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(54) **HIGH TEMPERATURE THERMAL ENERGY STORAGE SYSTEM**

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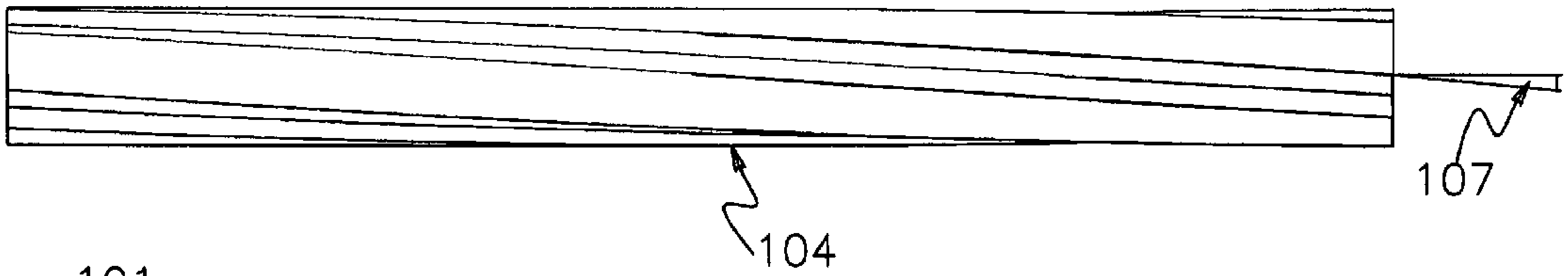
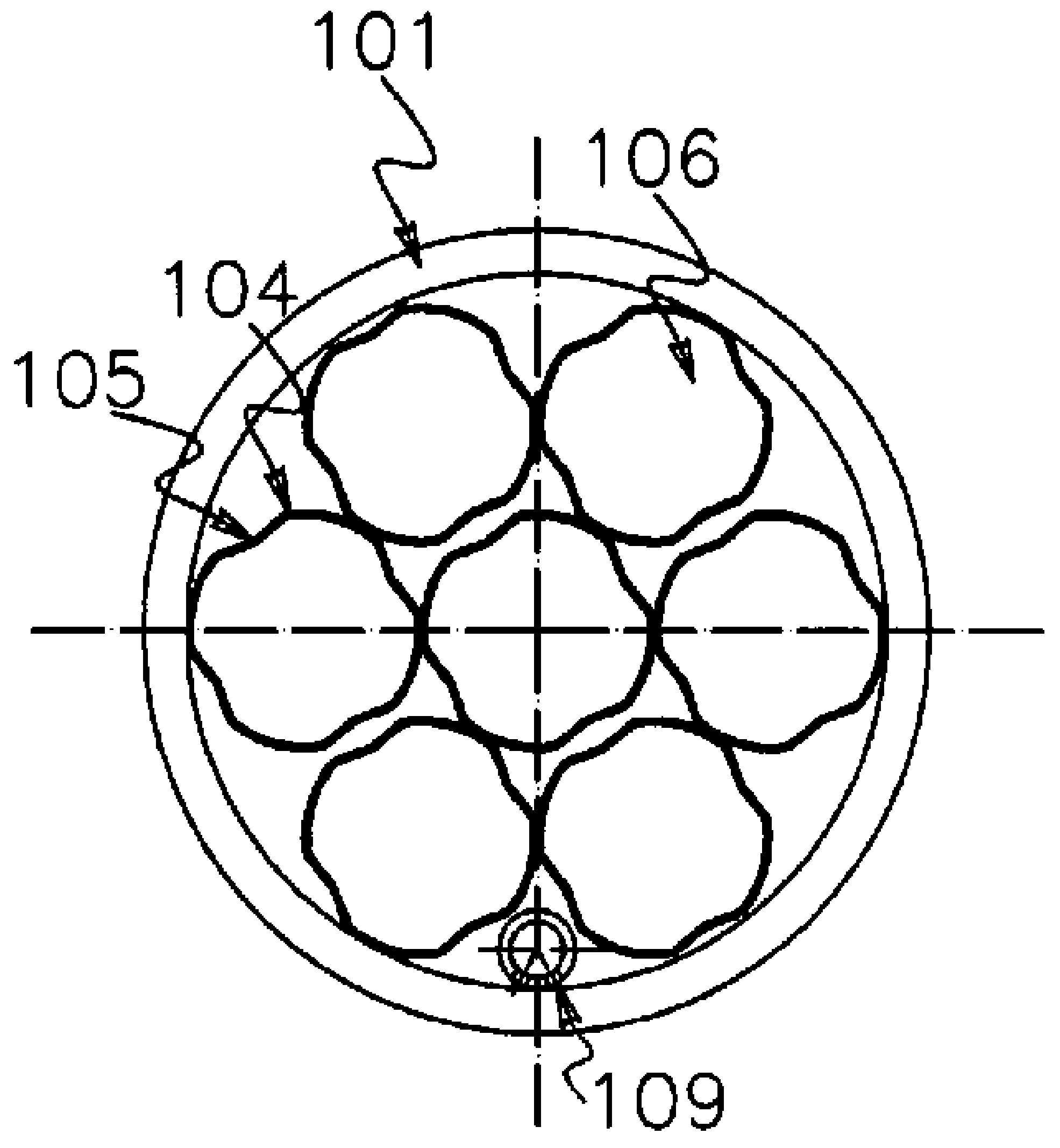
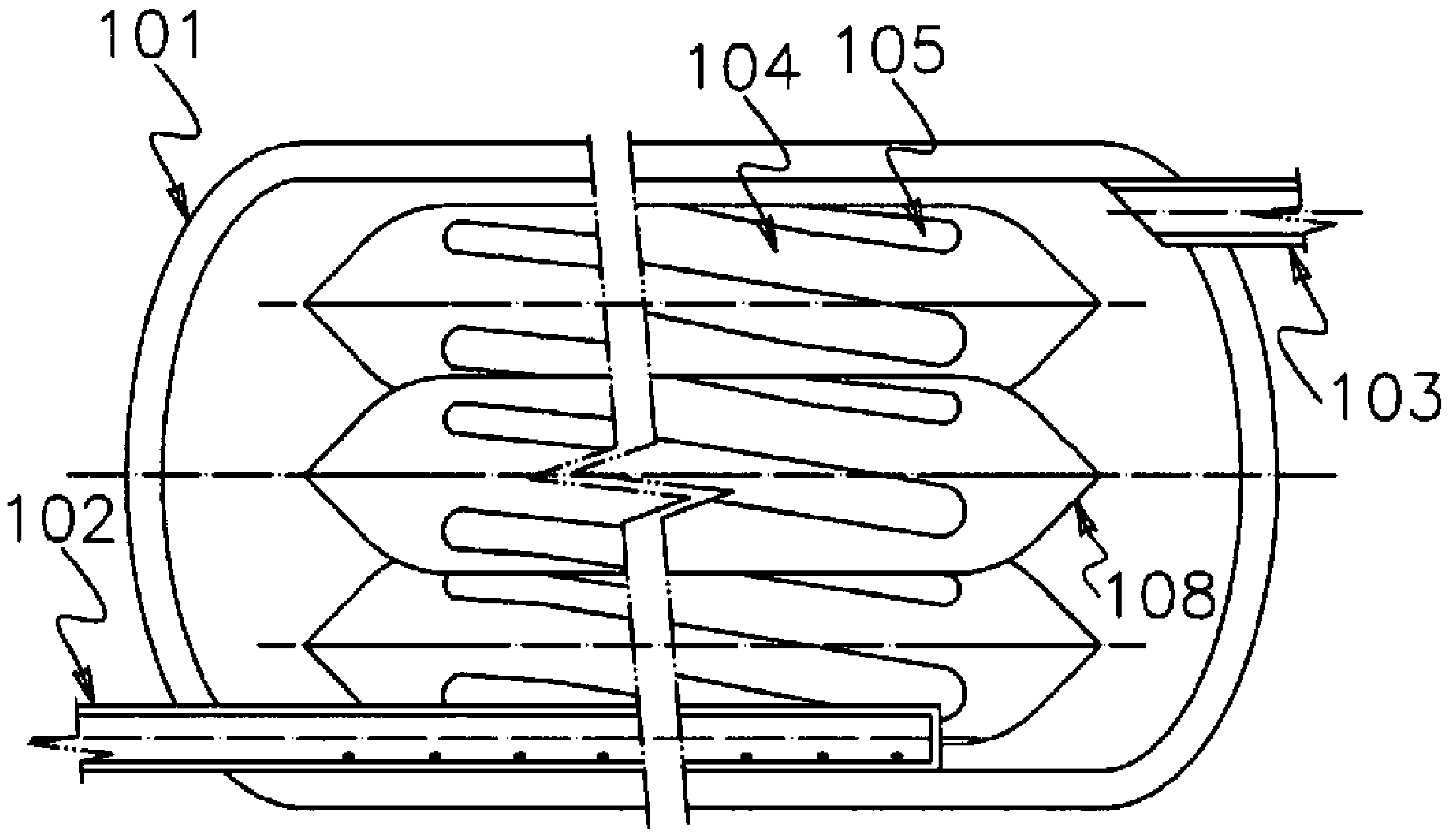
(57) **ABSTRACT**

High temperature thermal energy storage system comprised of solid-liquid phase change material that is fully encapsulated in helically grooved, sealed, thin-wall, metal tubes. Multitude of horizontally oriented, pressure-rated steam pipes or vessels filled with PCM tube capsules form a battery of thermal storage system. The steam pipes in the battery are connected through a common liquid-side distribution header system and a common steam-side distribution header system. Multitude of steam pipes stacked up to fill a block-shaped container space. This insulated enclosure provides the basis for simple fabrication, transport and filed-erection and forms the basic building block for a modular thermal storage system.







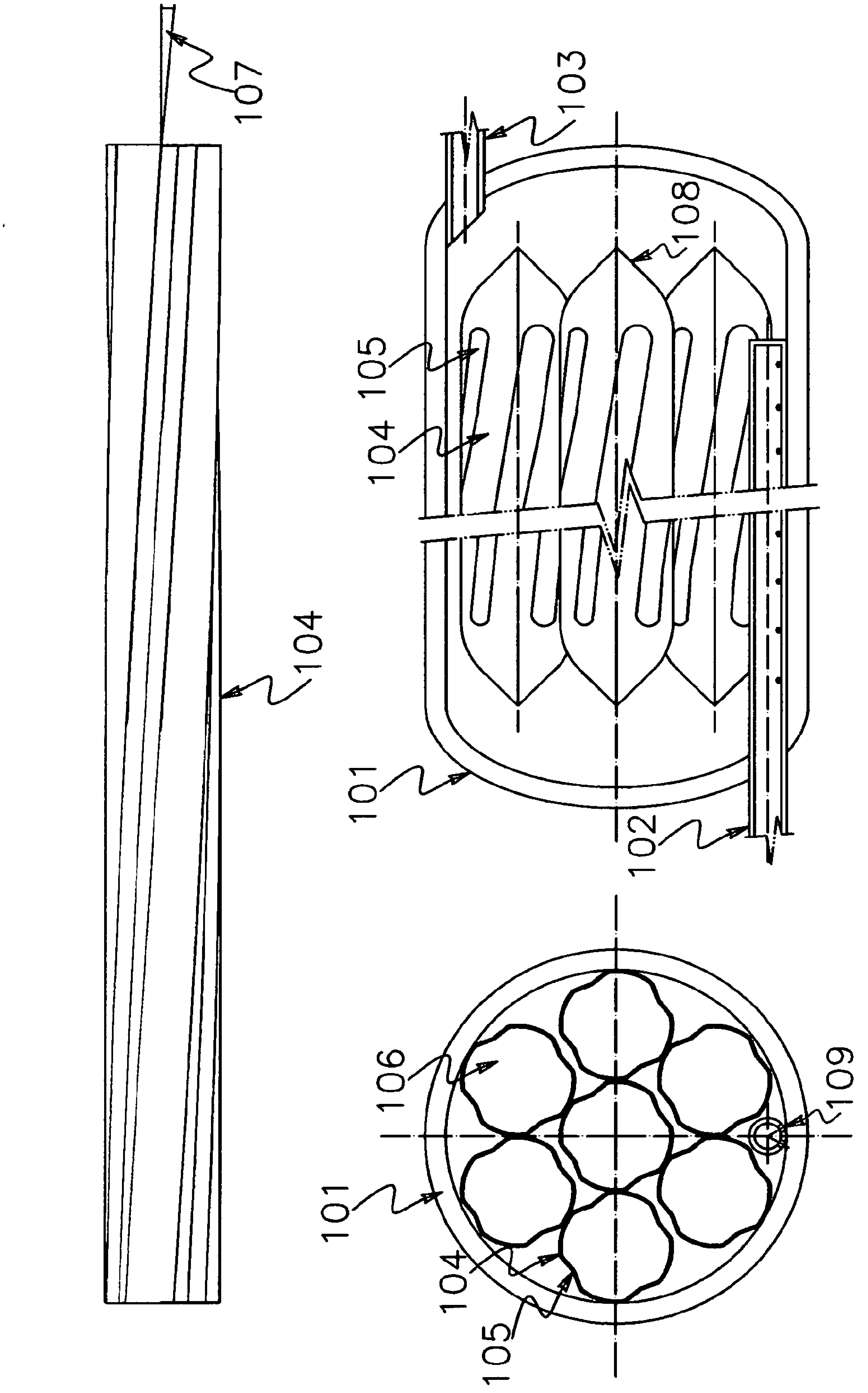


Figure 1

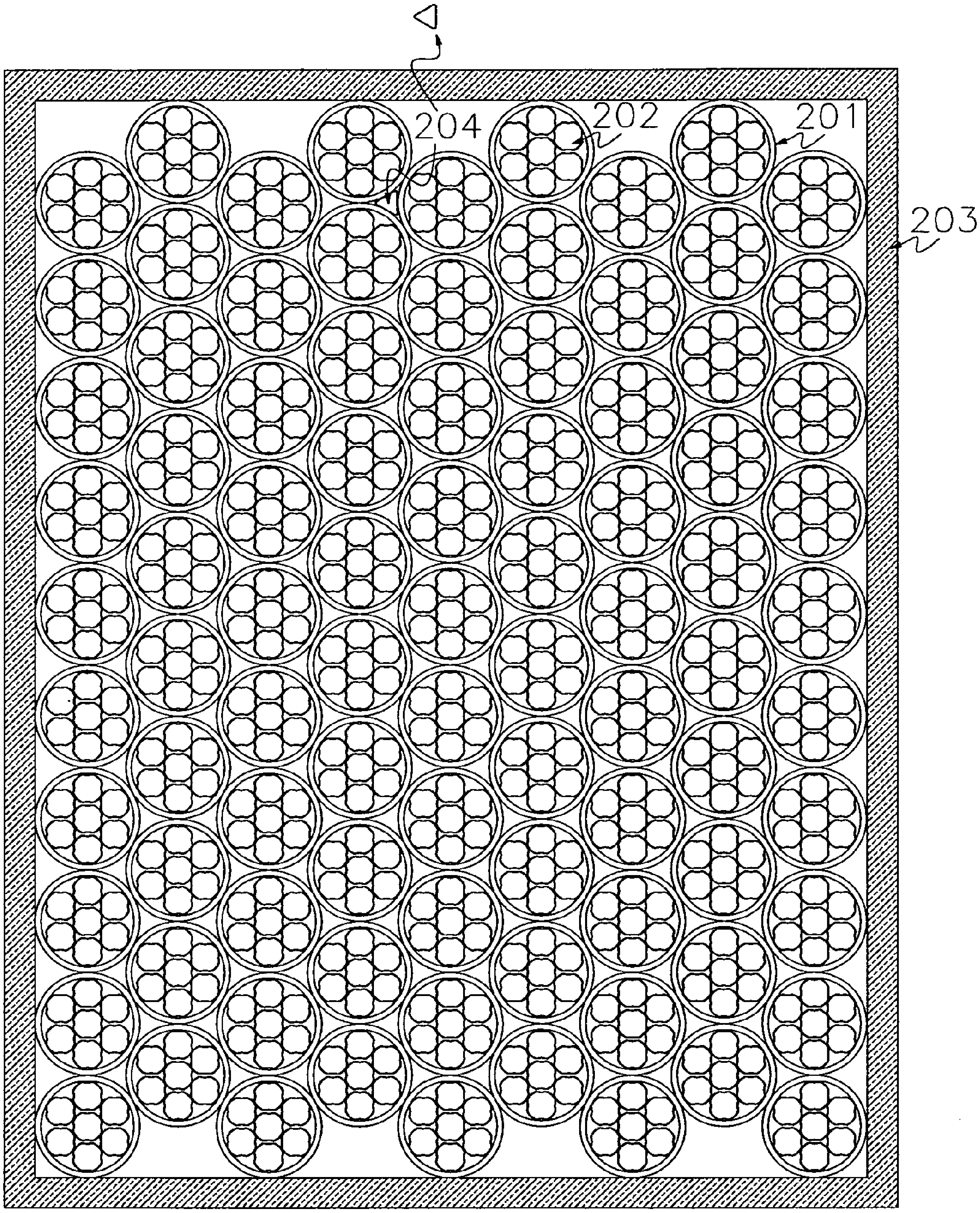


Figure 2

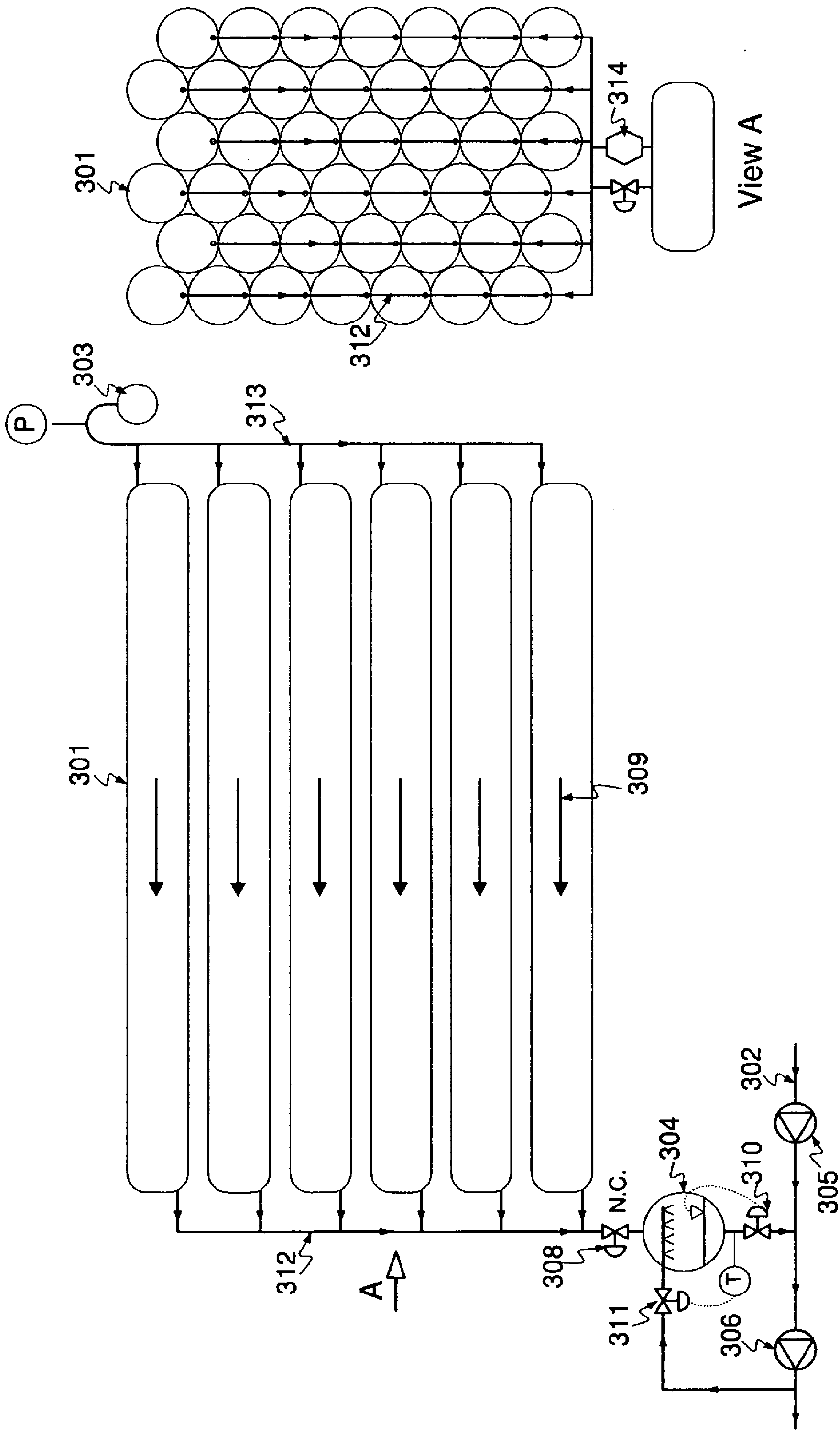

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Figure 3a

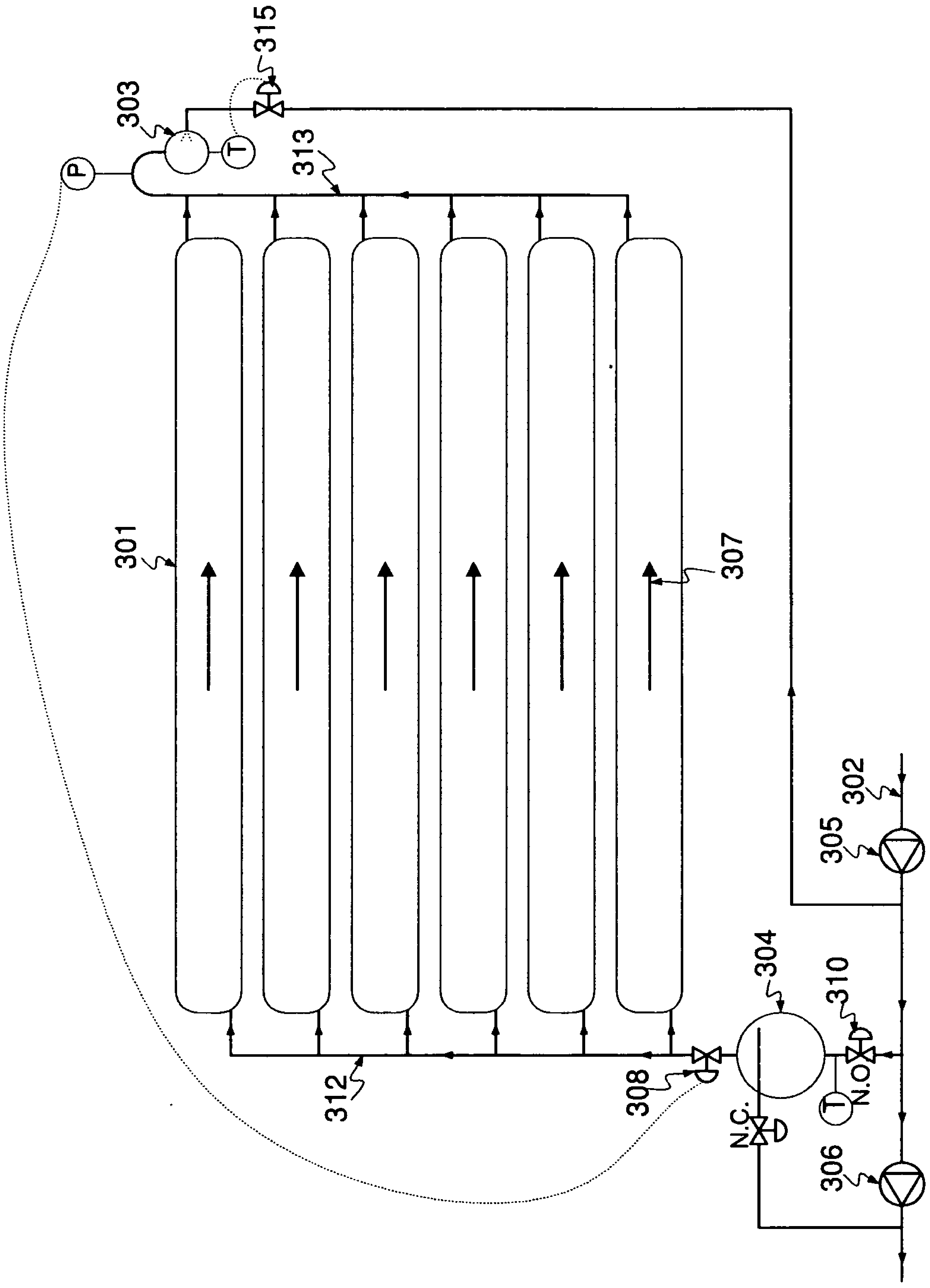

Figure 3b

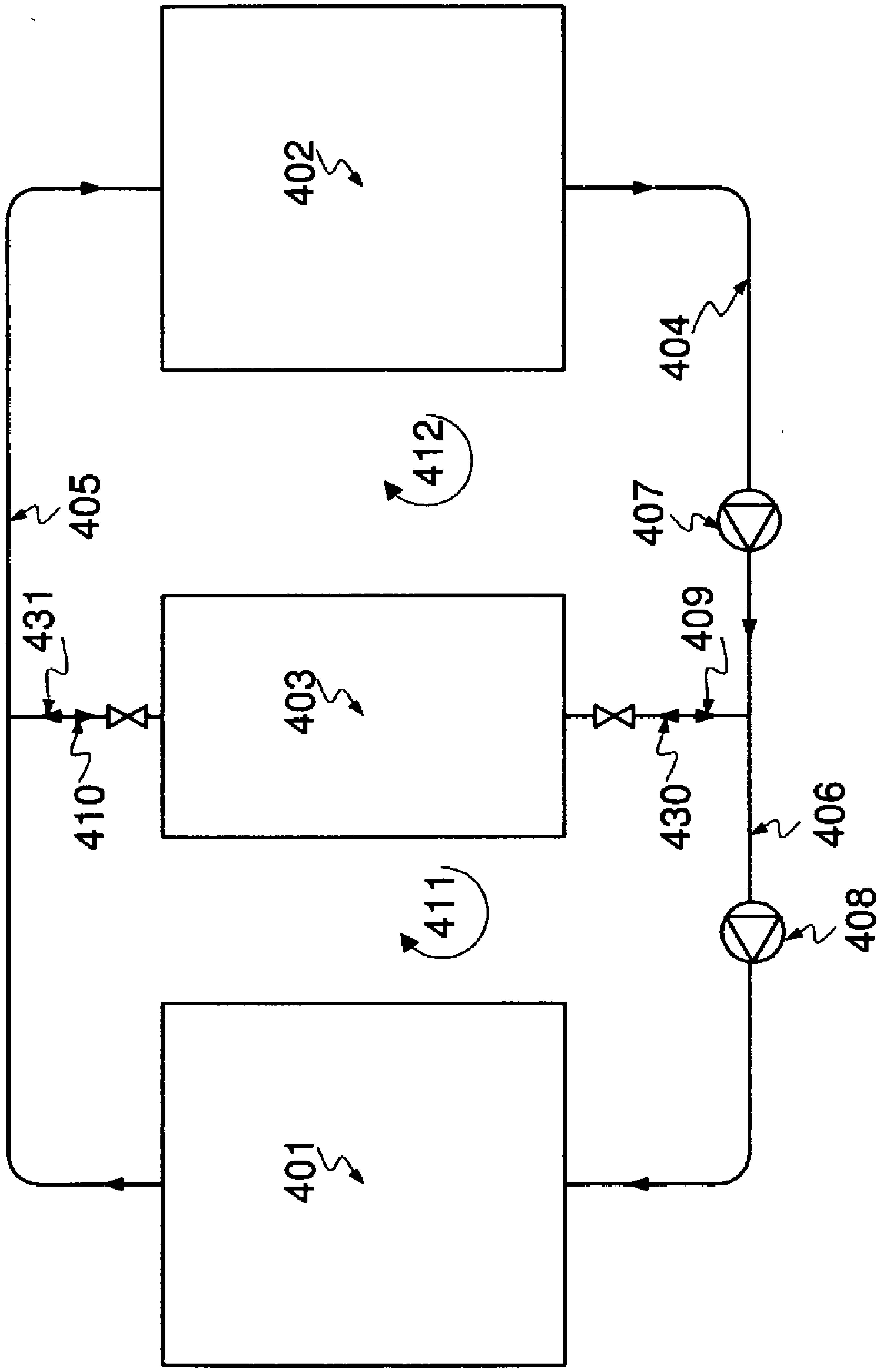

Figure 4a

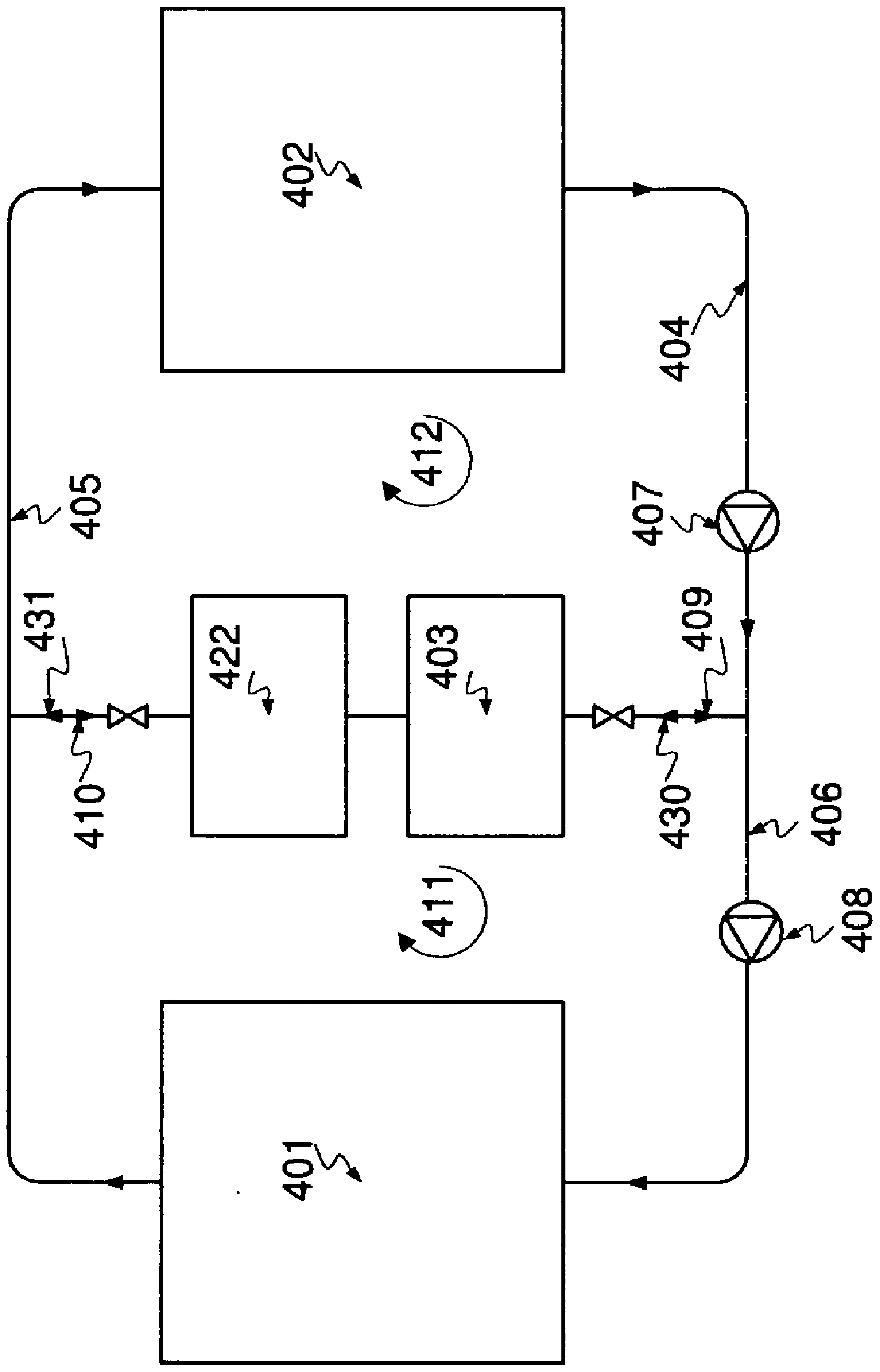

Figure 4b

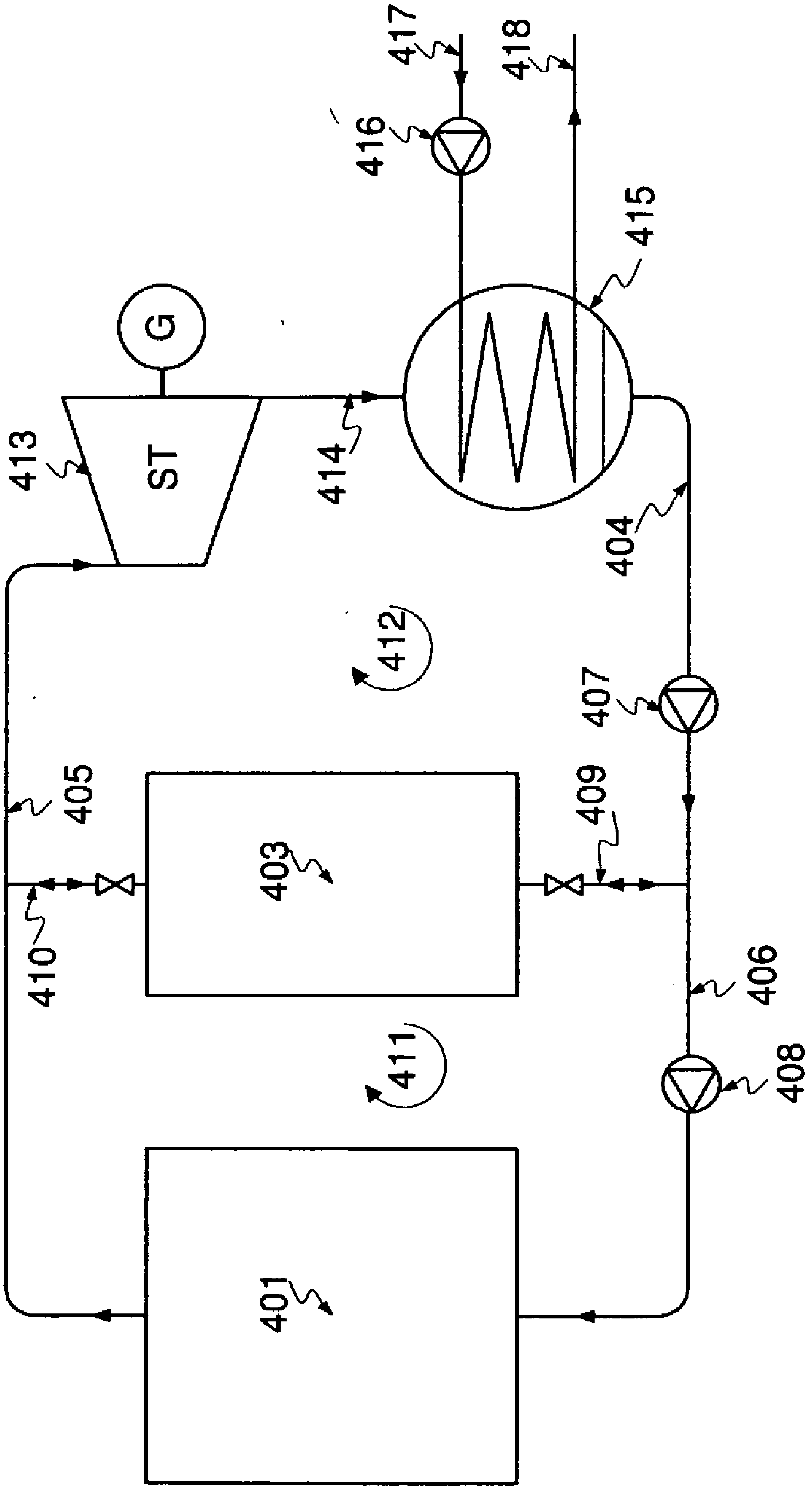
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Figure 4c

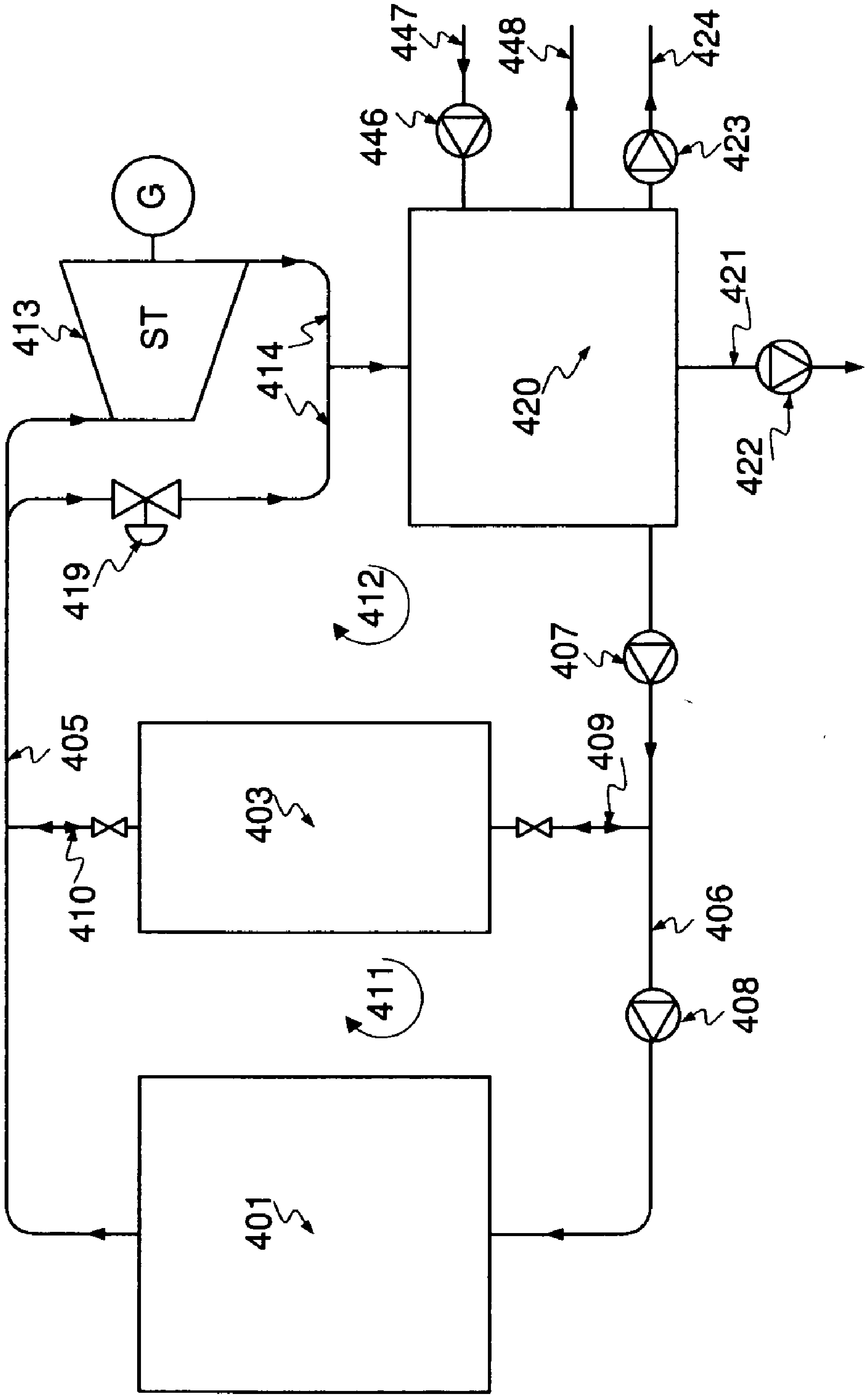
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Figure 4d

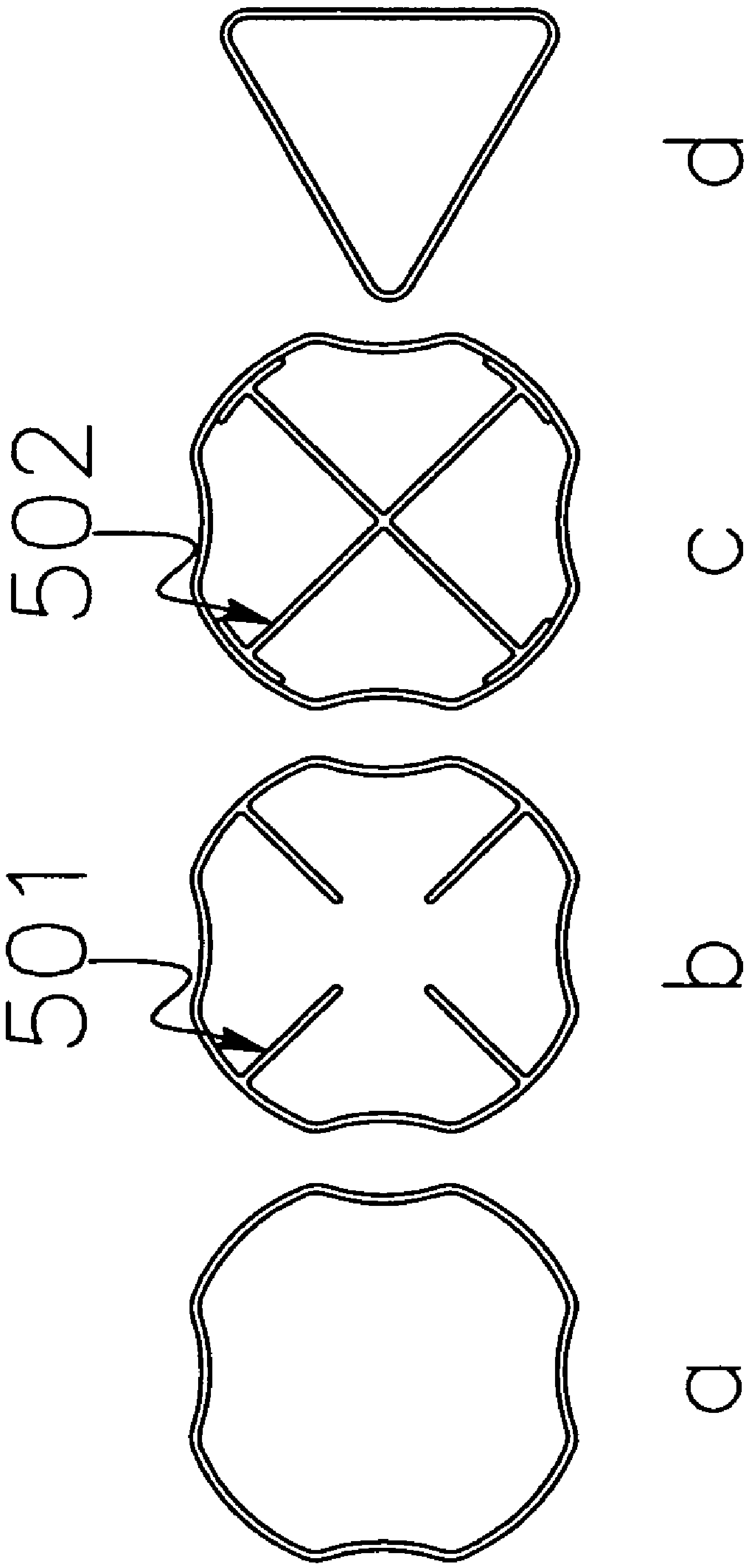

Figure 5

HIGH TEMPERATURE THERMAL ENERGY STORAGE SYSTEM

TECHNICAL FIELD

[0001] The present application generally relates to thermal storage systems and specifically to high temperature energy storage systems typically used in concentrated solar thermal plants.

BACKGROUND OF THE INVENTION

[0002] High temperature energy storage systems are particularly important for solar thermal applications because they provide continuity and stability of operation during daily solar cycles. Portion of the solar energy collected during the sunlit hours is stored at high temperatures and used during night of cloudy hours. Typical operating temperatures of such systems are between 200 to 1000 degrees Fahrenheit. A large variety of materials are used for thermal storage. Based on whether the materials change their physical state during the charge and discharge cycle, there are single-phase or phase-change processes. Most current technologies use single phase liquid or solid materials. Various salt mixtures in their molten state are applied for liquid storage, while solid state materials—such as high purity graphite and concrete—are not fully developed yet.

[0003] The most often used energy storage material in solar power systems is molten salt. This is a mixture of 60 percent sodium nitrate and 40 percent potassium-nitrate, commonly called saltpeter. It is used in liquid (single) phase to store thermal energy by increasing its temperature. It is utilized because it is possible to circulate it as a fluid, it is an efficient medium to store thermal energy and its operating temperatures are compatible with requirements of the currently applied high-pressure and high-temperature steam turbines. It is non-flammable, non-toxic and is commonly used in the chemical and metals industries as a heat-transfer fluid. There are two typical configurations of single-phase molten salt storage systems: In a single-storage tank system, stratification is used to separate the colder bottom from the hot upper layers. In two-tank systems the hot and "cold" liquids are kept in separate tanks.

[0004] Beside their benefits, there are considerable disadvantages of single-phase liquid-salt systems: Their melting temperatures are high (400-550° F.); therefore, to avoid freeze-up of critical components (piping, heat exchangers, pumps, valves etc) the complete system requires backup heating and constant circulation through most of the life cycle of the system. The liquid salt requires decoupling of typically three closed loops: primary heat transfer fluid (solar collection media) loop, heat storage media loop and power cycle working fluid loop. The decoupling of these high-temperature loops results in increased complexity and cost of fluid-handling as well as loss of efficiency caused by multiple stages of heat exchange. Another source of thermodynamic inefficiency results from the sliding temperature (or sensible heat) nature of the energy storage: The lowest temperature of the storage medium drives the power generation cycle efficiency.

[0005] Phase-change materials (PCMs) provide an alternative for thermal energy storage. PCMs have the potential of providing a more efficient means of energy storage as the temperature change is minimal or zero due to the latent heat of the phase change process. PCM systems typically operate near the solid-liquid equilibrium utilizing the latent heat of fusion (or melting). For high temperature storage required in concentrated solar applications, mostly inorganic salt mixtures are used because their melting temperature is in the desired range and because their relatively high phase-change enthalpy.

[0006] Single phase solid thermal storage—mostly concrete and purified graphite—systems are largely in a research and development phase. Their disadvantage is the difficult heat transfer between the storage media and the fluid of the primary loop as well as the working fluid.

[0007] Based on configuration and working principle, there are four main system arrangements: Single tank, Dual tank, Encapsulated and Solid state systems. Both the single and dual tank systems apply molten liquid storage materials. The single storage tank relies on stratification to separate the hot from the "cold" liquid layers in the tank. The tank is always full—the liquid level is constant. The hot liquid is charged and discharged from the top portion of the tank while the relatively colder liquid is pumped in and out from the bottom of the tank. In a dual tank system the liquid is pumped from the "cold" to the "hot" tank during the charging cycle and the direction of the flow is reversed during the discharge cycle. The tank levels vary during the cycle. The encapsulated systems use small pockets of thermal storage materials encapsulated and sealed-up in shells for permanent containment. The capsules are typically submerged in a heat transfer fluid. The solid state systems—as described above—have internal hollow or porous structures to facilitate the heat transfer between the thermal fluid and the solid storage material.

[0008] The currently known high temperature thermal storage systems have the following main challenges and disadvantages: The liquid, sensitive-heat systems are inherently complex and expensive because of the specialty equipment and materials required for fluid handling, flow-control and heat exchange. The encapsulated systems have a challenge caused by poor heat transfer from the primary heat transfer fluid to the thermal storage material encapsulated typically in spherical shells. The encapsulation process is also expensive as the capsule design needs to withstand high thermal expansions, high pressure and temperature conditions and at the same time provide high thermal conductivity. The low-cost, solid-state storage materials are typically poor thermal conductors and therefore they require high percentage of porous, hollow-space per active storage volume to improve the heat transfer rate. The high porosity results in low average density of the thermal storage system, thus lowering its efficiency, increasing size and cost.

SUMMARY OF THE INVENTION

[0009] The present application thus describes one embodiment of the invention that may take the form of helically grooved, thin-wall, tubular encapsulation of phase change material (PCM). A permanently sealed, flexible, thin wall tube may be the containment shell of the encapsulated PCM. A helical grooving or "rifling" rolled into the thin wall of the tube may provide the radial and lateral-axial flexibility of the capsule to accommodate the thermal expansion and contraction during the charging and discharging process. The length of the tube may be significantly larger than its diameter. The tube may be completely filled with molten liquid PCM and sealed off at manufacturing. The thermal contraction induced torsion of the helically rifled tube will result in a fractured, graveled solidification of the PCM.

[0010] The present application further describes one embodiment of the invention that may take the form of pressure rated steam pipe or vessel that may be filled with PCM tube capsules. Three or more tubes may form a bundle to closely fit into the larger steam pipe. The tube-capsule bundle may fill the entire length of the steam pipe. The steam pipe may have one or multitude of liquid water ports and one or multitude of steam ports. The liquid port may be used for feedwater inlet or condensate drain outlet. The steam port may be used for steam inlet or outlet. Multitude of horizontally oriented steam pipes (filled with PCM capsule tubes) may be stacked on each other to fill the thermal storage container space. The liquid water ports may be connected to a common water header and the steam ports may be connected to a common steam header. The container housing the steam pipes and encapsulated PCM, is insulated to minimize heat losses. To increase the thermal storage capacity and the thermal conductivity, the space between the steam pipes may be filled with thermal oil during the commissioning of the installation.

[0011] The present application further describes the flow of steam in a charging and discharging operation mode. In charging mode the steam flows from the heat source—that may be a solar thermal steam generator—to the multitude of steam pipes (PCM container vessels) of the storage container. The steam flows through the space left between the tubular capsules, heating and melting the PCM in the tubes and thereby storing the thermal energy. As the latent heat of the steam transfers into the capsules, the condensed steam drains out of the steam vessels through the liquid port. In discharging operation mode, the feedwater is pumped through the liquid ports of the steam pipes and flows through the hollow space between the capsules. The hot molten PCM inside the tube-capsules, heats the feedwater and the evaporated steam leaves the steam pipes at the steam ports.

[0012] These and other features of the present application will become apparent to one of ordinary skill in the art upon review of the following detailed description when taken in conjunction with the several drawings and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1** shows the arrangement of the tube bundle of encapsulated phase change material in the pressurized steam-pipe (or capsule vessel). It also depicts the general shape of the helically grooved tube-capsules. These sealed tube-capsules contain the phase changing materials that store most of the thermal energy. It also shows the steam inlet/outlet port and condensate-outlet/feedwater-inlet port of the capsule vessel.

[0014] FIG. **2** shows the vertical cross sections of the Thermal Storage Container Unit. The outer (envelope) walls of the container are thermally insulated and the capsule vessel pipes are stacked up on each other to fill up the volume of the container.

[0015] FIGS. **3** (*a, b*) depict the flow diagram of the thermal storage unit. **3***a* shows the flow of steam-in and condensate-out in thermal charging mode. **3***b* shows the flow of feedwater-in and stem-out in thermal discharging mode. These drawings also show the control methods used in both operating modes.

[0016] FIGS. **4** (*a, b, c, d*) show the flow diagrams of some solar steam generation systems. FIG. **4***a* shows the steam loop in a generic solar steam process with the thermal storage system. FIG. **4***b* shows the steam loop with designated pre-heater-evaporator and superheater storage unit. FIG. **4***c* shows the steam/water loops of solar steam power generation process and the duty of the thermal storage. FIG. **4***d* depicts the loops of integrated power generation and water desalination process with the thermal storage system.

[0017] FIGS. **5** (*a, b, c, d*) show the cross sections of some of the PCM tube capsules. FIG. **5***a* shows the cross section of a 4 groove-tube without fins. FIG. **5***b* shows a similar 4-grove helically extruded wall tube, FIG. **5***c* shows a 4-grove tube with a 4-fin insert. FIG. **5***d* shows a rounded triangular profile tube.

DETAILED DESCRIPTION

[0018] Referring now to the drawings, in which like numerals indicate like elements throughout the several views, FIG. **1** depicts one embodiment of the helically grooved tube-capsules **104**. The capsules may be formed from a thin wall metal tube by enrolling helical grooves along the length of the tubes or by extrusion or other metal forming procedure. The grooved tubes may resemble the rifled barrel of guns. The ratio of the length to the diameter of the tube is from 6 to 300. The angle **107** between the tangent of the helix of the grooves and the axis of the tube may be from 0 to 30 degrees. The shape of the profile of the groove **105** is curved that may be circular or oval. The number of the grooves on the tube may be from 2 to 12. The ratio of the depth of the groove to the diameter of the tube may be from 0.02 to 0.4. The purpose of the grooving is to provide radial and axial flexibility of the tube wall to accommodate the thermal expansion of the encapsulated phase change material. At the manufacturing process one end of the tube may be seal-welded **108** and filled with a molten phase change material **106** and seal-welded **108** on the other end to complete the encapsulation. The phase change material may have a melting temperature from 250 to 600 degrees Fahrenheit and it is generally referred as molten salt. It may or may not have eutectic properties and it may be a mixture of two or more compounds like Sodium Nitrate, Sodium Nitrite, Sodium Chlorate, Potassium Nitrate, Sodium Hydroxide, Potassium Bi-fluoride, Sodium Peroxide, Calcium Nitrate, etc.

[0019] FIG. **1** also shows the arrangement of the tube bundle of encapsulated phase change material in the pressure rated steam-pipe or capsule vessel **101**. The sealed tube-capsules form a bundle to fill the inside of the steam pipe or vessel. The free space between the tube capsules is available for passage of steam flow and collection of condensate. The enclosed steam vessel has one or multiple steam inlet and outlet ports **103** and one or multitude of condensate-outlet/feedwater-inlet ports **102**. The liquid side ports **102** have condensate collection and feedwater distribution nozzles **109**.

[0020] FIG. **2** shows the cross section of one embodiment of the thermal storage module or container. A plurality of horizontally oriented steam pipes or pressure vessels that are filled with PCM capsule tubes **202**, may be stacked on each other to fill the thermal storage container space. The battery of steam vessels in the module are connected through a steam side and water side distribution system. The walls of the container **203** provide the structural integrity and thermal insulation of the enclosure. The space between the steam pipes may be utilized in two ways: One alternative is that additional PCM capsule tubes **204** may be placed to increase the mass-to-volume ratio. The profile of the tube may be a rounded triangle **204** that fits the space in-between three adjacent steam pipes. The other alternative is that the space between the steam pipes may be filled with thermal oil during the commissioning of the installation to increase the thermal storage capacity and the efficiency of heat transfer between the steam pipes.

[0021] FIG. 3*a* depicts the process flow of the thermal storage module in thermal charging mode. The superheated or saturated steam supplied by the steam generator flows through the steam header **303** and steam distributors (or risers) **313** to the battery of horizontal steam vessels **301**. The steam flow **309** passes through the steam vessel **301** and heats up the relatively cold PCM capsule tubes inside the vessels. The phase change material is heated and in the process undergoes gradual melting in the tubes and thus the heat is stored in the PCM capsules. The condensed steam (liquid condensate) is drained through the liquid risers/distributors **312** and steam trap **314** into the condensate receiver **304**. The liquid level in the receiver is controlled by a level control loop and valve **310** and the temperature of the condensate output is controlled by a temperature control loop and control valve **311**. The main condensate supply pump **305** may or may not supply the condensate **302** which may or may not be blended with the condensate from the receiver and the condensate flow is forwarded by a feedwater pump **306** to the steam generator.

[0022] FIG. 3*b* depicts the process flow of the thermal storage module in thermal discharging mode. In general the flow pattern of the charging mode reverses in the discharging mode. The condensate **302** from the main steam load is supplied by the condensate pump **305** and is pumped through valve **310** and the completely filled receiver vessel **304**. The liquid condensate enters into the battery of pressure vessels through the distribution system **312**. The heat stored in the PCM tubes heats and evaporates the liquid and the generated steam leaves the battery and it is collected thru the collection risers **313** to the steam header **303**. The pressure of the generated steam is controlled by control loop and valve **308**. The temperature of the steam is controlled by a de-superheater loop and valve **315**.

[0023] FIG. **4***a* depicts the typical use of the present application in a generic solar steam process. In the charging mode the steam is supplied by the solar steam generator **401** to the steam load (steam consuming process) **402** and to the thermal storage system **403**. The condensate is collected by the condensate line **404** and pumped by condensate pump **407**. The leaving condensate **409** from the thermal storage is mixed with process condensate and the feedwater **406** is pumped by the feedwater pump **408** to the solar steam generator **401**. The loop connecting the solar steam generator **401** and the thermal storage system **403** is referred to as the primary loop **411**. The loop connecting the steam process **402** and the thermal storage system **403** is referred to as the secondary loop **412**. In the discharging mode the direction of the flow through the thermal storage **403** reverses: condensate **430** is pumped through the thermal storage and steam **431** is supplied to the main steam supply line **405**.

[0024] FIG. **4***b* depicts a specialized configuration of the present application whereby the duties of the thermal storage system is split into a designated preheating and evaporation system **403** and a designated superheating **422** system. In the discharging cycle, saturated steam is generated in the designated evaporator block and the saturated steam flows to the superheater block for additional heating. The benefit of such configuration is that the composition of the PCM material can be optimized for the two different functions and thereby cost savings and/or efficiency improvement can be achieved.

[0025] FIG. **4***c* depicts the typical use of the present application in a generic power generation system. The function of the thermal storage system is identical to the one described and depicted in FIGS. **4***a* and **4***b*. The main components of the power generation system are the steam turbine generator **413**, the steam condenser, and the condenser cooling water system **415** through **418**.

[0026] FIG. **4***d* shows the typical use of present application in an integrated solar desalination and power generation system. The low-pressure exhaust steam of the steam turbine is used as heating source of the desalination system **420**. Seawater **447** is supplied to the desalination system by the seawater pump **446** and cooling water **448** is discharged to the sea along with concentrated brine **424**. Distilled water **421** is supplied for users by the distilled water pump **422**.

[0027] FIGS. **5** (*a, b, c, d*) show the cross sectional configurations of some of the PCM tube capsules. One of the disadvantages of the high temperature PCMs is that they have poor heat transfer properties. This limitation can result in reduced storage heat rate or in other words reduce the ability of the system to quickly capture-store or release the heat. To promote and improve the heat transfer in the storage material, heat transfer fins may be applied inside the tube. These fins extend in radial direction from circumference to the center of the tube and extend in axial direction along the length of the tube. While a plurality of grooves and fins may be formed the number of grooves and fins shown in FIG. **5** have a four groove and fin design. FIG. **5***a* shows the cross section of a tube without fins. FIG. **5***b* shows a similar 4-grove helically extruded wall tube where the fins (**501**) are integral part of the wall of the tube. FIG. **5***c* shows a 4-grove tube with a 4-fin insert. The profile of the extruded insert (**502**) has a "T" shape where the top portion of "T" is pressed against the inside wall of the tube during the grooving process. FIG. **5***d* shows the profile of the tube that may be used to fill the space between the pressurized steam pipes as it is described on FIG. **2**.

I claim:

1. A helically or axially grooved metal tube capsule wherein the ratio of the length to the diameter of the tube is from 6 to 300 and wherein the capsule may be formed from a thin wall tube and wherein the helical grooving along the length of the tubes may be formed by rolling or other metal-forming procedure and wherein the grooved tubes may resemble the rifled barrel of guns and wherein the profile of the groove is curved to facilitate radial and axial flexibility of the tube-capsule and wherein the number of the grooves on the tube may be from 2 to 12 and wherein the ratio of the depth of the groove to the diameter of the tube may be from 0.02 to 0.4 and wherein the angle between the tangent of the helix of the grooves and the axis of the tube may be from 0 to 30 degrees.

2. The helically or axially grooved metal tube capsule of claim **1** wherein the inside of the tube has heat transfer fins to promote the heat transfer in radial direction and wherein the fins extend in radial direction from circumference toward the center of the tube and extend in axial direction along the length of the tube and wherein the fins may be integral part of the wall manufactured by extrusion or similar process along with the wall of the tube or the fins may be inserted separately in the tube and pressed against the inside wall during the plastic deformation process of grooving.

3. The helically or axially grooved metal tube capsule of claim **1** wherein the tube is filled with a molten phase change material and hermetically sealed to complete the encapsulation and wherein the phase change material may or may not have eutectic properties and it may be a mixture of two or more molten-salt compounds such as Sodium Nitrate, Sodium Nitrite, Sodium Chlorate, Potassium Nitrate, Sodium Hydroxide, Potassium Bi-fluoride, Sodium Peroxide, Calcium Nitrate, etc.

4. The bundle of sealed PCM tube capsules of claim **1** filling a pressure rated steam-pipe or vessel wherein the free space between the grooved tube capsules is available for steam and condensate flow and wherein steam pipe or vessel has one or multiple steam ports and one or multitude of condensate/feedwater ports.

5. The multitude of pressure rated steam-pipes or vessels of claim **3** connected to form a battery wherein the steam pipes of the battery are connected through a common liquid-side distribution header system and a common steam-side distribution header system.

5. The battery of steam-pipes or vessels of claim **4** stacked up to fill a block-shaped container space wherein the battery is housed in a thermally insulated enclosure designed for structural integrity and wherein the battery enclosed in the housing forms one module of the high temperature thermal storage system.

* * * * *