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(54) **FLOW CONTROL SYSTEMS AND METHODS FOR A PHASE CHANGE MATERIAL SOLAR RECEIVER**

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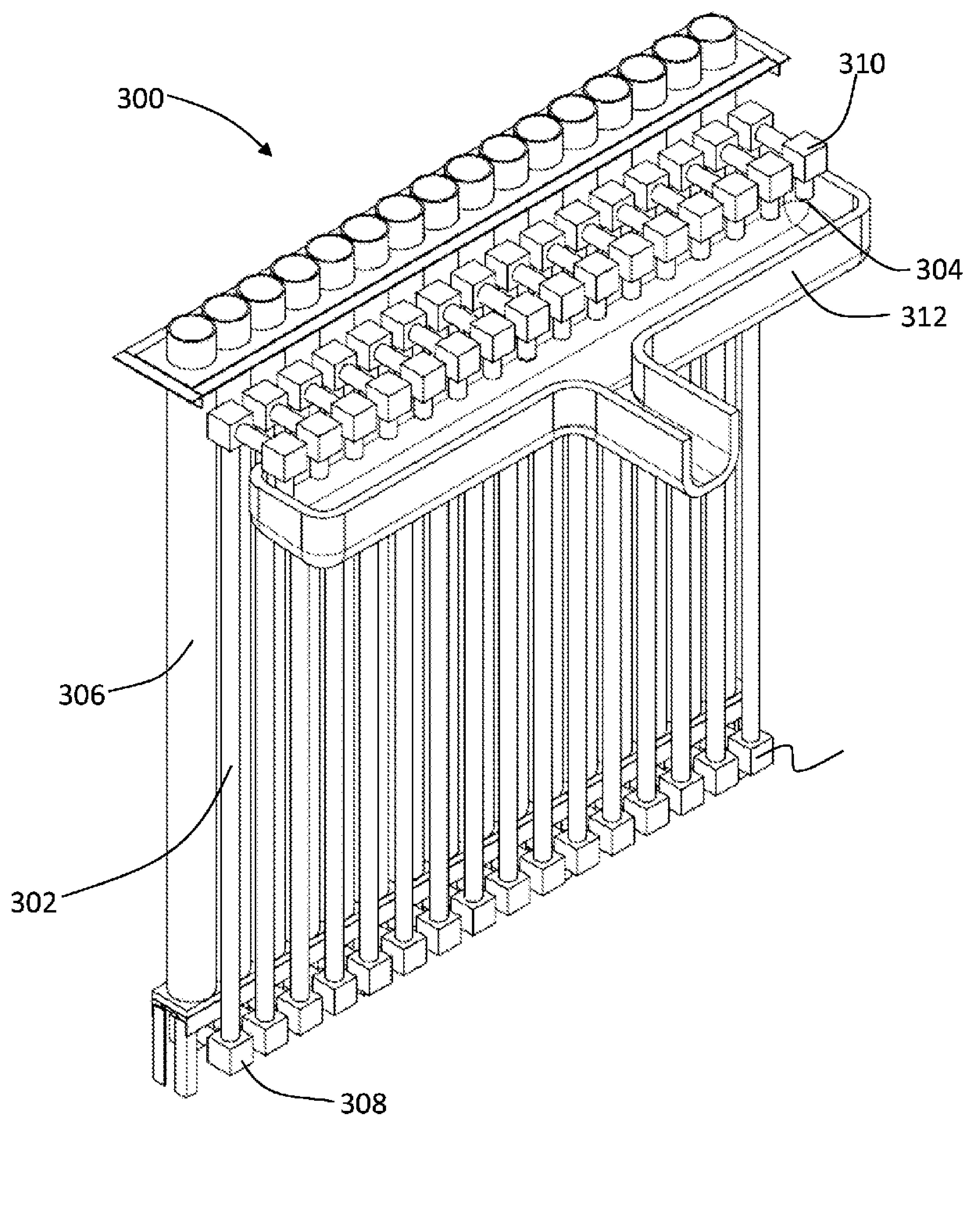
(57) **ABSTRACT**

Disclosed embodiments include concentrating solar power (CSP) systems and solar receivers for CSP systems configured to provide inlet and outlet heat transfer material flow control. The disclosed embodiments feature heat transfer material flowing in and open heat transfer material circuit. Certain embodiments may be implemented with a solid-liquid phase change material as the heat transfer material. Alternative embodiments include methods of heat transfer material flow control in a CSP system and CSP systems configured as described.



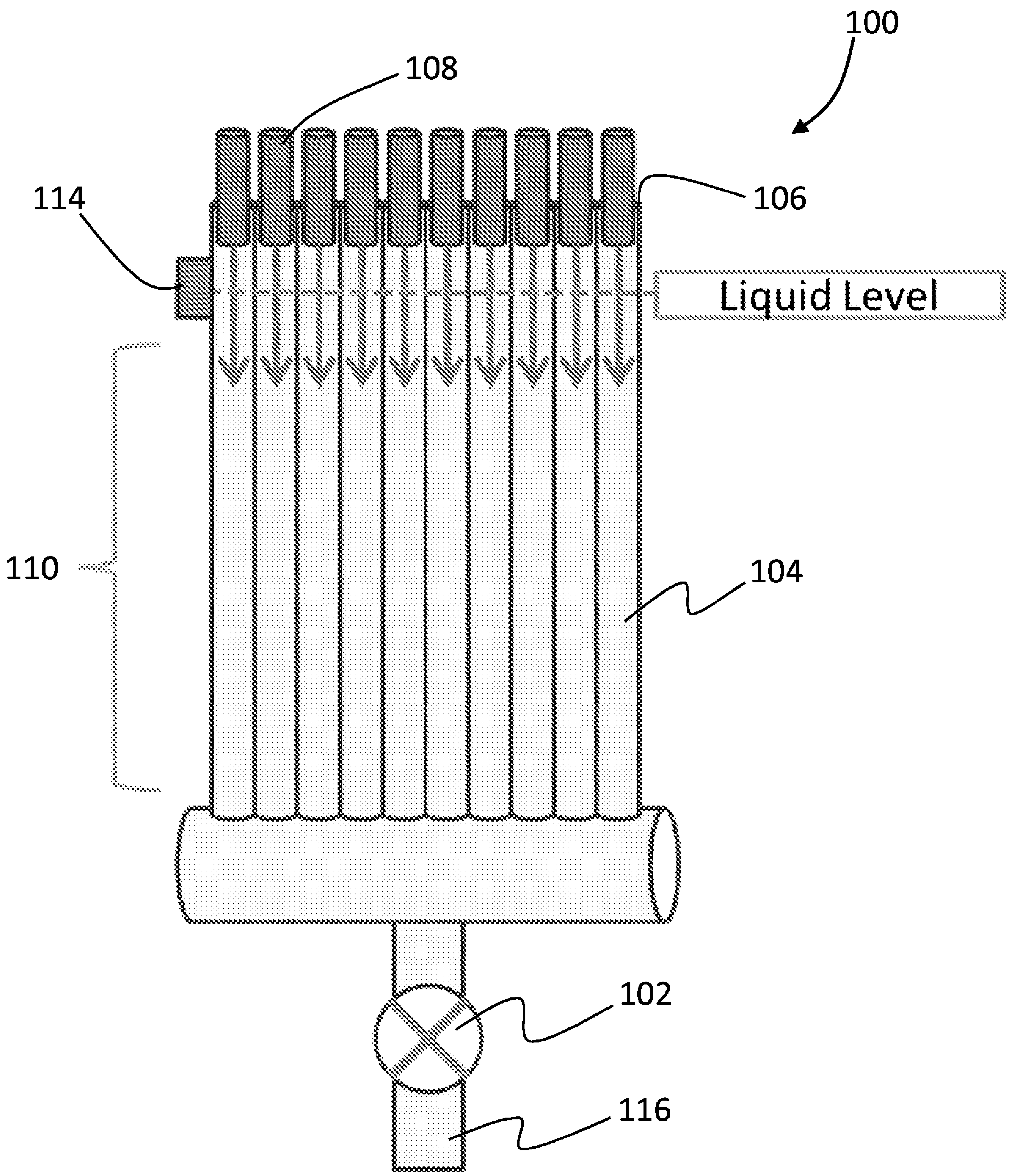


Fig. 1

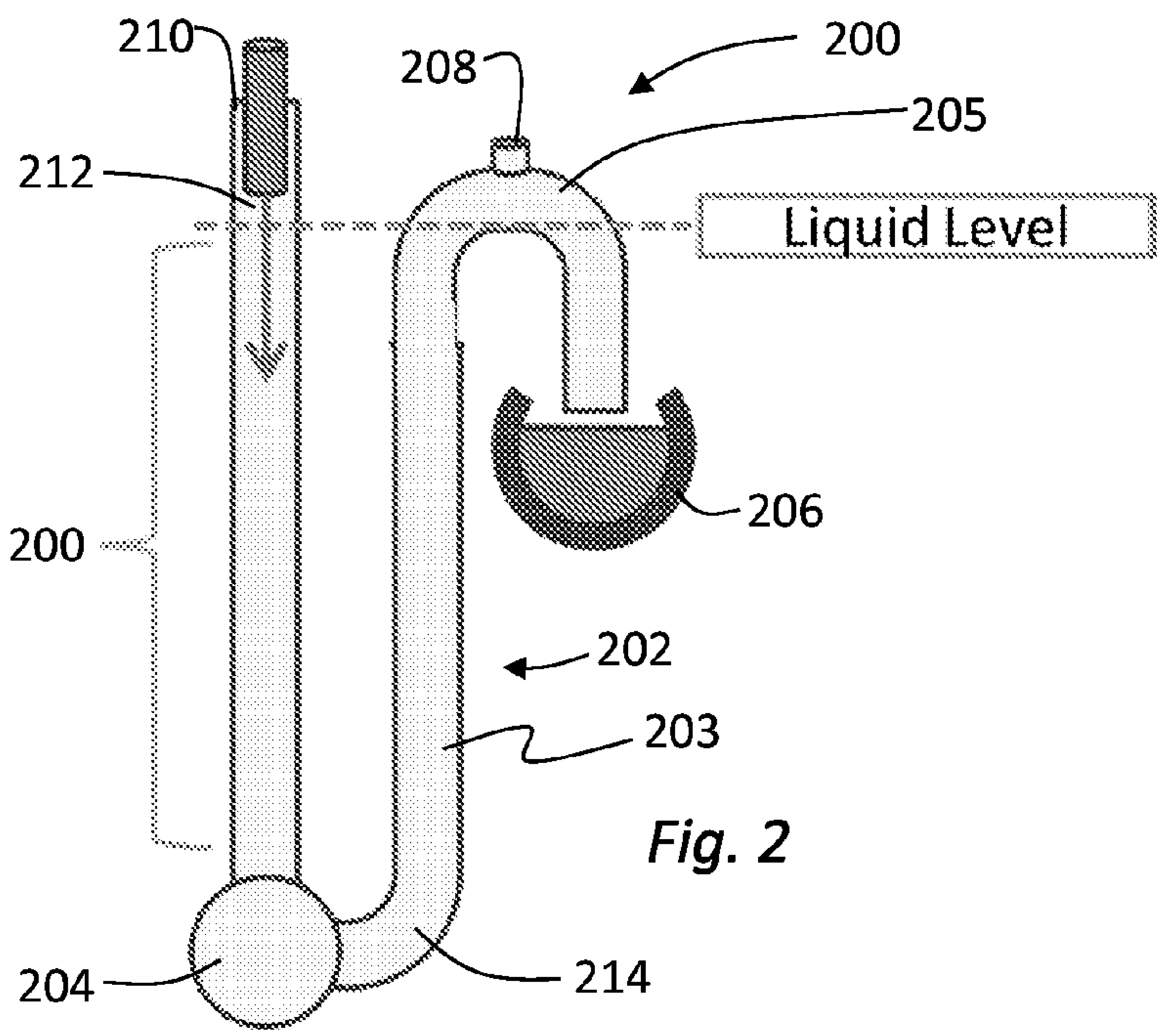

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Fig. 2

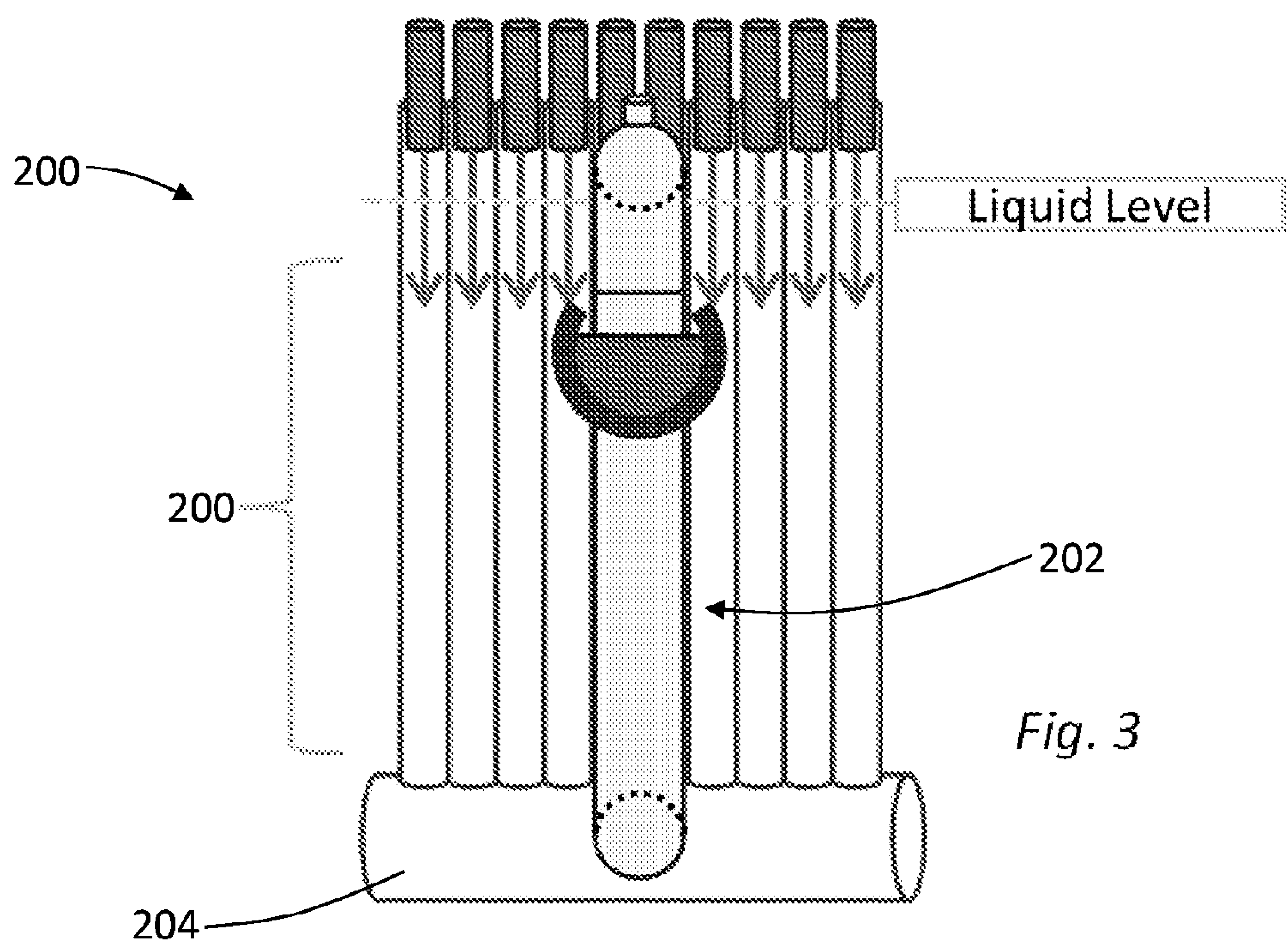
200
Liquid Level
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Fig. 3

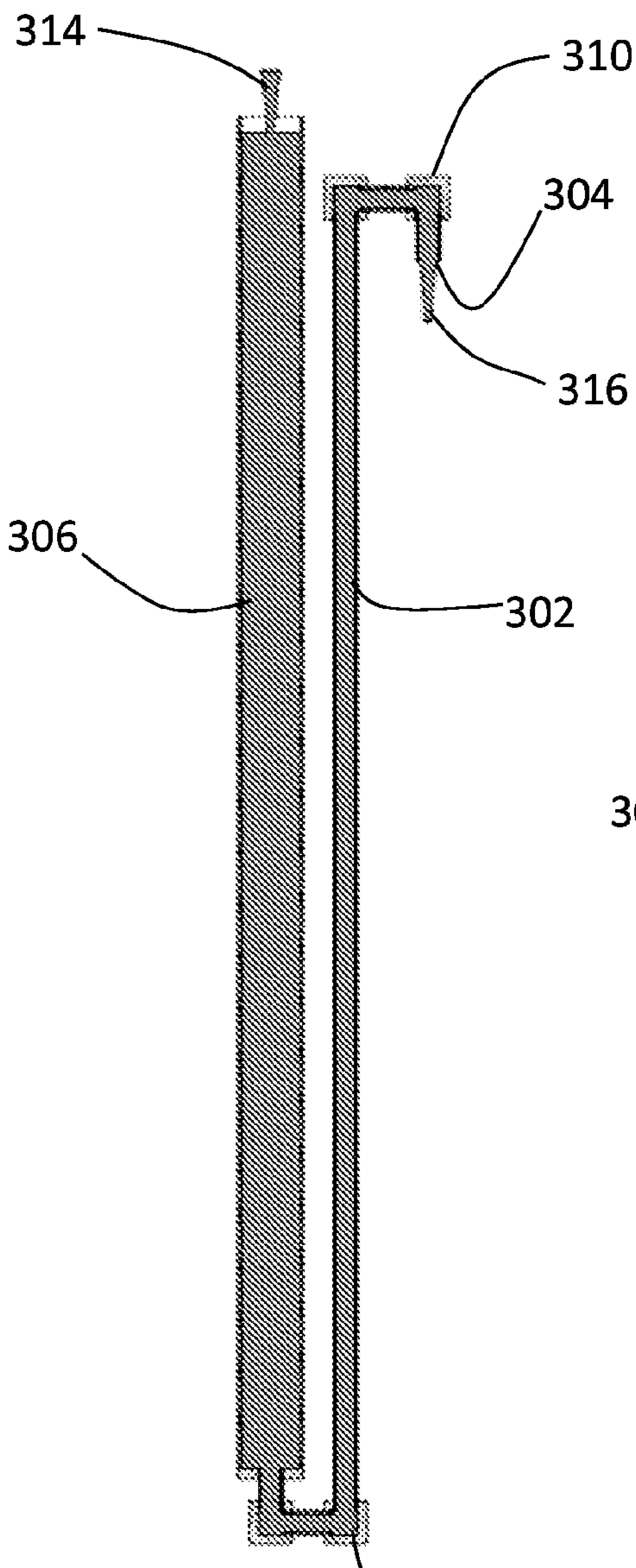

Fig. 4A

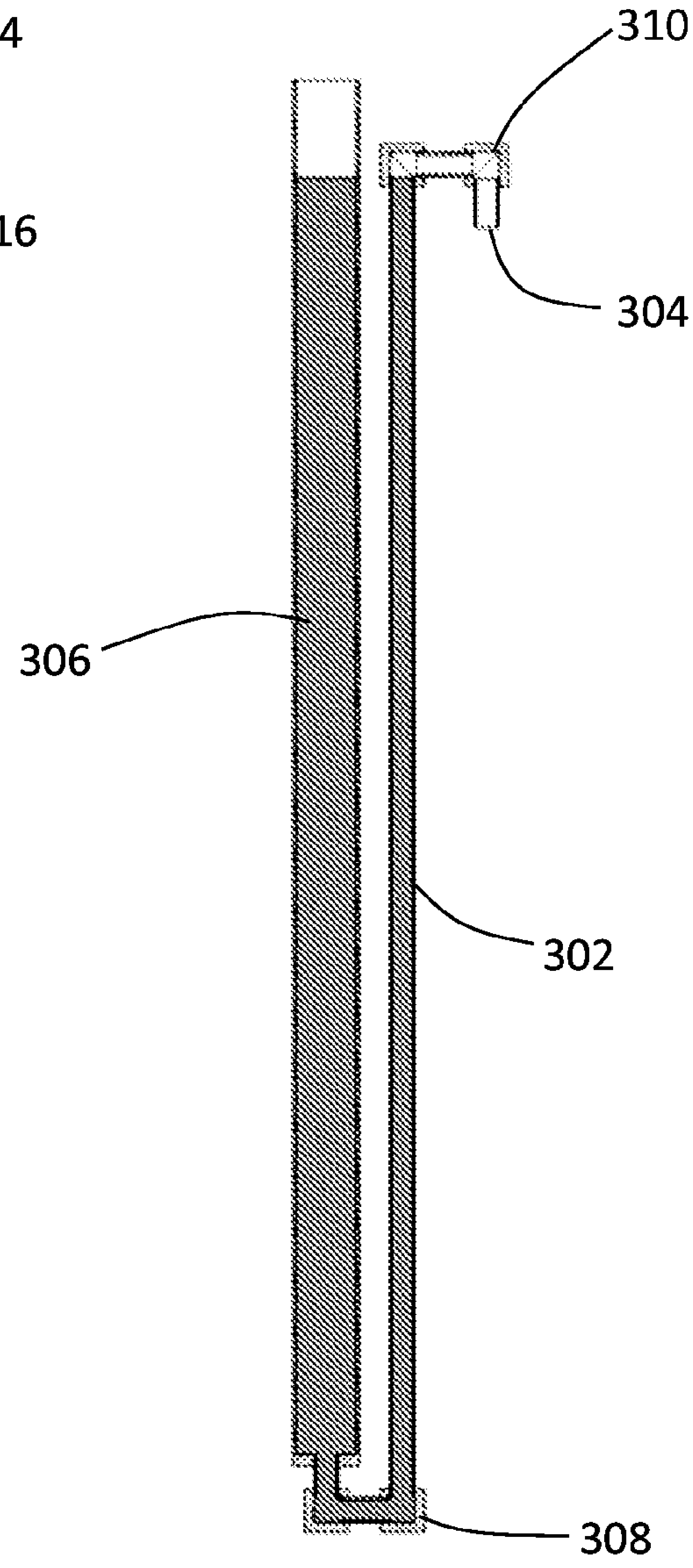

Fig. 4B

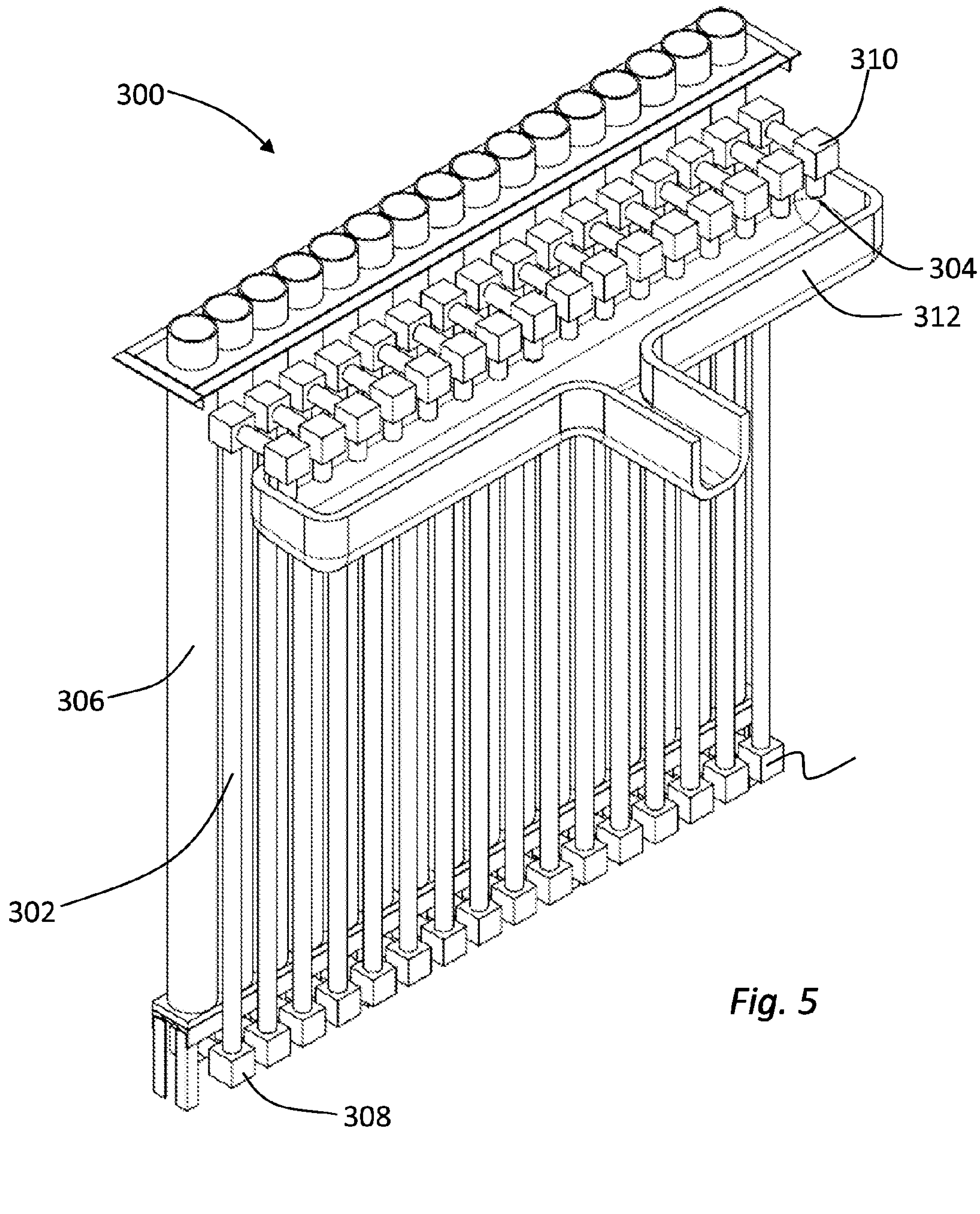

Fig. 5

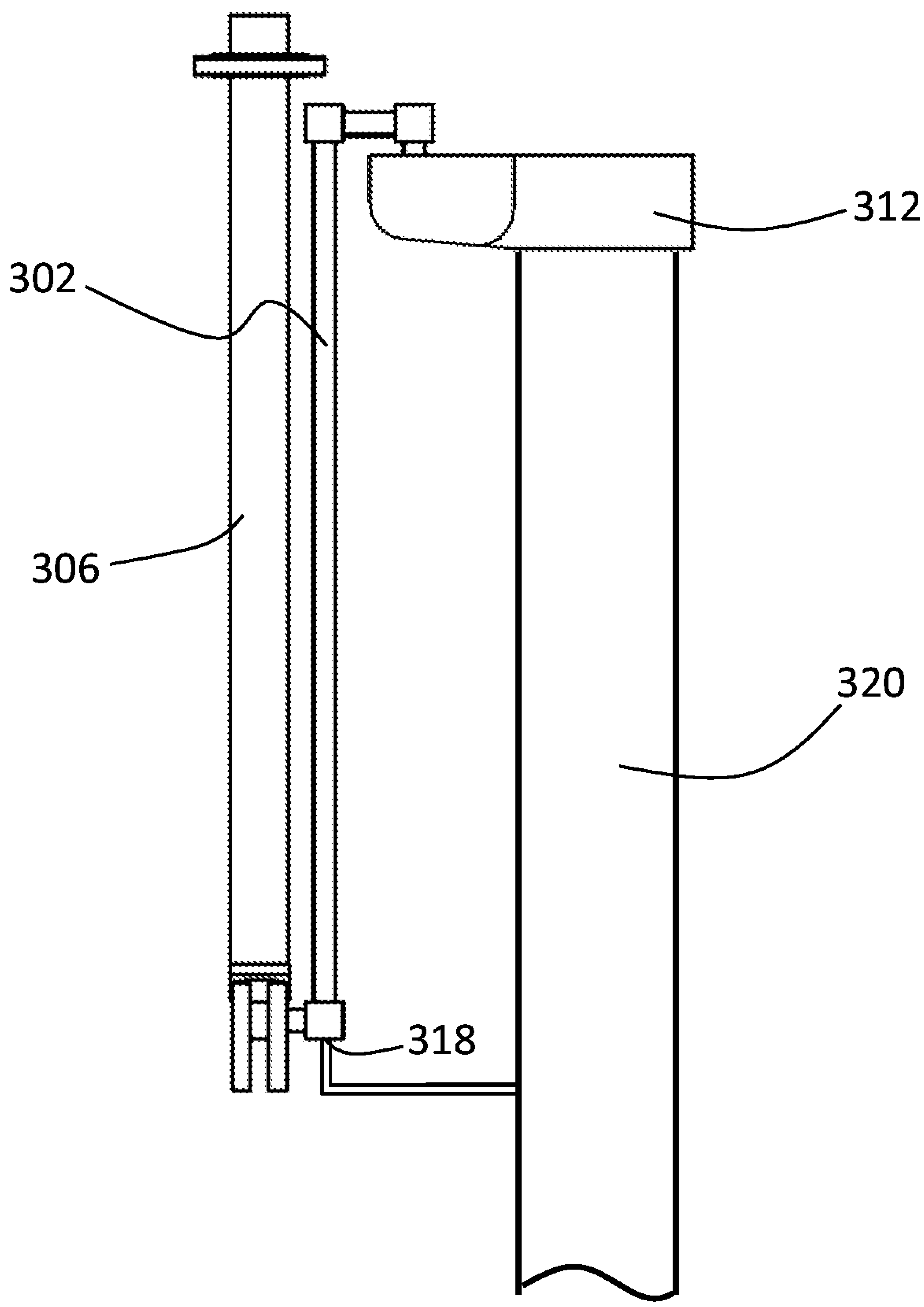

Fig. 6

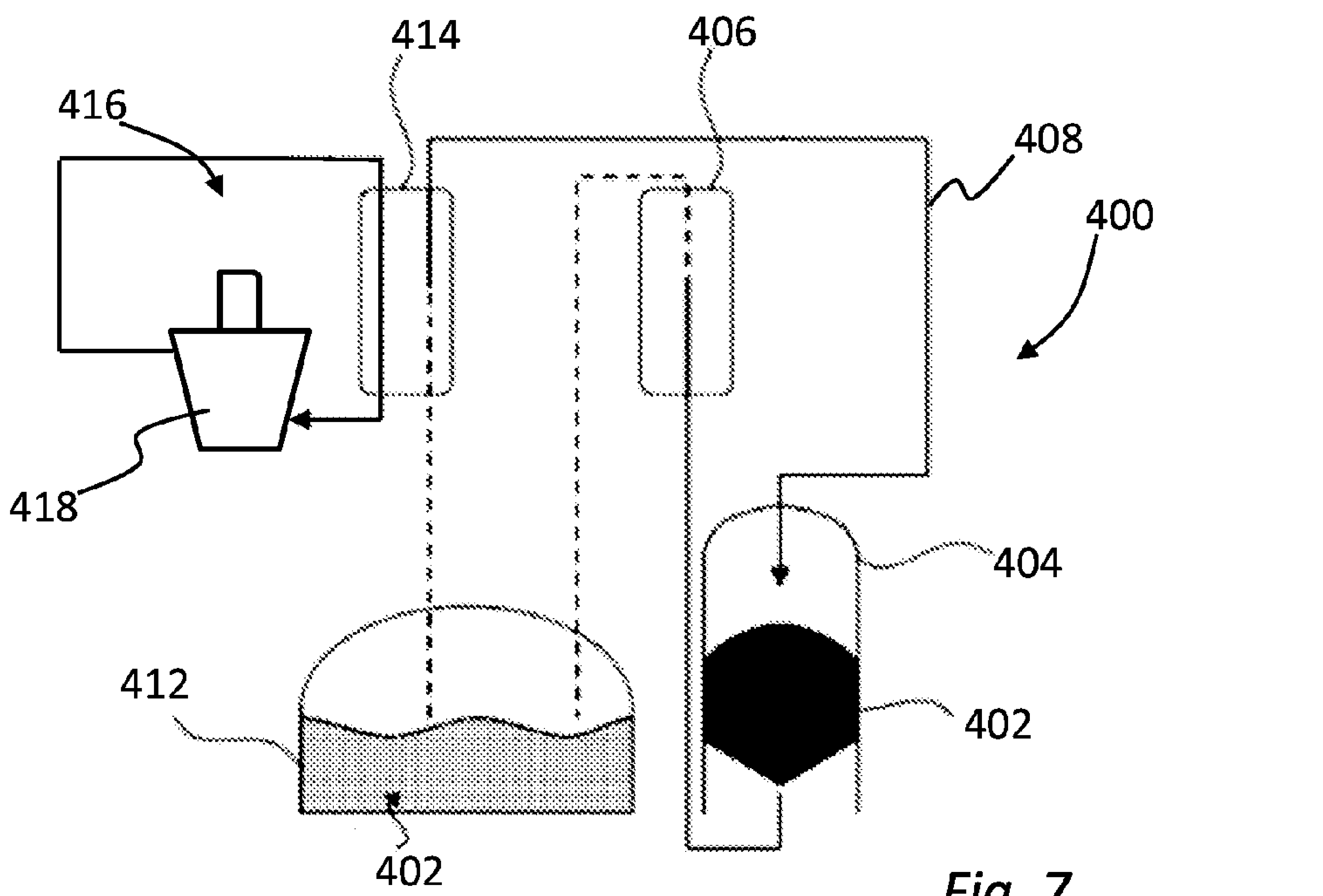
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Fig. 7

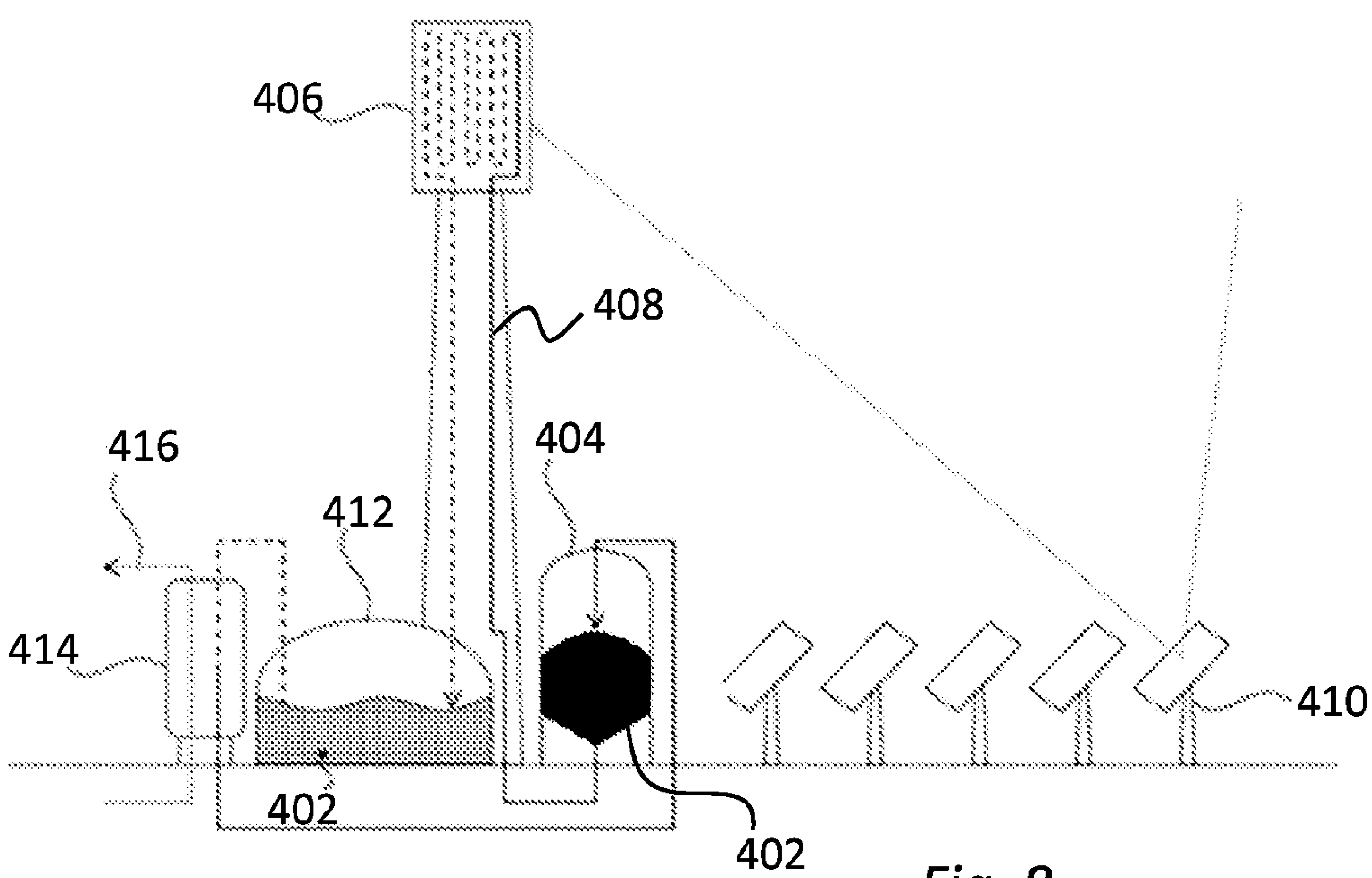
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Fig. 8

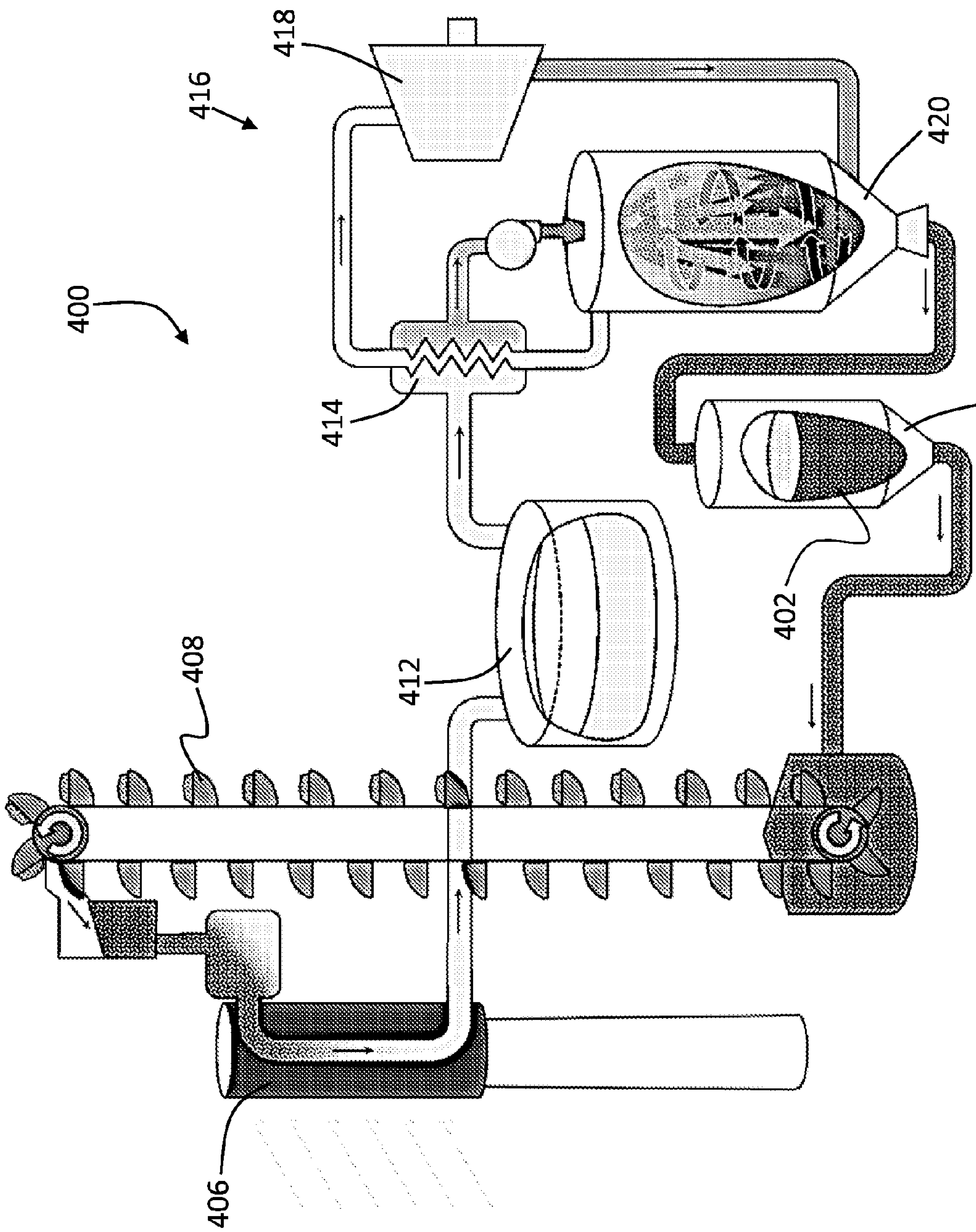

Fig. 9

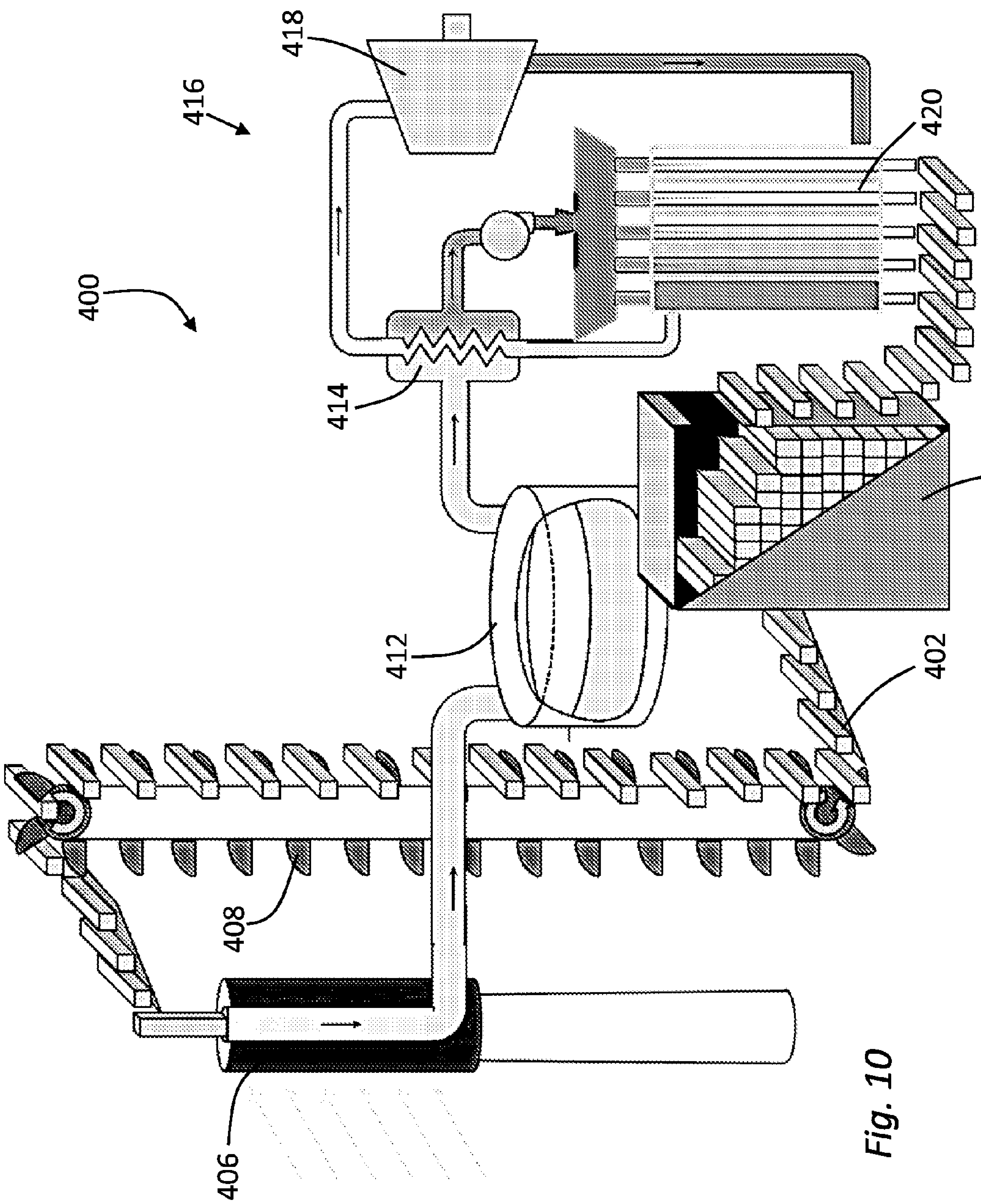

Fig. 10

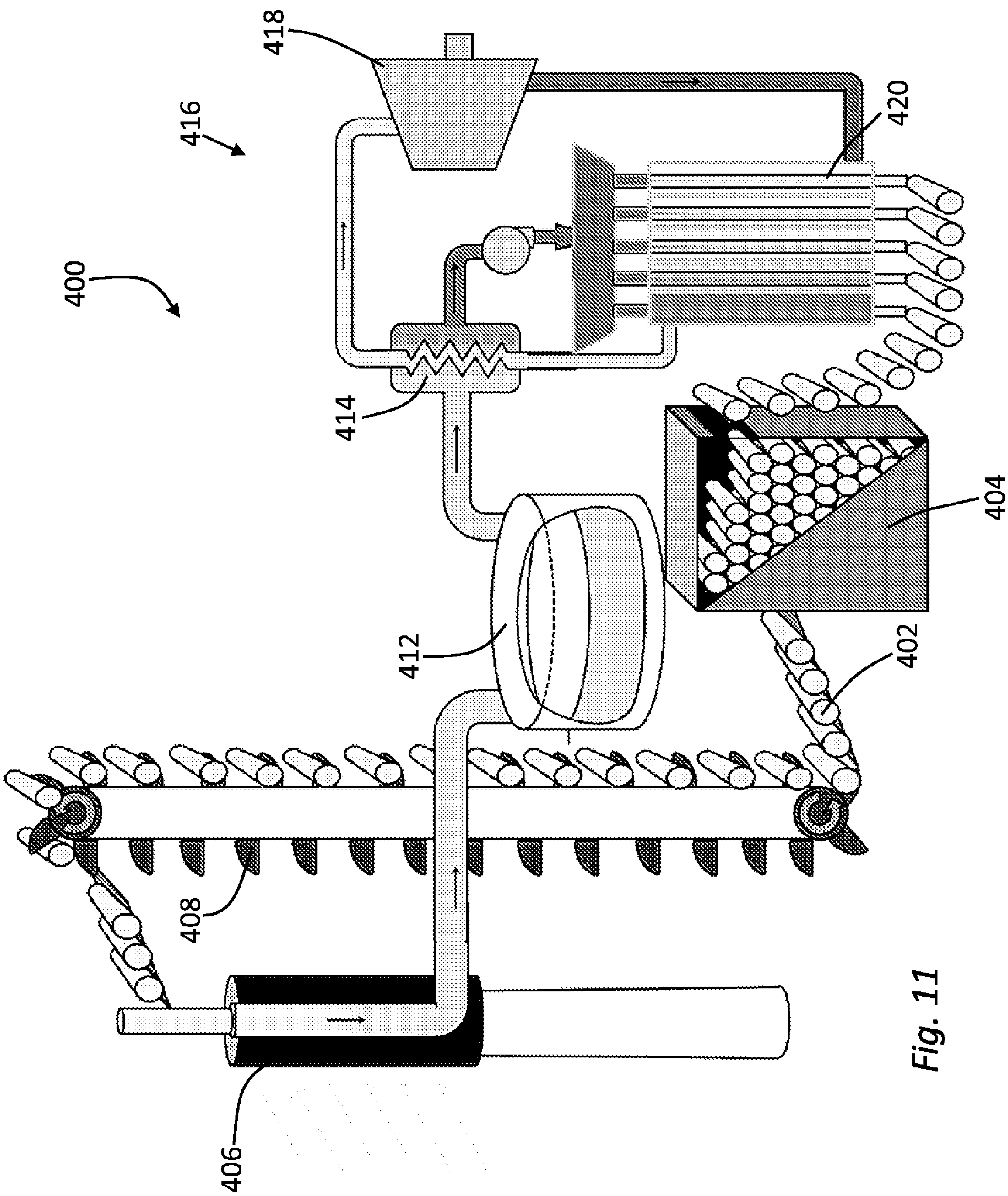

Fig. 11

FLOW CONTROL SYSTEMS AND METHODS FOR A PHASE CHANGE MATERIAL SOLAR RECEIVER

TECHNICAL FIELD

[0001] The embodiments disclosed herein relate generally to concentrating solar power ("CSP") technology and more particularly to receiver flow control systems and methods for CSP technologies that utilize a heat transfer material undergoing solid to liquid phase change within an open or partially open heat transfer material circuit.

BACKGROUND

[0002] Concentrating Solar Power (CSP) systems utilize solar energy to drive a thermal power cycle for the generation of electricity. CSP technologies include but are not limited to parabolic trough, linear Fresnel, central receiver or "power tower," and dish/engine systems. Considerable interest in CSP has been driven by renewable energy portfolio standards applicable to energy providers in the southwestern United States and renewable energy feed-in tariffs in Spain. CSP systems are typically deployed as large, centralized power plants to take advantage of economies of scale.

[0003] Previously disclosed CSP systems often utilize oil, molten salt or steam to transfer solar energy from a solar receiver to a power generation block. These heat transfer materials typically flow in a system of pipes or ducts as a gas or liquid and are thus generally referred to as "heat transfer fluids". Typical heat transfer fluids are flowed through heat exchange apparatus to heat a separate "working fluid" to an operational temperature which is then used in a power generation cycle to drive turbines and generate electric power.

[0004] Existing receiver designs typically include receiver tubes which are part of a closed heat transfer fluid circuit. Closed circuits are typically not open to the ambient atmosphere during normal operation and therefore comprise a substantially closed set of pipes, conduits, pumps, valves and other elements. Accordingly, a fixed flow rate of heat transfer fluid enters and exits the receiver because the closed nature of the heat transfer fluid circuit causes heat transfer fluid mass to be conserved through the receiver and no additional mass is allowed to enter the receiver. Therefore, in a conventional heat transfer fluid design, the heat transfer fluid flow rate exiting the receiver must be equal to the heat transfer fluid inlet flow rate. A closed heat transfer fluid circuit therefore allows relatively simple control of heat transfer fluid flow rates within the receiver from a single point, such as a pump feeding the receiver.

[0005] Certain CSP system and receiver designs may feature a solid heat transfer material. One known system features falling solid particles that are illuminated and heated by concentrated solar flux, as described by Evans et al. in 1985 "Numerical Modeling of a Solid Particle Solar Central Receiver" Sandia Report SAND85-8249. A solid particle CSP design can produce higher theoretical maximum temperatures, and therefore can take advantage of higher theoretical power cycle efficiencies. Unfortunately, convective losses for a solid particle receiver system are high, in large part due to the interaction of the falling particles and the air within the receiver. If a window is used to limit air-particle interactions, other design challenges arise which can affect overall system efficiency, window absorption for example. In addition, the use of windows in a solar receiver increases the difficulty of maintaining acceptable window transparency and avoiding breakage.

[0006] A parabolic solar trough having a solid-liquid phase-change material confined within the receiver is described in U.S. Pat. No. 4,469,088. This solid-liquid phase change material design allows for simultaneous heating of a separate, stationary thermal energy storage material and the heat transfer fluid. However, because heat exchange between the thermal energy storage material and heat transfer fluid must take place in this design in the receiver itself, as opposed to an insulated central storage facility, overall system efficiency is limited due to prohibitive overall heat losses during charging, discharging, and standby operations.

[0007] CSP tower and trough systems that employ materials having a solid-liquid phase change are also described in U.S. Pat. No. 4,127,161 and W. Steinmann, and R. Tamme, "Latent heat storage for solar steam systems" Journal of Solar Energy 130(1) Engineering (2008). In these systems however, the thermal storage system is physically remote from the receiver, leading to inherently transient system performance and complicated operating strategies, as well as thermal degradation through the use of indirect heat exchangers.

[0008] Systems featuring a solid to liquid phase change material as the heat transfer fluid cannot conveniently be implemented with a closed loop heat transfer fluid circuit. Therefore, heat transfer fluid flow control in a solid to liquid phase change material receiver can be problematic.

[0009] The embodiments disclosed herein are directed toward overcoming one or more technical limitations including but not limited to the problems discussed above.

SUMMARY OF THE EMBODIMENTS

[0010] Certain embodiments disclosed herein include concentrating solar power (CSP) systems and solar receivers for CSP systems configured to provide inlet and outlet heat transfer material flow control. The disclosed embodiments feature open heat transfer material circuits. Certain embodiments may be implemented with a solid-liquid phase change material as the heat transfer material. Alternative embodiments include methods of heat transfer material flow control in a CSP system and CSP systems configured as described herein.

[0011] One embodiment is a solar receiver, having one or more receiver tubes with each tube having a separate or shared inlet and outlet. In use, a portion of each receiver tube is typically oriented vertically and is placed within a zone of concentrated solar illumination. Solid-phase or liquid-phase heat transfer material is fed into the receiver tube inlet. A pressure equalizing pipe is provided in fluid communication with each receiver tube outlet opposite the inlets. The pressure equalizing pipe or pipes comprise a riser portion which typically rises to a point above the top of the zone of solar illumination. The pressure equalizing pipe terminates in an outlet which provides for the flow of liquid heat transfer material into a launder or other liquid collection system. A gap is provided between the outlet of the pressure equalization pipe and the launder which provides for passive pressure equalization between the upper portion of the pressure equalizing pipe and the inlet to the one or more receiver tubes. In some embodiments, the pressure equalizing pipe also includes a vent in the upper portion which serves to provide or supplement pressure equalization.

[0012] Liquid heat transfer material may therefore flow from the upper portion of the pressure equalizing pipe to other portions of the heat transfer fluid circuit without affecting the fluid level in the receiver tubes. The pressure equalizing pipe thus provides for passive equalization of the flow rate of liquid-phase or solid-phase heat transfer material into the receiver and the flow rate of liquid-phase heat transfer material out of the receiver.

[0013] An alternative embodiment is a solar receiver having one or more receiver tubes with each tube having a separate or shared inlet and outlet. In use, a portion of each receiver tube is typically oriented vertically and is placed within a zone of concentrated solar illumination. Solid-phase or liquid-phase heat transfer material is fed into the receiver tube inlets and heated liquid-phase heat transfer material flows from the receiver tubes through one or more outlets. The solar receiver also includes at least one valve operatively associated with the receiver tubes and a liquid level sensor, also operatively associated with the receiver tubes. The liquid level sensor provides for the sensing of the level of liquid heat transfer material within the receiver tubes. The liquid level sensor also provides feedback to the valve to selectively control the level of the liquid heat transfer material within the one or more receiver tubes. In this manner, the flow rate of solid heat transfer material into the solar receiver and the flow rate of liquid heat transfer material out of the receiver can be equalized and the liquid heat transfer material level within the receiver tubes can be maintained within the solar illumination zone.

[0014] Alternative embodiments disclosed herein include CSP systems including solar receivers with flow control apparatus as described above.

[0015] Other alternative embodiments include methods of controlling the flow rate of a solid to liquid phase changing heat transfer material within a heat transfer material circuit including a solar receiver using the systems described above.

[0016] Other alternative embodiments are methods of generating power using the systems described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] FIG. **1** is a schematic diagram of a solar receiver with flow control provided by a liquid level sensor and valve.

[0018] FIG. **2** is a schematic diagram of a solar receiver with flow control provided by a pressure equalizing tube.

[0019] FIG. **3** is an alternative view of the solar receiver with flow control provided by a pressure equalizing tube of FIG. **2**.

[0020] FIG. **4**A is a schematic diagram of a solar receiver tube and associated elements with flow control provided by an alternative embodiment of pressure equalizing tube, showing heat transfer material flowing through the receiver.

[0021] FIG. **4**B is a schematic diagram of a solar receiver tube and associated elements with flow control provided by an alternative embodiment of pressure equalizing tube, showing heat transfer material levels balanced within the receiver.

[0022] FIG. **5** is an isometric view of a solar receiver featuring flow control provided by one or more pressure equalizing tubes.

[0023] FIG. **6** is a schematic diagram side view of the solar receiver of FIG. **5**.

[0024] FIG. **7** is a schematic diagram of a Concentrating Solar Power (CSP) system.

[0025] FIG. **8** is a schematic diagram of an alternative CSP system.

[0026] FIG. **9** is a schematic diagram of an alternative CSP system featuring pilled solid-phase heat transfer material.

[0027] FIG. **10** is a schematic diagram of an alternative CSP system featuring rectangular billet solid-phase heat transfer material.

[0028] FIG. **11** is a schematic diagram of an alternative CSP system featuring round cross section billet or rod type solid-phase heat transfer material.

DETAILED DESCRIPTION

[0029] Unless otherwise indicated, all numbers expressing quantities of ingredients, dimensions, reaction conditions and so forth used in the specification and claims are to be understood as being modified in all instances by the term "about".

[0030] In this application and the claims, the use of the singular includes the plural unless specifically stated otherwise. In addition, use of "or" means "and/or" unless stated otherwise. Moreover, the use of the term "including", as well as other forms, such as "includes" and "included", is not limiting. Also, terms such as "element" or "component" encompass both elements and components comprising one unit and elements and components that comprise more than one unit unless specifically stated otherwise.

[0031] Certain embodiments disclosed herein include CSP systems featuring the use of solid-liquid phase change material as a heat transfer material. In the disclosed systems, the solid-liquid phase change occurs at some point in an open heat transfer material circuit. In some embodiments phase change occurs within the solar receiver. In other embodiments the solid-liquid phase change occurs in a thermal energy storage system or other element of or location within the heat transfer material circuit. Other embodiments disclosed herein feature an open heat transfer material circuit but may not necessarily utilize a solid-liquid phase change material as a heat transfer material.

[0032] The term "heat transfer material" is used herein instead of the more commonly used "heat transfer fluid" because in certain stages of the described systems, the heat transfer material is moved, stored or utilized as a non-fluid solid. An open heat transfer material circuit is defined herein as a circuit which is open at some point to the ambient atmosphere or to a cover gas at ambient or circuit inlet pressure during normal operation.

[0033] Certain CSP systems featuring the use of solid-liquid phase change material as a heat transfer material are described in co-owned and co-pending PCT patent application PCT/US2012/045425 entitled; "Concentrating Solar Power Methods and Systems with Liquid-Solid Phase Change Material for Heat Transfer" the content of which application is incorporated herein for all matters disclosed therein.

[0034] As defined herein, a solid-liquid phase change material is a material which exists in a solid phase at cooler operating temperatures but melts to a liquid phase at hotter operating temperatures. One benefit of utilizing a phase change material as the heat transfer material of a CSP system is the high energy density realized by exploiting the latent heat as well as the sensible heat of a suitable heat transfer material. The energy storage density of a suitable heat transfer material can typically be doubled by exploiting the latent heat storage of a phase change transition.

[0035] Phase change materials suitable for use as a heat transfer material include salts, organic and inorganic polymers, and metals. In particular, the heat transfer material could be comprised of a nitrate, carbonate, bromide, chloride, fluoride, hydroxide, or sulfate salt, zinc, boron, beryllium, lead, magnesium, copper, aluminum, tin, antimony, manganese, iron, nickel or silicon, an alloy of any metals, a plastic, a wax organic material or a miscible or immiscible mixture of any of the above that is capable of storing heat in a sensible and latent form. The specific choice of a heat transfer material is determined by specific application requirements. The various flow control systems and methods described herein can be adapted to a heat transfer material of any type which undergoes a solid to liquid phase change at some point in an open heat transfer circuit.

[0036] As noted above, existing receiver designs typically include receiver tubes which are part of a closed heat transfer fluid circuit. In closed circuit designs, a fixed flow rate of fluid enters and exits the receiver because heat transfer fluid mass is conserved through the receiver and no additional mass is allowed to enter the receiver. Another characteristic of a closed heat transfer fluid circuit design is the absence of substantial communication between the heat transfer fluid and the ambient atmosphere at any point of the circuit during normal operation. Therefore, in a conventional closed circuit designs, the heat transfer fluid flow rate exiting the receiver must be equal to the heat transfer fluid inlet flow rate.

[0037] On the contrary, certain systems, particularly those utilizing a solid/liquid phase change material as the heat transfer material, cannot easily be configured to have a closed heat transfer material circuit. For example, an open receiver system is required if a phase change-heat transfer material is admitted to the receiver in the form of billets, rods or other relatively large solid structures. In some, but not all embodiments of systems featuring solid phase change-heat transfer material input to a receiver, the flow rate of liquid heat transfer material leaving the receiver is independent of the flow rate of solid heat transfer material entering the receiver. The difference can be made up by air filling the receiver. Therefore, if solid heat transfer material is added to the receiver at 10 kg/s but gravity causes the heated liquid heat transfer material to drain at 20 kg/s, the height of phase change material in the receiver tubes would rapidly decrease creating a dry-out condition. Heat transfer material dry-out must typically be avoided in any CSP receiver design because and empty receiver tube can rapidly overheat and fail. Passive level equalization, as disclosed herein ensures that the liquid level remains sufficiently high enough to avoid a dry out or partial dry out condition regardless of the position of any solid in the receiver or the addition of further heat transfer material input.

[0038] Therefore, certain systems and methods disclosed herein which utilize solid heat transfer material input are configured to equalize the solid inlet and liquid outlet flow rates to maintain a constant fill-level in the receiver tubes during CSP operation. In other disclosed embodiments of receiver designs configured to accept liquid input to the receiver, the inflow of liquid heat transfer material has a direct impact on the effective head pressure at the outlet, and therefore the flow rate leaving the receiver, even though the heat transfer material circuit is not configured as a closed circuit.

[0039] Certain qualities of phase change materials suitable for use as a heat transfer material make equalized inlet and outlet flow control problematic. For example, one of the primary motivations for using a phase change material such as a metal alloy as heat transfer material is the ability to achieve substantially higher CSP operational temperatures. Unfortunately, material corrosivity is frequently exacerbated at high temperatures. Therefore, systems configured to operate at high temperatures and in highly corrosive environments must use exotic materials to contain and control the molten phase change material. In particular, metal components have very short useful lifetimes above 750° C. under cyclic thermal stress and when facing high corrosion. Therefore, simple flow control methods using conventional metal pumps or valves may not be suitable for the implementation of a CSP receiver configured to use a solid to liquid phase change heat transfer material.

[0040] In view of the foregoing challenges, one system and method of achieving flow rate equalization in an open heat transfer material circuit is illustrated in FIG. **1**. FIG. **1** shows a receiver **100** featuring a valve **102** having liquid level feedback control. In particular, the receiver **100** features multiple receiver tubes **104** which are open at a top end **106**. The receiver tubes **104** are configured to have solid billets or rods of heat transfer material **108** loaded into the top end **106**. In alternative configurations, the solid heat transfer material could be loaded in an alternative form, including but not limited to rods, prill or other solid shapes. During operation, the heat transfer material is melted and heated to a working temperature by concentrated sunlight while contained within the solar illuminated area **110** of a receiver tube **104**.

[0041] Flow control may be accomplished with a valve **102** in communication with a liquid level sensor **114**. The valve **102** and liquid level sensor **114** may communicate using digital or analog signals of any suitable type. The valve **102** will include a motorized ball or gate or other structure providing for automated operation in response to feedback from the liquid level sensor **114**.

[0042] The liquid level sensor **114** may determine the melted heat transfer material level continuously or periodically. The liquid level sensor **114** may measure liquid level at one or more discrete points. The liquid level sensor **114** may operate on any known optical, electronic, mechanical or other sensing principle and may in certain instances be implemented as an array of sensors, for example with one or more sensors associated with each receiver tube **104**. In any configuration, the liquid level sensor detects the height of molten, liquid heat transfer material in the receiver tubes and provides the valve **102** (or multiple valves) with feedback sufficient to equalize inlet and outlet heat transfer material flow rates.

[0043] In the embodiment illustrated in FIG. **1**, a single valve **102** is operationally positioned on the receiver downcomer **116** and thus in fluid communication with each receiver tube **104**. Alternatively, one or more valves could be placed on the header outlet of each panel, or on each receiver tube.

[0044] During operation, the valve is automatically partially closed when the liquid heat transfer material level within the receiver drops below a designated operational fluid level, which is selected to be above the level defined by the illumination area **110**. Similarly, when the liquid level rises above the designated operational fluid level, the valve or valves are partially opened. Thus, the liquid heat transfer material level is maintained above the area receiving solar flux but below the open top end **106** of any receiver tube during operation.

[0045] A significant technical challenge presented by any valve and feedback based system or level control method is building a valve that can withstand the operating conditions presented by a molten, potentially highly corrosive, heat transfer material. Known process control valves are typically cast out of steel, nickel alloy, or other metals. However, certain material such as aluminum, silicon, chloride salts, and fluoride salts that are suitable for use as phase change heat transfer materials are extremely corrosive to these metals at high temperatures. Since the valves must maintain tight seals and moderate-to-high control accuracy, very little corrosion can be permitted.

[0046] Valve corrosion potentially may be addressed by at least two alternative methods. The first method includes fabricating the valve from ceramic materials. Silicon carbide and silicon nitride are examples of materials which may be suitable for casting into valve components. Alumina is an example of an alternative material which may be suitable for machining into valve components. The second method consists of coating high temperature metals with ceramics or other metals which can withstand the corrosion but which may not exhibit sufficient mechanical strength or have sufficiently low cost to justify fabricating the entire valve out of the selected material. One example of a ceramic coated metal design would be a 347 stainless steel valve with the wetted valve components coated in a suitable thickness of boron nitride or tantalum.

[0047] An alternative method of receiver flow control in a CSP system utilizing either a solid to liquid phase change heat transfer material or a liquid heat transfer material in an open heat transfer material circuit features the use of a passive pressure-equalizer system as shown in FIGS. **2-8**. For example, in the embodiments of FIG. **2** and FIG. **3**, the receiver **200** includes a pressure-equalizing pipe **202** rising in a riser portion **203** from the header **204** to the designated heat transfer material liquid level. From the upper portion **205** of the pressure-equalizing pipe **202**, the liquid heat transfer material may flow back down toward collection piping **206** in communication with a downcomer. As shown in the embodiment of FIGS. **2-3**, the pressure-equalizing pipe **202** may include an opening **208** or other venting structure in the upper portion **205** which provides for pressure equalization with the pressure at the receiver inlet **210**. Therefore, liquid heat transfer material will spill into the collection/downcomer piping **206** at the same rate as heat transfer material enters the receiver tubes, passively maintaining the liquid level in the receiver tubes **212**.

[0048] A significant challenge is presented by the foregoing passive methods of flow control because the relatively complex flow path of the system must be constructed from materials that are suitably temperature and corrosion tolerant, which materials may be dissimilar, difficult to form, or difficult to join. For example, in the embodiment of FIGS. **2-3**, the header pipe **204** which collects the heat transfer material from the receiver tubes **212** has a somewhat complicated geometry that cannot be cast or machined from a ceramic material at low cost with adequate strength. Accordingly, the header pipe **204** may be made of metal with a corrosion-resistant coating or liner. The elbow joint **214** and upper portion U joint of the pressure-equalizing pipe **202** may be cast from a ceramic such as silicon carbide. However, silicon carbide cannot be welded to metal so another type of joining must be used to attach the various pipe sections which joining method must be able to withstand extreme and cyclic thermal stresses. For example, one representative combination of materials and joining techniques may be a 347 stainless steel header pipe having a cast alumina liner brazed to an alumina pressure-equalizing piping system provided with metal jacketing for additional strength.

[0049] As shown in FIGS. **4-6**, an alternative approach to accomplish passive flow control utilizes a receiver **300** that includes an individual riser tube **302** and outlet **304** for each receiver tube **306**. This configuration eliminates the need for a complicated and difficult to manufacture header. Each receiver **300** will typically consist of multiple main receiver tubes **306** used to absorb solar radiation, a pair of elbows **308** or a "U" joint at the bottom of the receiver tube **306** that reverse the flow of material into riser tube **302** that runs back up the length of the receiver tube **306** opposite the direction of incident solar flux. This riser tube **302** terminates in another pair of upper elbows **310** or an upper "U" joint which again reverses the heat transfer material flow, allowing the heat transfer material to drain into a launder **312**, with the outlet **304** being located at the minimum acceptable liquid level.

[0050] The receiver embodiments of FIGS. **4-6**, consist primarily of simple tubes and relatively easy to manufacture elbows and can be constructed from a ceramic, for example SiC components that are sintered simultaneously as a substantially monolithic structure. Alternatively, the individual components may be fired separately and then assembled using available high temperature adhesives. In either case, the configuration of elements within the receiver **300** of FIGS. **4-6** eliminates the need to create fluid tight joints between dissimilar materials having different coefficients of thermal expansion. Also, the open-circuit pouring of heat transfer material from the outlet **304** into the launder **312** both serves as the vent for the riser **302** to allow pressure equalization and prevent siphoning and to eliminate the need for a fluid tight joint. In addition the gap between the outlet **304** and launder **312** provides for the compensation of differential thermal expansion between the various receiver components

[0051] The receiver embodiments of FIGS. **4-6** inherently balance flow by allowing positive head pressure from the main receiver tube **306** to cause the liquid heat transfer material level to rise in the riser **302** until it overflows, similar to the vented pressure equalizing embodiment of FIGS. **2-3**. Thus, as shown in FIG. **4**A, during use, heat transfer fluid inflow **314** is balanced with a heat transfer fluid outflow **316** without the use of valves, pumps or other moving flow control apparatus. As shown in FIG. **4**B, when heat transfer fluid stops flowing into the receiver, the liquid level in each receiver tube **306** will equalize with the liquid level in each riser tube **302** at or just above the height of the outlet **304**. In this manner, the receiver will always be maintained full of heat transfer material, which will guard against a possible over-temperature event that could occur in a dry receiver tube.

[0052] The receiver embodiments of FIGS. **4-6** may be implemented to utilize liquid heat transfer materials, or solid heat transfer materials that are melted into liquids within the main receiver tube or elsewhere within the heat transfer material circuit. In any case the heat transfer material will leave the main receiver tube **306** and flow through the riser tubing **302** as a liquid.

[0053] One variation the foregoing embodiments includes a dual-purpose metering hole that allows the receiver to be drained if desired, for example at the end of the day. The optional metering hole **318** (FIG. **8**) may be located in one or more of the bottom elbows **308** for example. The metering hole **318** may be sized such that during normal operation a small portion of the heat transfer material, for example approximately 10% of the designed flow rate, will flow through this hole to the primary outlet piping **320** connected to the launder. In this manner, the majority of the heat transfer fluid flow can be regulated by controlling inflow of material into the receiver inlet, which will provide an adequate level of control during daily operation. Then, at the end of the day the receiver can be completely drained by simply stopping the inflow of material and waiting for the liquid heat transfer fluid present in the receiver to drain out.

[0054] The embodiments of FIGS. **4-6** have the significant advantage of eliminating the need for a header to connect the various receiver tubes (See, for example the header **204** of FIG. **3**). Rather, the outlet of each receiver tube drains into an open air launder **312**, or possibly a launder containing a cover gas, thereby minimizing or eliminating the need for fluid tight joints to a separate header. The receiver **300** of FIGS. **4-6** provide several operational advantages over more conventional flow control designs. For example, since the connection to the launder is not required to be gas tight, the configuration of FIG. **4-6** also eliminates the need for a vent at the top of each riser. The use of riser and outlet elements, **302** and **304** respectively, eliminates the need for a flow control valve which can be difficult to implement with certain heat transfer fluids, molten aluminum for example. Additionally, the disclosed configuration has the advantage of incorporating a gap between the outlet **304** and the launder **312** with no connection required between the individual outlets **304**, therefore providing much easier compensation for the thermal expansion of the various components.

[0055] The receiver configuration of FIGS. **4-6** features separate tubes and elbows at every joint. This is not a limiting embodiment or configuration. Alternatively, a suitable high-temperature ceramic material could be machined, cast or simultaneously sintered to form a monolithic structure replacing selected tubes and elbows and therefore reducing the overall part count of a receiver. For example, a single part could be designed and fabricated that would serve as two elbows and the riser tube used to connect them.

[0056] The receiver configurations, open-ended heat transfer material circuits and methods of flow rate control described herein can be implemented in a CSP system utilizing a heat transfer material which undergoes a solid-to liquid phase change at an operational temperature. Furthermore, the heat transfer material utilized in the various embodiments disclosed herein may, when in a solid phase, be processed to have one or more of many alternative forms, shapes, or structures. In some embodiments the heat transfer material is delivered to a solar receiver in at least a partially solid phase. For example, the heat transfer material may be delivered to a solar receiver as a prill or prilled material. As used herein a "prill" is a granular and relatively free-flowing material. In alternative embodiments the heat transfer material may be processed and delivered to the receiver as an extruded or cast solid billet, a cylindrical solid billet or rod, a shredded solid, a particulate or granular solid, small plates, chips of any size, for example chips having dimensions of approximately 1.4"× 1.4"×7/8", or other suitable form.

[0057] In certain embodiments, the solar receiver is configured to heat the heat transfer material and cause at least some solid heat transfer material to melt. Alternatively the receiver can be supplied with liquid metal only, which is then heated to a selected "hot" operational temperature. In either configuration, a portion of the liquid heat transfer material can then be recirculated to melt solid heat transfer material in a separate melt tank, with or without the remainder of the hot liquid heat transfer material flowing to the hot storage tank.

[0058] The disclosed systems also include one or more heat exchangers in fluid and thermal communication with the solar receiver and receiving liquid heat transfer material directly or indirectly from the receiver. The heat exchanger(s) may be of any type or any level of sophistication needed to provide for heat exchange between the liquid heat transfer material and a power generation cycle working fluid. The heat exchanger(s) also provide for the cooling and solidification of liquid heat transfer material in conjunction with heating the working fluid if a phase change material is selected as the heat transfer material.

[0059] The heat exchanger elements and other subsystems are, for technical convenience, described and shown in the figures as simple schematic elements. All elements of a commercial system would be implemented with more complex apparatus.

[0060] Certain disclosed CSP system embodiments include material transport systems providing for the transportation of solid heat transfer material from the outlet of the heat exchanger to the solar receiver for reheating or to a melt tank for remelting. Thus, in these embodiments, some or all of the heat transfer material undergoes a thermal cycle including a solid to liquid phase change as solar energy is applied to the heat transfer material and a liquid to solid phase change as energy is exchanged with a working fluid.

[0061] One such CSP system **400** is schematically illustrated in FIGS. **7-8**. The system **400** features the use of a solid-liquid phase change heat transfer material **402** stored at the coolest portion of a thermal cycle in the form of prill in a cold storage tank or vessel **404**. Although designated a "cold" storage tank **404**, it is important to note that the term "cold" is relative. Typically the cold storage tank will house solid-phase heat transfer material at a temperature only somewhat below the heat transfer material melting point. Thus, the cold storage tank **404** must be insulated and fabricated from materials which are suitably durable at the desired temperatures.

[0062] The solid heat transfer material **402** (prilled in this example) is moved to the inlet of a solar receiver **406** with a material transport system **408**. In the solar receiver **406**, concentrated sunlight, for example, sunlight reflected from a field of heliostats **410**, heats the heat transfer material **402** causing a solid to liquid phase change in at least some of the heat transfer material and possibly causing additional heating of the liquid heat transfer material. Heat transfer material flow rates in the receiver may be controlled according to any of the methods and with any of the apparatus described above. Although the embodiments described herein and shown in the figures relate primarily to a tower-mounted receiver **406** illuminated by a field of heliostats **410**, the systems and methods disclosed herein could be implemented in alternative CSP plant configurations. For example, the systems and methods disclosed herein could be implemented in parabolic trough, linear Fresnel, or dish CSP systems as well.

[0063] Downstream from the solar receiver **406**, liquid heat transfer material **402** may be temporarily stored in a hot storage tank **412**. The hot storage tank **412** is the primary thermal energy storage (TES) of the system **400** and thus serves to balance system transient response and extend operations into periods such as the evening or night where solar flux is limited or unavailable. Thermal energy from the hot storage tank **412** may also be utilized to preheat system elements before sunrise, thereby allowing electricity to be generated at an earlier point in time each day. The hot storage tank **412** must be fabricated from a material such as steel lined with alumina brick which provides insulation and which is stable at the highest operating temperatures expected of liquid heat transfer material at the receiver outlet. Storage tanks designed for aluminum smelting operations may be repurposed as hot storage tanks **412** if an aluminum alloy is used as the heat transfer material. Although not shown in the figures it should be appreciated that suitable ducts, pipes and valves will be included in a commercial implementation to allow a plant operator to direct hot heat transfer material to and from the hot storage tank **412** to accomplish TES charging during periods of high solar flux or TES discharging as desired. Because heat transfer and thermal energy storage are achieved with the same phase change/heat transfer material, there is no thermal degradation arising from placing a heat exchanger between separate heat transfer and thermal energy storage fluids.

[0064] Heated liquid heat transfer material **402** is taken from the outlet of the solar receiver **406** or from the outlet of the hot storage tank **412**, or both, and flowed through a heat exchanger apparatus **414**. In the heat exchanger **414**, which may include several sub-elements or stages, heat exchange occurs between the heat transfer material and the working fluid of a power generation block **416**. The embodiments disclosed herein are not limited to any specific type of heat exchanger **414**, power generation block **416** or any specific working fluid. The high operating temperatures achievable with certain types of heat transfer material facilitate use with higher temperature thermodynamic power production cycles for example a supercritical CO_2 (s-CO_2) Brayton cycle. All types of power block **416** will include one or more turbines **418** which are operated by the heated working fluid to generate electricity. The power block **416** will typically include some or all of the following power block elements: turbines **418**, compressors, condensers, expansion stages, recuperators, heat exchangers and associated pipes, ducts, valves and controls.

[0065] The heat exchanger **414** may include separate heat transfer material and working fluid conduits such that heat is exchanged between the heat transfer material and working fluid without physical mixing of the heat transfer material and working fluid streams Alternatively, a direct contact heat exchanger may be utilized where liquid heat transfer material interacts directly into the working fluid of the power cycle. In a direct contact heat exchanger, direct physical contact between the heat transfer material and the working fluid heats the working fluid as the liquid heat transfer material is solidified. Once formed, the solid heat transfer material may be separated from the working fluid using a continuous slagging process. The solid heat transfer material can then be moved to the cold storage vessel **404** and/or receiver **406** with the solid transport system **418**.

[0066] The heat exchanger or downstream components may be selected to provide for the preparation and storage of solid heat transfer material having a specific form or size. For example, as shown in FIGS. **9-11**, the heat transfer material may be solidified in a solidification stage **420** which is represented as a priller in FIG. **9**, a billet extrusion apparatus in FIG. **10** and a rod extrusion apparatus in FIG. **11**. After solidification, the heat transfer material may be stored in cold storage **404** and delivered to the receiver **406** as an extruded or cast billet, rod, ingot or other larger solid form. Alternatively, solid heat transfer material can be delivered to the receiver in a prilled, granular, chipped, small plate, shredded or particulate form. In any embodiment, the flow control over the amount of heat transfer material input to the receiver and the amount of heat transfer material exiting from the receiver is provided as described above. System performance may be affected and in part controlled by managing the flow rate of heat transfer material in both phases through receiver tubes.

[0067] Various embodiments of the disclosure could also include permutations of the various elements recited in the claims as if each dependent claim was a multiple dependent claim incorporating the limitations of each of the preceding dependent claims as well as the independent claims. Such permutations are expressly within the scope of this disclosure.

[0068] While the invention has been particularly shown and described with reference to a number of embodiments, it would be understood by those skilled in the art that changes in the form and details may be made to the various embodiments disclosed herein without departing from the spirit and scope of the invention and that the various embodiments disclosed herein are not intended to act as limitations on the scope of the claims. All references cited herein are incorporated in their entirety by reference.

1. A concentrating solar power system receiver comprising:

at least one receiver tube having an inlet;

a pressure equalizing pipe in fluid communication with the receiver tube at an end of the receiver tube opposite the inlet, the pressure equalizing pipe comprising a riser portion and an outlet providing for passive pressure equalization between an upper portion of the pressure equalizing pipe and the inlet to the receiver tube; and

a launder positioned to receive liquid flowing from the outlet of the pressure equalization pipe, wherein a gap exists between the outlet of the pressure equalization pipe and the launder.

2. The concentrating solar power system receiver of claim **1** further comprising a vent in the pressure equalizing pipe.

3. The concentrating solar power system receiver of claim **1** further comprising a drain opening in fluid communication with the end of the receiver tube opposite the inlet.

4. The concentrating solar power system receiver of claim **1** further comprising multiple receiver tubes in fluid communication with the pressure equalizing pipe through one or more headers.

5. The concentrating solar power system receiver of claim **1** further comprising multiple receiver tubes in fluid communication with separate pressure equalization pipes which are not in fluid communication with other pressure equalization pipes.

6. The concentrating solar power system receiver of claim **1** wherein at least one of the receiver tube and the pressure equalizing pipe comprises a monolithic block simultaneously sintered with at least one elbow.

7. The concentrating solar power system receiver of claim **1** wherein the monolithic block comprises SiC.

8-12. (canceled)

13. A concentrating solar power system comprising:

a solid-liquid phase change heat transfer material contained within an open heat transfer material circuit;

a solar receiver configured to receive concentrated solar flux to heat a quantity of the heat transfer material and thereby cause a solid-phase portion the heat transfer material to melt to a liquid phase at a selected location in a heat transfer material circuit, the solar receiver further comprising;

at least one receiver tube having an inlet;

a pressure equalizing pipe in fluid communication with the receiver tubes at an end of the receiver tubes opposite the inlet, the pressure equalizing pipe comprising a riser portion and an outlet providing for passive pressure equalization between the upper portion of the pressure equalizing pipe and the inlet to the receiver tube; and

a launder positioned to receive liquid flowing from the outlet of the pressure equalization pipe, wherein a gap exists between the outlet of the pressure equalization pipe and the launder; and

a heat exchanger in fluid communication with the solar receiver, the heat exchanger receiving liquid heat transfer material and providing for heat exchange between the liquid heat transfer material and a working fluid of a power cycle.

14. The concentrating solar power system receiver of claim **13** wherein at least one of the receiver tube and the pressure equalizing pipe comprises a monolithic block simultaneously sintered with at least one elbow.

15. The concentrating solar power system receiver of claim **14** wherein the monolithic block comprises SiC.

16. The system of claim **13** further comprising:

a solidification stage providing for the solidification of the liquid heat transfer material; and

a melting stage separate from the solar receiver providing for the melting of solid-phase heat transfer material with thermal energy from liquid-phase heat transfer material.

17. The system of claim **13** further comprising:

a solidification stage providing for the solidification of the liquid heat transfer material;

a material transport system providing for transportation of heat transfer material from the solidification stage;

a hot storage tank in fluid communication with the solar receiver and the heat exchanger, the hot storage tank providing for thermal energy storage using the liquid heat transfer material as a thermal energy storage medium; and

an insulated cold storage tank in mechanical communication with the solidification stage and the solar receiver, the cold storage tank providing for thermal energy storage using the solid heat transfer material as a thermal energy storage medium.

18-20. (canceled)

21. A receiver flow control method comprising:

providing a solid-liquid phase change heat transfer material;

conveying the heat transfer material into a solar receiver configured to receive concentrated solar flux;

heating at least a portion of the heat transfer material in the solar receiver with concentrated solar flux;

flowing a liquid-phase heat transfer material from a lower portion of the solar receiver upward in a pressure equalizing pipe;

flowing the liquid-phase heat transfer material from an outlet in the pressure equalizing pipe into a launder; and

equalizing a pressure at an inlet to the solar receiver with a pressure at the outlet of the pressure equalizing pipe by providing a gap between the outlet of the pressure equalizing pipe and the launder.

22. The receiver flow control method of claim **21** further comprising;

transporting liquid heat transfer material to the receiver inlet; and

melting a solid-phase heat transfer material to a liquid phase in a portion of a heat transfer fluid circuit which is separate from the solar receiver.

23. The receiver flow control method of claim **21** further comprising;

transporting solid-phase heat transfer material to the receiver inlet using a material transport system; and

melting the solid-phase heat transfer material to a liquid phase in the solar receiver.

24. (canceled)

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