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(54) Title: APPARATUSES AND METHODS FOR THERMAL ENERGY STORAGE IN A DIRECT STEAM POWER PLANT

(57) Abstract: A thermal energy storage system, comprising: at least one pipe; at least one phase change material capsule; at least one reservoir containing a heat transfer fluid; and, a controller programmed to switch heat transfer fluid flow delivery between the at least one pipe and the at least one phase change material; wherein the same at least one pipe provides heat exchange by initially flowing steam therethrough during a charge cycle and water during a discharge cycle.

APPARATUSES AND METHODS FOR THERMAL ENERGY STORAGE IN A DIRECT STEAM POWER PLANT

RELATED APPLICATIONS

This application claims priority under PCT Article 8(1) from U.S. Pat. Appln. No. 61/424,709 filed on December 20, 2010, the disclosure of which is incorporated herein by reference.

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates generally to thermal energy storage, and particularly to providing apparatuses and methods for efficient and/or controlled charging and discharging of thermal energy.

Thermal storage is needed, for example, in solar thermal power plants in order to allow operation beyond sunlight hours, as well as to buffer against rapid fluctuations that can occur in available sunlight during a day with intermittent clouds. Providing reliable and dispatchable power to the grid is a major requirement for the success of solar thermal power technologies, and the addition of an effective thermal storage component can provide these capabilities. The technical requirements for effective storage include: high energy storage capacity, *e.g.*, enough for operation of the power plant during a period of typically 2, 4 or up to 8 hours; it should permit a high and stable rate of heat charging and discharging; it should have a minimum amount of heat losses; and/or it should have a minimum of thermodynamic loss, *i.e.*, the fluid temperature provided from the storage should be as close as possible to the fluid temperature that is provided during normal operation directly from solar heat.

Most solar thermal power plants use solar heat to evaporate water and superheat the steam at the operational conditions of a steam turbine, typically temperatures of 390°C -560°C, and pressures of 50 bar-150 bar. The most common thermal storage schemes for these solar plants use the sensible heat of liquids such as molten nitrate salts. Thermal storage charging is achieved by heating the storage liquid, either directly in the solar receiver, or in contact with another fluid that was heated in the solar receiver. The hot liquid is then stored in an insulated tank. For thermal energy discharge, the hot liquid passes through a heat exchanger that evaporates and superheats water, and the storage liquid is then stored in a "cold" tank waiting for the next charge cycle. However, most of the thermal energy is needed for the evaporation stage, which takes place at a nearly constant temperature (saturation temperature) that is determined by the operation pressure. For the typical range of pressures 50 bar-150 bar, the evaporation temperature is in the range of 250°C-350°C. The exchange of heat between the storage liquid at variable temperature and the evaporating water at constant temperature creates a significant thermodynamic inefficiency, which is typically described as "pinch point problem", "entropy generation", or "exergy destruction".

Phase Change Materials (PCM) can store and release energy at nearly constant temperature, and are therefore natural candidates for a thermal storage medium for water evaporation. Candidate materials are described in A. Hoshi, D. R. Mills, A. Bittar, and T. S. Saitoh, "Screening of high melting point phase change materials (PCM) in solar thermal concentrating technology based on CLFR," *Solar Energy,* vol. 79, pp. 332–339 2005, the disclosure of which is incorporated herein by reference. However, most of the candidate materials for the required temperature range (salts) have very low thermal conductivity and therefore the achievable rates of heat charging and discharging are too low. Other candidates (low melting temperature metals) have high thermal conductivity but also excessively high cost. Reviews of candidate PCM properties, costs and storage configurations are available, for example in the Hoshi article and in U. Herrmann and D. W. Kearney, "Survey of thermal energy storage for parabolic trough power plants," *Journal of Solar Energy Engineering,* vol. 124, pp. 145-152, 2002, the disclosure of which is incoporated herein by reference.

Several approaches to overcome the problem of low thermal conductivity have been suggested. The easiest approach based on conventional engineering practice is to add fins (extended surfaces). The steam tubes are equipped with external fins, and the spaces among the fins are filled with the PCM. These can be in various longitudinal or lateral fins similar to the conventional heat exchangers described in W.D. Steinmann and R. Tamme, "Latent Heat Storage for Solar Steam Systems" *Journal of Solar Energy Engineering,* vol. 130, pp. 011004-1 2008 and C. Guo and W. Zhang, "Numerical simulation and parametric study on new type of high temperature latent heat thermal energy storage system," *Energy Conversion and Management,* vol. 49, pp. 919–927, 2008, the disclosures of which are incorporated herein by reference. These fins improve somewhat the heat transfer but usually not enough. In any reasonable design that minimizes the mass of the fins relative to the PCM, the characteristic length scale for conduction through the PCM is still too large. Therefore the low thermal conductivity of the PCM still dominates the energy transport.

Another approach that had achieved some success in low-temperature applications (storing heat below 100°C) is a composite storage medium, incorporating a PCM within a highly conductive porous solid matrix. A steam/PCM heat exchanger is provided with steam tubes embedded in composite PCM medium. A typical method to produce the composite is creating the porous matrix from small particles having very high thermal conductivity (*e.g.*, expanded graphite), and infiltrating the liquid PCM into the matrix, such as described in J. Bacher, O. Öttinger, and M. Christ, "Latent heat storage material, latent heat storage unit containing the material, processes for producing the material and the unit and processes for using the material," US patent 7,235,301, 2007, the disclosure of which is incorporated herein by reference. The composite can increase the effective conductivity by up to two orders of magnitude relative to the pure PCM.

In low-temperature systems, the PCM within the porous matrix is typically paraffin or a salt hydrate. However, manufacturing of the composite with a salt suitable for higher temperature is not easy due to difficulties in wetting of the expanded graphite by the liquid salt. Some success was reported by cold mixing of the ingredients in solid powder form, compression, and then melting, see S. Pincemin, X. Py, R. Olives, M. Christ, and O. Oettinger, "Elaboration of Conductive Thermal Storage Composites Made of Phase Change Materials and Graphite for Solar Plant," *Journal of Solar Energy Engineering,* vol. 130, pp. 011005-1 2008, the disclosure of which is incorporated herein by reference. A composite with only 4% expanded graphite particles increased the effective conductivity by a factor of 5 relative to pure salt, see V. Morisson, M. Rady, E. Palomo, and E. Arquis, "Thermal energy storage systems for electricity production using solar energy direct steam generation technology," *Chemical Engineering and Processing,* vol. 47, pp. 499–507 2008, the disclosure of which is incorporated herein by reference. A similar approach incorporating a paraffin PCM within a mat of graphite fibers (50 μm diameter) with only 2% volume fraction of the fibers increased the conductivity by a factor of 6 relative to the pure PCM according to J. Fukai, M. Kanou, Y. Kodama, and O. Miyatake, "Thermal conductivity enhancement of energy storage media using carbon fibers" *Energy Conversion and Management,* vol. 41, pp. 1543-1556, 2000, the disclosure of which is incorporated herein by reference.

Such an improvement increases the rate of heat charging and discharging, but does not provide a full solution to the thermal conductivity limitation of the PCM. A longer-term storage requires a thicker layer of PCM around the steam tube, and even the improved thermal conductivity cannot avoid the development of temperature gradients through the thick layer, and the resulting thermodynamic inefficiency of the heat discharge.

Another approach described salt PCM encapsulated in long small-diameter cylindrical capsules, with the steam passing outside a bundle of capsules such as described in the Steinmann, et al. article. The main difficulty with this approach is that the entire large storage vessel must withstand the high steam pressure, leading to very high wall thickness of the vessel and very high cost. This approach therefore is not attractive.

Yet another approach proposed was heat storage from a high temperature air receiver using NaCl storage medium (melting point at 800°C) and a sodium liquid/vapor heat pipe as heat transfer mediator in R. Adinberg, A. Yogev, and D. Kaftori, "High temperature thermal energy storage," *Journal De Physique IV,* vol. 9, pp. 89-94, 1999, the disclosure of which is incorporated herein.

Storage with a mediating heat transfer fluid (HTF) was proposed for steam generation, using Zn/Sn alloy as the PCM, and an organic HTF as the mediating material in R. Adinberg, D. Zvegilsky, and M. Epstein, "Heat transfer efficient thermal energy storage for steam generation," *Energy Conversion and Management,* vol. 51, pp. 9-15, 2010 and as further detailed in R. Adinberg and M. Epstein, "Conception and design of a thermal energy storage system," in *5th IASME / WSEAS International Conference on Heat Transfer, Thermal Engineering and Environment (HTE'07)* Athens, 2007, the disclosures of which are incorporated herein by reference. The mediating HTF operates in a reflux or heat pipe mode, evaporating at the higher temperature side and condensing at the lower temperature side. The design in the Adinberg, et al. articles is far from isothermal, however, due to change in alloy composition as the Zn precipitates out of the liquid. Furthermore, heat transfer is driven by natural convection in the heat pipe, so there is no control over heat transfer rate, and the natural convection mechanism also requires two separate heat exchangers for charging and discharging.

It has been suggested that solar generated thermal energy can also be stored for providing steam for industrial processes. See Rainer Tamme, Thomas Bauer, Jochen Buschle, Doerte Laing, Hans Mueller-Steinhagen and Wolf-Dieter Steinmann, Latent heat storage above 120°C for applications in the industrial process heat sector and solar power generation, INTERNATIONAL JOURNAL OF ENERGY RESEARCH vol. 32 pp. 264-271, 2008.

SUMMARY OF THE INVENTION

An aspect of some exemplary embodiments of the invention relates to a system for thermal energy storage adapted to use the same heat exchange elements for both storing and discharging thermal energy utilizing both steam and water. In an embodiment of the invention, the system is provided with a chamber which includes at least a heat exchanger comprised of at least one pipe. Optionally, a bundle of pipes is used. Steam and/or liquid water flow through the pipes during charging and/or discharging and are in operative communication with water or steam reservoirs depending on which operation mode is being performed by the system, wherein in an embodiment of the invention steam is used for charging and water is used for discharging the thermal energy storage. In an embodiment of the invention, steam in the pipes during the charging cycle is derived from normal operation of the solar plant and water in the pipes which is turned into steam during discharge is utilized for operating the steam power portion of the plant from the stored thermal energy.

In an embodiment of the invention, the chamber is also provided with Phase Change Materials (PCM) which are used for storing thermal energy. In an embodiment of the invention, PCM are shaped such that one dimension is minimized for maximizing surface area of the PCM. For example, in some embodiments of the invention, the PCM are encapsulated in a thin material in the form of capsules, which are small in one dimension (*e.g.* thin). In an embodiment of the invention, a plurality of PCM capsules are used in a single sheet and/or array for retaining and discharging thermal energy.

In an embodiment of the invention, the chamber is provided with spray nozzles in operative communication with a reservoir. Optionally, the nozzles are located at the top of the chamber while the reservoir at the bottom of the chamber is at least partly refilled by gravity. In some embodiments of the invention, a HTF is used in the chamber to transfer thermal energy from the pipes to the PCM or in reverse, depending on the operation mode, whereby the HTF is conveyed to the spray nozzles from the reservoir and is recollected in the reservoir after a charging or discharging cycle.

In an embodiment of the invention, the at least one pipe and its paired PCM capsule (or array) form a set of heat exchanging and/or storage elements. In some embodiments of the invention, a plurality of these sets is provided to the thermal energy storage system for storing more energy than just one set alone. Optionally, at least one set is provided with a collection tray to collect liquid HTF from the set. In some embodiments of the invention, the system is provided with a liquid HTF return piping system to return HTF from the at least one collection tray to the reservoir. Optionally, a pump is used to supply at least some of the spray nozzles in the system with HTF from the reservoir. Optionally, liquid HTF being collected from a set is returned directly to the spray nozzles, skipping the reservoir. In some embodiments of the invention, operation of the valves and spray nozzles is controlled by a programmed controller, whether for deactivating one or more sets completely or for controlling charging or discharging rates of one or more sets.

In some embodiments of the invention, the thermal energy storage system charges and/or discharges thermal energy in a substantially isothermal process.

In an embodiment of the invention, the heat transfer rate is substantially controlled by varying the flow rate of the liquid HTF into the spray nozzles in combination with pipes and PCM capsules, rather than relying on natural convection between heat transport tubes and PCM.

In an embodiment of the invention, charging and/or discharging is used for providing steam for industrial processes.

An aspect of some exemplary embodiments of the invention relates to a method of storing and discharging thermal energy in a thermal energy storage system using one set of heat exchange elements. Steam is generated in any one of manners known in the art, for example using solar heat to evaporate water to superheated levels. This steam is introduced into pipes in a thermal storage chamber which causes evaporation of an HTF liquid being sprayed on the pipes, absorbing heat in the process. In an embodiment of the invention, the HTF vapor condenses on PCM capsules located in the chamber transferring the heat to the PCM capsules for storage.

In an embodiment of the invention, discharging is carried out by contacting liquid HTF with the previously heated PCM capsules, causing the HTF to evaporate. The HTF vapor contacts the pipes, through which flows liquid water instead of steam, condensing and transferring heat to the water, which in turn causes the water in the pipes to evaporate into steam to be used downstream for the purposes of electricity generation, in an embodiment of the invention.

In an embodiment of the invention, the method of storing and discharging thermal energy in a thermal energy storage system using one set of heat exchange elements and specifically selected PCM is substantially isothermal.

In an embodiment of the invention, the heat transfer rate is substantially controlled, for example by varying the flow rate of the liquid HTF into the spray nozzles in combination with pipes and PCM capsules, rather than relying on natural convection.

An aspect of some exemplary embodiments of the invention relates to a storage capacity expandable system storing thermal energy in PCM without regard for heat pipes and/or heat pipe length. In an embodiment of the invention, a chamber is provided with a heat exchanger and at least one separate PCM capsule. In an embodiment of the invention, the PCM is arranged in an array of PCM capsules. Optionally, the PCM array is comprised of capsules of PCM optimized to increase surface area of the capsules. In an embodiment of the invention, the heat exchanger comprises at least one steam or water containing pipe. In an embodiment of the invention, evaporated HTF is used in the chamber to transfer heat by movement of the evaporated HTF from the heat exchanger to the PCM or vice versa by, depending on whether charging or discharging is taking place. In an embodiment of the invention, a controller programmed to perform at least one of delivering heat transfer fluid to the exterior of the at least one pipe from the reservoir and controlling fluid flow within the at least one pipe based on the size of the array is provided to the system. Optionally, the system is provided with an auxiliary compartment containing heat transfer fluid for introducing to and withdrawing from the chamber to alter the pressure within the chamber.

An aspect of some exemplary embodiments of the invention relates to a method for controlling the heat transfer rate in a thermal energy storage system. In an embodiment of the invention, heat transfer is accomplished by evaporating and condensing HTF on at least one pipe and/or on at least one PCM capsule. In some embodiments of the invention, by increasing or decreasing the amount of HTF being applied to the at least one pipe or the PCM array, the amount of evaporation and/or condensation in the system can be controlled, thereby controlling the heat transfer rate.

There is thus provided in accordance with an exemplary embodiment of the invention, a thermal energy storage system, comprising: at least one pipe; at least one phase change material element; at least one reservoir containing a heat transfer fluid; and, a controller programmed to switch heat transfer fluid flow delivery between the at least one pipe and the at least one phase change material; wherein the same at least one pipe provides heat exchange by initially flowing steam therethrough during a charge cycle and water during a discharge cycle.

In an embodiment of the invention, the at least one spray nozzle is in operative and controllable communication with the reservoir directed at each of the at least one pipe and the at least one phase change material capsule.

In an embodiment of the invention, the phase change material is located in at least one capsule.

In an embodiment of the invention, a plurality of phase change material capsules are located in an array.

In an embodiment of the invention, at least one spray nozzle is directed at the entire array.

In an embodiment of the invention, the at least one phase change material is a salt. In an embodiment of the invention, the at least one phase change material is chosen from the group of sodium nitrate, potassium nitrate, and a salt mixture containing at least one of sodium nitrate or potassium nitrate.

In an embodiment of the invention, the at least one phase change material is a metal.

In an embodiment of the invention, the heat transfer fluid is organic.

In an embodiment of the invention, the heat transfer fluid returns to the reservoir at least partially by gravity.

In an embodiment of the invention, the system further comprises a pump to pump heat transfer fluid from the reservoir to at least one spray nozzle.

In an embodiment of the invention, the controller is programmed to vary the flow rate of the heat transfer fluid to the at least one spray nozzle.

In an embodiment of the invention, the phase change material capsule is formed from a metal or metal alloy.

In an embodiment of the invention, the system further comprises an auxiliary compartment containing heat transfer fluid for introducing to and withdrawing from the system to alter the pressure within the system.

In an embodiment of the invention, the at least one pipe and the at least one phase change material capsule forms a set of heat storage elements and wherein the system is comprised of a plurality of sets.

In an embodiment of the invention, the system further comprises at least one collection tray associated with at least one set.

In an embodiment of the invention, the system further comprises a liquid HTF return piping system in liquid communication with the at least one collection tray and the at least one reservoir.

In an embodiment of the invention, the system further comprises a controller programmed to activate charging and discharging of each set in the plurality of sets.

In an embodiment of the invention, the system further comprises an auxiliary compartment containing heat transfer fluid for introducing to and withdrawing from the system to alter the pressure within the system.

In an embodiment of the invention, the system further comprises a system volume changing mechanism.

There is further provided in accordance with an exemplary embodiment of the invention, a method for storing thermal energy using one set of heat exchange elements, comprising: introducing steam into at least one pipe; delivering a heat transfer fluid in liquid form to the exterior of the at least one pipe; evaporating heat transfer fluid upon contact with the at least one pipe, absorbing heat by the heat transfer fluid in the process; condensing the heat transfer fluid vapor on at least one phase change material, transferring heat to the at least one phase change material from the heat transfer fluid; and, returning the heat transfer fluid liquid to a reservoir.

In an embodiment of the invention, the heat transfer fluid liquid is delivered to the at least one pipe by at least one spray nozzle.

In an embodiment of the invention, the steam saturation temperature is at least 100°C. In some embodiments of the invention, the steam saturation temperature is 250°C -350°C.

In some embodiments of the invention, the method further comprises discharging the stored thermal energy by introducing a water flow into the at least one pipe, delivering heat transfer fluid in liquid form to at least one thermally charged phase change material; evaporating heat transfer fluid upon contact with the at least one phase change material, absorbing heat in the process; condensing the heat transfer fluid vapor on the at least one water containing pipe, transferring heat to water in the pipe and evaporating it creating steam; and, returning the heat transfer fluid liquid to the reservoir. In an embodiment of the invention, delivering the heat transfer fluid in liquid form to at least one thermally charged phase change material is accomplished using at least one spray nozzle. In an embodiment of the invention, the steam saturation temperature is at least 100°C. In an embodiment of the invention, the steam saturation temperature is 250°C -350°C.

In an embodiment of the invention, the at least one phase change material is in a capsule.

There is further provided in accordance with an exemplary embodiment of the invention, a method for storing and discharging thermal energy using one set of heat exchange elements containing steam for charging and water for discharging, comprising: introducing steam into at least one pipe; delivering a heat transfer fluid in liquid form to the exterior of the at least one pipe; evaporating heat transfer fluid upon contact with the at least one pipe, absorbing heat by the heat transfer fluid in the process; condensing the heat transfer fluid vapor on at least one phase change material, transferring heat to the at least one phase change material from the heat transfer fluid, thereby storing the thermal energy; returning the heat transfer fluid liquid to a reservoir; introducing a water flow into the at least one pipe; delivering heat transfer fluid in liquid form to at least one thermally charged phase change material; evaporating heat transfer fluid upon contact with the at least one phase change material, absorbing heat in the process and thereby discharging the stored thermal energy; condensing the heat transfer fluid vapor on the at least one water containing pipe, transferring heat to water in the pipe and evaporating it creating steam; and, returning the heat transfer fluid liquid to the reservoir.

In an embodiment of the invention, the heat transfer fluid in liquid form is delivered to the at least one pipe and the at least one phase change material by at least one spray nozzle.

In an embodiment of the invention, the steam saturation temperature is at least 100°C. In some embodiments of the invention, the steam saturation temperature is 250°C -350°C.

In an embodiment of the invention, the at least one phase change material is in a capsule.

There is further provided in accordance with an exemplary embodiment of the invention, a storage capacity expandable thermal energy storage system, comprising: a chamber; at least one pipe in the chamber; an expandable phase change material array in the chamber separate from the at least one pipe; a reservoir containing a heat transfer fluid in fluid communication with the chamber; a controller programmed to perform at least one of delivering heat transfer fluid to the exterior of the at least one pipe from the reservoir and controlling fluid flow within the at least one pipe based on the size of the array.

In an embodiment of the invention, the system further comprises an auxiliary compartment containing heat transfer fluid for introducing to and withdrawing from the chamber to alter the pressure within the chamber.

There is further provided in accordance with an exemplary embodiment of the invention, a method for controlling the heat transfer rate in a thermal energy storage system comprising: evaporating heat transfer fluid on at least one of a pipe or phase change material array; condensing the heat transfer fluid on at least one of a pipe or phase change material array; altering the flow of a heat transfer fluid within the thermal energy storage system to either increase or decrease the rate of evaporating and condensing, thereby controlling the heat transfer rate in the system.

Unless otherwise defined, all technical and/or scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which the invention pertains. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of embodiments of the invention, exemplary methods and/or materials are described below. In case of conflict, the patent specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and are not intended to be necessarily limiting.

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the invention are herein described, by way of example only, with reference to the accompanying drawings. With specific reference now to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of embodiments of the invention. The figures are generally not shown to scale and any measurements are only meant to be exemplary and not limiting. In this regard, the description taken with the drawings makes apparent to those skilled in the art how embodiments of the invention may be practiced.

In the drawings:

FIG. 1 is a block diagram showing some components of a thermal energy storage system, in accordance with an exemplary embodiment of the invention;

FIG. 2 is a schematic drawing of a thermal energy storage system with only one set of heat exchange elements, in accordance with an exemplary embodiment of the invention; and,

FIG. 3 is a flowchart of a method for storing thermal energy using one set of heat exchange elements, in accordance with an exemplary embodiment of the invention;

FIG. 4 is a flowchart of a method for discharging thermal energy using one set of heat exchange elements, in accordance with an exemplary embodiment of the invention; and,

FIG. 5 is a schematic drawing of a thermal energy storage system with an array of individually controllable sets of pipes and PCM capsules, in accordance with an exemplary embodiment of the invention.

DESCRIPTION OF EMBODIMENTS OF THE INVENTION

Before explaining any embodiments of the invention in detail, it is to be understood that the invention is not necessarily limited in its application to the details of construction and the arrangement of the components and/or methods set forth in the following description and/or illustrated in the drawings. The invention is capable of other embodiments or of being practiced or carried out in various ways.

Referring now to the drawings, FIG. 1 is a block diagram showing some components of a thermal energy storage system 100, in accordance with an exemplary embodiment of the invention. A controller 102 is provided in some embodiments of the invention to control various performance aspects of the thermal energy storage system 100. In some embodiments of the invention, the controller 102 is configured to regulate flow of steam and/or water in at least one pipe 202 (described in more detail below), for example to match flow rate through the at least one pipe 202 with the evaporation and/or condensation rate of the steam and/or water therein as a result of the charging and/or discharging processes. In an embodiment of the invention, controller 102 is also programmed to control whatever pumps and/or valves as are necessary for the operation of the thermal energy storage system 100. For example, as will be explained in more detail below with respect to FIGS. 2-4, depending on whether the system 100 is charging or discharging, the flow of at least one fluid to a storage chamber 200 (described in more detail below) is changed.

At least one sensor 108 is used for detecting various operating conditions in the thermal energy storage system 100, for example detecting temperature and/or pressure within the storage chamber 200 and/or of various elements located within the chamber 200, and/or detecting flow rate of steam and/or water within at least one pipe 202, in an embodiment of the invention. It should be understood that, in an embodiment of the invention, a plurality of sensors 108 are optionally used for monitoring conditions in any of the components of the thermal energy storage system 100 described herein and that based on sensed information, the controller 102 will modify operation of the system 100 to match acceptable performance characteristics.

FIG. 2 is a schematic drawing of a thermal energy storage system 100 with only one set of heat exchange elements or pipes 202, in accordance with an exemplary embodiment of the invention. The chamber 200 of thermal energy storage system 100 comprises one region with at least one, possibly a bundle of pipes 202, and a second region with at least one, possibly an array of PCM elements 204. It should be noted that in an exemplary embodiment of the invention, the PCM array 204 is located in a separate region of the chamber 200 from the pipes 202, without physical contact with the pipes 202.

In an embodiment of the invention, high PCM surface area for convection heat transfer is achieved by encapsulating the PCM in small capsules that may have any shape that produces a small thickness of the PCM layer, such as cylinders, spheres, and/or rectangular boxes with one small dimension. Optionally, the PCM are generally linear in shape, like wires. In an embodiment of the invention, a HTF liquid fills the bottom part of the vessel in a reservoir 206 while a vapor of the HTF fills the rest of the vessel.

Many of these small capsules may be integrally formed within a single mechanical unit, for example by forming a large sheet with many small indentations, filling the indentations with the PCM, and then sealing the filled spaces with a second thin metal sheet to form a plurality of small capsules within a single unit. The PCM may be a salt or mixture of salts, and/or a metal or alloy of metals, selected according to the desired melting temperature and latent heat of solid-to-liquid phase change. For example, the PCM can be $NaNO_3$, with melting point of 406°C, or KNO_3 with a melting point of 334°C, or a mixture thereof with a melting point that varies with the composition of the mixture (relevant for state of the art power plants). In some embodiments of the invention, the PCM is a salt mixture containing $NaNO_3$ and/or KNO_3. The steam/water charge and discharge temperatures can then be approximately 408°C and 404°C, respectively, in an embodiment of the invention. Optionally, the PCM is a metal instead of a salt, for example tin, lead or zinc.

The amount of PCM, and therefore the amount of heat stored, in the Adinberg, et al. design (discussed in the Background section) is limited. In order to be effective, the length of the vertical tubes inside the PCM section of the Adinberg, et al. design cannot be very large or the passive flow of the HTF will be restricted. However, using the exemplary embodiment of the invention shown and described with respect to FIG. 2, it is possible to add PCM capsules to the array without substantial limitation, as long as liquid HTF is delivered in a sufficient amount and adequately dispersed amongst the PCM array to effectively carryout the discharge cycle. In an embodiment of the invention, the amount of HTF used in the system 100, and the corresponding size of reservoir 206, depends on the size of the PCM array 204 and/or the number of pipes 202 being used. Optionally, system 100 is configured with at least one of scalable pipe 202 sizes and/or number, PCM array 204 and/or reservoir 206. In some embodiments of the invention, controller 102 is programmed to perform at least one of delivering heat transfer fluid to the exterior of the at least one pipe from the reservoir and controlling fluid flow within the at least one pipe based on the size of the array.

The encapsulating material may be a metal, such as stainless steel, chosen for compatibility with the PCM, in an embodiment of the invention. Optionally, the encapsulating material is another metal such as copper or nickel, or even a specially selected alloy of metals. In some embodiments of the invention, the encapsulation material is also selected because of its ability to be thin enough to be flexible, so that any change in the PCM volume during phase change can be accommodated by elastic deformation of the capsule wall, without the need to leave a vacant bubble inside the capsule, but strong enough to handle the stresses of the repeated elastic deformation. The encapsulating material is also chosen for its operability in a high temperature environment, up to at least a few hundred degrees C for example.

A pump and valve system 106 is optionally provided to withdraw HTF liquid from the bottom or reservoir 206 of the chamber 200 and convey the liquid through a system of pumps and valves (valves are not shown in FIG. 2 and it should be understood that pipes are also used to provide fluid communication between the reservoir 206, pumps, valves and the chamber 200) to the exterior of pipes 202 and/or the PCM array 204. In an embodiment of the invention, spray nozzles 208, 210 are located above the pipes 202 and above the PCM capsules 204, respectively.

The HTF is optionally chosen from the group of commercially available organic Heat Transfer Fluids, such as Dowtherm A (made by The Dow Chemical Company). The HTF should have an evaporation temperature that matches the needed range of storage temperatures. For example, Dowtherm A can provide a phase change temperature between 255°C and 355°C, by changing the pressure in the chamber 200 between 0.97 bar and 5.8 bar, respectively. For other storage applications, for example steam generation for industrial processes, HTFs with different properties are optionally used, for example, having lower phase change temperatures and/or a broader range of phase change temperatures.

In an embodiment of the invention, the chamber 200 is optionally provided with auxiliary compartment 110 allowing liquid from the chamber 200 to be withdrawn and returned, thereby changing the pressure in the chamber 200 between the charge and discharge modes, creating the appropriate temperature difference between the HTF, the pipes 202, and the PCM capsules 204. Additionally, alternatively, and/or optionally, a mechanism to change the volume of the compartment (e.g. a large piston) is used to create at least a portion of the change in pressure.

FIG. 3 is a flowchart of a method for storing thermal energy using one set of heat exchange elements or pipes 202, in accordance with an exemplary embodiment of the invention. When charging (300) the storage, a steam flow is introduced (302) into the pipes 202, in an embodiment of the invention. In some embodiments, the steam is generated using an external process, for example using solar heat to evaporate water, typically at saturation temperatures of 250°C-350°C, corresponding to pressures of about 50 bar-150 bar.

The pump delivers (304) the HTF liquid to the exterior of pipes 202, for example through spray nozzles 208 above the pipes 202, in an embodiment of the invention. The liquid evaporates (306) on contact with the steam filled pipes 202, absorbing heat in the process. The vapor condenses (308) at the PCM capsules 204, which are at slightly lower temperatures than the vapor, transferring heat to the PCM capsules 204, and the liquid HTF after condensation returns (310) to the reservoir 206, by gravity in some embodiments of the invention.

FIG. 4 is a flowchart of a method for storing thermal energy using one set of heat exchange elements or pipes 202, which is the same set used for storing the thermal energy, in accordance with an exemplary embodiment of the invention. When discharging (400) the energy storage system 100, a compressed water flow is introduced (402) to the pipes 202 at the saturation temperature, in an embodiment of the invention. The pump delivers (404) the liquid HTF the exterior of the PCM array 204, for example through the spray nozzles 210 above the PCM capsules 204, while the HTF evaporates (406) at the PCM capsules 204, absorbing the stored heat in the process. The vapor condenses (408) at the water-filled pipes 202, which are at slightly lower temperatures than the vapor, transferring heat to the water and causing it to evaporate in the pipes 202. The liquid HTF returns (410) to the reservoir 206, optionally by gravity.

It should be noted that during charging, steam continuously enters the at least one pipe 202 and gradually condenses such that at every position there is a mixture of vapor and liquid in varying proportions, and 100% liquid water leaves at the exit end of the at least one pipe 202. The reverse occurs for discharging as the liquid gradually evaporates.

In some embodiments of the invention, controller 102 and/or a control system is used to switch which nozzles are being used depending on whether the system is charging or discharging. Additionally, and/or optionally, the control system is used to alter HTF flow for setting a desired heat transfer rate, for example by restricting or increasing flow through valves. By altering the amount of HTF being applied to the at least one pipe 202 or the PCM array 204, the amount of evaporation and/or condensation occurring in the system 100 can be controlled, thereby controlling the heat transfer rate. It should be understood that the control system is configured to control any number of valves and pumps in the pump and valve system 106 as may be necessary to accomplish the switching and/or altering of HTF flow.

Using the exemplary embodiments described with respect to FIGS. 1, 2 and 3, it is possible to achieve more isothermal charging and discharging over some of the references discussed in the background section. Basically, the temperature variations during storage charging and discharging are caused by two distinct factors. The first factor is the variation of the temperature of the PCM itself during phase change. In an alloy of metals such as described in the Adinberg, et al. publications, the selective precipitation leads to a large variation that can reach 10's of degrees C. In a pure PCM (*i.e.* single material, not alloy or mixture) the phase change can be done with very little variation, possibly 2-4 degrees from full liquid to full solid. This is nearly isothermal. Therefore, a single material PCM could be chosen to be used in capsules 204 in the inventive thermal energy storage system described in FIG. 2.

The second factor occurs when using a PCM with low thermal conductivity such as salt or mix of salts. Charging or Discharging of thermal energy is achieved via thermal conduction into the bulk of the PCM. Due to the low thermal conductivity, a temperature gradient develops in the direction into the material. During charging, the temperature of the entering steam should be about 10-20 degrees higher than the temperature of the bulk PCM, to drive the heat flux into the PCM. During discharge, the temperature of the entering water (to be evaporated) should be 10-20 degrees lower than the temperature of the PCM, to create the reverse gradient for heat extraction. So discharging can be at a temperature 20-40 degrees lower than charging.

However, in the exemplary embodiments described herein with respect to FIG. 2 the thermal resistance of conduction is reduced so that the temperature differences needed to drive the heat transfer can be much smaller, for example in the range of 2-3 degrees C. So the difference between charging and discharging thermal energy can be 4-6 degrees C total, which is much closer to isothermal than 20-40 degrees C as described in the background references.

Furthermore, power plants sometimes operate in part load, when there is less demand from the grid. Sometimes the power plant is offline when there is no demand. In such cases it is sometimes desirable to minimize the heat transfer from the PCM to the surroundings, which is difficult to do when the heat transfer system relies on natural convection such as described in the background references, particularly Adinberg, et al. In contrast, in exemplary embodiments of the invention, such as those described in FIG. 2, heat transfer is substantially controlled by reducing or stopping the flow of liquid HTF from the reservoir, reducing thermal energy losses during down times for the power plant.

In an embodiment of the invention, charging and/or discharging is used for providing steam for industrial processes, possibly instead of providing steam for power production. The storage concept and the operation of the storage charge and discharge is the same as described herein, in some embodiments of the invention. For typical industrial steam applications, however, the desirable saturation temperature is approximately 100°C and above for typical industrial processes corresponding to 1 bar of pressure.

Referring to FIG. 5, a schematic drawing of a thermal energy storage system 500 with an array of individually controllable sets of heat exchange and/or storage elements is shown, in accordance with an exemplary embodiment of the invention. In an embodiment of the invention, thermal energy storage system 500 is comprised of a plurality of storage elements 100, as described with respect to FIG. 2, with optional modifications to account for having multiple sets of pipes 502 and PCM capsules 504, rather than just one set. In an embodiment of the invention, each pairing (or "set") of pipes 502 and PCM capsules 504 optionally operates independently of the others. Optionally, some or all of the sets operate simultaneously, depending on the energy storage needs of the system 500 operator.

Adaptations to accommodate a plurality of sets optionally include: a liquid HTF collection tray 512 for at least one of the sets (optionally, at least one set drains directly into reservoir 506), a liquid return piping system 514 to communicate liquid HTF from the liquid HTF collection tray(s) 512 to the reservoir 506, and a pump 516 for conveying liquid HTF from the reservoir 506 to the various spray nozzles (508, 510) located proximally to the heat exchange elements (pipes 502, PCM capsules 504, respectively) of each set. In some embodiments of the invention, at least one set is turned "off" by deactivating or closing the valves 518 which supply liquid HTF to the heat exchange elements thereby preventing any liquid HTF from coming into contact with the pipes 502 or PCM capsules 504.

In some embodiments of the invention, at least one pump 516 is used to convey HTF from collection tray(s) 512 to reservoir 506. Optionally, reservoir 506 is gravity fed by run-off from collection tray(s) and/or from sets that directly drain into reservoir 506. In some embodiments of the invention, spray nozzles 508, 510 are gravity fed from a reservoir positioned above the sets. Optionally, a first reservoir feeds the sets with HTF, a second reservoir collects run-off HTF and a pump and piping system connects the second reservoir to the first reservoir to recycle the HTF from the collecting reservoir to the feeding reservoir.

As with system 100, different valves 518 are activated depending on whether the system is charging or discharging. It should also be understood that while only a single pump and only four (4) sets are shown, as many pumps, as much pumping power and/or liquid HTF return piping are used as is sufficient to render operational as many sets in the array as are present. It should also be understood that system 500 is not limited to four (4) sets, there could be fewer or more depending on the needs of the operator.

In an embodiment of the invention, a controller (not shown) is programmed to control operation of the system 500, similar to controller 102 of system 100. For example, the controller is provided with operative communication to at least the pump 516 and a plurality of valves 518 which feed a plurality of spray nozzles 508, 510 in a plurality of sets. During charging, depending on the storage needs of the operator, controller causes HTF to be pumped to a plurality of nozzles 518 which convey HTF to a plurality of pipes 502 via a plurality of spray nozzles 508, thereby causing HTF to evaporate on the pipes 502 and condense on the PCM capsules 504 and charging a plurality of sets. It should be understood that discharging is effectuated by utilizing spray nozzles 510 instead of spray nozzles 508, such as described elsewhere herein, only with a plurality of sets rather than just one set.

In an embodiment of the invention, each set is sealed in its own module such that operation of a set does not interfere with or affect the operation of another module in the system 500.

In some embodiments of the invention, collection tray 512 is used for a plurality of sets. In some embodiments of the invention, all of the sets drain into the reservoir. Optionally, there is a plurality of reservoirs.

The terms "comprises", "comprising", "includes", "including", “having” and their conjugates mean "including but not limited to". This term encompasses the terms "consisting of" and "consisting essentially of".

The phrase "consisting essentially of" means that the composition or method may include additional ingredients and/or steps, but only if the additional ingredients and/or steps do not materially alter the basic and novel characteristics of the claimed composition or method.

As used herein, the singular form "a", "an" and "the" include plural references unless the context clearly dictates otherwise. For example, the term "a compound" or "at least one compound" may include a plurality of compounds, including mixtures thereof.

Throughout this application, various embodiments of this invention may be presented in a range format. It should be understood that the description in range format is merely for convenience and brevity and should not be construed as an inflexible limitation on the scope of the invention. Accordingly, the description of a range should be considered to have specifically disclosed all the possible subranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed subranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6 etc., as well as individual numbers within that range, for example, 1, 2, 3, 4, 5, and 6. This applies regardless of the breadth of the range.

Whenever a numerical range is indicated herein, it is meant to include any cited numeral (fractional or integral) within the indicated range. The phrases "ranging/ranges between" a first indicate number and a second indicate number and "ranging/ranges from" a first indicate number "to" a second indicate number are used herein interchangeably and are meant to include the first and second indicated numbers and all the fractional and integral numerals therebetween.

It is appreciated that certain features of the invention, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the invention, which are, for brevity, described in the context of a single embodiment, may also be provided separately or in any suitable subcombination or as suitable in any other described embodiment of the invention. Certain features described in the context of various embodiments are not to be considered essential features of those embodiments, unless the embodiment is inoperative without those elements.

Although the invention has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, it is intended to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the appended claims.

All publications, patents and patent applications mentioned in this specification are herein incorporated in their entirety by reference into the specification, to the same extent as if each individual publication, patent or patent application was specifically and individually indicated to be incorporated herein by reference. In addition, citation or identification of any reference in this application shall not be construed as an admission that such reference is available as prior art to the present invention. To the extent that section headings are used, they should not be construed as necessarily limiting.

WHAT IS CLAIMED IS:

1. A thermal energy storage system, comprising:

at least one pipe;

at least one phase change material;

at least one reservoir containing a heat transfer fluid; and,

a controller programmed to switch heat transfer fluid flow delivery between the at least one pipe and the at least one phase change material;

wherein the same at least one pipe provides heat exchange by initially flowing steam therethrough during a charge cycle and water during a discharge cycle.

2. A thermal energy storage system of claim 1, wherein at least one spray nozzle is in operative and controllable communication with the reservoir directed at each of the at least one pipe and the at least one phase change material capsule.

3. A thermal energy storage system of claim 1, wherein the phase change material is located in at least one capsule.

4. A thermal energy storage system of claim 1, wherein a plurality of phase change material elements are located in an array.

5. A thermal energy storage system of claim 4, wherein at least one spray nozzle is directed at the entire array.

6. A thermal energy storage system of claim 1, wherein the at least one phase change material is a salt.

7. A thermal energy storage system of claim 1, wherein the at least one phase change material is a metal.

8. A thermal energy storage system of claim 1, wherein the heat transfer fluid is organic.

9. A thermal energy storage system of claim 1, wherein the heat transfer fluid returns to the reservoir at least partially by gravity.

10. A thermal energy storage system of claim 1, further comprising a pump to pump heat transfer fluid from the reservoir to at least one spray nozzle.

11. A thermal energy storage system of claim 1, wherein the controller is programmed to vary the flow rate of the heat transfer fluid to the at least one spray nozzle.

12. A thermal energy storage system of claim 3, wherein the phase change material capsule is formed from a metal or metal alloy.

13. A thermal energy storage system of claim 1, wherein the at least one phase change material is chosen from the group of sodium nitrate, potassium nitrate, and a salt mixture containing at least one of sodium nitrate or potassium nitrate.

14. A thermal energy storage system of claim 1, further comprising an auxiliary compartment containing heat transfer fluid for introducing to and withdrawing from the system to alter the pressure within the system.

15. A thermal energy storage system of claim 1, wherein the at least one pipe and the at least one phase change material element forms a set of heat storage elements and wherein the system is comprised of a plurality of sets.

16. A thermal energy storage system of claim 15, further comprising at least one collection tray associated with at least one set.

17. A thermal energy storage system of claim 16, further comprising a liquid HTF return piping system in liquid communication with the at least one collection tray and the at least one reservoir.

18. A thermal energy storage system of claim 15, further comprising a controller programmed to activate charging and discharging of each set in the plurality of sets.

19. A thermal energy storage system of claim 1, further comprising an auxiliary compartment containing heat transfer fluid for introducing to and withdrawing from the system to alter the pressure within the system.

20. A thermal energy storage system of claim 1, further comprising a system volume changing mechanism.

21. A method for storing thermal energy using at least one set of heat exchange elements, comprising:

introducing steam into at least one pipe;

delivering a heat transfer fluid in liquid form to the exterior of the at least one pipe;

evaporating heat transfer fluid upon contact with the at least one pipe, absorbing heat by the heat transfer fluid in the process;

condensing the heat transfer fluid vapor on at least one phase change material capsule, transferring heat to the at least one phase change material capsule from the heat transfer fluid; and,

returning the heat transfer fluid liquid to a reservoir.

22. A method according to claim 21, wherein the heat transfer fluid liquid is delivered to the at least one pipe by at least one spray nozzle.

23. A method according to claim 21, wherein the steam saturation temperature is at least 100°C.

24. A method according to claim 23, wherein the steam saturation temperature is 250°C -350°C.

25. A method according to claim 21, further comprising discharging the stored thermal energy by introducing a water flow into the at least one pipe, delivering heat transfer fluid in liquid form to at least one thermally charged phase change material capsule; evaporating heat transfer fluid upon contact with the at least one phase change material capsule, absorbing heat in the process; condensing the heat transfer fluid vapor on the at least one water containing pipe, transferring heat to water in the pipe and evaporating it creating steam; and, returning the heat transfer fluid liquid to the reservoir.

26. A method according to claim 25, wherein delivering the heat transfer fluid in liquid form to at least one thermally charged phase change material is accomplished using at least one spray nozzle.

27. A method according to claim 25, wherein the steam saturation temperature is at least 100°C.

28. A method according to claim 25, wherein the steam saturation temperature is 250°C -350°C.

29. A method for storing and discharging thermal energy using at least one set of heat exchange elements containing steam for charging and water for discharging, comprising:

introducing steam into at least one pipe;

delivering a heat transfer fluid in liquid form to the exterior of the at least one pipe;

evaporating heat transfer fluid upon contact with the at least one pipe, absorbing heat by the heat transfer fluid in the process;

condensing the heat transfer fluid vapor on at least one phase change material capsule, transferring heat to the at least one phase change material capsule from the heat transfer fluid, thereby storing the thermal energy;

returning the heat transfer fluid liquid to a reservoir;

introducing a water flow into the at least one pipe;

delivering heat transfer fluid in liquid form to at least one thermally charged phase change material capsule;

evaporating heat transfer fluid upon contact with the at least one phase change material capsule, absorbing heat in the process and thereby discharging the stored thermal energy;

condensing the heat transfer fluid vapor on the at least one water containing pipe, transferring heat to water in the pipe and evaporating it creating steam; and,

returning the heat transfer fluid liquid to the reservoir.

30. A method according to claim 29, wherein the heat transfer fluid in liquid form is delivered to the at least one pipe and the at least one phase change material capsule by at least one spray nozzle.

31. A method according to claim 29, wherein the steam saturation temperature is at least 100°C.

32. A method according to claim 29, wherein the steam saturation temperature is 250°C -350°C.

33. A thermal energy storage system, comprising:

a chamber;

at least one pipe in the chamber;

an expandable phase change material capsule array in the chamber separate from the at least one pipe;

a reservoir containing a heat transfer fluid in fluid communication with the chamber;

a controller programmed to perform at least one of delivering heat transfer fluid to the exterior of the at least one pipe from the reservoir and controlling fluid flow within the at least one pipe based on the size of the array.

34. A storage capacity expandable thermal energy storage system of claim 33, further comprising an auxiliary compartment containing heat transfer fluid for

introducing to and withdrawing from the chamber to alter the pressure within the chamber.

35. A method for controlling the heat transfer rate in a thermal energy storage system comprising:

evaporating heat transfer fluid on at least one of a pipe or phase change material array;

condensing the heat transfer fluid on at least one of a pipe or phase change material array;

altering the flow of a heat transfer fluid within the thermal energy storage system to either increase or decrease the rate of evaporating and condensing, thereby controlling the heat transfer rate in the system.

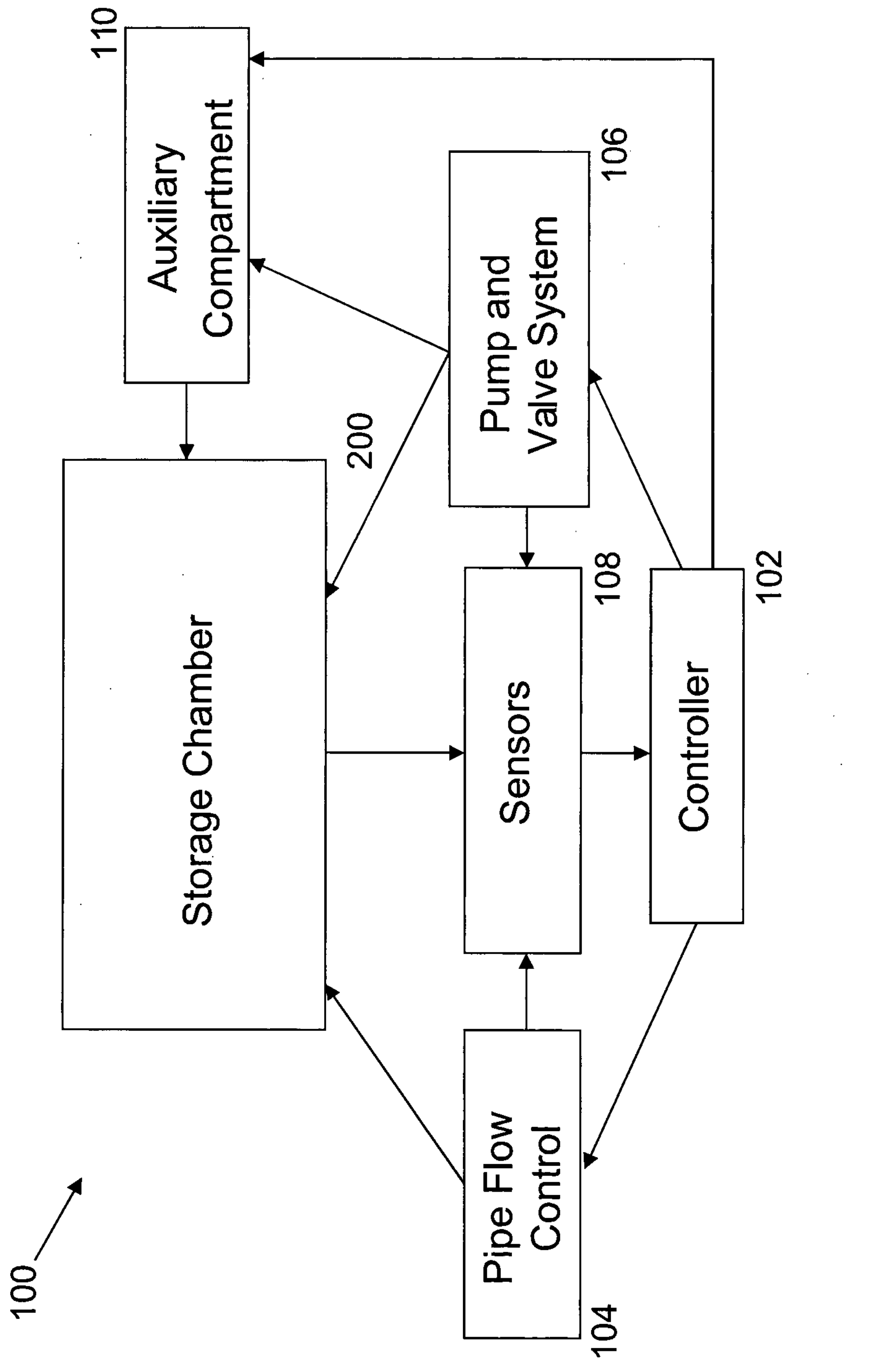
Auxiliary Compartment
110
Pump and Valve System
106
200
Storage Chamber
Sensors
108
Controller
102
Pipe Flow Control
104
100

FIG. 1

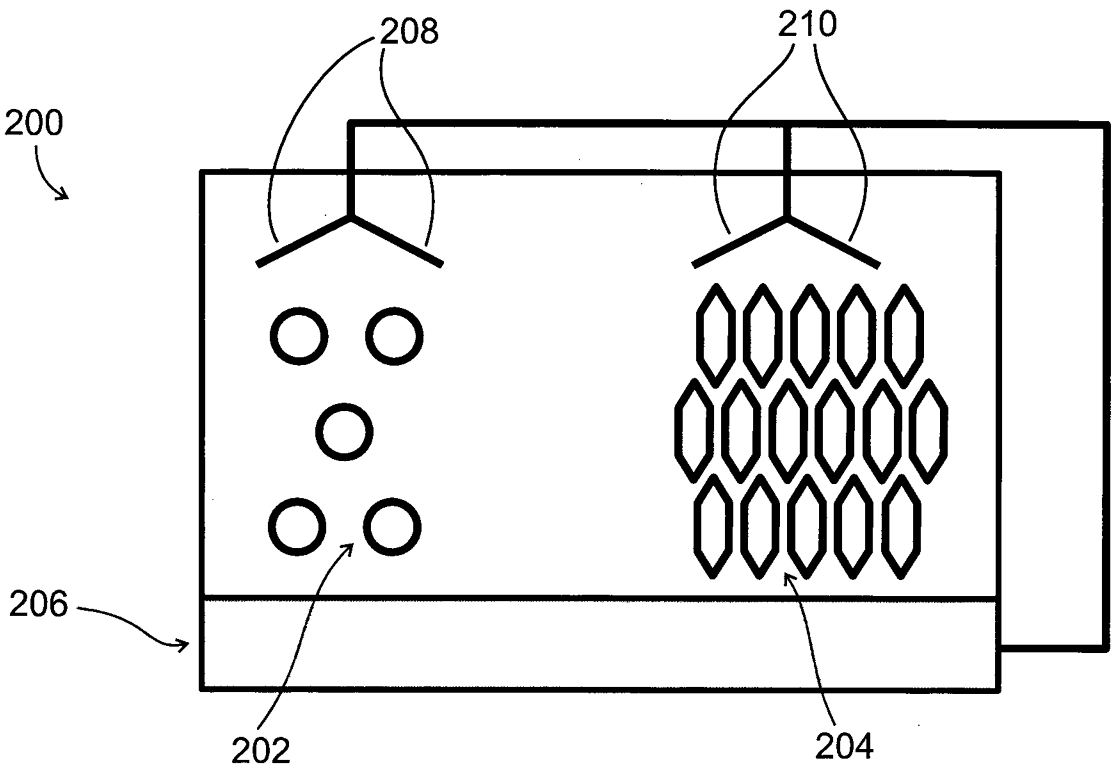

FIG. 2

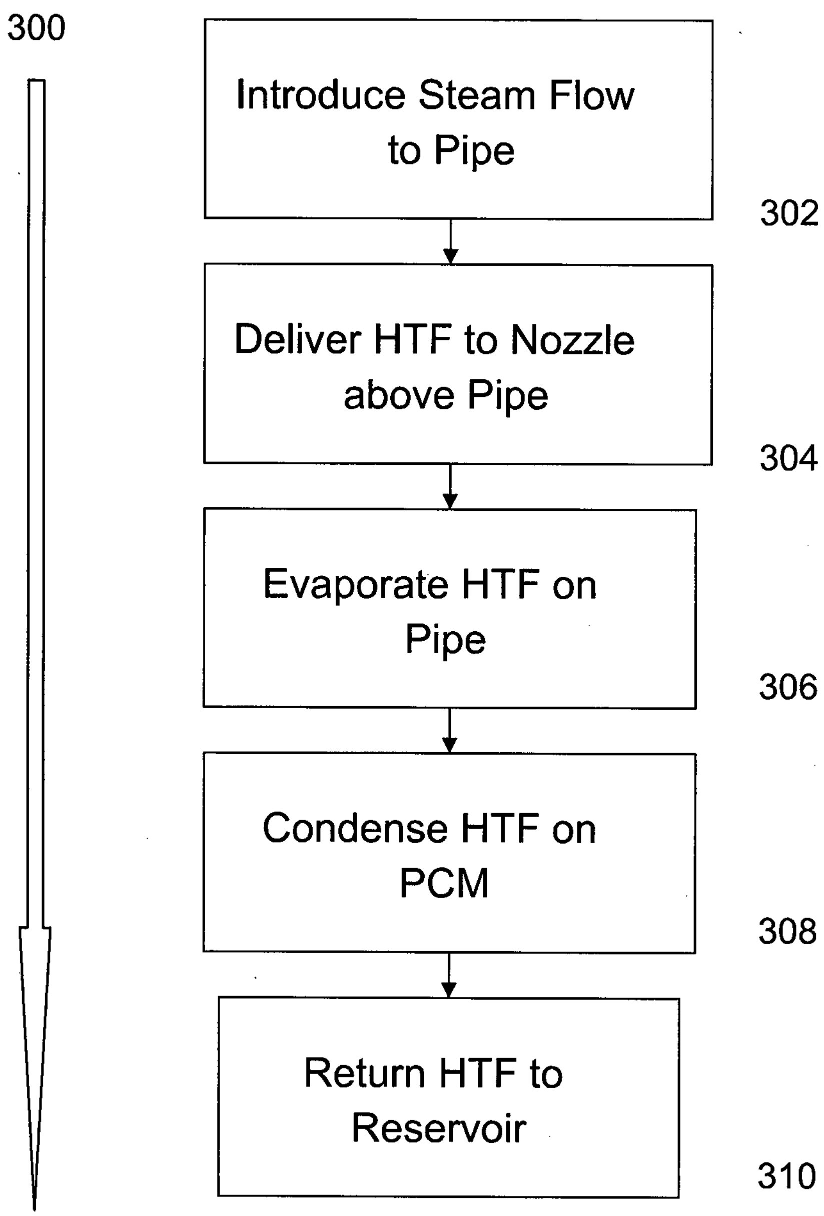
300
Introduce Steam Flow to Pipe
302
Deliver HTF to Nozzle above Pipe
304
Evaporate HTF on Pipe
306
Condense HTF on PCM
308
Return HTF to Reservoir
310

FIG. 3

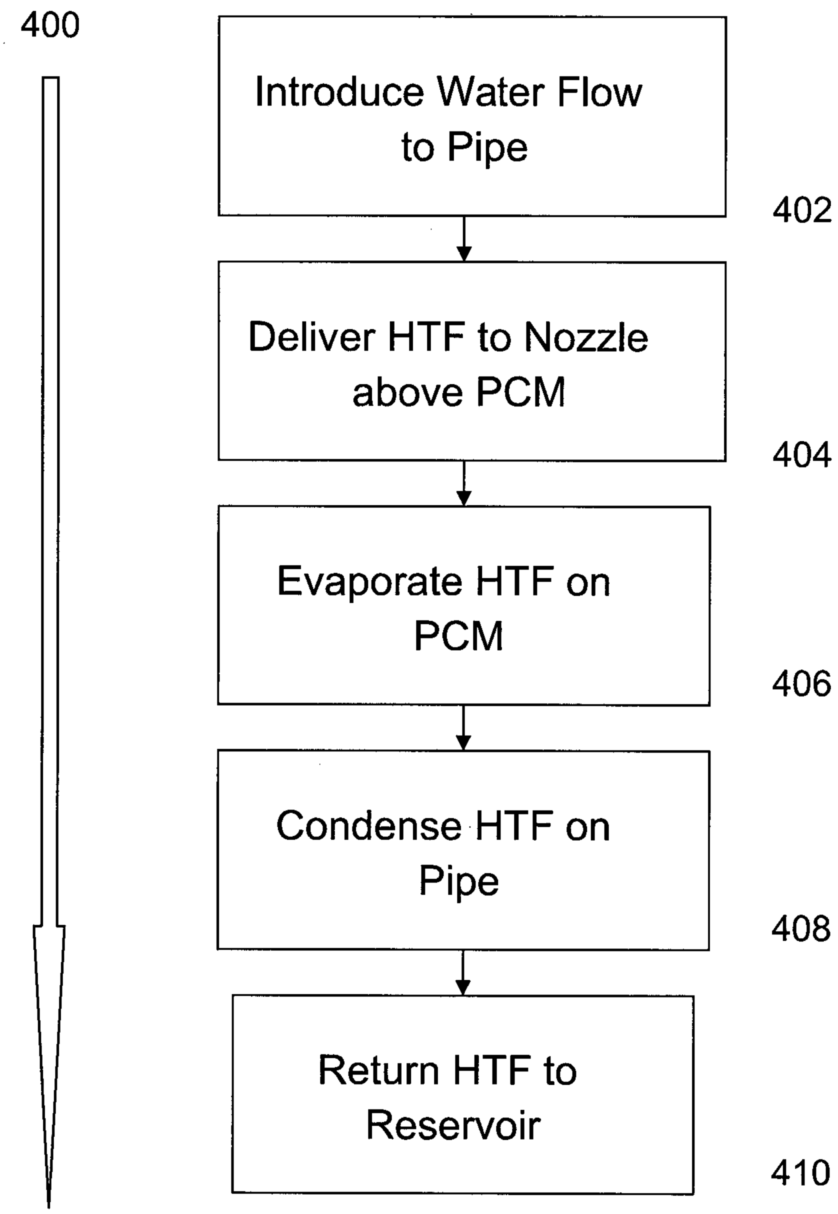
400
Introduce Water Flow to Pipe
402
Deliver HTF to Nozzle above PCM
404
Evaporate HTF on PCM
406
Condense HTF on Pipe
408
Return HTF to Reservoir
410

FIG. 4

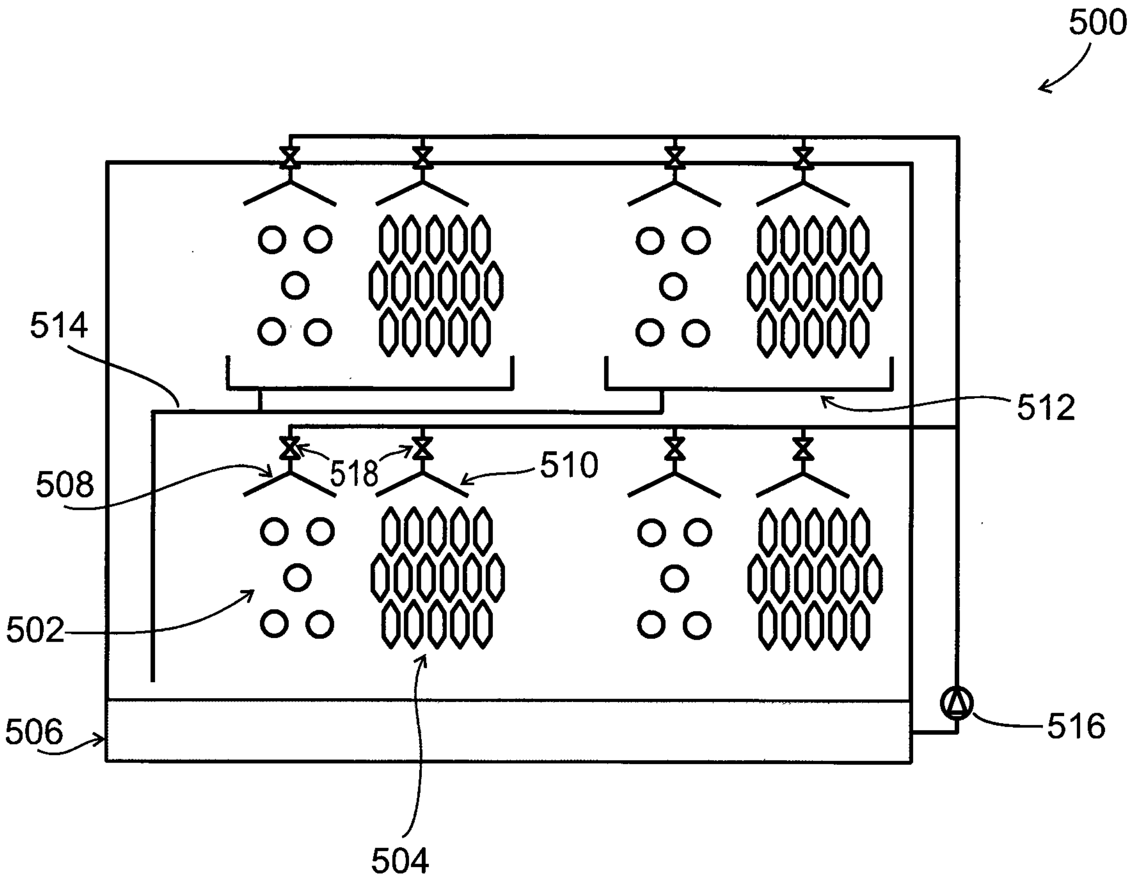

FIG. 5