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(54) **THERMAL ENERGY STORAGE SYSTEM**

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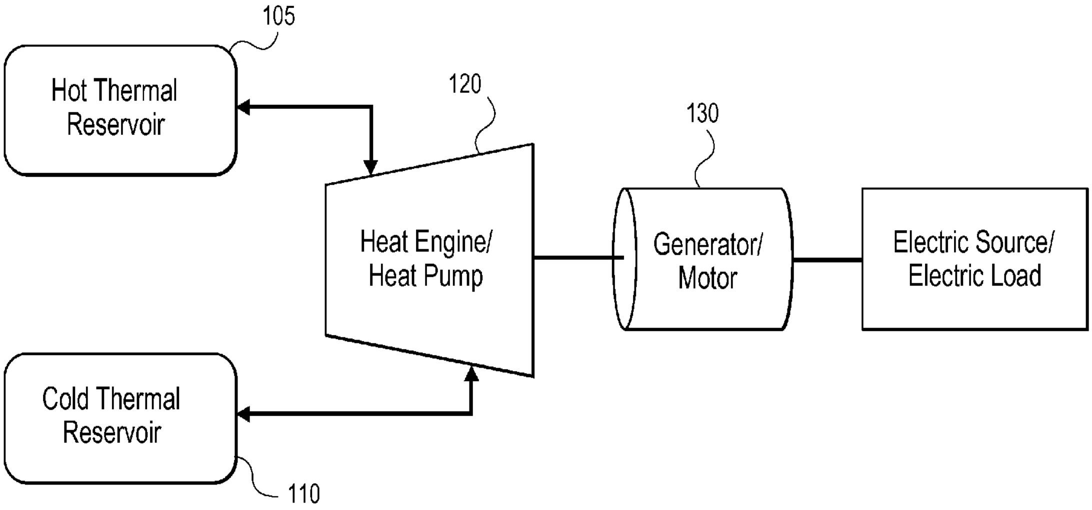
(57) **ABSTRACT**

A variety of energy storage and retrieval systems are described. Generally "hot" and "cold thermal reservoirs are provided. The "hot" reservoir holds both liquid and saturated vapor phase working fluid. The "cold" reservoir holds working fluid at a lower temperature than the hot reservoir. A heat engine/heat pump unit: (a) extracts energy from vapor passing from the hot reservoir to the cold reservoir via expansion of the vapor in a manner that generates mechanical energy to facilitate retrieval of energy; and (b) compresses vapor passing from the cold reservoir to the hot reservoir to facilitate the storage of energy. In some embodiments, the heat engine/heat pump takes the form of a reversible positive displacement heat engine that can act as both an expander and a compressor. To facilitate the storage and retrieval of electrical energy, an electric motor/generator unit may be mechanically coupled to the heat engine/heat pump unit.



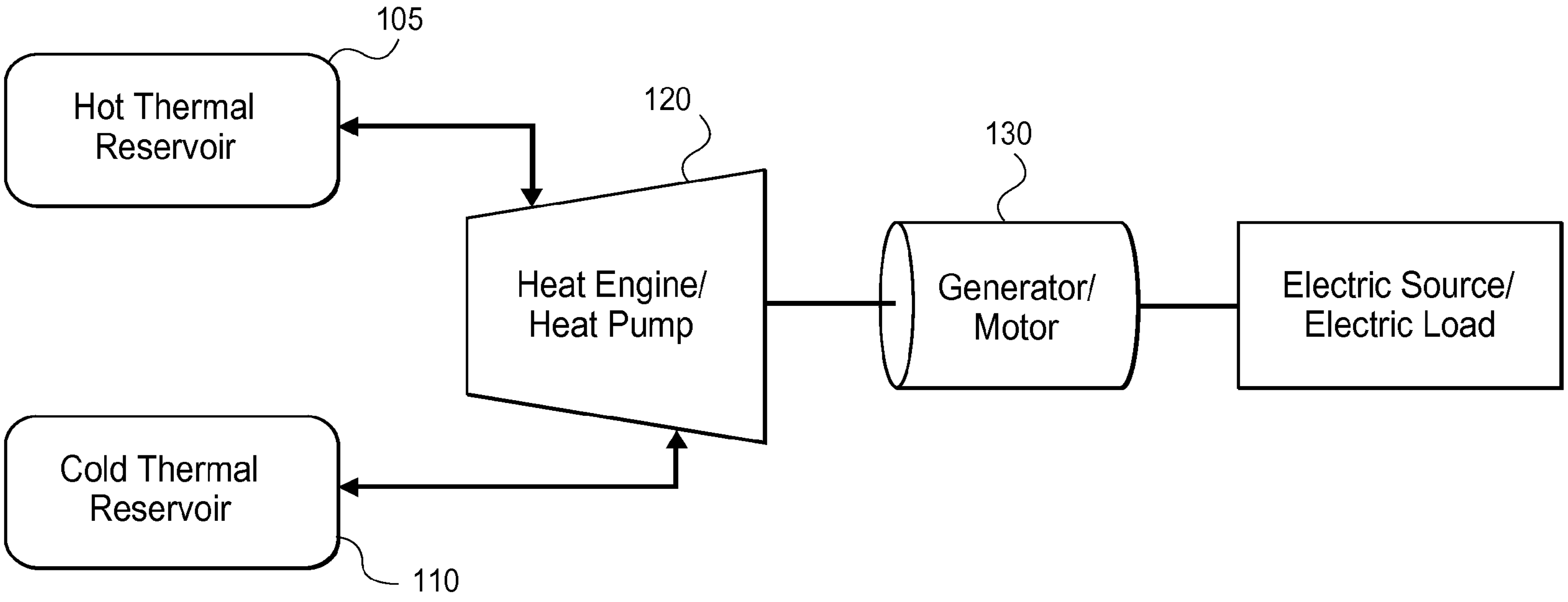

105
Hot Thermal Reservoir
120
Heat Engine/ Heat Pump
130
Generator/ Motor
Electric Source/ Electric Load
Cold Thermal Reservoir
110

FIG. 1

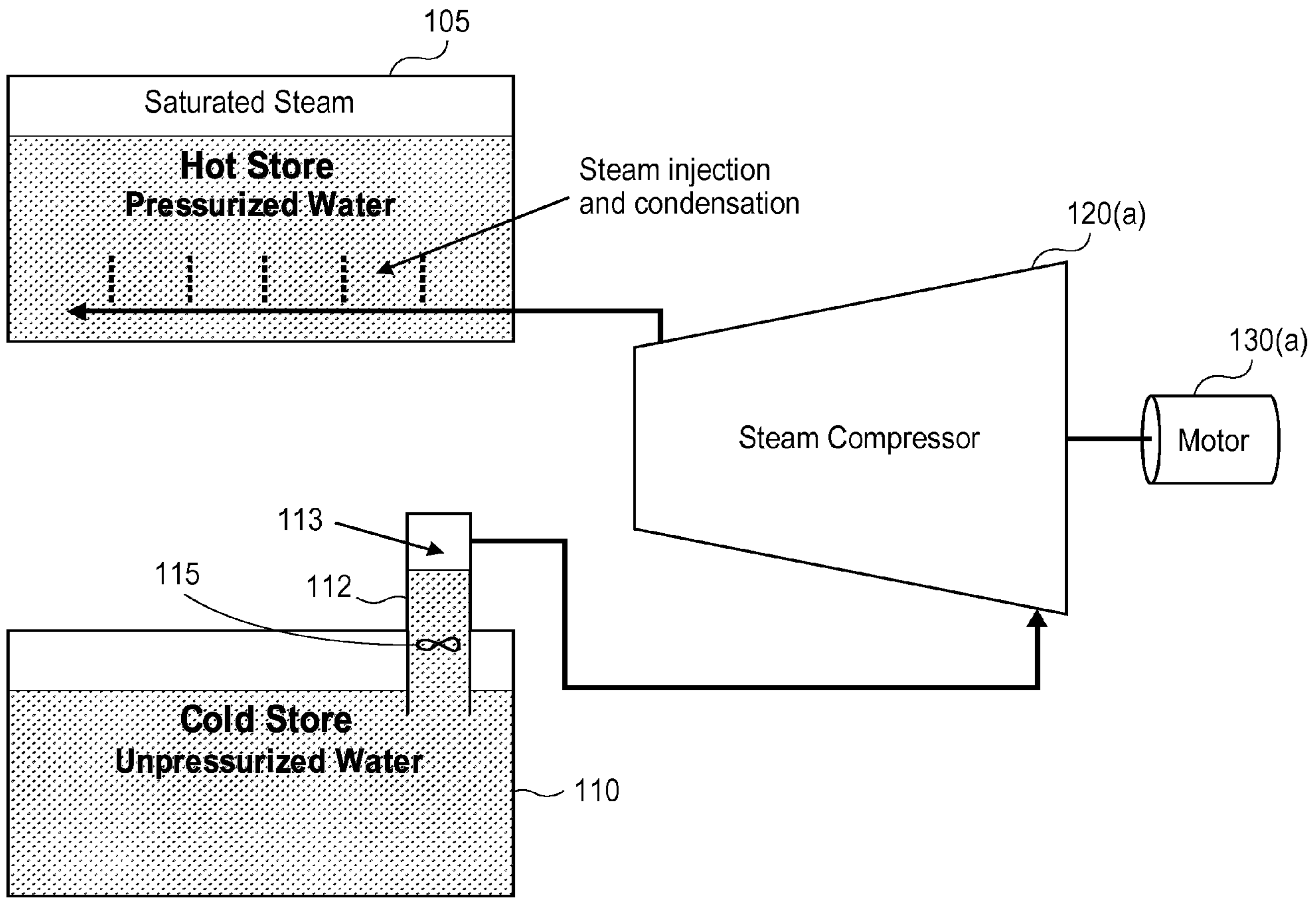

105
Saturated Steam
Hot Store
Pressurized Water
Steam injection
and condensation
120(a)
130(a)
Steam Compressor
Motor
113
115
112
Cold Store
Unpressurized Water
110

FIG. 2(a)

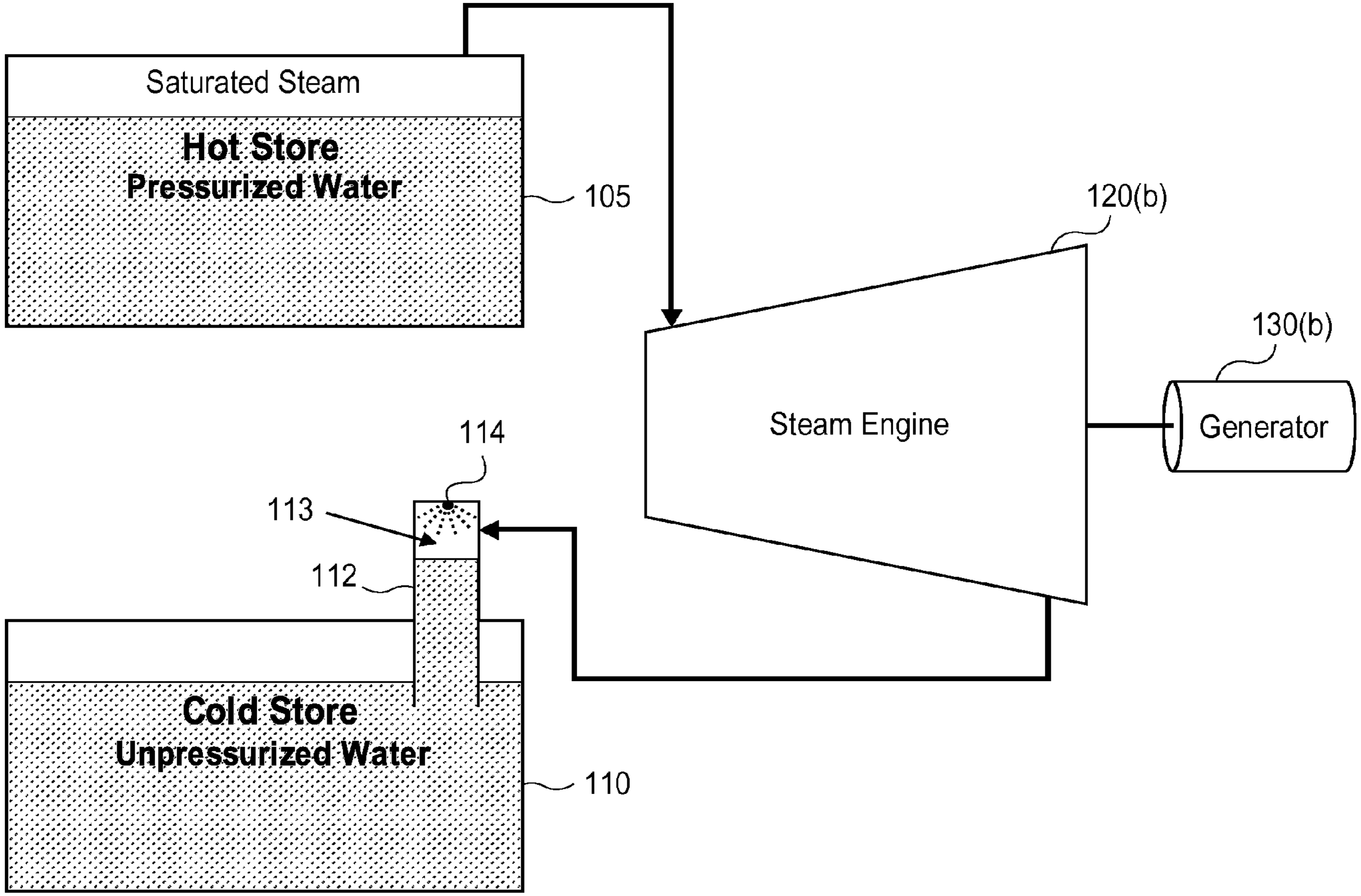

Saturated Steam
Hot Store
Pressurized Water
105
120(b)
130(b)
Steam Engine
Generator
114
113
112
Cold Store
Unpressurized Water
110

FIG. 2(b)

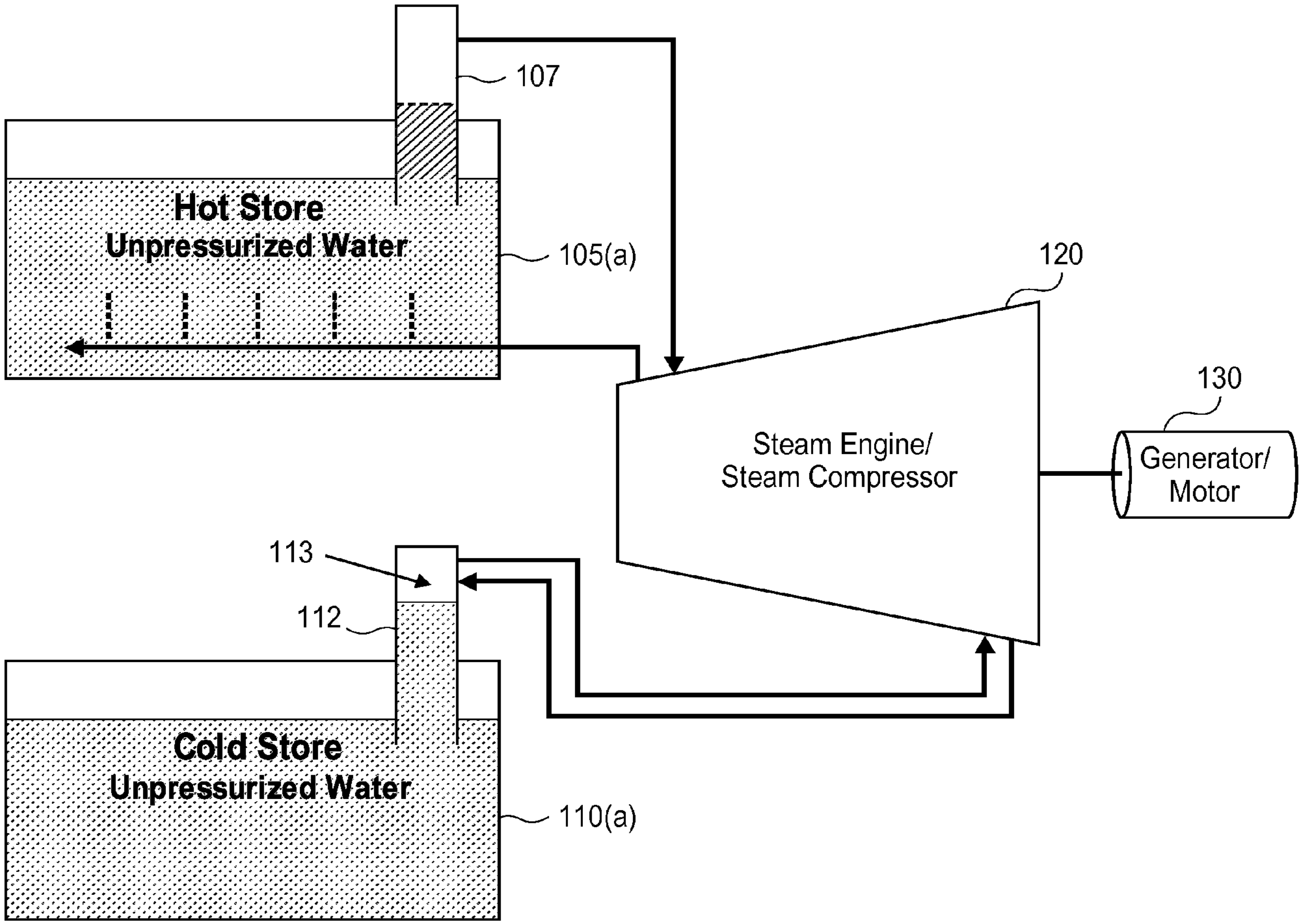

107
Hot Store
Unpressurized Water
105(a)
120
Steam Engine/
Steam Compressor
130
Generator/
Motor
113
112
Cold Store
Unpressurized Water
110(a)

FIG. 3

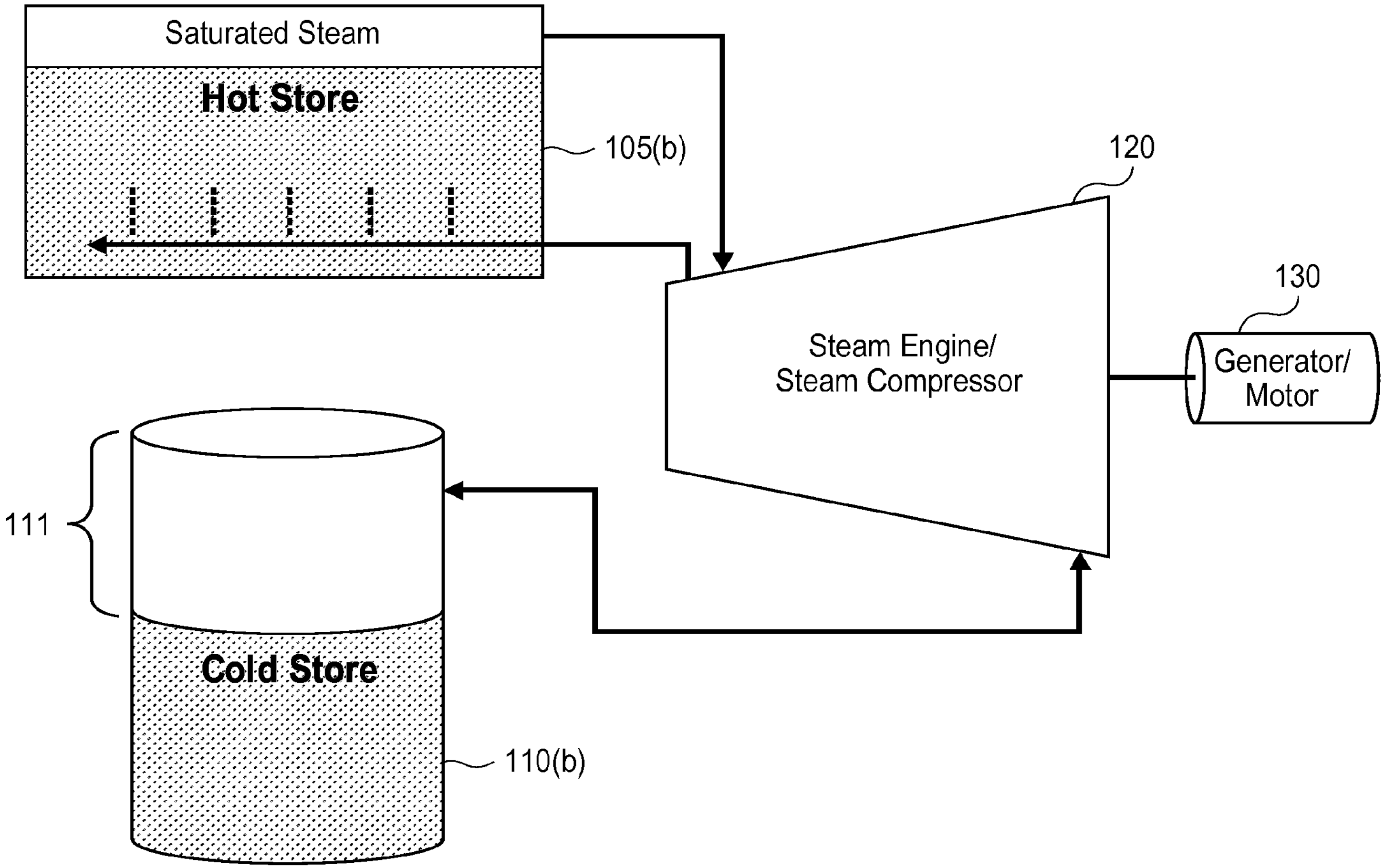

Saturated Steam
Hot Store
105(b)
120
Steam Engine/
Steam Compressor
130
Generator/
Motor
111
Cold Store
110(b)

FIG. 4

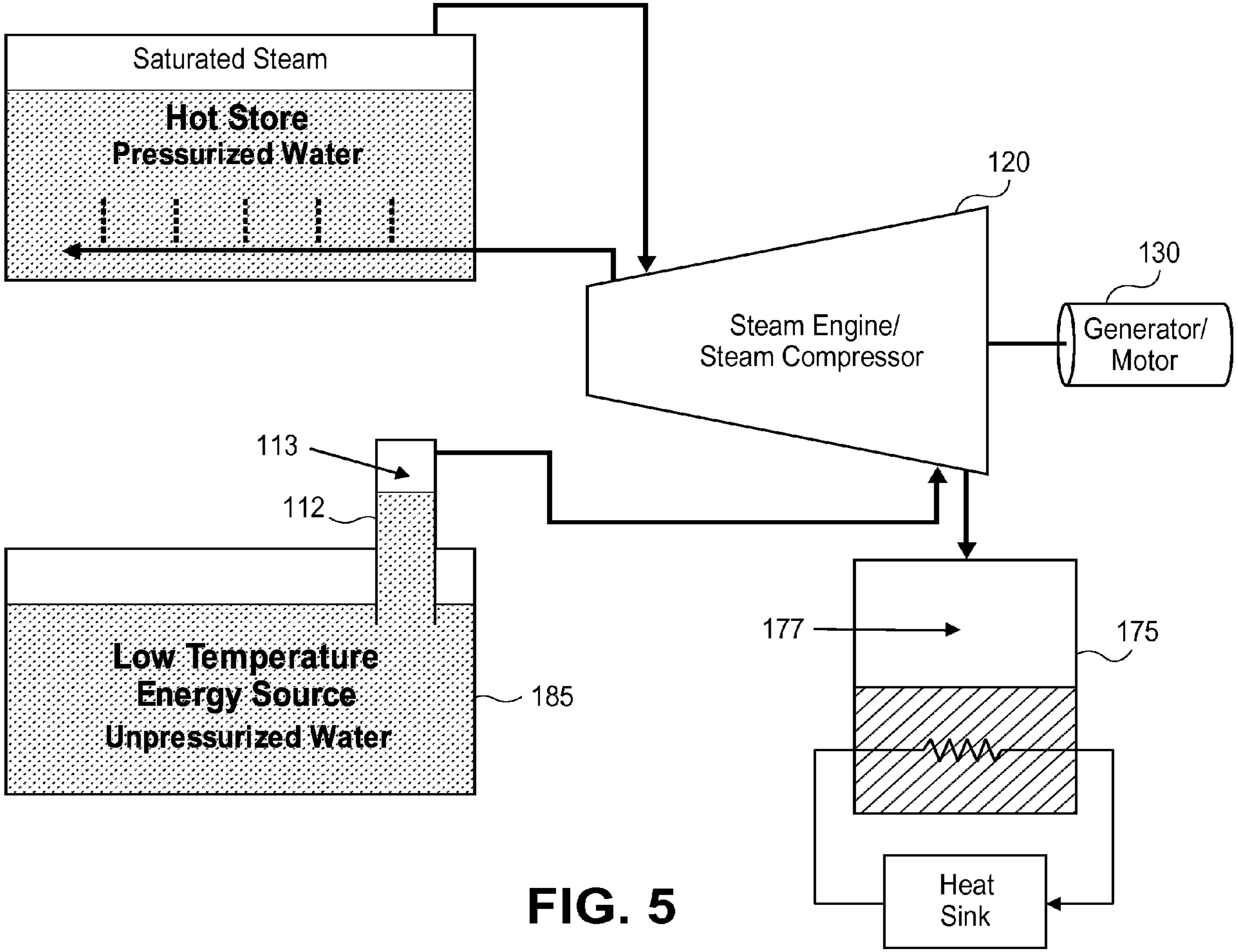

Saturated Steam
Hot Store
Pressurized Water
120
130
Steam Engine/
Steam Compressor
Generator/
Motor
113
112
177
175
Low Temperature
Energy Source
Unpressurized Water
185
Heat
Sink

FIG. 5

THERMAL ENERGY STORAGE SYSTEM

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/559,318, filed Nov. 14, 2011, which is hereby incorporated by reference in its entirety for all purposes.

BACKGROUND

[0002] The present invention relates generally to thermal energy storage systems. More particularly, it relates to systems that store thermal energy making use of a phase change such as liquid water/steam.

[0003] There are many circumstances in which it is desirable to store electrical energy in order to resolve temporal mismatches between energy supply and demand. By way of example, the availability of some alternative energy sources such as solar energy and wind energy can vary significantly over the course of a day and the output of devices that harvest such energy, (e.g., photovoltaic collectors or wind turbines) is often mismatched with the demand for the electrical energy that such devices produce. Another example of the mismatch between supply and demand is embodied in baseline electricity generating facilities such as nuclear powerplants which are generally designed to provide a substantially steady electrical output while the demand for electricity tends to vary significantly over time.

[0004] The mismatch between supply and demand can make bulk electrical energy storage desirable and over the years, a wide variety of systems and devices have been proposed and/or used to facilitate such storage and retrieval electrical energy. One of the most familiar examples of a device designed to store electrical energy is an electrical battery. Although batteries tend to work well for relatively small-scale energy storage applications, they tend to be cost prohibitive in larger scale energy storage systems. An example of a larger scale energy storage system that has been used in grid scale electrical energy storage applications is pumped hydro-electric power and storage. In a pumped hydro-electric power storage system, power is generated by a turbine which extracts the potential energy of water flowing from an upper reservoir to a lower reservoir. When demand for power is low, and there is an excess of supply from other power sources at low cost, the turbine can be reversed to pump water from the lower reservoir to the upper reservoir, thereby storing energy as gravitational potential energy. At a later time, when the demand for power is higher, the water stored in the upper reservoir can be used to drive the turbine to generate electrical power.

[0005] Other medium and large scale energy storage systems have utilized mechanisms such as thermal energy, compressed air, flywheels, electrical capacitors and chemical energy as the energy storage mechanisms. Although such conventional energy storage systems have a number of benefits, there are continuing efforts to develop cost effective energy storage systems having relatively high round trip energy recovery efficiencies. Such devices can make it practical to acquire or purchase electricity and store the associated energy when energy availability is higher than demand and its price and/or value is low, and to retrieve and utilize or sell such energy when energy availability is less than demand and its price and/or value is high.

SUMMARY OF THE INVENTION

[0006] A variety of energy storage and retrieval systems are described. Generally "hot" and "cold thermal reservoirs are provided. The "hot" thermal reservoir is arranged to hold a working fluid in both a liquid phase and a saturated vapor phase state. The "cold" thermal reservoir is arranged to hold the working fluid in a second state having a lower temperature than the working fluid in the hot thermal reservoir. A heat engine/heat pump unit is arranged to: (a) extract energy from working fluid passing from the hot reservoir to the cold reservoir via expansion of the working fluid in a manner that generates mechanical energy to facilitate retrieval of energy from the energy storage and retrieval system; and (b) compress working fluid passing from the cold thermal reservoir to the hot thermal reservoir to facilitate the storage of energy in the energy storage and retrieval system.

[0007] A variety of different materials can be used as the working fluid. In some preferred embodiments, water is used as the working fluid. When water is used as the working fluid, it passes through the heat engine/heat pump unit as steam. In such embodiments, the heat engine/heat pump unit may take the form of a steam engine.

[0008] The heat engine/heat pump may take the form of a reversible heat engine that can act as both an expander and a compressor or separate devices may be used as the expander and compressor. In some embodiments, a reversible positive displacement heat engine (e.g. a piston steam engine) is used as the heat engine/heat pump. By way of example, unaflow, universal unaflow and counter-flow steam engines work well. In some preferred implementations, the heat engine includes adjustable valves and a controller arranged to vary the timing of the opening and closing of the valves relative to a crankshaft angle.

[0009] In order to facilitate the storage and retrieval of electrical energy, an electric motor/generator unit may be mechanically coupled to the heat engine/heat pump unit. The electric motor/generator is arranged to drive the heat engine/heat pump unit during the compression of working fluid and to generate electricity during the expansion of the working fluid. The electric motor/generator may be implemented as a single reversible unit or as separate motor and generator devices.

[0010] The hot and cold reservoirs may take the form of pressure vessels or unpressurized reservoirs. When an unpressurized reservoir is used, a sub-atmospheric pressure chamber may be provided to facilitate sub-atmospheric flashing of working fluid to vapor (e.g., liquid water to steam) and/or sub-atmospheric condensation of vapor to a liquid. When a pressurized vessel is used as the hot reservoir, the working fluid in the hot reservoir may be stored at a pressure substantially above ambient atmospheric pressure.

[0011] In some alternative embodiments, the cold store may be replaced by the combination of a condenser arranged to condense steam and a separate low temperature thermal energy source arranged to provide steam having a lower temperature than the hot reservoir.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The invention and the advantages thereof, may best be understood by reference to the following description taken in conjunction with the accompanying drawings in which:

[0013] FIG. **1** is a schematic diagram of a heat engine/heat pump based energy storage and retrieval system in accordance with one embodiment of the invention.

[0014] FIG. **2**(*a*) is a schematic diagram of an energy storage and retrieval system having a pressurized hot reservoir and an unpressurized cold reservior with a sub-atmospheric pressure flashing chamber operating in an energy storage mode.

[0015] FIG. **2**(*b*) is a schematic diagram of the energy storage system of FIG. **2**(*a*) operating in an energy retrieval mode.

[0016] FIG. **3** is a schematic diagram of an energy storage and retrieval system having unpressurized hot and cold reservoirs.

[0017] FIG. **4** is a schematic diagram of an energy storage and retrieval system having pressurized hot and cold reservoirs.

[0018] FIG. **5** is a schematic diagram of an energy storage and retrieval system having a low temperature source and a separate low temperature sink

[0019] In the drawings, like reference numerals are sometimes used to designate like structural elements. It should also be appreciated that the depictions in the figures are diagrammatic and not to scale.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0020] A number of thermal energy based energy storage and retrieval systems are described. In general, the described storage systems utilize a working fluid having a substantial heat capacity and make use of a phase change to help improve the storage capacity of the system (e.g. a liquid water/steam phase change).

[0021] Referring next to FIG. **1**, a basic architecture of a heat engine/heat pump based electrical energy storage and retrieval in accordance with one embodiment of the invention will be described. The storage system **100** includes a "hot" thermal reservoir **105** and a "cold" thermal reservoir **110**. A heat engine/heat pump **120** is used to convey a working fluid between the two thermal reservoirs **105** and **110**. In the illustrated embodiment, the heat engine/heat pump **120** is coupled to a generator/motor **130** which in turn is coupled to an electric source and the electric load as appropriate. When operating the system **100** in a manner that stores energy, electricity from an electrical source powers motor **130** which in turn drives heat pump **120**. The heat pump compresses a vapor form of the working fluid drawn from the cold thermal reservoir **110** which inherently heats the working fluid as well. The compressed working fluid is then stored in the hot thermal reservoir **105**.

[0022] When operating system **100** in a manner that retrieves energy, the heat engine/heat pump **120** is operated in a heat engine mode. The heat engine **120** drives generator **130** which in turn generates electricity which can be used to power an electrical load, delivered to the power grid, or utilized in any other desired manner. Although a system that receives and delivers electrical energy is illustrated, it should be appreciated that in alternative embodiments, mechanical energy (such as a rotating shaft driven by a wind turbine or other device) could drive the heat pump and/or the mechanical output of the heat engine could be used directly as desired.

[0023] The hot thermal reservoir **105** holds working fluid at a higher temperature than the cold thermal reservoir **110** although the actual temperatures of the reservoirs may vary widely. Thus, as used herein, the labels "hot" and "cold" are merely intended to indicate the relative temperatures of the reservoirs as opposed to the specific temperatures of the working fluid within the reservoirs or their temperatures relative to ambient temperatures or any specific reference temperature. As will be described in more detail below, the thermal reservoirs **105** and **110** may take a wide variety of forms and may store either pressurized or unpressurized working fluid.

[0024] In the described embodiments, steam is used as the working fluid within the heat engine/heat pump **120** and therefore water/steam is stored in the thermal reservoirs **105** and **110**. However, it should be appreciated that in alternative embodiments, a wide variety of other working fluids could be used in place of water. By way of example, various water based mixtures (e.g., water/ammonia mixtures), fluorocarbons, ammonia, hydrocarbons and other refrigerants and/or mixtures that include any of these fluids can be used in alternative embodiments. In general, it is desirable to store the working fluid primarily in a liquid phase so that a phase change can be used advantageously to improve the storage capacity of the system.

[0025] To facilitate a working explanation of the energy storage and retrieval system **100**, FIGS. **2**(*a*) and **2**(*b*) schematically illustrate the operation of one suitable configuration of system **100**. In this embodiment, the cold thermal reservoir **110** (also referred to as a "cold store") holds unpressurized water, whereas hot thermal reservoir **105** ("hot store") holds pressurized water. FIG. **2**(*a*) schematically illustrates the operation of an energy storage system in an energy storage mode, whereas FIG. **2**(*b*) illustrates the operation of the system in an energy retrieval mode. In the energy storage mode illustrated in FIG. **2**(*a*), steam is drawn from the cold store **110** and compressed by heat pump **120**(*a*). The pressurized steam is injected into the hot store **105** where it is condensed by its contact with water within the hot store. The introduction and condensation of the compressed steam has the effect of warming the hot store thereby facilitating the storage of thermal energy. As will be appreciated by those familiar with art, an adiabatic compression of a gas (e.g. steam) has the effect of significantly warming the gas and therefore, the compressed steam will generally be much warmer than the steam from the cold store **110** that served as the source for the heat pump **120**(*a*).

[0026] Since the hot store **105** is pressurized, there will inherently be both saturated steam and pressurized water within the hot store. Although there may be some temperature stratification within the reservoir, there will generally be a thermodynamic equilibrium between the saturated steam and the liquid water at the liquid/vapor boundary (i.e., the water surface). As compressed steam is introduced to the hot store, both the temperature and the pressure of the hot store will increase while generally maintaining a thermodynamic equilibrium at the liquid/vapor boundary. To help reduce temperature stratification within the hot store, it is often desirable to inject the steam near the bottom of the hot store as illustrated in FIG. **2**(*a*) so that the injected steam will contact the liquid water as it rises through the reservoir, thereby facilitating condensation of the injected steam. Although the illustrated injection of incoming steam into the liquid water works well to facilitate condensation and reduce temperature stratification, it is not required as other mechanisms can be used to accomplish the same function(s).

[0027] Since the hot thermal reservoir is effectively a closed system, the actual operating pressure of the hot store at any time will be highly dependent on its current temperature (i.e., higher temperatures=higher pressures). As more compressed steam is added to the hot store, both its temperature and pressure will continue to rise. However, it is desirable to set some limit as to the maximum operational temperature/pressure for the hot store. In practice, the maximum operational temperatures/pressures tend to be dictated by economic constraints, with a primary constraint being the cost of the vessel(s) used as the hot thermal reservoir. Currently, there are a number of pressure vessels (tanks) commercially available that are rated to pressures of about 17 or 18 bar gauge (i.e., about 17 or 18 atmospheres). At a pressure of 17 bar gauge (about 250 psig) the temperature of the water and steam within the hot store would be about 207° C. Since such pressure vessels are commercially available at relatively low costs, it may be desirable to design a system such that the maximum operational pressure of the hot store **105** is in that range. However, that is by no means a requirement and the maximum operational pressure of the hot store may be widely varied to meet the needs of any particular application.

[0028] As indicated above, the cold store **110** serves as a source of steam for the heat pump **120**(*a*). In the embodiment of FIG. **2**(*a*), the cold store **110** is unpressurized. Although the bulk of the water in the cold store **110** is unpressurized, a column **112** is provided to facilitate sub-atmospheric flashing (boiling) of steam. As is well known, water boils at a temperature of about 100° C. at normal atmospheric pressures. However, at lower pressures, water will flash (boil) into steam at lower temperatures (and of course water boils at higher temperatures at higher pressures). For example, at a pressure of 0.1 bar absolute, water will boil at a temperature of about 46° C., at a pressure of 0.05 bar absolute, water will boil at a temperature of about 33° C. and at a pressure of 0.02 bar absolute, water will boil at a temperature of about 17.5° C. This property of water can be used to generate steam at temperatures well below 100° C. even when the water within an associated store is unpressurized.

[0029] In the embodiment illustrated in FIG. **2**(*a*), a flashing column **112** is provided in conjunction with the cold thermal reservoir. The flashing column **112** opens at a level below the waterline within the cold thermal reservoir **110** and extends above the surface of the water within the reservoir **110**. When air is evacuated from the column, a vacuum (relative to ambient pressure) is generated within the column, which has the effect of drawing the surface of the water within the column to a higher level than the surrounding water at ambient pressure. If the height of the column is sufficient and the evacuation of air complete, some of the water within the column will flash (boil) such that saturated steam fills the column above the waterline. The chamber formed by the portion of the column above the waterline is sometimes referred to herein as a flashing chamber **113**. The saturated steam within the flashing chamber will equalize to a temperature and pressure that is in equilibrium with the water at the water surface within the column **112**. Therefore, like in the hot store **105**, the temperature and pressure of the steam within flashing chamber **113** will vary as a function of the temperature of the adjacent water. The actual height of the flashing column **112** may be widely varied based on the design goals of any particular thermal storage system, but when steam is used as the working fluid, column heights of at least about 9.4 meters are generally preferred to generate the desired sub-atmospheric steam pressures within the flashing chamber **113**.

[0030] In the energy storage mode, steam is drawn from the flashing chamber **113** and compressed by the heat pump **120**(*b*) as illustrated in FIG. **2**(*a*). When steam is drawn from the flashing chamber, the pressure within the flashing chamber drops, which causes more water to vaporize (flash) to bring the chamber **113** back into equilibrium. Since the latent heat of vaporization of water (and other working fluids) is relatively high, vaporization of some of the water into steam extracts heat from the surrounding water thereby effectively cooling the surrounding water. Therefore, as steam is drawn from the flashing chamber **113**, the temperature of the water within the cold thermal reservoir **110** will gradually drop.

[0031] When a flashing column is used, the actual design of the column may be widely varied in order to meet the needs of any application. Typically, it will be important to provide sufficient water surface area within the flashing chamber(s) to ensure that steam can be generated at a rate high enough to supply the heat pump **120**(*b*) at the desired flow rates. In some applications it will also be desirable to provide a mechanism for circulating water around the cold thermal reservoir **110** and the flashing column **112**. This mixing of the water helps reduce the risk of temperature stratification within the flashing column **112**. Specifically, it should be appreciated that when a significant amount of steam is being generated, the water at the flashing surface will cool relatively quickly and thermosiphoning alone may not be sufficient to maintain the temperature of the water at the flashing surface at close to the same temperature as the main body of water within the cold store **110**—especially if the diameter or width of the column (and thus the flashing surface area) is small relative to the column height. It is generally undesirable for water at the surface of the flashing chamber to be at a temperature that is significantly below the temperature of underlying body of water since that would cause a reduction in the temperature and pressure of the steam being supplied to the heat pump **120**(*b*) which would reduce the overall efficiency of the system.

[0032] A variety of mechanism can be used to enhance circulate of the water within the cold store and flashing chamber. For example, impellers, propellers and other mixing devices can be appropriately positioned within the cold store (e.g. in the column **112**) and used to enhance circulation and mixing. In various other embodiments, two or more columns may be used to enhance circulation.

[0033] Referring next to FIG. **2**(*b*), operation of the energy storage system **100** in an energy retrieval mode will be described. During energy retrieval, steam is drawn from the hot store **105** and passed through steam engine **120**(*b*) as illustrated in FIG. **2**(*b*). The steam engine expands the steam extracting energy from the steam in a manner that produces useful mechanical work such as the rotation of a drive shaft. The drive shaft can then be used in any desired manner, as for example, to power a generator **130**(*b*) that generates electricity, to drive a pump or to drive other machinery. The steam supplied to the steam engine **120**(*b*) is typically drawn from a location near the top of the hot store, although this is not a requirement.

[0034] When steam is drawn from the hot store **105**, the pressure within the store will decrease, which in turn causes more water to vaporize (flash) to bring the hot store **105** back towards equilibrium. Such vaporization of some of the liquid water into steam extracts heat from the surrounding water thereby effectively cooling the surrounding water. Therefore, as steam is drawn from the hot store **105**, the temperature and pressure of the water/steam within the hot store will gradually drop.

[0035] As will be appreciated by those familiar with heat engines, the adiabatic expansion of a gas will cause the temperature of the gas to drop significantly during the expansion process. Thus, the expanded steam exhausted by the steam engine **120**(*b*) will be substantially cooler than the input steam and may be returned to the cold store **110**. In order for the steam engine to get the most work out of the steam (and therefore to operate most efficiently), it is generally desirable to exhaust the steam at as low of a pressure as possible. As such, it is often desirable to exhaust steam from the steam engine at a pressure that is below atmospheric pressure. Since the pressure within the flashing chamber **113** is below atmospheric pressure, the flashing chamber serves as a good location to receive the exhaust from the steam engine.

[0036] Conceptually, when steam is delivered to the flashing chamber **113**, the pressure within the flashing chamber increases, which causes some of the steam within chamber **113** to condense to bring the chamber **113** back into equilibrium. Thus, in the energy retrieval mode, flashing chamber **113** effectively acts as a sub-atmospheric condensation chamber. The condensation of some of the steam back into liquid water adds heat to the cold store thereby effectively warming the surrounding water. Therefore, as steam is introduced to the flashing chamber **113**, the temperature of the water within the cold thermal reservoir **110** will gradually rise.

[0037] As steam is injected into the cold store, precautions are preferably taken to help insure efficient condensation of the steam and good thermal mixing of the condensate with the water in the cold store. One way to enhance condensation within the chamber **113** is to spray water droplets into the chamber as steam is introduced to the chamber. The water droplets enhance condensation of the steam since steams tends to condense on the droplets. Such spraying can be accomplished by a sprayer **114** which draws water from the cold store and sprays a shower of water from the top (or near the top) of the column, thereby effectively creating a shower of water within the condensation chamber **113**. A simple pump (not shown) may be used to draw water from any suitable location in the cold store and spray it into the condensation chamber to thereby enhance condensation. Other conventional condensation enhancing mechanisms such as drip trays and Raschig rings, trays or other structures arranged to enhance the exposed surface area of water (not shown) can be used as well.

[0038] It is also desirable to insure that there is good mixing between water at the surface of the flashing chamber and the underlying water in the cold store. Without good mixing, the temperature at the surface will rise relative to the underlying pool as the energy from the condensing steam heats the water near the surface. Higher temperatures at the water/vapor boundary have the effect of increasing the pressure within chamber **113**. The increased pressure within chamber **113** means the steam can be expanded less in the steam engine, which reduces the work that can be extracted from the steam, thereby reducing the overall Round Trip Efficiency of the energy storage and retrieval process. The same mixing mechanisms used to enhance circulate of the water within the cold store during steam generation can also be used to circulate water during condensation.

[0039] The described energy storage and retrieval system **100** is well suited to facilitate thermal storage of energy. When excess electrical or mechanical energy is available, such energy can be used to drive the heat pump **120**(*a*) in a manner that compresses and heats working fluid (e.g. steam) drawn from the cold thermal reservoir **110** for storage in the hot thermal reservoir **105**. When it is desirable to retrieve energy from the storage system, hot, high pressure steam is drawn from the hot store and expanded in heat engine **120**(*b*) to extract useful work from the steam that can be used to generate electricity or for any other desired purposes. In an ideal system, in which the heat engine/heat pump **120** and the motor/generator **130** do not have any losses and there are no thermal or pressure losses (or gains) in the thermal reservoirs, the Round Trip Efficiency of the energy storage can be 100%. That is, the amount of useful energy that could be retrieved from the system would theoretically be the same as the amount of energy used to drive the system. Of course, a 100% round trip storage/retrieval efficiency (RTE) is not possible in a practical system, however even when the electricity is used to power the system and electricity is the form of the power ultimately output by the system, round trip storage/retrieval efficiencies on the order of 60-80% are believed to be readily obtainable using existing technology (e.g., using a positive displacement steam engine/compressor in conjunction with a motor/generator as described in more detail below) and even higher round trip efficiencies may be possible. Higher efficiencies are also possible in systems that would directly supply and/or utilize the mechanical power that drives and/or is output by the heat engine/heat pump since any inefficiencies of the motor/generator **130** would be eliminated. As will be apparent to those familiar with grid scale energy storage applications, there are a number of applications where round trip storage and retrieval efficiencies in the 60-80% range are economically viable.

Other Thermal Reservoir Configurations

[0040] In the embodiment illustrated in FIGS. **2**(*a*) & **2**(*b*), the hot thermal reservoir **105** is pressurized, whereas the cold thermal reservoir is not. However, that is not a requirement and both reservoirs may utilize either pressurized or unpressurized reservoirs. By way of example, FIG. **3** illustrates an arrangement in which both the hot store **105**(*a*) and the cold store **110**(*a*) are unpressurized vessels containing a quantity of water and space for humid air. In this embodiment, the hot store **105**(*a*) also includes a mechanism (e.g. column **107**) that facilitates the generation of steam at sub-atmospheric pressures like the steam generating column **112** described above with respect to FIG. **2**. The cold store may operate in the same fashion as described above with respect to FIG. **2**. Thus, both the hot and cold stores have mechanisms for generating steam at sub-atmospheric pressures.

[0041] An advantage of the type of system illustrated in FIG. **3** is that the cost of an unpressurized water vessel is potentially much cheaper than the cost of pressurized vessel which can help reduce overall system costs. A disadvantage is that the temperature and pressure difference between the hot and cold stores will be substantially less in the configuration of FIG. **3**. With a smaller temperature/pressure differential the volume of steam that must pass through the heat engine/heat pump **120** is much larger for a given system energy storage capacity. Thus a substantially larger heat engine/heat pump and larger thermal reservoirs would typically be required, both of which involve additional expense. Which configuration is more-cost effective in any particular implementation will be a function of the relative costs of the various components, the available space, etc.

[0042] Yet another embodiment is illustrated in FIG. **4**. In this embodiment, both the hot store **105**(*b*) and the cold store **110**(*b*) are pressure vessels. The hot store **105**(*b*) works in the same manner described above with respect to the pressurized hot store **105** of FIG. **2**. The cold store **110**(*b*) operates in a generally similar manner, but there is typically no longer a need for a separate flashing column Thus, during the storage of energy, steam for the heat pump can be drawn from the steam chamber region **111** of the cold store **110**(*b*) and during the retrieval of energy, steam exhausted from the steam engine can be directed back into the steam chamber region **111**. Like with the previously described embodiments, it will typically be desirable to spray water into the steam chamber region **111** when steam is being added to the cold store to enhance the condensation of steam.

[0043] From the foregoing, it should be apparent that the size, geometry and layout of the thermal reservoirs **105** and **110** may be widely varied within the scope of the invention. In practice, many tanks and vessels have a circular cross section although this is not required. In a pressurized hot stores, it is often preferable to orient the tank(s) in a generally horizontal manner as illustrated in FIGS. **2**-**4** (i.e., such that their length is greater than their height). This can be desirable because it gives more water surface area, which enhances transitions between the gas and liquid phases of the water. The horizontal orientation also potentially reduces the pressure differential between the top and bottom of the tank, which can be useful when steam is injected into liquid water near the bottom of a tank, as illustrated for example, in FIG. **2**(*a*). It should be appreciated that the pressure within the water column will increase with depth such that there is a higher pressure at the bottom of the tank than the pressure within the steam chamber at the top of the tank. Thus, injecting steam lower in the tank within the water column requires the input steam to be compressed more than if the steam is injected into the steam chamber region **111** above the waterline. Over-compression has the drawback of reducing the overall Round Trip Efficiency of the system and therefore an advantage of using shallower broader tanks is that less over-compression is needed it inject steam near the bottom of a shallower tank. Of course in other embodiments, the compressed steam can be introduced into the steam chamber region **111** and other mechanisms can be used as necessary to insure good condensation of the steam and to minimize thermal stratification within the tank.

[0044] When a sealed tank is used as the cold store, the tank should be capable of withstanding the vacuum pressure of the flashing chamber (e.g., up to 1 atmosphere of negative pressure). In some applications, the use of such vacuum pressure resistant tanks may be more cost effective than providing a non-pressurized tank with a flashing column **112**. By way of example cylindrical tanks having a height of at least 10 meters (as for example 12 meters to match shipping container length) work well for many applications.

[0045] In most of the examples given above, the thermal reservoirs are described primarily in the context of various tanks and pressure vessels. Although tanks and pressure vessels work quite well, it should be appreciated that a wide variety of different structures can be used as the thermal reservoirs when appropriate. By way of example, it available, a lake, pond or other defined body of water could be used as an unpressurized thermal reservoir—and particularly as the cold store. When readily available, the use of such bodies of water may have several potential advantageous. For example, if the total mass of water in a lake or pond it very substantially more than is used by the energy storage system, then the overall temperature of a lake used as a cold reservoir may not fluctuate significantly through the course of an energy storage and retrieval cycle. A cold store that maintains a relatively constant temperature tends to facilitate more efficient storage. In other embodiments cisterns and various in-ground containments can be used as one or both of the thermal reservoirs.

[0046] In most of the illustrated embodiments each of the thermal reservoirs takes the form of a single containment. However it should be appreciated that either or both of the reservoirs may be formed from any number of individual containment structures. Indeed, in some applications, modular containments may be preferable. For example, in one specific application a number of modular tanks each sized to fit within a shipping container may be used to form one of the thermal reservoirs (e.g., a cold store).

[0047] Typically it is desirable to insulate the hot store in order to avoid thermal losses in the primary energy store. Depending on the location and operating conditions, it may, or may not, be desirable to insulate the cold store. The reason that insulation may be less desirable on the cold store is that inefficiencies in the storage and retrieval process will typically add heat to the system and such heat tends to migrate to the low temperature store. More specifically, during a charge/discharge cycle, a portion of the energy lost due to inefficiencies of the compressor and heat engine will appear as a net heat flow into the cold store. This amount of heat typically needs to be removed from the system to prevent the temperature of the cold store from rising to an inefficient level over time. A variety of conventional mechanisms may be used to regulate the temperature of the cold store **110**. As such, some natural cooling of the cold store may be desirable to help maintain system balance.

[0048] Referring next to FIG. **5**, yet another alternative energy storage system configuration will be described. In this embodiment, the functionality of the cold store **110** described in the previous embodiments is effectively divided into two separate components, a low temperature sink **175** and a low temperature energy source **185**. This type of configuration can be advantageous when there is an available source of heat, such as waste heat from an industrial process or a thermal power plant. In other aspects, the system may be substantially the same as any of the previously described embodiments.

[0049] In the illustrated configuration, the hot store **105**(*c*) is an insulated pressure vessel containing water and a saturated steam space that operates as described above. The low temperature energy source may take the form of an unpressurized water vessel heated by any suitable heat source. The low temperature sink **175** is a condenser cooled by an available heat sink The heat sink may take any suitable form and the most appropriate heat sink may vary by location. By way of example, a stream or other body of water, evaporative coolers, fin-fan coolers or a variety of other heat exchangers may be used to cool the condenser.

[0050] In general, the low temperature energy source **185** is maintained at a temperature that is higher than the sink **175**. When storing energy, water in the low temperature energy source **185** is flashed into steam as previously discussed with respect to the cold store **110**. As before, a column or other suitable vessel structure may be used to facilitate sub-atmospheric flashing of the steam. The temperature of the water and thus the saturated steam supplied by the source **185** is generally higher than it would be if a cold store was used. Since the temperature of the water is higher, the pressure of the steam input to the heat pump **120**(*a*) is higher which means that less energy is required to compress the steam for storage in the hot store **105**.

[0051] When retrieving energy, the steam engine **120**(*b*) exhausts steam into the low temperature sink **175** (as opposed to the source **185**). The sink **175** condenses the steam and is cooled by the available heat sink Like the cold store, the sink **175** includes a sub-atmospheric condenser **177** that facilitates condensation of the exhaust steam at sub-atmospheric pressures. In general, the temperature of the sink **175** is cooler than the temperature of the source **185**. Since the temperature of water within the sink's condensation chamber is lower than the temperature of the source, the pressure within the condenser **177** (and thus the pressure at which condensation occurs) is lower as well. Therefore, steam can be exhausted from the steam engine **120**(*b*) at a lower pressure than it could if the steam was returned to source **185**. This allows the steam engine to extract more energy from the expansion of the steam, thereby improving the efficiency of the storage and retrieval system.

[0052] It should be appreciated that in an ideal system operating with the arrangement of FIG. **5**, more energy is available for extraction from the steam in the hot store **105** than is required to compress the steam during energy storage. Thus, from the standpoint of an electrical system that drives the heat pump and utilizes electrical energy from the steam engine, the electrical system is theoretically able to withdraw more electricity during retrieval than was used during storage which suggests a Round Trip Efficiency of greater than 100% from the standpoint of the electrical system. Of course, this isn't free energy, rather, the system effectively converts the thermal energy from the low temperature heat source **185** to electrical energy. However, if such thermal energy is waste heat and therefore essentially free, it can be put to use in a manner that improves the apparent Round Trip Efficiency of the energy storage system **100**.

[0053] Optionally, condensate from the condenser in sink **175** can be recirculated to low temperature heat source **185** where it is heated before being used to generate steam. An advantage of such recirculation is that it potentially reduces the system's overall consumption of water.

[0054] It should be apparent that there are a number of industrial and power generation processes that generate waste heat which could be utilized in the type of system illustrated in FIG. **5**. If such waste heat is carried by water, such water can potentially be stored directly in the low temperature heat source **185**. Alternatively, one or more appropriate heat exchangers may be used to warm the water stored in the source **185**.

[0055] The size of the reservoirs that are suitable for use as the hot and cold thermal reservoirs **105**, **110** can vary with the desired energy storage capacity of the system, the pressure ratings of the vessels, tanks or other structures used as the reservoirs and/or flashing columns, the operating temperatures ranges (which may be dictated in part by the permissible operating pressure ranges), etc. By way of example, to give a rough scale of a suitable system size, a system designed to deliver 1 Megawatt (MW) of power for 10 hours (and thus has over 10 MW hours of storage capacity) could be implemented using a 170,000 gallon hot store that can be pressurized to about 17 bar (about 250 psi) and a 500,000 gallon unpressurized cold store. In this particular example, the cold store has about 3 times the volume of the cold store. However, it should be appreciated that the actual relative volumes of the hot and cold store may vary widely and that the relative prices of the vessels that are available for use as the thermal reservoirs may strongly influence the ultimate reservoir sizes selected for any particular power storage capacity.

[0056] It should be appreciated that the size of the hot store can generally be reduced if the vessel used as the hot store can withstand higher operating temperatures and pressures. Conversely, the size of the hot store will have to increase if the vessel used can only withstand lower operating temperatures and pressures or if the hot store is unpressurized. Furthermore, it should be appreciated that the volume of the cold reservoir can significantly affect the required volume of the hot reservoir as well. More specifically, as indicated above, during operation in the energy storage mode, thermal energy is withdrawn from the cold store **110** thereby cooling the cold store and thermal energy is added to the hot store **105** thereby heating the hot store. Thus, the temperatures of the thermal reservoirs will diverge during energy storage. Conversely, during energy retrieval, thermal energy is withdrawn from the hot store **105** thereby cooling the hot store and thermal energy is added to the cold store **110** thereby heating the cold store. Thus the temperatures of the thermal reservoirs will converge during energy retrieval. As the temperatures converge, the amount of energy that can be retrieved from steam drawn from the hot store will decrease.

[0057] It should be appreciated that the temperature of a cold store that is the same size as the hot store will vary significantly more than the temperature of a cold store that has three times (3×) the volume of the hot store. Thus, given identical hot stores a system that has a 3× cold store will have the ability to extract more energy than a system with a cold store that is the same size as the hot store. By extension, if a still larger cold store is use (e.g. a 10× cold store) it is possible to extract even more energy from a hot store of the same size. If a relatively large body of water such as a lake that has many, many times the volume of the hot store, then the cold store may stay substantially the same temperature throughout an energy storage and retrieval cycle. Such a system would have the ability to extract even more energy given an identical hot store which provides a larger usable energy storage capacity. Thus, it should be apparent that selection of the relative sizes of the hot and cold reservoirs will often be based primarily on the cost benefit analysis given available resources, tanks and pressure vessels.

[0058] Either of the hot and cold thermal reservoirs may be implemented as single tank, vessel or reservoir, or may be implemented as multiple tanks, vessels and/or reservoirs. By way of example, a 500,000 gallon hot store could be implemented as seventeen 30,000 gallon pressure vessels which might each be about 40 feet long and 12 feet in diameter.

Steam Engine

[0059] The heat engine/heat pump **120** can be implemented in a variety of different manners. Although a variety of heat pumps and heat engines including steam turbines may be used, one class of heat engines that is particularly well suited for use as the heat engine/heat pump **120** are positive displacement piston steam engines. One advantage that piston steam engines have over turbines and other conventional heat pumps and heat engines is their relatively high operating efficiencies over a wide range of inlet and exhaust pressures and temperatures. This is particularly useful in the described energy storage and retrieval systems because it allows the temperatures and pressures of both the hot and cold thermal reservoirs to vary significantly over the course of an energy storage and retrieval cycle without drastically reducing the system's round trip energy storage and retrieval efficiency.

[0060] Another advantage of piston steam engines is that they can operate relatively efficiently over a range of steam mass flow rates which allows the system to efficiently draw or deliver energy even in the face of variable energy supply and demand. This capacity meshes well in applications where the energy available for storage at any given time may vary significantly during the course of a day, such as is inherent in solar and wind farms. It also fits extremely well in applications that have variable demand for energy during retrieval (which are many).

[0061] Many piston steam engines are reversible in that they may be operated as both as a heat engine (expander) and as a heat pump (compressor). This can be advantageous because it allows a single machine to be used as both the heat pump and the heat engine. Although a reversible device is useful in many applications, it is not required. Rather, when desired, separate devices can be used as the heat pump and the heat engine and the heat pumps/heat engines shown in the drawings are intended to represent both approaches. This may be desirable, for example, when separate expanders and compressors are less expensive and/or more efficient than a reversible device. Furthermore, it should be appreciated that more than one steam engine (or other devices) may be used in parallel as the heat engine/heat pump in order to deliver the desired throughput.

[0062] It should also be appreciated that despite the fact that positive displacement piston steam engines are not currently popular, piston steam engines are a very mature technology. Indeed, piston steam engines were the dominant source of power well into the 20th century. Accordingly, there are a number of existing piston steam engine designs that may be used as the heat engine/heat pump. These include single stage steam engines and multi-stage (multiple expansion stages) steam engines, etc. In some specific applications, a single or multi-stage Unaflow, Universal-Unaflow or counter-flow piston steam engine may be used. One such engine has been developed by the Applicant and is based on the Skinner Universal-Unaflow steam engine from the 1930s.

[0063] The actual number of serial stages that are desirable and appropriate for any particular application will vary in accordance with a number of factors including the expected temperature differential between the thermal reservoirs, the availability of steam separators and water injectors, costs and other factors. In some applications, a single stage of expansion may be preferred whereas in other multiple stages (typically in the range of 2-5 serial stages) would be preferred.

[0064] Unaflow steam engines and Universal-Unaflow steam engines are piston based steam engines that utilize poppet valves to control the introduction of steam into the cylinder that serves as an expansion chamber. Conventionally, the timing of the valves has been controlled by a camshaft. However, it should be appreciated that other known valve timing control mechanisms can be used as well. For example, electronic solenoids may be used to open and close the valves which facilitates electronic control the timing of the opening and closing of the valves if desired. Regardless of the mechanism used, there are several advantages to providing a wide range of control over the relative timing of the opening and closing of the valves. For example, in order to maximize efficiency, it is generally preferable for the compression ratio of the steam engine/heat pump to relatively closely match the pressure ratio between the pressures of the hot and cold stores. Varying the timing of the opening and closing of the intake and exhaust valves is one good way to accurately control the compression ratio of the engine. Varying the intake valve cutoff timing also provides a good mechanism for controlling the mass flow rate of steam through the steam engine which allows good control of the power generated by the steam engine during expansion.

[0065] Adjustable valve timing can also be very useful in facilitating reversible operation of the steam engine such that the steam engine may be operated as either an expander (a traditional steam engine) or as a compressor (heat pump). Conceptually, many steam engines, including piston and other positive displacement steam engines may be operated as either an expander or a compressor. The primary difference is that in the expander mode, high pressure steam is drawn into the expansion chamber and is used to drive a piston that delivers useful work to a crankshaft, whereas in the compressor mode, an electric motor (or other suitable power source) powers the crankshaft which drives the pistons to compress steam within the chamber (which now acts as a compression chamber instead of an expansion chamber). If the timing of the opening and closing of the valves remains the same (relative to crank angle), then to change from expansion to compression, the rotational direction of the crankshaft must be reversed. This requires stopping the steam engine and reversing its direction. This works fine in energy storage systems where rapid shifts between power consumption and power generation are not required—such as when storage is expected to occur primarily at night when electricity rates are low and retrieval is expected to occur primarily during other parts of the day when electricity rates are higher. However, there are also a number of applications, such as load balancing, where the ability to quickly shift between power storage and power delivery modes is quite valuable (i.e., shifting modes in seconds rather than minutes). In a piston based steam engine, this type of rapid shifting between power generation and power storage modes is possible if the crankshaft can continue to rotate in the same direction when shifting modes. This can be accomplished by altering the relative timing of the opening and closing of the valves—whose functions (intake and exhaust) are, of course, reversed when the operational mode is reversed.

[0066] As is well known, anything close to the adiabatic compression of steam will cause the superheating of the steam. Too much superheating of the steam may be undesirable since it can lead to thermal losses in the system. Therefore, in some embodiments, one or more water injectors are provided to spray water into the steam before or during compression so that some of the thermal energy generated during compression is absorbed by vaporization of the injected water. The injector(s) may be arranged to inject water directly into each cylinder during compression or they may be arranged to inject the water into the steam prior to its introduction into a compression cylinder. In general it is desirable to keep the compressed steam that exits the steam engine during compression at a state that is close to saturation so that excess superheating does not occur. However, that is not a requirement. It should be appreciated that the desired amount of water to inject will vary as a function of several different factors such as the compression ratio currently in use, the mass flow rate of steam passing through the cylinder(s), the entrance temperature and pressure, etc. Therefore, it is preferable to control the volume of water injected at any given time based on the operating state of the engine so that a point close to saturation can be achieved in the compressed steam exiting the steam engine. If more than one compression stage is used, then water injection may be desired for each compression stage, although again, this is not a requirement.

[0067] Conversely, adiabatic expansion of saturated steam can cause some of the steam to condense during the expansion. It is generally undesirable to introduce wet steam (i.e., steam that includes water droplets) into a cylinder because the condensation can erode inlet valve ports. Therefore, in multi-stage steam engines, it is often desirable to pass the steam through a steam separator (not shown) between sequential stages in order to remove most of the water droplets from the steam. It may also be desirable to pass the steam through a steam separator before it enters the first (or only) expansion chamber (cylinder). Any water condensed by the steam separators can be returned to one of the thermal reservoirs (typically the cold reservoir) to help capture the energy contained therein. A variety of different conventional steam separators can be used to remove water droplets from the steam. By way of example, mesh steam separators work well.

[0068] In other embodiment it may be desirable to superheat the steam before it enters the steam engine and/or to reheat the steam between sequential stages. This can be accomplished through the use of an optional superheater that heats steam drawn from the hot store before it enters the steam engine, and/or an optional reheater that heats steam between sequential stages of the steam engine. Although the use of superheaters and/or reheaters is possible, they are often not cost effective unless the heat source(s) used to power the superheaters and/or reheaters are waste heat sources or other very low cost energy sources.

Additional Features

[0069] It should be apparent that the various described energy storage systems are well suited for the delivering low cost bulk energy storage and retrieval with a high Round Trip Efficiency. Storage and retrieval intervals can be as short as a few seconds and as long as hours or days. Intermittent power sources such as wind and solar tend to exacerbate the mismatch between energy supply and demand, thus increasing the need for such energy storage and retrieval systems.

[0070] Although only a few embodiments have been described in detail, it should be appreciated that the invention may be implemented in many other forms without departing from the spirit or scope of the invention. For example, the specific construction and layout of the hot and cold thermal reservoirs and the specific devices used as the heat pumps and heat engine may be widely varied. The hot and cold stores may each be implemented as a single tank or as multiple separate tanks. When multiple tanks are used for one of the stores, the working fluid within the different tanks in the same store may be a substantially the same temperature or at different temperatures. As previously mentioned, one or more reversible heat engine(s)/heat pump(s) may be used as the expander/compressor or separate devices may be used for expansion and compression. Similarly, in electricity storage and retrieval applications, a reversible motor/generator may be used to drive/be driven by the heat engine/heat pump, or separate motor(s) and generator(s) may be used. The described systems are readily scalable and may be used in a variety of different energy storage applications, including grid scale energy storage and retrieval applications.

[0071] It should also be appreciated that if sources of low cost heat are readily available, such heat can be used to help improve the efficiency of the system. One such arrangement was illustrated in FIG. **5** where waste heat was used to warm (or provide) the water that serves as the source of the low temperature steam used for compression. In other embodiments appropriate heaters or heat exchangers could be used to either superheat steam from the hot store **105** before it is introduced to the heat engine **120**(*b*) or to reheat steam between expansion stages. As will be appreciated by those familiar with the art, superheating steam before expansion and/or reheating steam between expansion stages helps avoid problems and inefficiencies that can be induced by condensation of steam during the expansion process and can reduce or eliminate the need for the use of steam separators. Of course, the best use of the available heat will depend in part on the temperatures that can be obtained. Thus, when desired and appropriate, a superheater (not shown) may be provided between the hot store **105** and the heat engine to superheat steam before it enters the steam engine **120**(*b*) and/or one or more reheaters (not shown) may be provided to reheat steam at appropriate stage in the expansion process.

[0072] Effective Round Trip Efficiencies of at least 60, 70 and even 80% can be attained using the described approach. Although higher Round Trip Efficiencies are generally desirable, cost considerations may dictate the system design and thus the attainable Round Trip Efficiency. However, systems having 60-80% (or higher) Round Trip Efficiencies are believed to be economically viable in a number of specific applications.

[0073] The described embodiments should be considered illustrative and not restrictive and the invention is not to be limited to the details given herein, but may be modified within the scope and equivalents of the appended claims.

What is claimed is:

1. An energy storage and retrieval system comprising:

a first thermal reservoir arranged to hold water and saturated steam in a first state;

a second thermal reservoir arranged to hold water and steam in a second state having a lower temperature than the first state; and

a reversible positive displacement steam engine arranged to,

(a) extract energy from steam passing from the first thermal reservoir to the second thermal reservoir via expansion of the steam in a manner that generates mechanical energy to facilitate retrieval of energy from the energy storage and retrieval system, and

(b) compress steam passing from the second thermal reservoir to the first thermal reservoir to facilitate the storage of energy in the energy storage and retrieval system,

whereby water and steam serve as a working fluid for the energy storage and retrieval system.

2. An energy storage and retrieval system as recited in claim **1** further comprising an electric motor/generator mechanically coupled to the steam engine, the electric motor/generator being arranged to drive the steam engine when the steam engine is operated as a heat pump and arranged to generate electricity when the steam engine is operated as a heat engine.

3. An energy storage and retrieval system as recited in claim **1** wherein the steam engine is selected from the group consisting of a unaflow steam engine, a universal unaflow steam engine and a counter-flow steam engine.

4. An energy storage and retrieval system as recited in claim **1** wherein the first thermal reservoir includes a pressure vessel arranged to hold the working fluid in the first thermal reservoir at a pressure substantially above ambient atmospheric pressure.

5. An energy storage and retrieval system as recited in claim **1** wherein the second thermal reservoir is arranged to hold unpressurized working fluid and includes a sub-atmospheric pressure chamber that facilitates sub-atmospheric flashing of liquid water to steam and/or sub-atmospheric condensation of steam to a liquid water state.

6. An energy storage and retrieval system as recited in claim **1** wherein the second thermal reservoir includes a pressure vessel arranged to hold steam at sub-atmospheric pressures and facilitates sub-atmospheric flashing of liquid water to steam and/or sub-atmospheric condensation of steam to a liquid water state.

7. An energy storage and retrieval system as recited in claim **1** wherein the steam engine includes a crankshaft and at least one working chamber and each working chamber has an associated reciprocating piston coupled to the crankshaft and a plurality of associated valves that facilitate the introduction of steam into the working chamber and the exhaustion of steam from the working chamber and wherein the timing of the opening and closing of the valves is variable such that: (a) the steam engine can be operated in both an expansion mode and a compression mode with the crankshaft rotating in the same direction; and (b) the timing of the opening and closing of the valves relative to the crankshaft angle may be varied to facilitate altering an expansion/compression ratio of the steam engine.

8. An energy storage and retrieval system as recited in claim **1** wherein the steam engine includes a water injector for adding water to steam passing through the steam engine for compression before the compressed steam is exhausted from the steam engine to the first thermal reservoir.

9. An energy storage and retrieval system as recited in claim **1** wherein the steam engine includes:

a plurality of sequential expansion stages; and

a steam separator for removing water from partially expanded steam between an associated pair of the expansion stages.

10. An energy storage and retrieval system as recited in claim **1** wherein a Round Trip Efficiency of the energy storage and retrieval system is at least 70 percent.

11. An energy storage and retrieval system as recited in claim **1** wherein the second thermal reservoir includes first and second stages, wherein the first stage receives and condenses steam exhausted from the steam engine after expansion by the steam engine and the second stage operates as a source of steam for compression by the steam engine.

12. An energy storage and retrieval system as recited in claim **11** further comprising:

a heat source arranged to directly or indirectly heat working fluid in the second stage of the second thermal reservoir; and

a cooling unit for removing heat from working fluid in the first stage of the second thermal reservoir.

13. An energy storage and retrieval system as recited in claim **1** further comprising a heater for at least one of:

superheating steam drawn from the first thermal reservoir before such steam is passed through the steam engine; and

reheating steam between expansion stages of the steam engine.

14. An energy storage and retrieval system as recited in claim **1** further comprising an electric motor/generator mechanically coupled to the steam engine, the electric motor/generator being arranged to drive the steam engine when the steam engine is operated as a heat pump and arranged to generate electricity when the steam engine is operated as a heat engine, and wherein:

the steam engine is selected from the group consisting of a unaflow steam engine and a universal unaflow steam engine;

the first thermal reservoir includes a pressure vessel arranged to hold the working fluid in the first thermal reservoir at a pressure substantially above ambient atmospheric pressure; and

the second thermal reservoir includes a pressure vessel arranged to hold steam at sub-atmospheric pressures and facilitates sub-atmospheric flashing of liquid water to steam and sub-atmospheric condensation of steam to a liquid water state.

15. An energy storage and retrieval system as recited in claim **14** wherein the steam engine includes a crankshaft and at least one working chamber and each working chamber has an associated reciprocating piston coupled to the crankshaft and a plurality of associated valves that facilitate the introduction of steam into the working chamber and the exhaustion of steam from the working chamber and wherein the timing of the opening and closing of the valves is variable such that: (a) the steam engine can be operated in both an expansion mode and a compression mode with the crankshaft rotating in the same direction; and (b) the timing of the opening and closing of the valves relative to the crankshaft angle may be varied to facilitate altering an expansion/compression ratio of the steam engine.

16. An energy storage and retrieval system as recited in claim **2** wherein the electric motor/generator includes at least one motor and at least one generator that is separate from the motor.

17. An energy storage and retrieval system comprising:

a first thermal reservoir arranged to hold working fluid in a first state that includes liquid phase and saturated vapor phase work fluid;

a second thermal reservoir arranged to hold working fluid in a second state having a temperature that is lower than the temperature of the working fluid in first thermal reservoir; and

a heat engine/heat pump unit arranged to,

(a) extract energy from working fluid vapor passing from the first thermal reservoir to the second thermal reservoir via expansion of the working fluid in a manner that generates mechanical energy to facilitate retrieval of energy from the energy storage and retrieval system, and

(b) compress working fluid vapor passing from the second thermal reservoir to the first thermal reservoir to facilitate the storage of energy in the energy storage and retrieval system.

18. An energy storage and retrieval system as recited in claim **17** further comprising an electric motor/generator arranged to drive the heat engine/heat pump unit when the heat engine/heat pump unit is operated in a manner that conveys working fluid vapor from the second thermal reservoir to the first thermal reservoir and for generating electricity when the heat engine/heat pump unit is operated in a manner that conveys working fluid vapor from the first thermal reservoir to the second thermal reservoir.

19. An energy storage and retrieval system as recited in claim **17** wherein the first thermal reservoir includes a pressure vessel arranged to hold working fluid in the first thermal reservoir at a pressure substantially above ambient atmospheric pressure.

20. An energy storage and retrieval system as recited in claim **17** wherein the second thermal reservoir is arranged to facilitate sub-atmospheric flashing of liquid working fluid to a vapor state and/or sub-atmospheric condensation of vapor working fluid to a liquid state.

21. An energy storage and retrieval system as recited in claim **17** wherein the working fluid is selected from the group consisting of:

(a) a mixture that includes water;

(b) a fluorocarbon or a mixture that includes a fluorocarbon;

(c) ammonia or a mixture that includes ammonia; and

(d) a hydrocarbon or a mixture that includes a hydrocarbon.

22. An energy storage and retrieval system comprising:

a first thermal reservoir arranged to hold working fluid in a first state that includes liquid phase and saturated vapor phase work fluid;

a low temperature thermal energy source arranged to provide vapor phase working fluid in a second state having a lower temperature than the first state;

a condenser arranged to condense vapor phase working fluid; and

a heat engine/heat pump unit arranged to,

(a) extract energy from working fluid vapor passing from the first thermal reservoir to the condenser via expansion of the working fluid vapor in a manner that generates mechanical energy to facilitate retrieval of energy from the energy storage and retrieval system, and

(b) compress working fluid vapor passing from the low temperature thermal energy source to the first thermal reservoir to facilitate the storage of energy in the energy storage and retrieval system.

23. An energy storage and retrieval system as recited in claim **22** wherein the heat engine/heat pump unit is a reversible positive displacement steam engine and the working fluid is water.

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