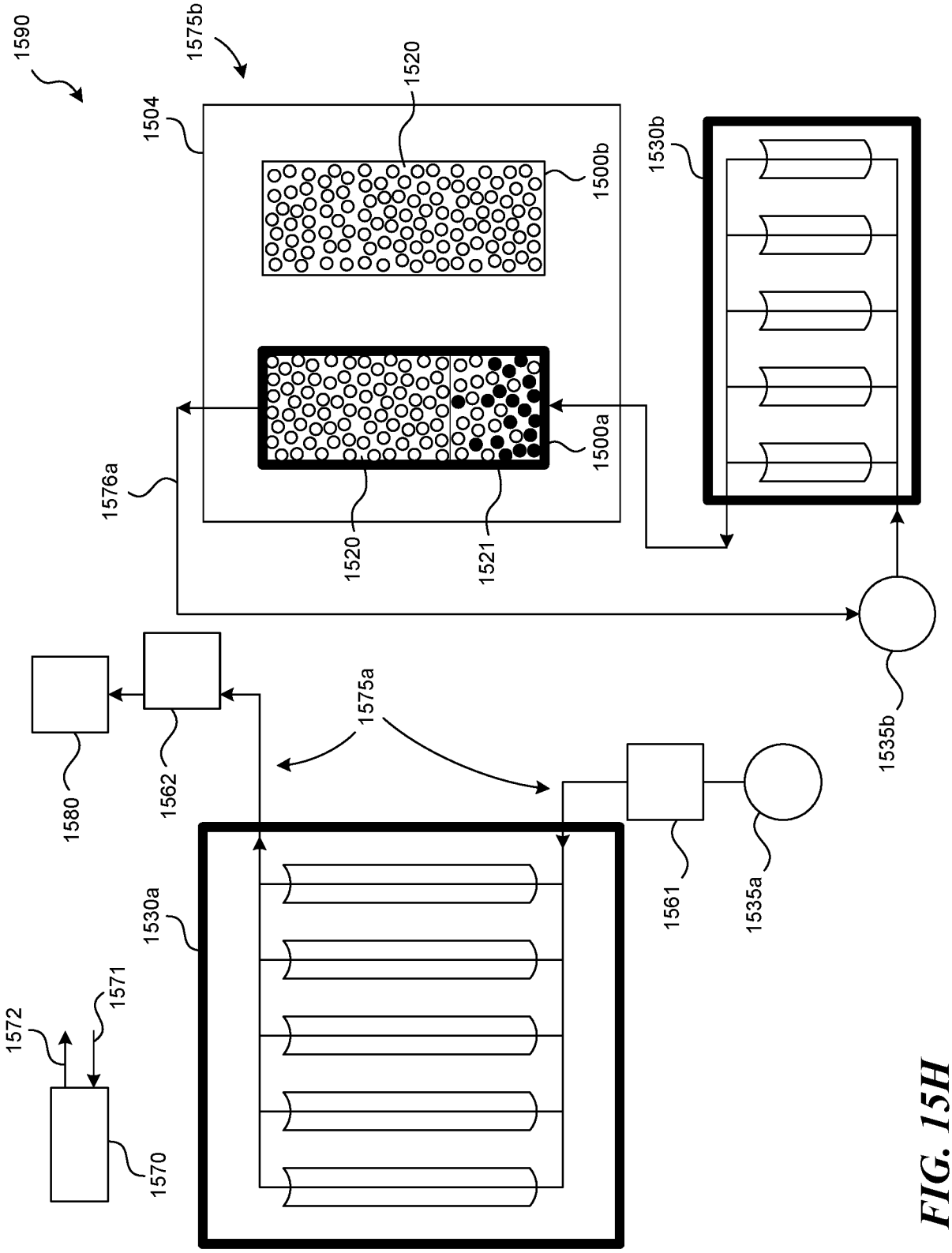

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FIG. 15H

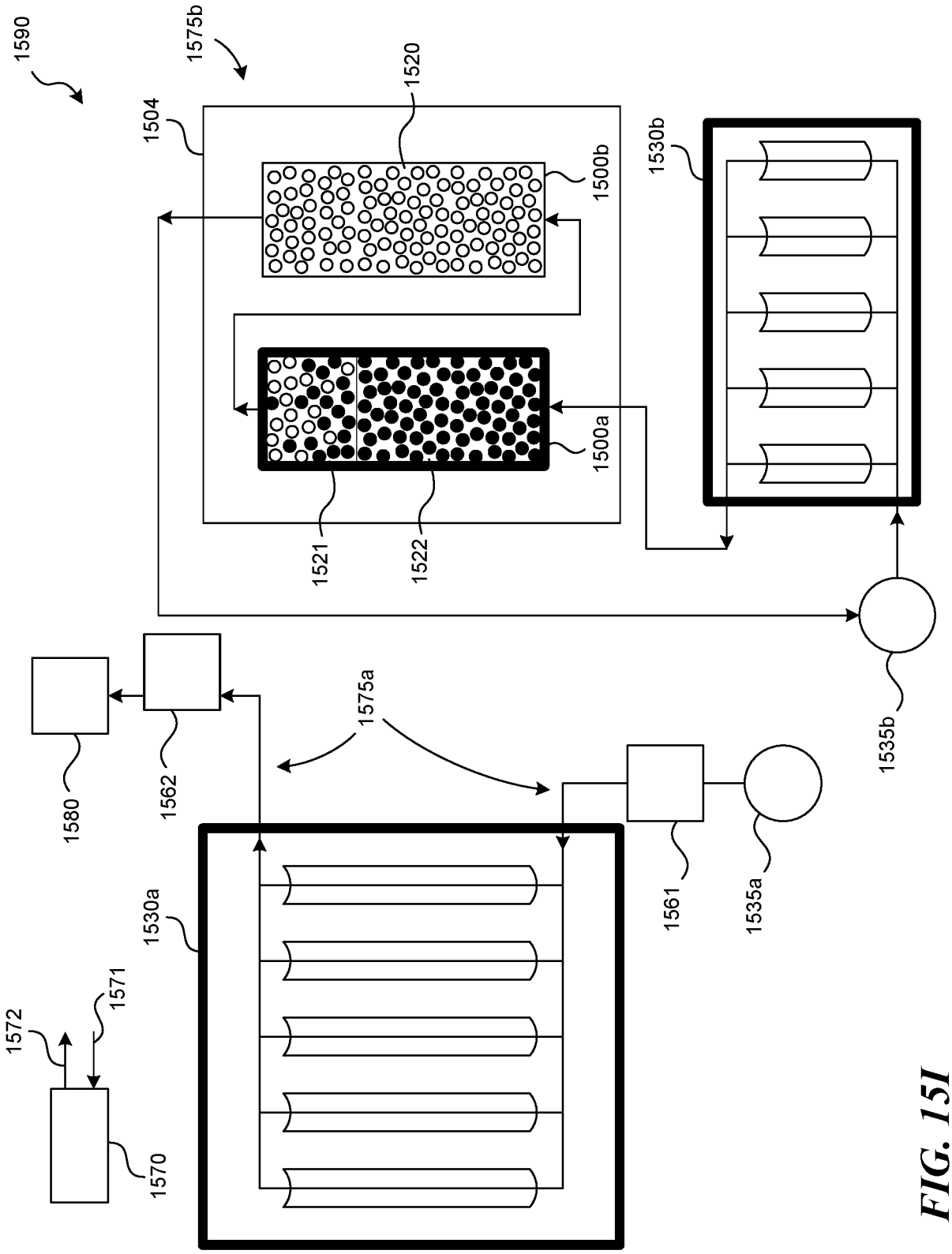

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FIG. 15I

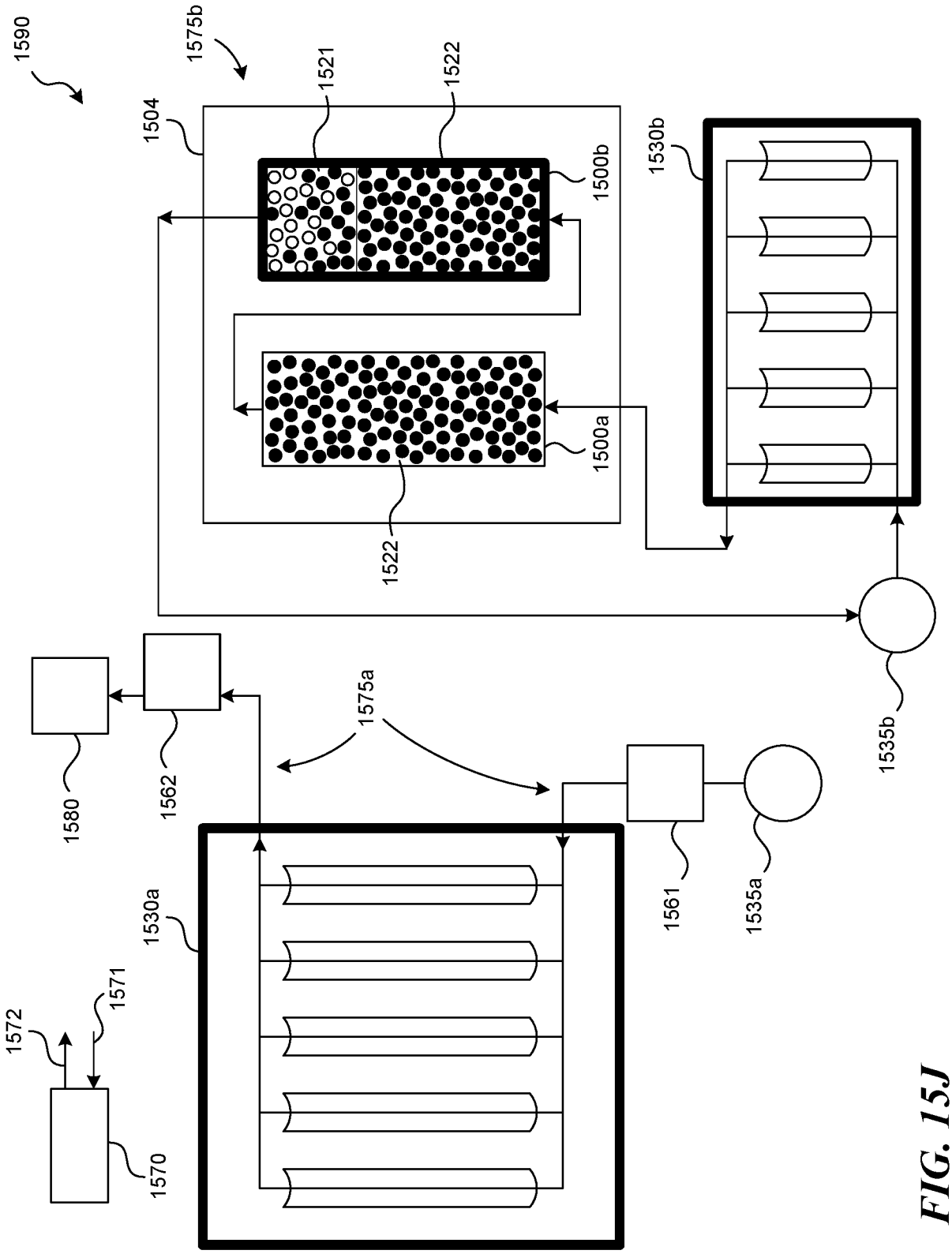

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FIG. 15J

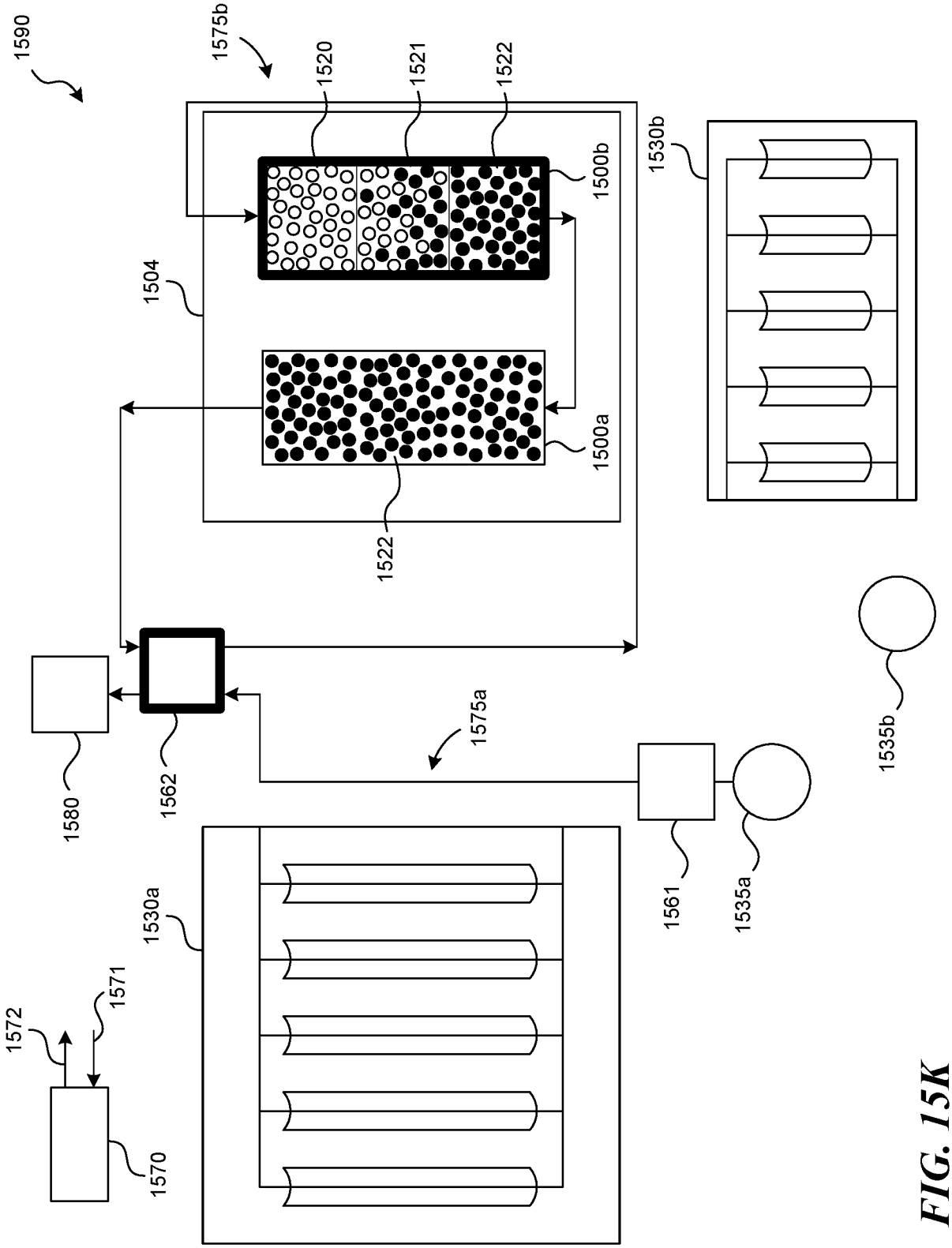

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FIG. 15K

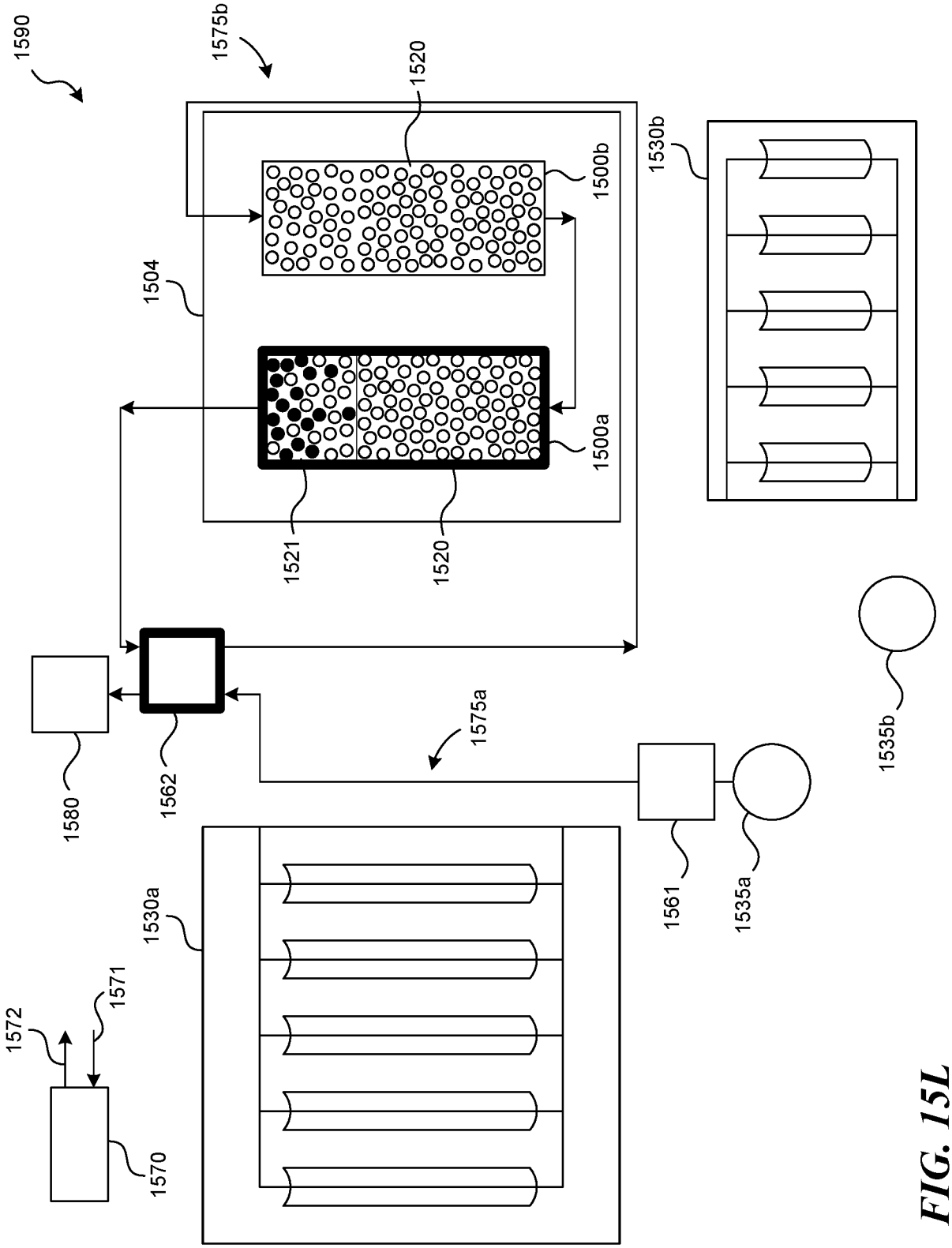

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FIG. 15L

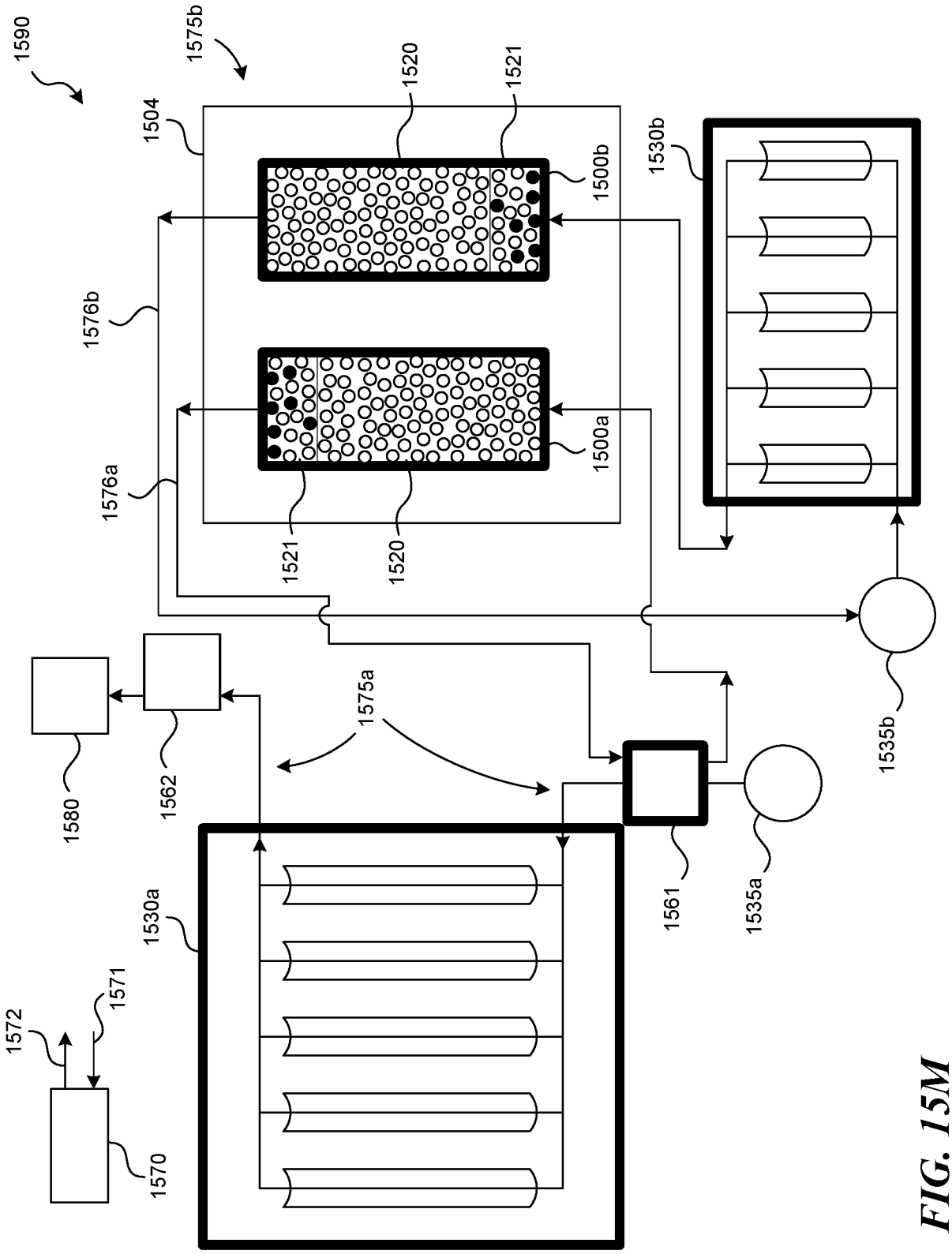

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FIG. 15M

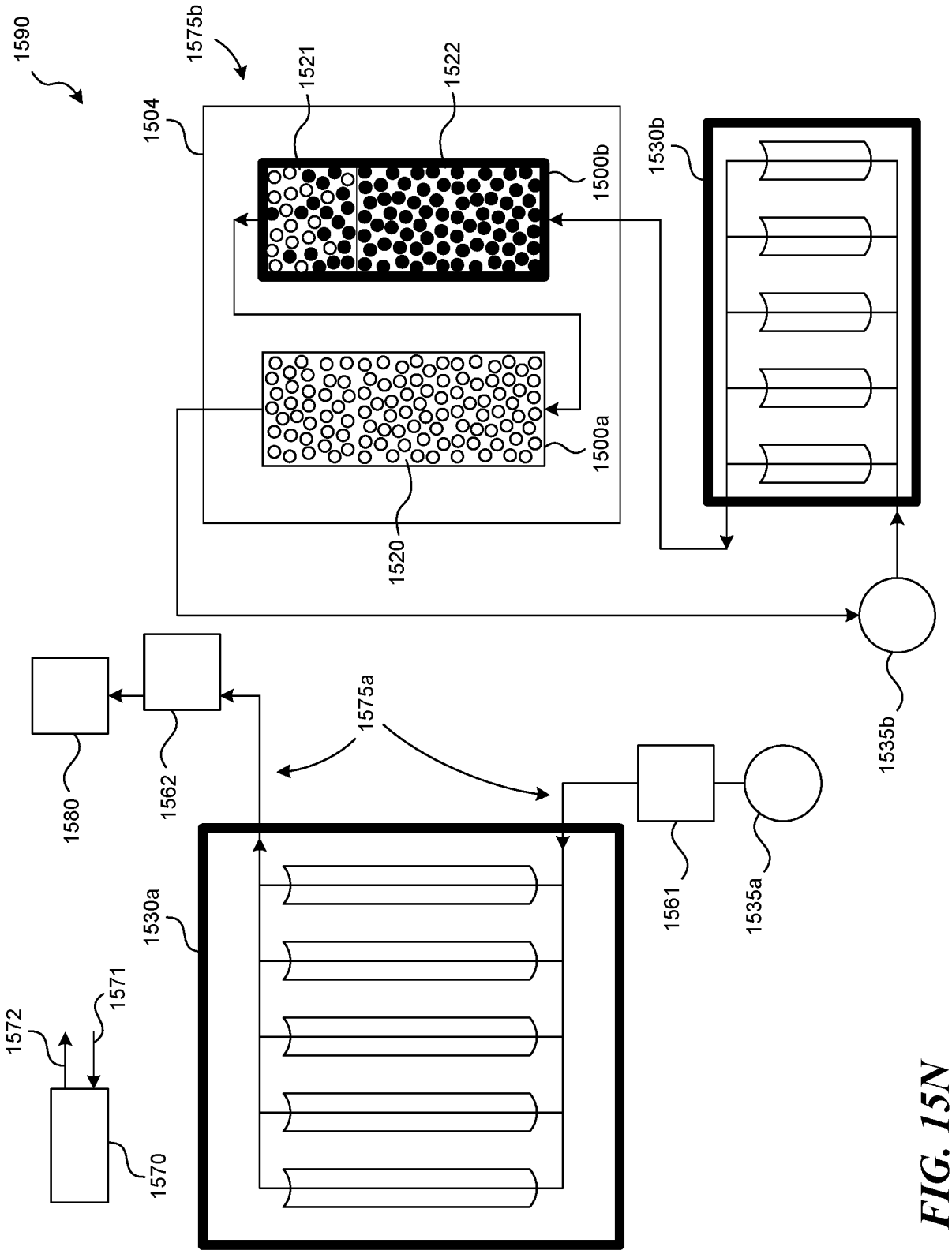

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FIG. 15N

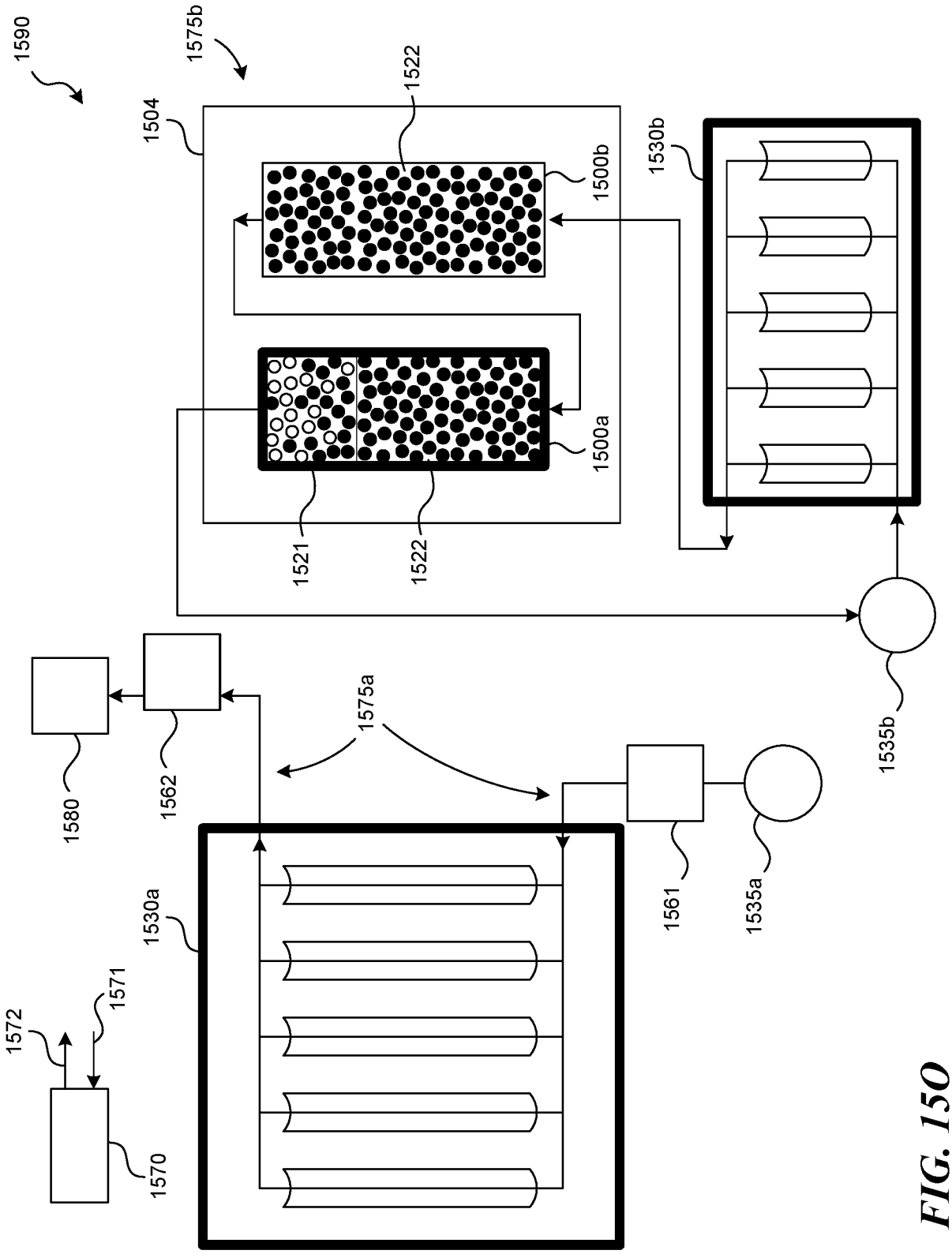

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FIG. 15O

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/018480

A. CLASSIFICATION OF SUBJECT MATTER

F24J 2/34(2006.01)i, F24J 2/40(2006.01)i, F24J 2/10(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F24J 2/34; F03G 6/06; F01K 3/00; F24J 3/02; F25B 13/00; F24J 2/40; F24J 2/10

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: solar, field, heat storage, heat exchanger, fluid network, controller, receiver, concentrator

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2012-107478 A1 (ALSTOM TECHNOLOGY LTD.) 16 August 2012 See page 1, lines 28-30, page 8, line 15 - page 9, line 10, claims 1, 2, 8, 9 and figure 1.	12-17,20,22-32
Y		1-11,18,19,21
Y	US 2015-0107246 A1 (BINDINGNAVALE RANGA, KRISHNA KUMAR) 23 April 2015 See paragraphs [0058], [0059] and figure 1.	1-11,18,19
Y	US 4452229 A (POWERS, KIM) 05 June 1984 See column 4, line 59 - column 5, line 37 and figures 1, 2.	21
A	US 2014-0352304 A1 (ARIAS et al.) 04 December 2014 See paragraphs [0018]-[0027] and figure 2.	1-32
A	US 4143642 A (BEAULIEU, ADRIAN A.) 13 March 1979 See claim 1 and figure 1.	1-32

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 May 2017 (26.05.2017)	**29 May 2017 (29.05.2017)**

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Korean Intellectual Property Office
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Authorized officer
LEE, Dal Kyong
Telephone No. +82-42-481-8440

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2017/018480

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