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(53) Abstract: Described herein is a thermal energy storage system that can be used to store thermal energy from superheated steam. The thermal energy storage system comprises a long conduit, and a thermal energy storage medium in thermal contact with the conduit along its length. The conduit may be substantially linear or non-linear (e.g. serpentine or coiled). The thermal properties of the thermal energy storage medium may be selected so that a thermal gradient is formed in the medium along the length of the conduit during charging, such that at least one zone of the thermal energy storage medium maintains a sufficient temperature so that superheated steam may be recovered from the thermal energy storage system upon discharge.

**FIG. 1B**
THERMAL ENERGY STORAGE FOR SUPERHEAT APPLICATIONS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit under 35 U.S.C. § 119(e) of U.S. Provisional Application Serial No. 61/146,241, filed January 21, 2009, the contents of which are incorporated herein by reference in their entirety.

BACKGROUND OF THE INVENTION

[0002] Thermal energy storage systems may, in various circumstances, be incorporated in thermal power plants and process or industrial steam systems, including those that employ nuclear reactors, package boilers and solar energy collector systems. The thermal energy storage systems may be required as buffers against transient demands that exceed the steady state output capacities of plants, against temporary reduction in input heat or, alternatively, to provide long term thermal energy storage when heat generating capabilities cannot, for various reasons, be synchronized with load demands. One or the other or all of these requirements may exist in relation to thermal power plants and in process or industrial steam systems, including those incorporating solar energy collector systems for use in generating thermal energy.

[0003] Solar energy collector systems may comprise, for example, parabolic trough systems, central receiver with 2-axis heliostat systems, or Linear Fresnel Collector (LFR) systems. LFR systems employ a field of reflectors and elevated receivers that are illuminated by reflected radiation for energy exchange with fluid that is carried through the receivers. An LFR system is typically employed in the heating of a working fluid for delivery to an electrical generating plant, either for admission directly to a turbine or for heat exchange with fluid that is expanded through the turbine. Heated working fluid may also be used in process or industrial steam systems. An example of a reflector that has been developed for use in a LFR system is disclosed in International Patent Applications numbered PCT/AU2004/000883 and PCT/AU2004/000884, both dated 01 July 2004, and an example of a receiver for such a system is disclosed in International Patent Application number PCT/AU2005/000208, dated 17 February 2005.

[0004] Solar energy collector systems function only when adequate incident solar radiation is present and, in order to prolong the duty cycle of solar-based power generation, to help to
accommodate transient reductions of solar radiation, or to provide a buffer against transient loads, thermal energy produced in excess of demand during periods of high-level solar radiation and/or low power consumption may be stored.

[0005] Thermal energy stored in the thermal energy storage system may be extracted by heating a working fluid, which may be delivered to an electrical generating plant, either for admission directly to a turbine or for heat exchange with a fluid that is expanded through the turbine. Steam turbines utilizing superheated steam are more efficient than those using saturated steam. Thus, thermal energy storage systems which can store thermal energy and can generate superheated steam upon discharging are desired. Additionally, thermal energy stored in the thermal energy storage system may be extracted for use in process or industrial steam systems. Superheated steam may additionally be desired for use in these applications.

[0006] All patents, patent applications, documents, and articles cited herein are herein incorporated by reference in their entirety.

BRIEF SUMMARY OF THE INVENTION

[0007] The invention provides thermal energy storage systems and methods for using the thermal energy storage systems to store thermal energy, wherein the source of the thermal energy is superheated steam. The thermal energy may be extracted from the thermal energy storage system as superheated steam at a later time point during discharge of the system. The thermal energy storage systems of the invention are comprised of one or more conduits arranged to carry a working fluid (e.g. water/steam) disposed within, and in thermal contact with, a thermal energy storage medium. The thermal energy storage system is charged by flowing superheated steam into the conduit(s), whereby heat is transferred from the steam to the medium for storage. The thermal energy storage system may be discharged at a later time point by flowing water into the conduit(s), whereby heat is transferred from the medium to the water, thereby producing superheated steam. As described in more detail below, by limiting thermal conductivity within the thermal energy storage medium in a longitudinal direction along the length of the conduit(s), superheated steam may be extracted from the thermal energy storage system upon discharge.
Briefly, in storage mode, a pressurized superheated steam flow passes into the conduit, and thermal energy (as sensible heat) from the steam is exchanged with and stored at a high temperature in the medium (the “superheat zone”). As the temperature of the superheated steam decreases due to heat exchange with the medium, the steam eventually reaches saturation temperature such that both steam and water are present in the conduit. Pressure remains substantially constant within the conduit. Thermal energy from the saturated steam/water is exchanged with and stored in the medium (the “latent heat zone”), causing additional steam to condense. Due to the thermal energy being released from the water/steam during condensation as latent heat, the temperature in the latent heat zone is relatively constant, and is lower than the temperature in the superheat zone. Eventually, essentially all of the steam will have condensed to water. In some variations, thermal energy from the hot water (as sensible heat) will exchange with and be stored in yet another zone of the medium (the “preheat zone”) at temperatures lower than the latent heat zone. An example of the temperature gradient initially created (at a time $t_0$) along the length of the conduit is shown in Figure 1A. As more superheated steam is flowed into the conduit (at a later time $t_1$), and more thermal energy is stored in the medium, the zones shown in Figure 1A shift to the right (see Figure 1B), or, within the context of the thermal energy storage system, the zones shift within the medium longitudinally along the length of the conduit towards the system exit. When the thermal energy storage system is fully charged, the system may or may not have a preheat zone. While not necessary to the operation of the system, it is preferred in some embodiments that sufficient heat from the working fluid be transferred to the thermal energy storage medium such that little or no steam exits the system, in order to avoid waste of thermal energy.

In discharge mode, water is flowed into the conduit (frequently in the reverse direction from the charging mode), and heat from the thermal energy storage medium is transferred into the water. As more heat is transferred into the water, the superheat, latent heat, and preheat zones within the thermal energy storage medium shift longitudinally along the length of the conduit towards the exit of the system (e.g. in Figure 1B, the zones shift to the left).

The temperature gradient created within the thermal energy storage medium along the length of the conduit is maintained by limiting thermal conductivity within the thermal energy storage medium in the longitudinal direction along the length of the conduit. The thermal storage
medium may in some variations be homogeneous in composition and/or structure along the length of the conduit, and in other variations, the composition and/or structure of the storage medium may vary along the length of the conduit. In some variations, the volume and/or mass of the storage medium that is in thermal contact with the conduit may vary along the length of the conduit. In some variations, a storage medium may be selected to have an intermediate thermal conductivity, high enough so that sufficient heat can be transferred to the medium within a desired storage time period without requiring excessive conduit lengths, but not so high that substantially thermal equilibration along the length of the conduit occurs within the storage period. As will be described in more detail below, limited thermal conductivity may be achieved by the particular materials used for the thermal energy storage medium and/or by physical barriers within the medium. Creation and maintenance of the temperature gradient may result in more efficient and effective utilization of stored heat, may increase efficient heat transfer into and out of the thermal energy storage medium, may increase the maximum temperature of the heated working fluid upon system discharge, and may increase the length of time in which superheated steam may be extracted from the thermal energy storage system.

[0011] For example, a thermal energy storage medium which has very high or infinite thermal conductivity within the medium longitudinally along the length of the conduit would quickly reach temperature equilibrium as heat is transferred from the medium into the working fluid during discharge, and the medium would not support two or more discernable temperature zones (e.g. superheat, latent heat, and preheat zones), but would have essentially a single temperature zone. The temperature of the working fluid exiting the system upon system discharge is limited by the temperature of the medium. Thus, as the temperature of the medium decreases upon thermal heat extraction, the temperature of the working fluid exiting the system will decrease accordingly. Although it is possible that superheated steam may be initially extracted from such a system, if the temperature of substantially the entire volume of the medium is initially heated to a superheat temperature, once sufficient heat is transferred out of the medium, the medium temperature would reach that of the latent heat zone. Once the medium is at the latent heat zone temperature, no additional superheated steam may be extracted from the thermal energy storage system, and saturated steam is produced. As more thermal energy is transferred into the working fluid, the medium temperature eventually reaches the preheat zone, and heated water is produced. Such a medium limits the ultimate temperature of the steam and the amount of
superheated steam which may be extracted from the thermal energy storage system, and additionally, if there is no practical use for the lower energy working fluid (i.e. saturated steam and heated water), wastes a large portion of the thermal energy stored within the medium.

[0012] In contrast, in the thermal energy storage system of the invention, the temperature gradient within the medium is maintained longitudinally along the length of the conduit, such that a superheat zone is maintained within the system for a much longer period of time, and superheated steam may be extracted over a much longer period of time.

[0013] In one aspect of the invention is a thermal energy storage system comprising: (a) a conduit arranged to carry a working fluid; and (b) a thermal energy storage medium; wherein the conduit is disposed within and in thermal contact with the thermal energy storage medium; wherein during charging or discharging of the thermal energy storage system with thermal energy, a temperature gradient is created in the thermal energy storage medium longitudinally along the length of the conduit. The temperature gradient may shift along the length of the conduit as the system continues to charge and/or discharge. The thermal energy storage system may generate superheated working fluid (e.g. superheated steam) upon discharge of the system.

In some embodiments, the thermal energy storage medium has a substantially homogeneous composition and/or structure along the length of the conduit. In some embodiments, the thermal energy storage medium composition and/or structure varies (e.g. in two or more discernible regions) along the length of the conduit. In some embodiments, the physical distribution of a thermal energy storage medium varies along the length of the conduit, e.g. so that a volume or mass of the medium in contact with the conduit at one end of the system is less than a volume or mass of the medium in contact with the conduit at an opposing end of the system. In some embodiments, the thermal energy storage medium is not pumped or otherwise moved under an external force. In some embodiments, the thermal energy storage medium comprises a highly viscous liquid or slurry, where convective heat exchange is low due to the high viscosity, and where conductive heat exchange is also low as compared to a metal such as iron or steel. In some embodiments, one or more regions of the thermal energy storage medium are physically separated from each other, for example by a thermally insulating material having a thermal conductivity much less than adjacent material. The conduit may be linear and/or follow a serpentine or coiled (e.g. helical) or other non-linear path within the thermal energy storage
medium. A conduit may be substantially in one plane (e.g. linear, serpentine), or may be three-dimensional (e.g. coiled). In some embodiments, the conduit is linear. In some embodiments, the conduit is serpentine. In some embodiments, the conduit is coiled. In some embodiments, the conduit is distributed non-uniformly within the thermal energy storage medium. The conduit may be placed more densely in one region within the thermal energy storage medium than in another region. In some embodiments, the conduit is serpentine, and the spacing period varies. In some embodiments, the conduit has a larger cross-sectional area in one region of the thermal energy storage medium than in another region. In some embodiments, the system may comprise a different volume (e.g. larger or smaller diameter) of thermal energy storage medium surrounding the conduit along its length as the conduit extends through or traverses the thermal energy storage medium.

[0014] In another aspect of the invention is a method for storing thermal energy, the method comprising: (a) flowing steam into a conduit disposed within and in thermal contact with a thermal energy storage medium, whereby heat is transferred from the steam to the medium for storage; and (b) forming a temperature gradient in the medium longitudinally along a length of the conduit, the temperature gradient in operation translating along the length of the conduit according to heat transfer between the steam and the medium. In some embodiments, sufficient heat is transferred from the steam to the medium such that water exits the conduit. In some embodiments, sufficient heat is transferred from the steam to the medium such that substantially no steam exits the conduit. In some embodiments, the temperature gradient is comprised of a superheat zone, a latent heat zone, and a preheat zone. In some embodiments, the temperature gradient is comprised of a superheat zone and a latent heat zone. In some embodiments, superheated steam may be extracted from the thermal energy storage system at a later time point. In some embodiments, at least a portion of the thermal energy storage medium within the superheat zone is fully saturated with thermal energy upon charging the system and the medium has a substantially uniform temperature along at least a portion of the conduit within the superheat zone.

[0015] In another aspect of the invention is a method for storing thermal energy, the method comprising: (a) flowing steam into a conduit disposed within and in thermal contact with a thermal energy storage medium, whereby heat is transferred from the steam to the medium for
storage; and (b) thermally saturating a zone of the medium with heat so that the zone has a substantially uniform temperature, wherein substantially no condensation of the steam occurs within the conduit in thermal contact with the medium in the zone.

[0016] It is to be understood that any of the thermal energy storage systems as described herein may be used in a method of storing thermal energy as described herein, and any of the methods of storing thermal energy as described herein may be used in conjunction with a thermal energy storage system as described herein. Accordingly, in additional aspects of the invention are: a method of storing thermal energy by use of a thermal energy storage system as described herein, and a thermal energy storage system for use in any of the methods as described herein.

[0017] In another aspect of the invention is a thermal energy power plant comprising a thermal energy storage system as described herein.

[0018] In another aspect of the invention is a process or industrial steam plant comprising a thermal energy storage system as described herein.

BRIEF DESCRIPTION OF THE FIGURES

[0019] FIGS. 1A-1B provide general graphical illustrations of the temperature of a thermal energy storage medium in thermal contact with a conduit as a function of position along the conduit for an example of a thermal energy storage system as described herein.

[0020] FIGS. 2A-2B provide side cross-sectional views of an example of a thermal energy storage system.

[0021] FIGS. 3A-3B provide illustrations of an example of a thermal energy storage system comprising first and second annular thermal energy storage regions.

[0022] FIG. 4 provides a schematic illustration of a variation of a thermal energy storage system in which a cross-sectional diameter of conduits within the system vary along the length of the conduits.
[0023] FIG. 5 provides a schematic illustration of a variation of a thermal energy storage system in which the conduits comprise multiple conduits feeding into a single conduit.

[0024] FIG. 6 provides a schematic illustration of a variation of a thermal energy storage system in which a mass or thermal mass of thermal energy storage medium surrounding and in thermal contact with a conduit varies along the length of the thermal conduit.

[0025] FIG. 7 provides a schematic illustration of a variation of a thermal energy storage system in which a packing density of a serpentine conduit varies along the length of the conduit.

[0026] FIG. 8 provides a schematic illustration of a variation of a thermal energy storage system in which two coiled conduits are embedded in a thermal energy storage medium, and the pitch of the coils varies along the length of the system, and the thermal properties of the medium vary along the length of the system.

[0027] FIGS. 9A-9C provide illustrations of examples of thermal energy storage systems in which the thermal energy storage medium is contained within a long cylinder, multiple cylinders positioned axially along the length of the conduit, or multiple coaxial cylinders.

DETAILED DESCRIPTION OF THE INVENTION

[0028] Unless defined otherwise or clearly indicated by context, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs.

[0029] Unless otherwise indicated, all numbers used in the specification and claims are to be understood as being modified in all instances by the term “about.” Accordingly, unless indicated to the contrary, the numerical parameters set forth in the following specification and attached claims are approximations that may vary depending at least upon the specific analytical technique.

[0030] In one aspect of the invention is a thermal energy storage system comprising: (a) a conduit arranged to carry a working fluid; and (b) a thermal energy storage medium; wherein the conduit is disposed within and in thermal contact with the thermal energy storage medium;
wherein during charging or discharging of the thermal energy storage system with thermal energy, a temperature gradient is created in the thermal energy storage medium longitudinally along the length of the conduit. The temperature gradient may shift along the length of the conduit as the system continues to charge and/or discharge. The thermal energy storage system may generate superheated working fluid (e.g. superheated steam) upon discharge of the system. In some embodiments, the thermal energy storage medium has a substantially homogeneous composition and/or structure along the length of the conduit. In some embodiments, the thermal energy storage medium composition and/or structure varies (e.g. in two or more discernible regions) along the length of the conduit. In some embodiments, the physical distribution of a thermal energy storage medium varies along the length of the conduit, e.g. so that a volume or mass of the medium in contact with the conduit at one end of the system is less than a volume or mass of the medium in contact with the conduit at an opposing end of the system. In some embodiments, the thermal energy storage medium is not pumped or otherwise moved under an external force. In some embodiments, the thermal energy storage medium comprises a highly viscous liquid or slurry, where convective heat exchange is low due to the high viscosity, and where conductive heat exchange is also low as compared to a metal such as iron or steel. In some embodiments, one or more regions of the thermal energy storage medium are physically separated from each other, for example by a thermally insulating material having a thermal conductivity much less than adjacent material. The conduit may be linear and/or follow a serpentine or coiled (e.g. helical) or other non-linear path within the thermal energy storage medium. A conduit may be substantially in one plane (e.g. linear, serpentine), or may be three-dimensional (e.g. coiled). In some embodiments, the conduit is linear. In some embodiments, the conduit is serpentine. In some embodiments, the conduit is coiled. In some embodiments, the conduit is distributed non-uniformly within the thermal energy storage medium. The conduit may be placed more densely in one region within the thermal energy storage medium than in another region. In some embodiments, the conduit is serpentine, and the spacing period varies. In some embodiments, the conduit has a larger cross-sectional area in one region of the thermal energy storage medium than in another region. In some embodiments, the system may have a different volume or mass (e.g. larger or smaller diameter) of thermal energy storage medium surrounding the conduit along its length as the conduit traverses or extends through the thermal energy storage medium.
[0031] In another aspect of the invention is a method for storing thermal energy, the method comprising: (a) flowing steam into a conduit disposed within and in thermal contact with a thermal energy storage medium, whereby heat is transferred from the steam to the medium for storage; and (b) forming a temperature gradient in the medium longitudinally along a length of the conduit, the temperature gradient in operation translating along the length of the conduit according to heat transfer between the steam and the medium. In some embodiments, sufficient heat is transferred from the steam to the medium such that water exits the conduit. In some embodiments, sufficient heat is transferred from the steam to the medium such that substantially no steam exits the conduit. In some embodiments, the temperature gradient is comprised of a superheat zone, a latent heat zone, and a preheat zone. In some embodiments, the temperature gradient is comprised of a superheat zone and a latent heat zone. In some embodiments, superheated steam may be extracted from the thermal energy storage system at a later time point. In some embodiments, at least a portion of the thermal energy storage medium within the superheat zone is fully saturated with thermal energy upon charging the system and the medium has a substantially uniform temperature along at least a portion of the conduit within the superheat zone.

[0032] In another aspect of the invention is a method for storing thermal energy, the method comprising: (a) flowing steam into a conduit disposed within and in thermal contact with a thermal energy storage medium, whereby heat is transferred from the steam to the medium for storage; and (b) thermally saturating a zone of the medium with heat so that the zone has a substantially uniform temperature, wherein substantially no condensation of the steam occurs within the conduit in thermal contact with the medium in the zone.

[0033] Various embodiments of the present invention are hereinafter described by way of example in the context of a thermal power plant (e.g. a Rankine cycle plant) that incorporates a solar energy collector system. However, the thermal energy storage systems described herein may also be used in the context of a steam plant (e.g. for industrial process heat, absorption cooling, food processing, sterilization, water desalination, chemical processing, or enhanced oil recovery), and the like. Additionally, other heating systems, such as fossil fuel fired boilers, package boilers, geothermal boilers, or a nuclear-reactor powered plant arranged to exchange thermal energy (heat) with a working fluid may be used to provide thermal energy to the storage
system. The description is provided by way of examples and with reference to the accompanying
drawings, which characterize some preferred embodiments but are by no means limiting.

[0034] Referring to Figs. 2A-2B, the thermal energy storage system 100 may in some
variations have at least two zones while charging: a superheat zone 110, a latent heat zone 120,
and optionally a preheat zone 130. Dashed lines in FIGS. 2A-2B indicate differentiation of the
zones. These zones shift (to the right for this particular illustration) as additional steam is added
to the thermal energy storage system (Fig. 2B) and additional heat is transferred into the thermal
energy storage medium. Additionally, a subzone of thermal energy storage medium may be
created within the superheat zone (e.g. “TS” in Figure 1B) which is thermally saturated, such
that the thermal energy storage medium within this subzone is at a substantially uniform
temperature after charging.

[0035] Limited heat is transferred within the thermal energy storage medium in a longitudinal
direction along the length of the conduit by way of convective heat transfer, or by way of
conductive heat transfer, especially as compared to a metal such as iron or steel in contact with
another piece of iron or steel. The heat transfer properties of the thermal energy storage medium
may be selected so that sufficient heat transfer occurs to enable a desired amount of energy
storage in the medium for a desired conduit length, but limited so that a thermal gradient formed
along the length of the conduit during charging is substantially preserved during a desired
storage period so that at least some of the storage medium is at a high enough temperature to
allow superheated steam to be recovered at the operating pressure. The desired storage period
may be selected according to source of steam and eventual application for stored thermal energy.
For example, for solar powered steam sources, the storage period may be about 2, 3, 4, 5, 6, 7, 8,
9, 10, 11, 12, 13, or 14 hours, or even longer. The limited convective and conductive heat
transfer may be due at least in part to intrinsic material properties such as high viscosity and/or
low thermal conductivity of the materials within the thermal energy storage medium, and/or the
limited heat transfer may be due at least in part to physical barriers, for example intervening
thermally insulating material 140 positioned at various locations within the thermal energy
storage medium along the length of the conduit. Various materials useful in these configurations
are discussed further below. However, it should be noted that in some variations, the thermal
energy storage medium has a substantially homogeneous composition along the length of the
conduit, e.g. the storage medium in thermal contact with the conduit in zones 110, 120, and 130 as shown in FIGS. 2A-2B has substantially the identical composition. In some variations, there are no insulating layers or physical barriers (e.g. barriers 140 as shown in FIGS. 2A-2B). In some variations, the mass or volume of the thermal energy storage medium in thermal contact with the conduit may differ between zones, e.g. the mass or volume of thermal energy storage medium in contact with the conduit in at least part of the superheat zone 110 may be smaller than that of the mass or volume of thermal energy storage medium in contact with the conduit in at least part of the latent heat zone 120 or the preheat zone 130. In some variations, the composition of the thermal energy storage medium may be different for different zones. It also should be noted that since the zones translate along the conduit in operation, variations in the composition, structure, or volume or mass of the storage medium may be selected to provide improved performance of the system, e.g. efficiency, amount of superheat steam recovered upon discharge, and/or temperature of superheat steam recovered upon discharge.

[0036] In storage mode, superheated fluid such as superheated steam passes into a conduit 111SH disposed within the thermal energy storage medium, and thermal energy from the superheated fluid is exchanged with and stored at a temperature $T_1$, wherein $T_1$ is greater than the temperature of condensation for the fluid at operating pressure (creating superheat zone 110). The operating pressure may be selected based on the source of the steam and/or the intended use of the steam. In some variations, the operating pressure may be, for example, about 50 bar, about 100 bar, about 150 bar, or about 200 bar. As shown in Figure 1A, the temperature $T_1$ of the thermal energy storage medium within the superheat zone 110 may be a range of temperatures above the fluid condensation temperature. The temperature of the superheated fluid decreases due to heat exchange with the thermal energy storage medium, and eventually the fluid reaches its saturation temperature so that vapor and liquid are both conveyed through the conduit 111LAT. Thermal energy from the saturated fluid exchanges with thermal energy storage medium (creating latent heat zone 120 at $T_2$), causing additional vapor to condense. Since the thermal energy transferred by the saturated fluid is from latent heat, $T_2$ is substantially the same throughout the latent heat zone. When all of the vapor has condensed, the condensed fluid (e.g. water) traverses the conduit 111PRE, and thermal energy transfers from the hot condensed fluid into the thermal energy storage medium (preheat zone 130). The temperature $T_3$ of the medium in the preheat zone is therefore less than the temperature $T_2$ in the latent heat zone, and as shown
in Figure 1B, $T_3$ may vary over the length of the preheat zone 130. As additional superheated fluid is added to the thermal energy storage system, these zones shift towards the exit of the system (to the right as illustrated in Figs. 1B and 2B). Upon completed charging of the system, the superheat region may extend the full length of the thermal energy storage system, two zones (superheat and latent heat) may be present in the thermal energy storage system, three zones (superheat, latent heat, and preheat), or more than three zones (e.g. superheat, latent heat, preheat, and unheated) may be present in the thermal energy storage system.

[0037] In thermal extraction/discharging mode, liquid (e.g. water) flows into the thermal energy storage system at a desired operating pressure in order to extract the thermal energy. Although in this currently described embodiment, the liquid flows into the thermal energy storage system in the reverse direction from the charging mode, in some embodiments, the liquid may flow into the thermal energy storage system in the same direction as in the charging mode. In this example, the optional preheat zone 130 is present upon initiating the discharge mode. The liquid flows through the conduit 111PRE into the preheat zone 130 where the liquid is heated to a temperature near its boiling point. The heated liquid continues traversing to the conduit 111LAT and passes through the latent heat zone 120, in which the liquid receives heat from the thermal energy storage medium of the latent heat zone and boils to form a saturated fluid stream. The saturated fluid subsequently passes to conduit 111SH through the superheat zone 110 of the thermal energy storage medium. The fluid exiting the latent heat zone and entering the superheat zone via the conduit may be saturated, may be superheated, or may be at the point where essentially all or all liquid has vaporized but has not yet been superheated. The fluid passing through the conduit within the superheat zone receives thermal energy from the superheat zone, and ultimately superheated fluid exits the superheat zone. As the system is continued to discharge, the zones will shift along the length of the conduit towards the exit of the system (e.g. in this embodiment to the left in Figure 2B).

[0038] This configuration and method of operation may provide more efficient and effective utilization of stored heat. Thermal energy is stored at a higher temperature(s) $T_1$ in the superheat zone of the thermal energy storage medium than would otherwise be possible if the thermal energy storage medium of the superheat zone had high thermal conductivity with the thermal energy storage medium of the latent heat zone. Additionally, the latent heat zone may be larger
than would otherwise be possible if the thermal energy storage medium of the latent heat zone had high thermal conductivity with the thermal energy storage medium of the preheat zone. It is to be understood that the “zones” as described herein describe approximate regions of thermal energy storage medium, that the boundaries between the zones may or may not be sharply defined, and that compositional differences, structural differences and/or insulating layers may or may not be present in the storage medium to help in forming the zones during charging and sustaining zones during a storage period. Accordingly, the thermal energy storage system of the invention may increase the maximum temperature of the extracted working fluid (e.g. superheated steam) upon system discharge and/or may increase the length of time in which superheated fluid (e.g. superheated steam) may be extracted from the thermal energy storage system. Additionally, the temperatures of the thermal energy storage medium in the superheat zone, latent heat zone, and preheat zone may also be near the temperature of the fluid exchanging heat with the thermal energy storage medium in each of the zones as well as near the temperature of the fluid heated or cooled by the thermal energy storage medium in each of the zones in later use. Without wishing to be bound by theory, the small temperature differential may also improve efficiency of heat transfer.

[0039] In some variations, a thermal energy storage medium varies along the length of the conduit so as to comprise one or more discernible regions in the storage medium. While such regions of thermal energy storage medium along the length of the conduit do not need to be thermally isolated from one another (i.e. allowing essentially no heat transfer between the regions), they should be sufficiently thermally isolated and/or thermal convection and conduction along the length of the conduit should be sufficiently suppressed such that the thermal energy storage medium can maintain a thermal gradient for a sufficient length of time during storage and subsequent discharge of the system such that fluid heated to the desired temperature (e.g. superheated steam) may be extracted from the thermal energy storage system for the desired length of time (e.g. a steady flow).

[0040] In some variations, the thermal energy storage medium can maintain a thermal gradient for a sufficient length of time during discharge of the system such that fluid heated to the desired temperature (e.g. superheated steam) may be extracted from the thermal energy storage system for the desired length of time (e.g. a steady flow). While the thermal gradient within the medium
may in some instances decrease substantially during the storage period, the thermal gradient is maintained sufficiently during the discharge period such that fluid heated to the desired temperature (e.g. superheated steam) may be extracted from the thermal energy storage system for the desired length of time.

**Homogeneous and non-uniform storage medium material distribution**

[0041] In some embodiments, the thermal energy storage medium is substantially homogenous or comprises a substantially homogenous mixture, and may be comprised of one or more materials and/or components distributed in a uniform manner along the length of the conduit and/or extending radially outward from the conduit. In some embodiments, the materials and/or components of the thermal energy storage medium are distributed in a non-uniform manner along the length of the conduit and/or extending radially outward from the conduit. For example, the thermal energy storage system, part 200 of which is depicted in Figures 3A and 3B, may have two or more different thermal energy storage materials or components surrounding a pipe or other conduit 210. A first material 220 in contact with the conduit may have about the same thermal conductivity as or a higher thermal conductivity than a second material 230 contacting the first material. The first material provides a larger heat-exchange surface to contact the second material, which may store most of the thermal energy transferred from the working fluid. The first material may also provide better thermal contact with the conduit (e.g. by comprising a liquid or having a smaller particle size) than the second material. Additionally, the thermal energy storage medium may be the same along the full length of the conduit, or the thermal energy storage medium may vary along the length of the conduit. When the thermal energy storage medium is non-uniform (e.g. with respect to the cross-section of a conduit and/or along the length of the conduit), the non-uniformity may be present as a smooth (e.g. gradual) or step gradient of materials (e.g. a gradient from material A to material B, either continuously or in multiple discrete steps) and/or be present as a sharp division between the materials. Further variations are described in more detail below.

**Uniform and non-uniform conduit sizing and spacing**

[0042] A conduit may comprise multiple interconnected segments arranged in various configurations. A conduit may be substantially linear through the thermal energy storage
medium, or a conduit may follow any of a number of nonlinear paths, including coiled (e.g., helical), spiral, serpentine, and other winding or turning configurations. A serpentine portion of a conduit oscillates substantially within a plane, and may have, for example, angular or curved turns (see e.g. top and bottom figures in Figure 7, respectively). In some variations, multiple conduits may be used, e.g. arranged in a side-by-side manner or arranged in a nested or interpenetrating manner. For example, two or more substantially linear conduits may be arranged parallel to one another. Two or more serpentine conduits may be arranged in a side-by-side manner. Two or more coiled conduits may be arranged in an interpenetrating manner.

When multiple conduits are used, the conduits may have the same or differing configurations. As is described in more detail below, connections between multiple conduits may be changed in operation using valves or the like, e.g. so that multiple conduits may be charged in parallel but discharged in series. Conduit size and spacing within the thermal energy storage medium affects density of conduit and conduit surface area (and thus heat exchange area). The desired density and surface area of conduit may be determined by, for example, the thermal energy storage medium used (e.g. thermal conductivity), particular working fluid, fluid flow rate, operating temperature range, and the like. In some embodiments, the conduits are sized and spaced uniformly throughout the thermal energy storage medium. In some or all regions of the thermal energy storage medium, the conduits may also be sized and/or spaced non-uniformly. For example, in one instance as depicted in Fig. 4, conduits 330 in a first region 310 of the thermal energy storage system may have a smaller diameter than conduits in a second region 320 of the thermal energy storage system. Alternatively or additionally, as depicted in Fig. 5, some or all of the small diameter conduits 401, 402, 403, 404 of the first region 410 may merge into larger diameter conduits 405, 406 of the second region 420 of the thermal energy storage system. In this instance, the second region has fewer conduits than the first region has. Alternatively or additionally, as depicted in Figure 6, the amount (e.g., thermal mass as defined by the product of mass and heat capacity) of thermal energy storage medium around and in thermal contact with a particular section of a conduit may vary. Alternatively or in addition, the conduit 501 of Fig. 7 may follow a nonlinear path in a region, and the packing density (e.g. pitch of a coiled, helical, or serpentine configuration) of conduit in a first region 510 may differ from a packing density of conduit in a second region 520. For instance, a conduit 502 may have a serpentine (or coiled, helical, etc.) configuration with uniform spacing period, so that adjacent conduit portions are
spaced the same distance from one another. The conduit spacing period in a first region 510 may differ from the conduit spacing period in a second region 520.

[0043] In some variations, it may be desired to increase the surface area (and thus heat exchange area) of the conduit per unit of volume or mass (or thermal mass) of thermal energy storage medium in the superheat zone, e.g. by lengthening the conduit, and/or by adjusting the outer diameter of the conduit. In some cases, it may be desired to use longer conduits having smaller diameters within a superheat zone. Without wishing to be bound by theory, use of longer conduits within the superheat zone may permit the use of smaller-diameter conduits within that zone, thus increasing the length of the conduit within the superheated zone and thus increasing the dwell time of the working fluid and more efficient heat exchange in the zone. Additionally, the smaller-diameter conduits may increases fluid velocity in comparison with a larger-diameter conduit. Increasing a ratio of surface area of conduit to unit thermal mass of thermal energy storage medium and/or adjusting dwell time within the conduit may ensure rapid heat transfer in the superheat zone, allowing the superheat zone to be more compact with better utilization of the medium than it would otherwise have to be if conduit of the same diameter were used throughout the thermal energy storage system. Additionally, as described in more detail herein, decreasing the amount (e.g. thermal mass) of thermal energy storage medium around and in contact with a particular section of a conduit (e.g. by increasing the packing density of conduit or by directly decreasing the volume or mass or thermal mass of thermal energy storage medium around the conduit) within the superheat zone may facilitate creation of the thermal saturation subzone.

[0044] In various embodiments, the conduit within the latent heat zone may be of larger diameter and/or surrounded by a greater volume or mass or thermal mass of thermal energy storage medium than in another zone (e.g. the superheat zone). Without wishing to be bound by theory, since it is more efficient to transfer heat into and out of a liquid, the relative surface area of the conduit per unit volume of the working fluid may be decreased, and thus the conduit may be of larger diameter. Additionally, since the majority of heat transferred into the thermal energy storage medium is generally from latent heat, a greater amount (e.g. thermal mass) of thermal energy storage medium may be present surrounding and in thermal contact with the conduit in
the latent heat zone (e.g. by decreasing the packing density of conduit or by directly increasing the radius of thermal energy storage medium around the conduit).

[0045] A third zone (e.g. preheat zone), if present, may have the same or different density of conduits, conduit spacing period, and/or heat exchange area per unit volume of conduit and/or thermal energy storage medium as either of the first and second zones of the thermal energy storage system. In some variations, a third zone has a higher ratio of mass, thermal mass, or volume of thermal energy storage medium per unit surface area of a conduit within that zone.

[0046] While the various configurations of conduit were discussed above with respect to zones, it is to be understood that these zones are not static regions within the thermal energy storage system, but may shift along the length of the conduit during charging and discharging of the system. Thus, discussion of having certain conduit configurations within a particular “zone” indicates that the configuration may be present in at least a portion of the zone during at least a portion of the charging or discharging time.

[0047] Fig. 8 depicts an example of a thermal energy storage system 800 in which two coiled conduits (e.g. pipes) 801 depicted by the solid and dotted lines having varying spacing or period between adjacent courses of the pipe as the pipe winds its way from one side of the thermal energy storage system to the other side of the thermal energy storage system. It should be noted that in some variations, where more than one conduit or pipe may be used, the conduits may be displaced from each other and/or interpenetrating. The two coils in Fig. 8 may be, for example, displaced from each other horizontally and offset vertically, or may be interpenetrating. The thermal energy storage medium 813 in the lower region 830 where a pipe has larger period spacing differs from the thermal energy storage medium 812 in the middle region 820, and each thermal energy storage medium differs from the thermal energy storage medium 811 in top region 810. The composition, mass, thermal mass, or volume of thermal energy storage medium for each region may be selected based on the available thermal energy to be captured, temperature, and size of the region, for instance. In some variations, the composition of the thermal energy storage medium may be substantially constant along the length of the conduit, but the volume or mass of the storage medium may be less in one region compared to another region. The thermal energy storage mediums may comprise more than one different dry materials, or one or more of the thermal energy storage mediums may comprise a liquid, e.g.
molten salt, at operating temperature. If multiple pipes are used, adjacent pipes may be displaced linearly so that one of the pipes is spaced apart from the other pipe in portions of each region of the thermal energy storage medium in order to increase or maximize contact with and thermal energy conduction into all areas of the thermal energy storage medium. The pipes may be spaced to help provide a reasonably even temperature distribution in a cross-section of each region.

**Thermal Saturation**

[0048] In some embodiments, a subzone is created within at least a portion of the superheat zone (see “TS” in Figure 1B). In this subzone (the “thermal saturation subzone”), the thermal energy storage medium is saturated with heat, such that the subzone is substantially isothermal (i.e. at a substantially uniform temperature), both radially from the conduit as well as lengthwise along the conduit. Without wishing to be bound by theory, creation of the thermal saturation subzone may permit more efficient heat extraction from the medium, and higher maximum temperature of the extracted working fluid. In the superheat zone, the working fluid is a gas, and it is generally more difficult to transfer heat into a gas than into a liquid. The thermal saturation subzone increases the length (and thus dwell time) of conduit in thermal contact with thermal energy storage medium at its maximum temperature. Additionally, since in these embodiments there is no thermal gradient radially out from the conduit, there may be a more rapid flow of heat into the working fluid, since there is no radial thermal gradient to work against such heat flow. To assist with achieving thermal saturation within at least a portion of the superheat zone, the packing density of conduit (e.g. increasing density), thermal energy storage medium materials (e.g. increasing thermal conductivity and/or thermal contact) and/or size (e.g. decreasing amount such as mass, thermal mass or volume of thermal energy storage medium around and in thermal contact with the conduit), and/or thermal interface between the fluid and thermal energy storage medium (e.g. increasing surface area of the conduit increases heat transfer) may be adjusted. For example, in some embodiments, the radius of the thermal energy storage medium around the conduit is smaller in the thermal saturation subzone than in another zone (e.g. latent heat zone). Without wishing to be bound by theory, with a smaller radius of thermal energy storage medium, the thermal energy storage medium may reach thermal saturation more quickly and readily.
A description of various components of a thermal energy storage system and the incorporation of a thermal energy storage system into a larger system are described below. These components may of course be incorporated as appropriate into any of the thermal energy storage systems discussed herein.

**Conduit(s)**

The conduit(s) may be made from any material and in any configuration suitable for transporting the working fluid to be used in the thermal energy storage system. Any suitable diameter or closed cross-sectional shape may be used, and the conduits further may be made out of any material suitable for transferring heat from the working fluid to the medium and vice versa. The conduits, for example, may be metal, a polymeric material, silicon carbide, fused zirconia or other very high strength ceramics. Non-limiting examples of metal conduits include those comprising carbon steel, low carbon steel, medium carbon steel, stainless steel, black iron, carbon-manganese steel, mild steel, and low alloy steels containing nickel chromium, molybdenum, vanadium, copper, niobium, or titanium. In some embodiments, the conduits comprise low carbon steel. In some embodiments, the conduits comprise medium carbon steel. In some embodiments, the conduits comprise pipes. In some embodiments, the conduits are ASTM A106 Grade B seamless steel pipes or ASTM A210 carbon steel pipes. In some embodiments, the conduits meet local code requirements for the temperature and pressure ranges of intended use (e.g. boiler code such as promulgated by a standards setting organization such as ASTM, ASME or ISO). In some embodiments, the external surface of the conduits are corrosion resistant with regards to the storage medium. In some instances, the conduits may be conduits formed in or bored through the thermal energy storage medium. The conduits may optionally comprise the fluid channeling devices as described in U.S. Patent Application Serial No. 12/135,124 filed June 6, 2008, and titled “Granular Thermal Energy Storage Mediums and Devices for Thermal Energy Storage Systems”, which is incorporated by reference herein in its entirety, and may further optionally include one or more of the thermally conductive heat transfer elements, also as described therein.

In some embodiments, the conduits comprise pipes. In general, the pipes may have a diameter of about 0.25” to about 16”. Pipe diameters listed herein indicate the nominal inside diameter of the pipe. In some embodiments, the diameter of the pipes is about 0.25” to about 4”.

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In some embodiments, the diameter of the pipes is about 0.5” to about 2.0”. In some embodiments, the diameter of the pipes is about 0.5” to about 1.0”. In some embodiments, the diameter of the pipes is about 0.25” to about 0.5”. In some embodiments, the diameter of the pipes is about 1” or less. In some embodiments, the diameter of the pipes is about 0.75” or less. In some embodiments, the diameter of the pipes is about 0.5” or less. In some embodiments, the diameter of the pipes is about 0.5”. In some embodiments, the diameter of the pipes is at least about 0.5”. In some embodiments, the thickness of the pipe walls is about 1 to about 16 mm, for example about 1 to about 3 mm. In some embodiments, the thickness of the pipe walls is about 2.1 mm. In some embodiments, the thickness of the pipe walls is at least about 0.75 mm. In some embodiments, the pipes are Schedule 5 pipes. In some embodiments, the pipes are Schedule 10 pipes. In some embodiments, the pipes are Schedule 40 pipes. Generally, smaller diameter pipes are more effective at transfer of heat between the working fluid and the thermal storage medium, due to their greater surface area per unit volume. However, the lower limit of effective pipe size may be controlled by corrosion limits.

[0052] As described above, the conduit(s) may be configured within the thermal energy storage medium in any arrangement suitable for transporting the working fluid, in order to store thermal energy within the medium. In some embodiments, the conduit(s) are horizontal. In some embodiments, the conduit(s) are vertical. In some embodiments, the conduit(s) are linear. In some embodiments, the conduit(s) are serpentine. In some embodiments, the conduit(s) are curved. In some embodiments, the conduit(s) are coiled.

[0053] A conduit arrangement that is not linear from entry to exit of a thermal energy storage system, especially where the conduits are pipes, may be adopted to allow the pipe to flex or twist somewhat during thermal cycles. This configuration distributes stresses from thermal expansion and contraction along much more of the conduit length and limits the extent of conduit extension that must be accommodated at the thermal energy storage system’s entry and exit. A serpentine or coiled conduit path may therefore be adopted, and the conduit spacing period may be uniform or may vary as discussed previously.

[0054] A thermal energy storage system having pipes may also have one or more joints (e.g. swivel joints) incorporated along a length of pipes to form articulated piping, especially where the pipe is not linear from entry to exit of a thermal energy storage system. A joint (e.g. a swivel
joint) may permit easier out-of-plane movement and relieve stresses that might otherwise damage piping in the short or longer term. Articulated piping may be incorporated into any thermal energy storage system described above. A joint (e.g. a swivel joint) may be e.g. an area where two pipes were welded together. The dissimilar shape of the weld and imperfect alignment of the two pipes upon welding provide a natural point along a pipe for out of plane motion such as swiveling to take place.

[0055] The preferred length and density of the conduit(s) for a particular thermal energy storage system may depend on factors such as the particular thermal energy storage medium used (e.g. conductivity, heat capacity, thermal contact, etc), the diameter of the conduit(s), the total amount of energy to be stored by the system, the charging and/or discharging response time required by the system, the length of time for which constant output is desired, the particular materials that comprise the conduit(s), the particular working fluid used, the temperature range at which the working fluid operates, the flow rate of the working fluid, and the like. In some embodiments it is preferred that the conduit(s) be long enough (within the context of a particular thermal energy storage system) such that no working fluid vapor (e.g. steam) exits the system, thus reducing wasting of energy from the working fluid. In some embodiments, when the working fluid is water, and the conduit(s) are vertically arranged pipes, the height of the pipes is about 120 m. In some embodiments, the conduit is about 12 m along one or more axes. For example, the overall dimensions of a serpentine conduit within a thermal energy storage system may be about 12 m in height, and 12 m in width (with the length of the conduit being longer than 12 m). The conduit(s) may be arranged and/or shaped in order to maximize conduit length within a particular size of a thermal energy storage system unit. For example, a thermal energy storage system unit, comprised of the conduit disposed within a volume of thermal energy storage medium, may be 12m x 12m x 12m. A conduit which is placed vertically within this thermal energy storage medium has a maximum of 12m in length. However, by inclining the conduit from vertical, or by introducing bends into the conduit, a longer conduit may fit within the thermal energy storage medium. Thus, by using inclined serpentine shapes, coils, or other such shapes, a longer conduit may be made to fit within a particular size thermal energy storage system, and thermal energy storage may be optimized in three dimensions.
Working Fluid

[0056] Various embodiments of the present invention are described herein in the context of using water (or in its vapor/gaseous stage, steam) as the working fluid within the thermal energy storage system, and directly using the steam generated by extraction of the thermal energy stored within the thermal energy storage system (e.g. for direct admission to a turbine, for heat exchange with a fluid that is expanded through a turbine, or for use as process or industrial steam, etc.). However, it is to be understood that other fluids may be used as the working fluid in the thermal energy storage system. For example, the working fluid may in various embodiments comprise a water mixture (e.g. water plus ammonia), a hydrocarbon (e.g. pentane), carbon dioxide, air, or other suitable fluid. The working fluid may be used directly (e.g. to drive a turbine), or may exchange heat with a second fluid (e.g. an organic fluid used in organic Rankine-cycle turbines that is expanded through the turbine). As will be apparent to one of skill in the art, certain fluids may be useful in some applications but not others.

Thermal Energy Storage Medium Materials

[0057] When used in the context of an element of a thermal energy storage medium, “material” as used herein indicates e.g. rock, gravel, sand, silt, soil, ceramic, as well as specific types, chemical compositions, or isolated fractions thereof. Thus, a “material” may be, for example, rock, quartzite rock, alumina, or clay (e.g. clay may be an isolated fraction of some soils). When used in the context of an element of a thermal energy storage medium, “component” as used herein indicates a particular material of a particular size class (i.e. having a particular size range for the component particles). For example, a component may be sand of about 0.1 to about 2 mm in size. In another example, a component may be basalt rock of about 50 to about 60 mm in size. When used in the context of an element of a thermal energy storage medium, “constituent” as used herein indicates a mixture of two or more components.

[0058] Non-limiting examples of materials which may be useful for thermal energy storage include, for example, aggregate (e.g. rock (e.g. quartzite, granite, basalt, silicates, limestone, shale, hematite, alumina, periclase (MgO), etc.), gravel (e.g. quartzite, granite, basalt, silicates, limestone, shale, hematite, alumina, periclase (MgO), etc.), concrete pieces), sand, soil (e.g. topsoil and/or subsoil), clay, silt, soil organic material, metals, metal oxides (e.g. hematite, iron,
sand, alumina, periclase (MgO), glass (e.g. recycled glass), silicates, metal carbonates, graphite, metal nitrates, metal nitrites, metal nitrides (e.g. aluminium nitride), molten salts (e.g. nitrate and nitrite salts of lithium, sodium, potassium, and calcium), soluble minerals (e.g. soluble carbonates and nitrates), and liquids (e.g. silicone, mineral oil, glycerol, sugar alcohols, retene, tetracosane). Rock generally comprises particles which are greater than about 50 mm in size. In some embodiments, rock comprises granite, quartzite, basalt, a silicate, carbonate, nitrate, and/or oxide. In some embodiments, rock comprises granite, quartzite, basalt, and/or silicates. In some embodiments, rock comprises a carbonate, nitrate, and/or oxide which is naturally present in rock. In some embodiments, rock comprises a carbonate and/or oxide which is naturally present in rock. Gravel generally comprises the same materials as rock, with a size range of about 2 mm to about 50 mm. “Medium gravel” comprises gravel of about 25 mm. “Fine gravel” comprises gravel of about 6 mm. Sand frequently comprises a high percentage of silicates, but may in addition to or instead of silicates, may comprise one or more of any of the materials of rock or gravel, with a size range of about 0.06 mm to about 2 mm. “Coarse sand” comprises sand of about 1.5 mm. “Fine sand” comprises sand of about 0.3 mm. “Very fine sand” comprises sand of about 0.08 mm. Silt comprises particles of about 4 microns to about 60 microns, and may comprise organic material and/or any of the materials of rock, gravel, or sand. Generally, while the specific composition of “soil” may vary depending on the location of the soil sample, soil may comprise one but in general soil comprises a mixture of two or more (e.g. three, four, or more) of the following: rock, gravel, sand, clay, silt, and organic material. When soil is used as a material, the soil may be unwashed or washed (e.g. to remove organic material and/or clay). In some embodiments, the materials used in the thermal energy storage system do not decompose at the operating temperature range of the system.

[0059] Rock may in some embodiments be monolithic rock, crushed rock and/or quartzite. Gravel may in some embodiments be monolithic gravel, crushed gravel and/or quartzite. Quartzite has the highest conductivity at 250°C of all the types of minerals reported by Clauser and Huenges in their 1995 paper titled “Thermal Conductivity of Rocks and Minerals”, Rock Physics and Phase Relations, A Handbook of Physical Constants, American Geophysical Union (1995), the disclosure of which is herein incorporated by reference in its entirety. The conductivity of the quartzitic minerals, at 250°C, is between about 2.5 and about 4 W/(m.K).
The “size” of a particle of a material may be either the length of the longest dimension of the particle, or when the particle is spherical or approximately spherical, may be the diameter of the particle. In some embodiments, the size is the length of the longest dimension. In some embodiments, the size is the diameter.

The various materials may be used alone or be mixed, and may be used in their naturally occurring form, in crushed form, or in a consolidated form, such as in the form of bricks or blocks, provided that when the thermal energy storage medium is a “granular thermal energy storage medium”, the consolidated forms are granular materials of the medium (i.e. the medium as a whole is not bound together, such as with conduits encased in concrete). The medium materials when in consolidated form may comprise, for example, concrete blocks composed of low fraction cement, or bricks formed from, for example, bonded aluminium oxide particles. The materials may in some embodiments be smoothed, either naturally (e.g. river pebbles) or artificially.

Additionally, the medium may optionally be wet or dry compacted to maximize density and conductivity, but this compaction may be moderated to avoid frictional stress on the conduits, and additionally, in the case of granular thermal energy mediums, the medium will retain its granular integrity after exposure to water. When wet compaction is used, the inclusion of the smallest particles, in particular of clays, of less than about 15 microns, in some embodiments less than about 10 microns, may facilitate compaction but may also lead to shrinkage on drying, causing high thermal stresses. In general, for the granular thermal energy storage mediums, when clay is present, it is present in a low enough concentration such that if the medium gets wet, the medium will retain its granular integrity and the clay will not act as a binder.

**Thermal Energy Storage Mediums**

Generally, the thermal energy storage medium may comprise one or more materials, components, and/or constituents. Various examples of mediums are described below. When placed within a thermal energy storage system of the invention, the medium is arranged such that heat convection and conduction within the medium is suppressed along the length of the conduit, such that a temperature gradient is created in the thermal energy storage medium along the
length of the conduit during thermal charging and/or discharging of the system. The temperature
gradient may be sustained over time to such an extent that superheated working fluid may be
extracted from the system for a sustained period of time (e.g. at least about 30 minutes, at least
about 1 hour, at least about 2 hours, at least about 3 hours, at least about 4 hours, at least about 6
hours, at least about 8 hours). Various methods may be used to suppress convection and
conduction, for example, the medium itself may suppress convection and conduction
longitudinally (e.g. solids or mixtures of solids having low overall conductivity, viscous molten
salt slurries, etc. as described below), and/or through physical means (e.g. thermally insulating
baffles and/or barriers placed within the medium and/or physical isolation of regions of
medium). Examples of specific embodiments for physical separation of the medium are
described below with reference to specific mediums. However, it is to be understood that the
physical thermal isolation methods described herein may or may not be used in conjunction with
other types of mediums described herein. Additionally, it is further to be understood that the
examples of mediums described herein may be used in conjunction with one or more physical
thermal isolation methods as described herein.

[0064] When thermal conduction is suppressed solely by the particular materials used as the
thermal energy storage medium, the thermal conductivity (at the operating temperature of the
system) of each of the thermal energy storage medium materials is generally less than about 30,
less than about 20, less than about 15, less than about 10, less than about 5, less than about 4,
less than about 3, less than about 2, less than about 1, about 0.1 to about 5, about 0.3 to about 5,
about 0.5 to about 5, about 0.5 to about 4, about 0.5 to about 3, about 1 to about 3, about 2 to
about 3 W/(m-K). However, in some instances the thermal conductivity of the bulk of the
materials used in the thermal energy storage medium may fall within these ranges, and a smaller
portion of one or more materials may have a higher conductivity, provided that the overall
thermal conductivity of the thermal energy storage medium provides the useful thermal gradient
characteristics as described herein. In general, the overall thermal conductivity of the medium,
when no physical thermal isolation barriers are present, is generally less than about 30, less than
about 20, less than about 15, less than about 10, less than about 5, less than about 4, less than
about 3, less than about 2, less than about 1, about 0.1 to about 5, about 0.3 to about 5, about 0.5
to about 5, about 0.5 to about 4, about 0.5 to about 3, about 1 to about 3, about 2 to about 3
W/(m-K). As described in more detail below, in some embodiments, the thermal energy storage
medium comprises a viscous slurry (e.g. of one or more molten salts and one or more solid particulate materials such as sand or soil). In some variations, as regions of thermal energy storage medium regions become increasingly well-insulated from one another through physical means, materials having a higher thermal conductivity may optionally be used in the thermal energy storage medium, and the overall thermal energy storage medium conductivity may be increased.

[0065] In some embodiments, the thermal energy storage medium comprises two or more components distributed heterogeneously within the medium such that one or more physical properties of the medium vary with distance from the one or more conduits. For example, the thermal energy storage medium may comprise a gradient of components, e.g. in thermal conductivity decreasing radially outward from the conduits. Examples of suitable mediums include those described in U.S. Provisional Patent Application Serial No. 61/059,748 filed June 6, 2008, and titled “Thermal Energy Storage System Comprising Varying Physical Properties and Methods For Use” which is incorporated herein by reference in its entirety.

[0066] In some embodiments, the thermal energy storage medium comprises: (a) a first annulus of a highly thermally conductive material in contact with the conduit and having a conductivity K1 and (b) a second (outer) annulus of a conductive material in contact with the first annulus and having a conductivity K2, which may be about equal to or lower than K1 (see e.g. Figures 3A and 3B, in which 220 represents the first annulus, and 230 represents the second annulus). In some embodiments, the first and/or the second annulus may comprise more than one material or component. In general, K1 may be at least about 1, at least about 2, at least about 3, at least about 5, at least about 10, at least about 15, at least about 20, or at least about 30 W/m-K, and K2 may range from about 0.1 to about 4, about 0.3 to about 4, about 0.3 to about 3, about 0.3 to about 2, about 0.3 to about 1.5, about 0.1 to about 0.5 W/m-K, at the operating temperature range of the system.

[0067] In order to maximize efficiency of heat transfer to the thermal energy storage medium, the material in the first annulus may be selected for high thermal conductivity and additionally, may have high thermal contact with the conduit. Use of more thermally conductive material(s) may further permit use of shorter lengths of the conduit(s), which lowers the costs of the conduit material (e.g. metal), since heat may be transferred into and out of the working fluid more
efficiently. High thermal contact may be achieved by using, for example, a small particle size of the material, in order to avoid gaps between the conduit and the medium. Alternatively or in additional, liquid materials (e.g. molten salts such as nitrate or nitrite salts of lithium, sodium, potassium or calcium) may be used to achieve high thermal contact with the conduit(s). An example of material in the first annulus includes, for example, alumina (K of about 10-30 W/m-K). Having a first annulus comprised of a highly conductive material with high thermal contact with the conduit effectively increases the surface area of the conduit, permitting more efficient transfer of heat to the second annulus material.

[0068] Since the materials which are highly effective as first annulus materials may in some instances be prohibitively expensive to use for the entire thermal energy storage system (e.g. alumina), it may be advantageous to combine an inner annulus as described above with a second (outer) annulus comprised of a less expensive material(s) which may have a lower conductivity, for example, sand or soil (K of approximately 0.3 to about 0.5 W/m-K), low-cost granulated ceramics, or a mixture thereof. The materials themselves may be inexpensive, and additionally, may advantageously be found near to the site of the thermal energy storage system, minimizing transportation costs for the material(s) to the site of operation.

[0069] The relative radial cross-sectional thickness of the first and second annulus may vary depending on the specific thermal energy storage medium materials used, the costs of the materials used, the flow rate of the working fluid, the response time required by the system during charging and discharging, the amount of energy to be stored by the system, etc. In some embodiments, the second annulus may be thicker than the first annulus. In some embodiments, the second annulus is about two times thicker, or at least about two times thicker, than the first annulus. Poor thermal conductivity of a storage material can be matched with an appropriate radius ratio between a first and second annulus such that under peak heat flow conditions, heat will not be supplied or withdrawn too quickly for the outer annulus to conduct. In some embodiments, the volume, mass or thermal mass of the material(s) in the second annulus is about 2-3 times the volume, mass or thermal mass of the material(s) in the first annulus. In some embodiments, the volume, mass, or thermal mass of the material(s) in the second annulus is greater than about 3 times the volume, mass, or thermal mass of the material(s) in the first annulus.
The thermal energy storage medium materials may be present in various configurations, for example, a continuous long cylinder (see Figure 9A) or series of smaller cylinders/canisters (see Figure 9B) surrounding a conduit. The medium may directly contact the conduit and/or may contact the conduit via an inner cylinder wall. Additionally, the cylinders may have an inner wall between a first and a second annulus (see Figure 9C). Any suitable storage mediums described herein or otherwise known may be used with such configuration variations. For example, for a continuous long cylinder configuration as illustrated in FIG. 9A, a viscous slurry comprising one or more molten salts and a particulate filler such as sand or soil as described herein may be used to fill the cylinder surrounding and in thermal contact with the conduit. For a configuration as illustrated in FIG. 9C, a thermally conductive liquid such as one or more molten salts or a viscous slurry may be used to fill the volume of the first annulus around a conduit defined by the inner cylinder wall, and a storage medium that is a solid (e.g. particulate or granular) or a slurry may be used to fill the volume of the second outer annulus. Additionally, the cylinder(s) (e.g. such as those shown in Figs. 9A-9C) may optionally be surrounded by additional thermal storage medium, which may be the same or different from the medium(s) inside the cylinder(s). For example, the cylinder(s) may be surrounded by one or more of e.g. soil, sand, rock, gravel, a slurry, or the like. In some variations, the cylinder(s) are set into the ground, and are surrounded by a medium comprising the ground soil. Without wishing to be bound by theory, such configurations may in some variations improve the efficiency of heat transfer from the working fluid to the storage medium. For example, the medium contained within the cylinder(s) may have high thermal conductivity, and the cylinder(s) provide a relatively larger surface area to the medium outside the cylinder(s), thus improving transfer of heat into the medium outside the cylinder(s).

When a configuration incorporating a long cylindrical form of the storage medium in thermal contact with a cylinder (such as illustrated in FIGS. 9A-9C) that is filled with a liquid or slurry, it may be desired to control or localize convection along the length of the cylinder, so as to aid in the formation of a thermal gradient along the length of the conduit as described herein. That is, in some variations a long cylinder configuration may encourage local isolated circulation patterns with limited axial conductivity so as to enable formation of a sustainable axial thermal gradient within the thermal energy storage medium. For example, a highly viscous slurry may be used in a continuous long cylinder (e.g. as illustrated in FIGS. 9A and 9C), where the highly
viscous nature of the medium limits convection, thereby allowing formation of an axial gradient that can be sustained over a desired storage time. In other variations, a long cylindrical form may be physically subdivided so that convection along the length of the cylinder is limited to lengths of those subdivisions. Any type of subdivision may be used so as to effectively limit convection along the length of the cylinder, e.g. baffles, flow control devices, and the like. In some variations, a long cylindrical form may be subdivided into a series of discrete cylinders arranged in a generally colinear manner as illustrated in FIG. 9B. The series of individual cylinders may be used to permit convection within each cylinder, but sufficiently isolate the cylinders from each other so that substantially no inter-cylinder flow occurs, thus creating the thermal gradient along the length of the conduit. The series of individual cylinders may advantageously be configured to accommodate linear thermal expansion. In some embodiments, the series of individual cylinders may be separated by a gap (e.g. about 1 cm), to allow for thermal expansion of the individual cylinders upon heating. Any suitable thermal energy storage material may be disposed within the cylinders to effectively receive and store heat from a working fluid in the conduit during charging, and to provide heat to a working fluid upon discharge. For example, the individual cylinders may be at least partially filled with one or more molten salts (such as nitrate or nitrite salts of lithium, potassium, sodium or calcium) or, in some variations, a slurry (e.g. one or more molten salts mixed with soil or sand). It should be noted that the series of individual cylinders may be surrounded by another thermal energy storage medium, e.g. soil, sand, rock, gravel, a slurry, or the like. Thus, the gap may optionally comprise a band or other sealing means between the gaps, to prevent the thermal energy storage medium materials (e.g. sand, soil) from entering the gap zone. If the gap is not sealed, a storage medium such as sand or soil may ingress into the gap over time as the individual cylinders expand and contract, causing ratcheting which may eventually damage the system. Additionally, the gap may help to maintain the temperature gradient, as the gaps act as thermal insulators. The cylinders may be comprised of, for example, steel or ceramic tubes, e.g. steel pipes where the particular steel has been selected for the operational pressures and temperatures of the system. The cylinders may optionally be surrounded by a thin wall sand-filled cylinder to modularize for easy installation and removal if a weld cracks. In some embodiments, the cylinder diameter is about 20 cm, for a conduit comprised of 1 to 2 inch diameter pipe.
In some embodiments, e.g. for a configuration such as illustrated in FIGS. 9A and 9B, the thermal energy storage medium in direct contact with the conduit comprises a slurry that is, in turn, comprised of a liquid (e.g. oil, molten salt) and one or more solid materials. Since liquids make excellent contact with the conduit, a slurry that wets all surfaces avoids thermal contact problems associated with dry mediums. Molten salts convect like water at elevated temperatures, and additionally, unlike some liquids, molten salts do not have a vapor pressure, making them safer for use in a high temperature system, and are often cheaper than oils. However, liquids (such as oils) with vapor pressure may be used in the slurry, optionally in conjunction with a N₂ blanket. The molten salts are molten and preferably do not decompose at the operating temperatures of the storage system. For example, when water is used as the working fluid, the operating temperature range is about 200 to about 500 °C. Examples of molten salts include, for example, nitrate and nitrite salts of lithium, sodium, potassium, and calcium. Molten salts useful in the invention frequently have melting temperature of at least about 150°C. In various embodiments, the molten salt comprises a 50/50 (by weight or volume) mixture of NaNO₃ and KNO₃ (stable to 540°C). Addition of CaNO₃ as a minor component to this mix will lower the melting point of the mixture.

One or more additional (solid) materials (e.g. aggregate, sand, or soil (optionally with the organic material removed)) may be added to the molten salt, and in some variations, may be added in sufficient quantities so that the mixture has the properties of a viscous slurry. It may be preferred to increase the amount of solids relative to the amount of salt, provided that the surfaces of conduit(s) are wet: increasing the amount of e.g. sand in the slurry may reduce the cost of the thermal energy storage medium, and increase the overall conductivity of the slurry. In some embodiments, the overall K of the slurry is about 0.5 to about 4, about 0.5 to about 3, about 0.5 to about 2, about 1 to about 3, about 1.5 to about 3, about 2 to about 3 W/(m-K). In some embodiments, the ratio of solid:liquid (e.g. sand:salt) is at least about 2:1 (by weight or volume). The additional solid materials in some embodiments may be filtered or otherwise selected by particulate size; a uniform size of particulate is less like to ratchet or settle within the slurry. In some variations, the average particle size and particle size distribution may be selected so that the particles form a physically stable network or framework surrounded by the liquid component, wherein the particles in the network or framework generally do not move relative to each other.
[0074] The overall conductivity of the slurry medium may affect the conduit length required to efficiently extract the energy available from the working fluid. For example, when water/steam is the working fluid, a K of about 2.5 corresponds to a conduit length of about 120m. A lower K may require a longer length of conduit, and a higher K may effectively utilize a shorter length of conduit.

[0075] In some embodiments, the slurry may be viscous, to suppress convection within the slurry but still yield sufficiently to accommodate thermal expansion of the conduit and to wet the surface of the conduit to ensure excellent thermal contact. In some embodiments, the slurry may have a viscosity of approximately 50,000 to about 250,000, or approximately 50,000 to about 500,000, or approximately 50,000 to about $1 \times 10^6$ centipoise at operating temperatures. For example, in various embodiments, the slurry may have the viscosity approximating that of room temperature wet unset concrete, ketchup, or peanut butter. The viscosity of the slurry can be affected by selecting the particle size of the solid, the type of solid, and the amount of solid. In some variations, increasing the amount of solids (e.g. sand) in the slurry will increase the viscosity. In some variations, decreasing the particle size of the solid will increase the viscosity.

[0076] The advantages of the molten salt slurries described herein, in comparison with prior molten salt thermal energy storage two-tank systems, is that the current slurry mediums do not require salt pumps or heat traces for operation, lowering maintenance costs and costs associated with operation of the system.

[0077] Further examples of suitable mixtures which may be incorporated in the thermal energy storage system of the invention are described in U.S. Patent Application Serial No. 12/135,124 filed June 6, 2008, and titled “Granular Thermal Energy Storage Mediums and Devices for Thermal Energy Storage Systems,” which is incorporated by reference herein in its entirety, especially with respect to mixtures for thermal energy storage materials.

[0078] The particular thermal energy storage medium used for a particular thermal energy storage system may depend on factors such as the operating temperature of the system, the total amount of energy to be stored by the system, the charging and/or discharging response time required by the system, the length of time for which constant output is desired, the particular
materials that comprise the conduit(s), the diameter of the conduit(s), the particular working fluid used, the flow rate of the working fluid, and the like.


[0080] The thermal energy storage system may be located above ground level, below ground level, or partially below ground level. When located at least partially below ground level, the local soil available on site by digging the containment pit may advantageously be used in the thermal energy storage medium, thus lowering transportation costs of shipping materials to be used at the site of the system. Such soil may be filtered to remove organic material and also to sort the material by grain radius. When the storage system is located above ground, various methods of containment of the medium, such as concrete walls, may be used, as will be apparent to one of skill in the art.

**Thermal Energy Storage System Operation**

[0081] Typically, the thermal energy storage system accepts superheated steam directly from the field, via the conduit(s). Reverse flow of the working fluid through the conduit is frequently used for discharging and extracting heat from the system. However, in some embodiments, the working fluid is flowed into the system in the same direction when charging as well as discharging the system. Additionally, by utilizing valves that operate various portions of the system, other flow configurations are possible. For example, multiple conduits may be charged and/or discharged in parallel or sequentially. Heat storage modules formed of multiple conduits connected by header systems can be arranged in parallel to accept the peak volume of superheated or saturated steam on charging, and provide the desired peak volume of steam upon discharge. Alternatively or additionally, the interconnecting pipework can be rearranged with some of the modules in series on charging to change the effective length of the conduits.
Alternatively or additionally, the interconnecting pipework can be rearranged with some of the modules in series and the charging to change the output fluid flow rate characteristics for output time. In another example, two conduits may be charged in parallel, and then discharged in antiseries, such that when discharging the working fluid flows in the reverse direction through the first conduit, but then flows in the original direction (compared with the charging direction) through the second conduit. At least two superheated charged modules charged in parallel over a shorter period can be reconnected with the hot ends connected during discharge; fluid flow from the cold end to the hot end of the first, traveling then through the hot end of the second, will subsequently heat the colder end of the second and exit there, resulting in a steady flow of superheated steam at constant temperature for more hours than the charging time, although this constant temperature may be about 20 to about 50 °C, or about 20 to about 60°C below the peak supply superheating temperature. Additionally, the thermal energy storage system can be tailored to seasonal energy output by valving off certain portions of the system. Other variations in interconnection of modules will be apparent to one of skill in the art.

[0082] When superheated steam is used as the working fluid, the system may be suitable for up to about 600°C in operation. The system may be suitable for operation at pressures of about 25, about 50, about 75, about 100, about 150, or about 200 bar, or even higher pressures. In some embodiments, the system may deliver for some hours (e.g. at least about 0.5, at least about 1, at least about 2, at least about 3, at least about 4, at least about 6, at least about 8, at least about 10, at least about 12, at least about 14 hours) a constant volume and temperature of superheated steam close to but below the original superheated temperature of the steam from the field, provided the working fluid flow is held constant on discharge. In some embodiments, the change in temperature of the thermal energy storage medium contacting the conduit between charging and discharging is relatively uniform along the length of the conduit. Without wishing to be bound by theory, it is believed that this may increase the efficiency for transferring heat in and out of the thermal energy storage medium. In some embodiments, this change in temperature between charged and discharged states is about 60°C. In some embodiments, this change in temperature between charged and discharged states is about 100°C. In some embodiments, corrosion of the conduit(s) is reduced compared with other thermal energy storage systems, as the zone in which the working fluid boils is distributed over a relatively larger area.
Generally, the amount of energy to be stored and the rate at which energy must be extracted in operation affect the preferred embodiments for conduit length and diameter, particular thermal energy storage medium used, amount of thermal energy storage medium per unit length of the conduit, the flow rate and volume of the working fluid, etc.

Any of the thermal energy storage systems discussed above may be incorporated into a conventional, nuclear, or solar thermal energy power plant, or process or industrial steam plant, and may be utilized to capture heat from an appropriate fluid stream to store thermal energy for later use. In one instance, superheated steam is generated in a conventional power plant, e.g. coal or natural gas fired. In another instance, superheated steam is generated in a nuclear reactor. In a third instance, superheated steam is generated using solar energy from a tower, linear Fresnel array, or trough collector. In a fourth instance, superheated steam is generated using steam generated from a conventional power plant with a solar powered booster (e.g., admission of steam generated with solar energy into a portion of the steam circuit of the conventional plant to augment steam generated using other than solar energy). In some variations, a portion of the superheated steam may be used to drive a Rankine-cycle turbine to generate electricity, and a portion of the superheated steam may enter a thermal energy storage system as discussed above. In some variations, a portion of the generated steam may be used as process steam (e.g. for enhanced oil recovery, food processing, desalination, refrigeration and the like) and a portion of the steam may enter a thermal energy storage system as described above. Thermal energy at high temperature is transferred to and stored in a superheat zone of the thermal energy storage system, while thermal energy from latent heat and optionally from superheated steam is stored in a latent heat zone of the thermal energy storage system. Condensed hot water may leave the latent heat zone and be transferred directly to insulated hot water storage tanks, or heat may be extracted from the hot water and stored in a preheat zone of the thermal energy storage system. The stored thermal energy may be used and superheated steam may be generated by supplying water to the optional preheat zone and/or to the latent heat zone of the thermal energy storage system to vaporize the water, and saturated steam may then pass to the superheat zone where the saturated steam is superheated. One or more valves may be used to control pressure within the thermal energy storage system. The superheated steam is therefore of high quality because of the high temperature that can be achieved by the inventive thermal energy storage system and can be used to drive a Rankine-cycle turbine or can be used in another process if desired.
[0085] Variations and modifications may be made in respect of the power plant and thermal energy storage system as above described without departing from the scope of the invention as described and as defined in the following claim.
CLAIMS

1. A thermal energy storage system comprising:

(a) a conduit arranged to carry a working fluid; and

(b) a thermal energy storage medium;

wherein the conduit is disposed within and in thermal contact with the thermal energy storage medium; wherein during charging and/or discharging of the thermal energy storage system with thermal energy, a temperature gradient is created in the thermal energy storage medium longitudinally along the length of the conduit.

2. The system of claim 1, wherein the temperature gradient shifts along the length of the conduit as the system charges and/or discharges.

3. The system of any one of claims 1-2, wherein the system generates superheated working fluid upon discharge of the system.

4. The system of claim 3, wherein the superheated working fluid is superheated steam.

5. The system of any one of claims 1-4, wherein the thermal energy storage medium has a substantially homogeneous composition and/or structure along the length of the conduit.

6. The system of any one of claims 1-4, wherein the thermal energy storage medium composition and/or structure varies along the length of the conduit.

7. The system of any one of claims 1-4, wherein the physical distribution of the thermal energy storage medium varies along the length of the conduit.

8. The system of any one of claims 1-7, wherein the thermal energy storage medium is not pumped or otherwise moved under an external force.
9. The system of any one of claims 1-8, wherein the thermal energy storage medium comprises a highly viscous liquid or slurry.

10. The system of claim 9, wherein the highly viscous liquid or slurry comprises molten salt.

11. The system of claim 10, wherein the highly viscous liquid or slurry further comprises sand and/or soil.

12. The system of claim 9, wherein the highly viscous liquid or slurry comprises molten salt and sand at a ratio of about 1:2.

13. The system of claim 9, wherein the overall conductivity of the highly viscous liquid or slurry is about 2-3 W/(m-K).

14. The system of any one of claims 1-13, wherein one or more regions of the thermal energy storage medium are physically separated from each other.

15. The system of any one of claims 1-14, wherein the conduit is substantially in one plane.

16. The system of any one of claims 1-14, wherein the conduit is coiled.

17. The system of any one of claims 1-16, wherein the conduit is distributed non-uniformly within the thermal energy storage medium.

18. The system of any one of claims 1-17, wherein the conduit has a larger cross-sectional area in one region of the thermal energy storage medium than in another region.

19. The system of any one of claims 1-18, wherein a different volume of thermal energy storage medium surrounds the conduit along its length as the conduit extends through or traverses the thermal energy storage medium.

20. A method for storing thermal energy, the method comprising: (a) flowing steam into a conduit disposed within and in thermal contact with a thermal energy
storage medium, whereby heat is transferred from the steam to the medium for storage; and (b) forming a temperature gradient in the medium longitudinally along a length of the conduit, the temperature gradient in operation translating along the length of the conduit according to heat transfer between the steam and the medium.

21. The method of claim 20, wherein sufficient heat is transferred from the steam to the medium such that water exits the conduit.

22. The method of claim 20, wherein sufficient heat is transferred from the steam to the medium such that substantially no steam exits the conduit.

23. The method of any one of claims 20-22, wherein the temperature gradient is comprised of a superheat zone and a latent heat zone.

24. The method of any one of claims 20-22, wherein the temperature gradient is comprised of a superheat zone, a latent heat zone, and a preheat zone.

25. The method of any one of claims 20-24, wherein superheated steam may be extracted from the thermal energy storage system at a later time point.

26. The method of any one of claims 20-25, wherein at least a portion of the thermal energy storage medium within the superheat zone is fully saturated with thermal energy upon charging the system and the medium has a substantially uniform temperature along at least a portion of the conduit within the superheat zone.
FIG. 2A

FIG. 2B

SUBSTITUTE SHEET (RULE 26)
The PIM Thermal Storage Allows the Use of a Long Pipe of Variable Spacing and Non-uniform Medium Thermal Properties to Optimize the Efficiency of the System to Meet Different Thermal Output Requirement.

FIG. 8
**INTERNATIONAL SEARCH REPORT**

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(8) - F24J 2/34 (2010.01)
USPC - 126/617

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

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC(8) - F24J.204, 2/34 (2010.01)
USPC - 60/641.6; 126/617, 618, 620

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatBase

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>US 4,146,057 A (FRIEDMAN et al) 27 March 1979 (27.03.1979) entire document</td>
<td>1-4</td>
</tr>
</tbody>
</table>

Further documents are listed in the continuation of Box C.

* Special categories of cited documents:

  "A" document defining the general state of the art which is not considered to be of particular relevance

  "E" earlier application or patent but published on or after the international filing date

  "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

  "O" document referring to an oral disclosure, use, exhibition or other means

  "P" document published prior to the international filing date but later than the priority date claimed

  "R" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

  "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

  "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

  "&" document member of the same patent family

Date of the actual completion of the international search 09 March 2010

Date of mailing of the international search report 24 MAR 2010

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
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Authorized officer: Blaine R. Copenhaver
PCT Helpdesk: 571-272-4300
PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)
### INTERNATIONAL SEARCH REPORT

**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.: because they relate to subject matter not required to be searched by this Authority, namely:
   
2. ☐ Claims Nos.: because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☑ Claims Nos.: 5-19, 25, 26 because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:  

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:  

**Remark on Protest**

☐ The additional search fees were accompanied by the applicant’s protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant’s protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (2)) (July 2009)