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(54) **THERMAL ENERGY STORAGE SYSTEMS AND METHODS**

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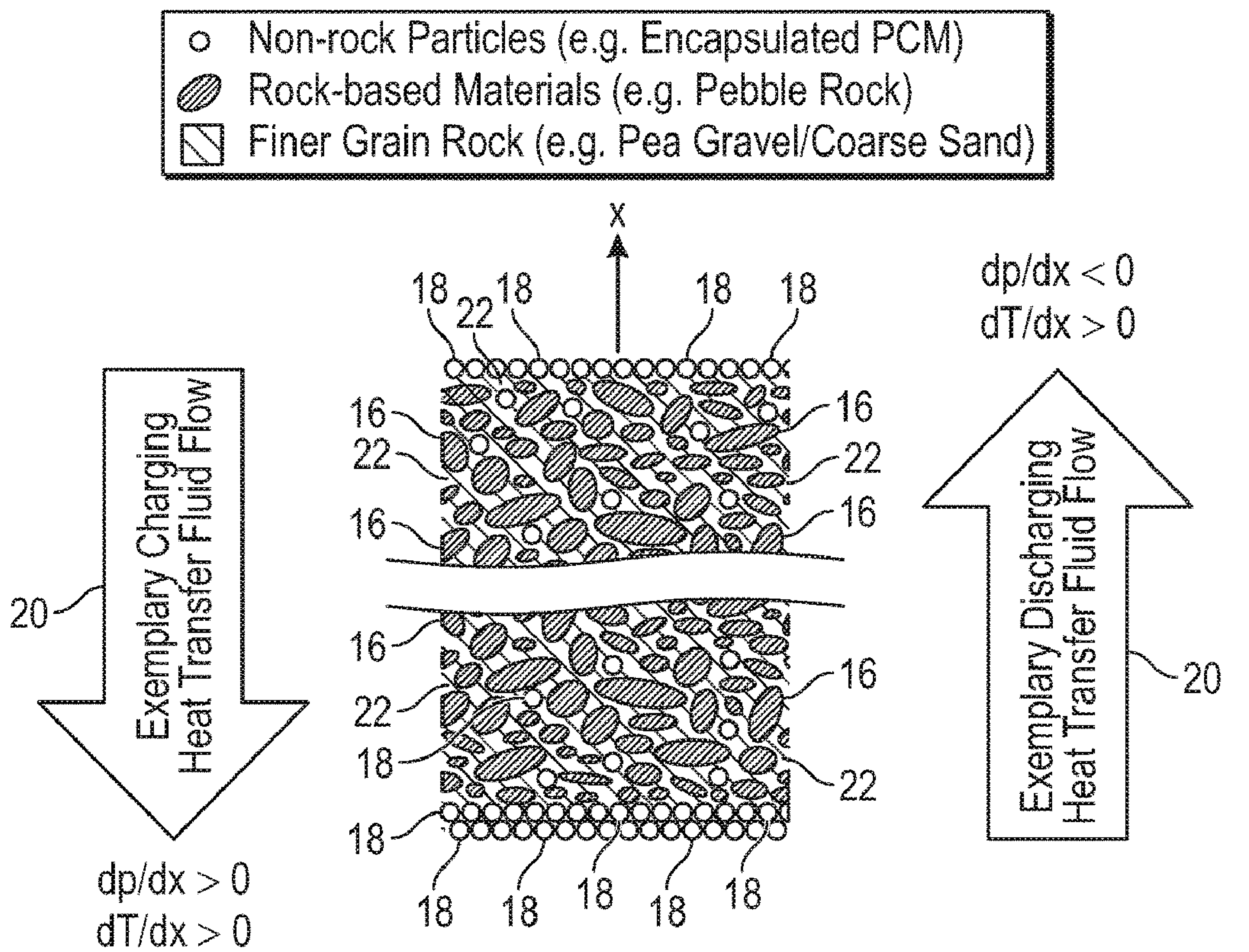
(57) **ABSTRACT**

Thermal energy storage systems and methods are provided including a bed, a blend of aggregates packed in the bed, and a high-density heat transfer fluid flowing through the blend of aggregates. The blend of aggregates includes rock materials and may also include non-rock materials. The heat transfer fluid flows through the blend of aggregates such that heat is transferred between the heat transfer fluid and the blend of aggregates. The porosity of the aggregates increases heat transfer and the high density of the heat transfer fluid reduces the pressure gradient of the heat transfer fluid. In exemplary embodiments, the heat transfer fluid is a liquid comprised of carbon-based molecules. Methods of safely storing and releasing energy are provided in which axial thermal conductivity of the bed is minimized and inadvertent pressure release failures are mitigated.



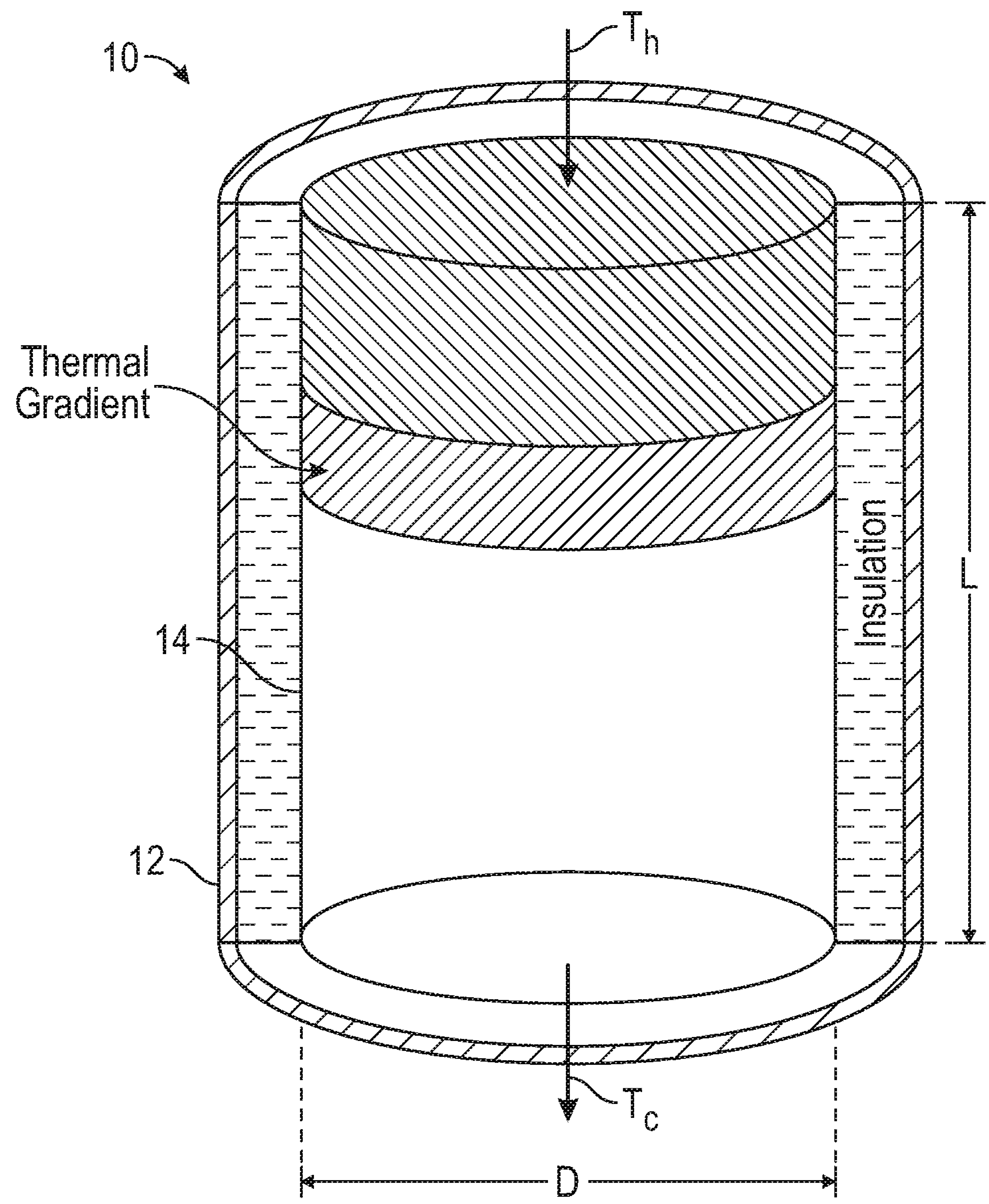


FIG. 1

							ΔT (C):	100	
Material	Density (kg/m^3)	Average Porosity	Specific Heat (c_{tr}) $(J/kg/K)$	Average Thermal Conductivity $(W/m/K)$	Thermal Diffusivity (m^2/s)	Volumetric Specific Energy Storage $(kWhr/m^3/K)$	Cost per Unit Mass ($/tonne)	Energy Capacity Cost ($/kWhr)	Relative Cost
Coarse Sand, dry	1555	0.39	800	0.2	1.61E-07	0.346	$ 14	$ 0.63	2.0%
Coarse Gravel, dry	1680	0.34	800	0.7	5.21E-07	0.373	$ 20	$ 0.90	2.9%
Scrap Metal	400	0.83	490	0.2	1.19E-06	0.054	$ 35	$ 2.57	8.2%
Scrap Metal (Prepared)	1000	0.58	490	0.6	1.19E-06	0.136	$ 50	$ 3.67	11.8%
Concrete, Light	1000	<0.05	960	0.2	2.08E-07	0.267	$ 100	$ 3.75	12.0%
Magnesium Oxide	3580	<0.05	900	40	1.24E-05	0.895	$ 150	$ 6.00	19.2%
Common Brick	1400	<0.05	900	0.8	6.35E-07	0.350	$ 154	$ 6.16	19.7%
Brown Corundum	4000	<0.05	420	30	1.79E-05	0.467	$ 75	$ 6.43	20.6%
Concrete, Stone	2400	<0.05	750	1.4	7.78E-07	0.500	$ 200	$ 9.60	30.8%
Graphite, amorphous	2100	<0.05	710	94	6.33E-05	0.414	$ 200	$ 10.14	32.5%
Solar Salt	1900	0.00	1500	1	3.51E-07	0.792	$ 1,300	$ 31.20	**100%**
Mineral Oil	800	0.00	2250	0.2	8.89E-08	0.500	$ 2,500	$ 40.00	**128%**

FIG. 2

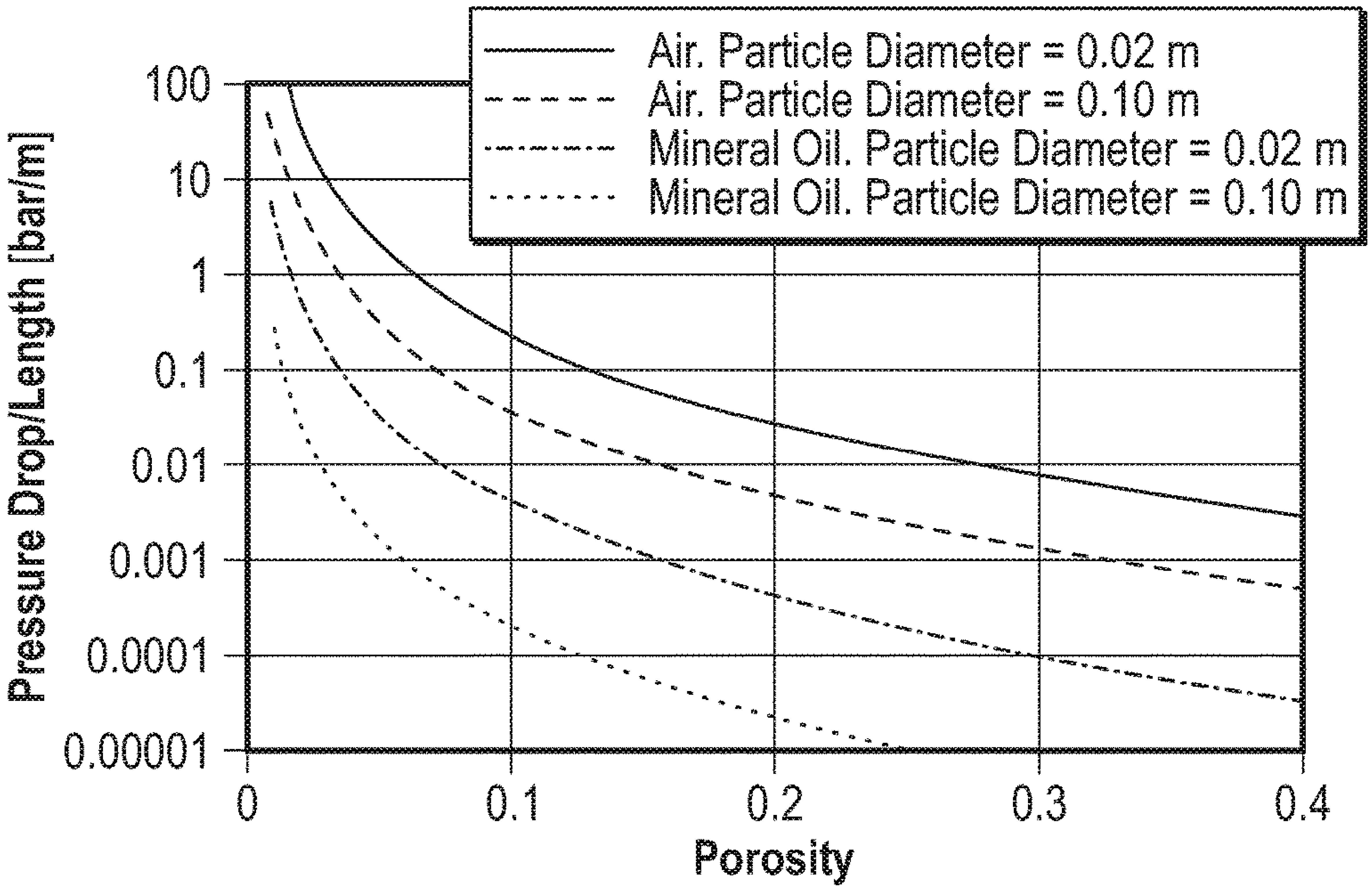

Air. Particle Diameter = 0.02 m
Air. Particle Diameter = 0.10 m
Mineral Oil. Particle Diameter = 0.02 m
Mineral Oil. Particle Diameter = 0.10 m
Pressure Drop/Length [bar/m]
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0
0.1
0.2
0.3
0.4
Porosity

FIG. 3

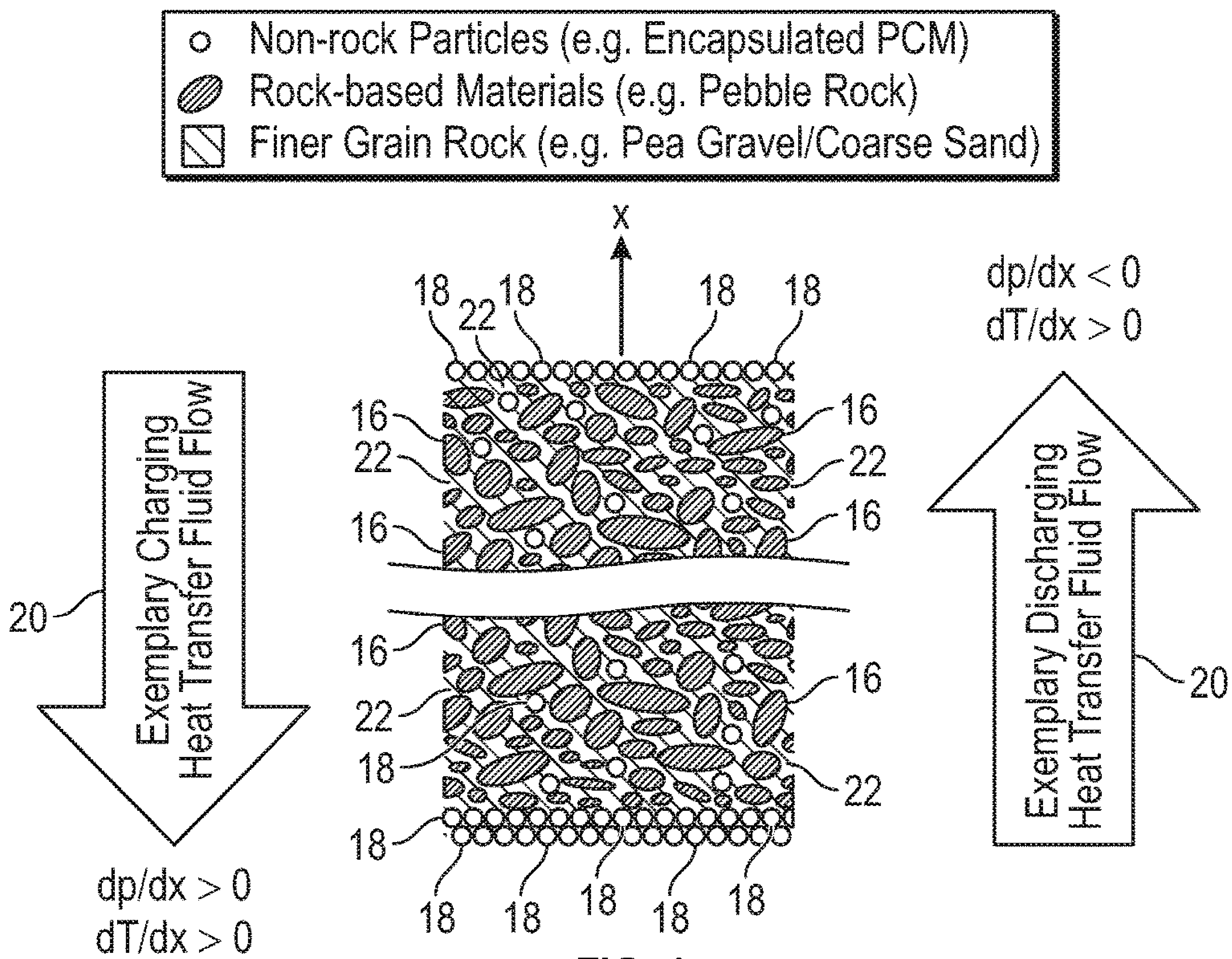

Non-rock Particles (e.g. Encapsulated PCM)
Rock-based Materials (e.g. Pebble Rock)
Finer Grain Rock (e.g. Pea Gravel/Coarse Sand)
x
dp/dx < 0
dT/dx > 0
Exemplary Charging Heat Transfer Fluid Flow
Exemplary Discharging Heat Transfer Fluid Flow
16
18
20
22
dp/dx > 0
dT/dx > 0

FIG. 4

THERMAL ENERGY STORAGE SYSTEMS AND METHODS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to and benefit of U.S. Patent Application Ser. No. 62/512,998, filed May 31, 2017, which is hereby incorporated by reference in its entirety.

FIELD

[0002] The present disclosure relates to thermal energy storage systems and methods. The present disclosure relates to systems and methods of storing and releasing energy using organic heat transfer fluids and energy storage media such as pelletized rock

BACKGROUND

[0003] There has been a longstanding need to develop a low-cost, cost-effective energy storage solution for grid scale utility energy storage, particularly for renewable energy production wherein the timeframes available for energy production typically do not occur or align well with grid scale energy demand. Currently, over the timespan of a day, the U.S. electric grid primarily provides energy on demand with the ability to effectively store <<5% of the energy produced over the course of the day. Much of this storage is currently associated with the use of existing hydroelectric facilities (e.g. dams) that allow one to pump water into reservoirs during "energy storage" events. This form of grid scale energy storage is not a cost-effective energy storage solution for new facilities typically not being the primary reason for damn construction and is already near capacity in the U.S. Current attempts to develop low cost energy storage solutions have results in levelized costs of energy for just the energy storage component that exceed the current levelized costs for energy production.

[0004] The cost of storage of energy in the form of electricity is typically much higher than the cost of storage of energy in the form of heat. This is due primarily to the much higher relative product lifecycle cost per unit energy stored for materials that support electrochemical reactions compared to the product lifecycle cost per unity energy stored for abundant low-cost materials that can store heat. Two primary renewable energy sources that could potentially support a large fraction of global energy demand, concentrated solar thermal heat and geothermal heat, are abundant renewable thermal energy sources that would benefit greatly from a low cost thermal energy storage solution (i.e. "thermal battery") that would enable energy storage and energy delivery during times of peak and/or substantive energy demand.

[0005] In conventional storage of thermal energy using passive thermal mass, several different architectures currently exist. One example is storing heat in a higher temperature working fluid such as molten salt by heating and/or cooling the working fluid. In this scenario, thermal energy is stored in the form of sensible heat through a difference in temperature of a unit mass of fluid between two temporal conditions (e.g. an initial state and an end state). A portion of the stored heat may also be stored in the phase change (e.g. enthalpy of fusion/melting) that may occur over a period of time within a volume of the storage medium when heat is added or removed. In other conventional thermal storage architectures, storage of heat has been demonstrated with solid thermal mass, e.g., heating concrete or bulk rock. One of the challenges in heating and cooling solid mass is the longer timeframes typically associated with adding and removing heat that limit how quickly thermal mass can be recharged and discharged, particularly in utility scale battery applications.

[0006] An additional factor that must be considered, particularly with sensible heat storage solutions, is the evolution of the temperature gradient (a.k.a. thermocline) that must exist in the thermal storage medium in order to allow heat to be transferred into or out of the energy storage medium. This temperature gradient and its spatial distribution and temporal evolution typically effectively reduces the energy storage capacity of the battery as well as negatively impacts the roundtrip storage efficiency. This occurs due to the fact that a certain quantity of energy may typically be required to be deposited to establish and/or overcome an existing temperature gradient in order to allow energy to flow in a desired direction. Unlike electrochemical energy storage solutions, the "quality," i.e., the temperature, of the delivered heat may typically change which can impact the downstream conversion efficiency and/or ability of a downstream process to fully utilize energy that was previously produced. Therefore, for at least the reasons outlined herein, careful management of the temperature distributions in a thermal energy reservoir are critical for ensuring high roundtrip efficiencies of thermal batteries while simultaneously minimizing the volume and cost associated with the energy storage medium of the thermal battery.

[0007] Most of the concentrating solar power industry is currently focused on inorganic heat transfer fluids, (e.g. molten salt) that freeze at temperatures much higher than ambient. These high freezing points can become a major operational and/or risk mitigation issue to make sure that freezing doesn't happen inadvertently (e.g. several days of cloud cover that results in the system cooling off) which in most cases would render the solar plant partially or fully inoperable for extended periods of time particularly in areas of the fluid system that cannot be readily heated. Furthermore, the molten salts can be very challenging to work with in terms of corrosion of materials.

[0008] Water has also been used as a "low cost" heat transfer fluid for concentrating solar; however, given that water dissolves so many compounds that change the behavior of corrosion with the metals that contain it, water can actually be very difficult to work with in terms of guaranteeing the longevity and integrity of the wetted fluid system over its operational life. It also can place a huge cost constraint on systems due to the fact that any system operating with over 15 psig of water vapor pressure typically requires a steam boiler operator, the OPEX cost of which over a typical lifetime of power purchase agreements can exceed the CAPEX installation cost of the hardware for smaller (~acre scale) systems.

[0009] Organic compound-based heat transfer fluids can resolve the freezing point, corrosion, and other cost issues associated with water and salts. Designing for organic compound-based heat transfer fluids, however, potentially introduces their own unique challenges. Organic compound-based heat transfer fluids can be flammable and/or create a pressure release hazard due to the natural vapor pressure of the fluid and/or additional gas pressure the fluid can generate if it decomposes into gas or combusts. Furthermore, in considering explosive energy potential due to inadvertent off-nominal interactions with the thermal battery (e.g. excess heating, excessive mechanical shock), the energy storage medium should be robust enough to contain stored energy without an inadvertent rapid energy release that creates a substantive operations hazard.

[0010] Energy release from a thermal battery can occur in many different forms, but typically for inadvertent structural damage to occur on very short timescales (<<10 seconds) all such explosive energy releases typically involve the inadvertent buildup of pressure. For example, in one scenario, rapid chemical reactions that may be initiated due to heating or mechanical impact, may convert some and/or all of the energy storage media in the battery into very low-density gases compared to the liquid and/or solid densities that initially comprised the battery. To keep these low-density gases contained in the same volume initially occupied by the battery, very large pressures may be generated. Alternatively, inadvertent rapid energy release from the battery may cause runaway heating to occur. This inadvertent heating may result in thermal damage or initiation of fire hazards that while less hazardous than explosive energy releases, may still result in substantive property damage and/or loss.

[0011] Candidate thermal battery energy storage media must address the constraints identified above while also being fundamentally very low cost over the lifetime of the use of the battery. For many utility scale energy applications, the associated product lifetimes can be quite long and may typically be equal to or greater than 20 years. These long timescales for utility batteries are much longer than conventional electrochemical batteries are typically designed to survive, much less operate. The thermal energy storage media for these utility scale energy applications should minimize maintenance requirements over these extended product lifetimes to help ensure the lifecycle cost of the thermal battery remains low.

[0012] In the design of any energy storage solution, three metrics that are considered important are: 1) the roundtrip charge/discharge efficiency; 2) the peak charging/discharging rate; and 3) the hazard potential for inadvertent rapid energy release. Metric **1** effectively determines what the energy cost is for effectively time-shifting energy delivery. High efficiency energy storage mechanisms are desirable in order to mitigate additional energy storage cost for time-shifting energy delivery. The metric **2** peak charging/discharging rate is very important to ensure that the energy storage solution can effectively support both the charging and discharging rates that would be required particularly in a utility scale energy operation where ramp rates for discharge and, in some cases, recharge as well can be very substantial. In California, the "duck curve" utility power demand profile places major constraints on the ramp rates for powerplants that can be quite challenging to meet for traditional batteries. Finally, the metric **3** is a metric typically derived in the form of a MIL-SPEC hazard classification from MIL-STD testing that determines the worst case high rate of energy release (and associated hazard) that can be produced when the energy storage system is exposed to extreme environments and/or threats that may be experienced particularly when operating in off-nominal conditions or scenarios.

SUMMARY

[0013] The present disclosure alleviates the problems of existing energy storage solutions by providing thermal energy storage systems and methods which use pelletized rock as the majority of the energy storage media and high-density heat transfer fluids, e.g., liquids, that do not have the high pressure drop issues across a packed bed that can more commonly be associated with low density heat transfer fluids such as gases (e.g. air, CO_2, etc.) and vapors (e.g. steam, etc.). Disclosed systems and methods use very low porosity, e.g., less than about 30%, and in many cases much lower, beds to get the surface area per unit volume high. This advantageously provides rapid charge and discharge rates for utility scale power and reduced cost to minimize the volume of expensive heat transfer fluid that needs to be used.

[0014] Exemplary embodiments provide a lower temperature, e.g., <325° C., thermal battery for lower temperature process heat applications in that temperature range, and in alternate exemplary embodiments, at temperatures less than about 250° C. or less than about 150° C. Most reasonable-cost heat transfer fluids that aren't toxic and can be readily handled have vapor pressures that rapidly climb above 300° C. Also, the costs associated with rated fittings and components start to climb rapidly at the higher pressures and temperatures above 300° C. Energy storage systems and methods disclosed herein can advantageously operate at a cost less than about $615/kWh while supporting a >35% efficient power cycle, a 90% efficient receiver panel, 4-14 hours of thermal energy storage with up to 99% energetic efficiency and up to 95% exergetic efficiency. In some cases, with slightly higher rated pressure vessels and associated cost for these system, the energy storage systems can be designed to operate at temperatures up to ~425° C. near the breakdown limit of high temperature, synthetic hydrocarbon compound heat transfer fluids.

[0015] Exemplary embodiments of a thermal energy storage system comprise a bed, a blend of aggregates packed in the bed, and a high-density heat transfer fluid flowing through the blend of aggregates such that heat is transferred between the heat transfer fluid and the blend of aggregates. In exemplary embodiments, the bed is a vertical cylinder. The blend of aggregates includes rock materials. The porosity of the aggregates increases heat transfer and the high density of the heat transfer fluid reduces the pressure gradient of the heat transfer fluid. In exemplary embodiments, the porosity of the aggregates is less than about 30% and the porosity may be about 10%. The heat transfer fluid may have a thermal conductivity of less than about 10% of the aggregates. In exemplary embodiments, the heat transfer fluid is a liquid with a fluid density of at least 0.4 g/cc at at least one location in the packed bed.

[0016] In exemplary embodiments, the blend of aggregates comprises one or more of sand, pebbles, washed rock, quartz, and magnetite. The blend of aggregates may further include non-rock materials. The rock-based material constituent may comprise about 80% or more of the blend of aggregates, and the non-rock materials about 20% or less of the blend of aggregates. The surface area of aggregate per unit volume may be about 215 m^2/m^3. The packed bed may store energy at temperatures less than about 325° C., and in exemplary embodiments, at temperatures less than about 250° C. or less than about 150° C. In some higher temperature applications, the packed bed may store energy at temperatures less than about 425° C. In exemplary embodiments, there is coarse filtering media at a base of the bed. In other embodiments, the heat transfer fluid is directed vertically up through the bed during charge/discharge cycles. The bed may include means to facilitate the management of rock particulate contamination.

[0017] Exemplary embodiments of a thermal energy storage system comprise a bed including a fluid inlet and a fluid outlet, a blend of aggregates packed in the bed, and a heat transfer fluid flowing through the blend of aggregates such that heat is transferred between the heat transfer fluid and the blend of aggregates. The blend of aggregates includes rock materials, and in some cases non-rock materials. The heat transfer fluid may be a liquid comprised of carbon-based molecules and, in exemplary embodiments, the heat transfer fluid is an oil. In exemplary embodiments, the heat transfer fluid does not freeze at temperatures above 100° C. In exemplary embodiments, the fluid viscosity of the heat transfer fluid ensures fluid pressure drop from the fluid inlet to the fluid outlet is less than about 5 psid under nominal conditions and less than about 100 psid under cold start-up conditions. In exemplary embodiments, the vapor pressure of the heat transfer fluid is less than about 300 psia at the highest design temperature of any portion of the bed in direct contact with the heat transfer fluid. In exemplary embodiments, the vapor pressure of the heat transfer fluid is less than twice atmospheric pressure at the highest design temperature of any portion of the bed in direct contact with the heat transfer fluid.

[0018] Exemplary methods of storing and releasing energy comprise packing a blend of aggregates in a bed, the aggregate particle sizes and distributions of which are designed to minimize porosity and temperature differences between the particles and the heat transfer fluid as well as minimize axial thermal conductivity of the bed, providing a liquid organic heat transfer fluid having a thermal conductivity of less than about 10% of the thermal conductivity of the individual aggregate particles, and directing the heat transfer fluid through the blend of aggregates such that heat is readily transferred between the heat transfer fluid and the blend of aggregates. The blend of aggregates includes rock materials. Over 85% of the stored thermal energy in the bed can be extracted in a charge/discharge cycle in less than 18 hours. In exemplary embodiments, over 85% of stored energy can be extracted in a charge/discharge cycle in less than six hours. Exemplary methods further include bed/heat transfer fluid design to minimize inadvertent explosive release of built-up gas pressure in the Thermal Battery in extreme operational scenarios. Exemplary methods may further comprise slowing the rate of release of inadvertent gas pressure buildup during off-nominal operations by at least one order of magnitude.

[0019] Accordingly, it is seen that systems and methods of storing and releasing energy are provided. These and other features and advantages will be appreciated from review of the following detailed description, along with the accompanying figures in which like reference numbers refer to like parts throughout.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] The above-mentioned features and objects of the present disclosure will become more apparent with reference to the following description taken in conjunction with the accompanying drawings wherein like reference numerals denote like elements and in which:

[0021] FIG. **1** is a front cut-away view of an exemplary embodiment of a thermal energy storage system in accordance with the present disclosure in this case illustrating a downward directed thermal battery charge heat transfer fluid flow;

[0022] FIG. **2** is a table listing exemplary candidate thermal storage media and energy capacity cost for 100° C. delta T (sensible heat storage);

[0023] FIG. **3** is a graph showing exemplary pressure drop characteristics of a packed bed of uniform spherical particles as a function of fluid density (e.g. air and oil) and particle diameter; and

[0024] FIG. **4** is a schematic depicting an exemplary embodiment of a packed bed thermal energy storage system in accordance with the present disclosure.

DETAILED DESCRIPTION

[0025] In the following detailed description of exemplary embodiments of the disclosure, reference is made to the accompanying drawings in which like references indicate similar elements, and in which is shown by way of illustration specific embodiments in which disclosed systems and devices may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the embodiments, and it is to be understood that other embodiments may be utilized and that logical, mechanical, functional, and other changes may be made without departing from the scope of the present disclosure. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present disclosure is defined by the appended claims. As used in the present disclosure, the term "or" shall be understood to be defined as a logical disjunction and shall not indicate an exclusive disjunction.

[0026] With reference to FIGS. **1** and **4**, a thermal energy storage system **10**, or thermal battery, comprises a bed **12** packed with energy storage media composed of a blend **14** of aggregates and a heat transfer fluid **20** that flows through the blend of aggregates so heat is transferred between the heat transfer fluid **20** and the blend **14** of aggregates. In exemplary embodiments, the aggregate blend **14** is comprised of pelletized rock materials **16** and non-rock materials **18**, which are not in the form of a rock constituent. The rock materials can be cheap, abundant, non-reactive, environmentally benign solid packing media such as sand, pebbles, washed rock, quartz, magnetite (iron oxide) and/or combinations of the above. One of the lowest cost sensible thermal energy storage media currently available is these types of rock in manually crushed or naturally pelletized form. More complex thermal storage media (e.g. concrete) may rapidly increase in cost to over 300% of the cost of the pelletized rock bed design discussed herein.

[0027] There are several ways to select and utilize the blend **14** of aggregates to increase efficiency of the system, reduce its cost, and/or reduce the volume of the packed bed **12**. Because rocks typically have both a much lower cost than heat transfer fluids (see FIG. **2**) as well as a higher heat capacity, reducing the void fraction is an effective way to reduce the total cost and reduce the total volume of the thermal battery. FIG. **2** lists several candidate sensible storage materials along with relative cost impacts assuming an average achievable 100° C. usable delta T on the store over the duration of the storage cycle.

[0028] Another factor in the selection of particles for the bed is the ability of the particles to naturally resist what is known as thermal ratcheting which is a process that breaks down the particles over many cycles of heating/cooling. Particles can be selected to be more robust to thermal ratcheting by, for example, using particles with material/geometric properties including, but not limited to, relatively smooth surfaces (e.g. wash rock/pebbles) and minimum internal void structure to minimize stress concentration factors, low thermal expansion coefficients, and/or high tensile strengths.

[0029] In exemplary embodiments and as discussed in more detail herein, the maximum particle size for the packed bed may be selected such that the Biot number (effective measure of temperature gradient in particle compared to temperature gradient across heat transfer fluid boundary layer) is less than about 0.5 when considering the heat transfer fluid as described below. The charging/discharging rate of the packed bed **12** is strongly influenced by the average Biot number of the particles in the bed. To meet the ramp rate requirements for peak discharge during "Duck Curve" evening hours in CA, average particle sizes less than ~2 cm may likely be required. Although this increases pressure drop in the bed, <1 bar/m pressure drop appears readily feasible with any porosities greater than about 2%. FIG. **3** is a graph showing pressure drop characteristics. In exemplary embodiments, the particle size distributions in the bed may be selected such that the largest particle is less than about 10 cm in mean diameter. In exemplary embodiments, about 50% or greater of the particles in the bed **12** may be less than about 5 cm in mean diameter.

[0030] Porosity in packed beds with uniformly sized and distributed particles are typically in the range of 30%-40%. However, it is possible to achieve smaller porosities by using a range of particle sizes—for example, by using smaller particles **22** to fill-in-the gaps between larger particles. In exemplary embodiments, a distribution of rock sizes is selected to ensure relatively poor sorting (i.e. small size rocks fill in the pore sizes of larger rocks) such that a total bed porosity of less than about 15% is achieved. In exemplary embodiments and as discussed in more detail herein, the porosity of the blend **14** of aggregates can increase heat transfer between the energy storage media and the heat transfer fluid **20**. In exemplary embodiments, the porosity is less than about 30% and can be as low as 10%. In exemplary embodiments, the porosity is greater than 2%. In exemplary embodiments the make-up of the rock-based energy storage media in the bed **12** may comprise more than about 30% by mass or volume of the non-rock materials **18** (e.g. concrete).

[0031] In exemplary embodiments, the packing structure is approximately uniform in the bulk of the packed bed. However, the presence of the containment wall may disrupt the packing structure such that the porosity approaches 1 at the wall surface. The porosity typically decreases to near its bulk value in approximately five particle diameters. The high porosity at the wall typically reduces frictional resistance to the flow and may lead to higher flow rates (also known as 'by-pass' flow) near the walls which would create a non-uniform flow distribution and affect the charge/discharge efficiency of the battery. In exemplary embodiments, carefully designing the radial distribution of particle sizes and packing structure particularly in the vicinity of support/retaining structure can reduce these undesirable effects near containment/retaining structures. In exemplary embodiments, the rock material and particle size distributions may be selected such that the bed porosity changes by less than about 5% absolute after 5,000 cycles due to additional thermal stress fracturing/bed settling during charging/discharging operations.

[0032] In the embodiments described above, low porosity packed beds are desirable to reduce the cost of the thermal battery. However, low porosities can substantially increase fluid velocity and pressure drop for fluid flow across the packed bed (FIG. **3**). The cost driven objective to achieve lower porosity packed beds tends to emphasize the need to reduce pressure drop losses and fluid-velocity-related bed degradation by using a high-density heat transfer fluid rather than gas/vapor heat transfer fluid. A suitable density for a high-density heat transfer fluid would be in the range of about 0.4 g per cc to about 1.5 g per cc. In exemplary embodiments, the heat transfer fluid is a liquid that is operated to ensure it does not vaporize at the higher operating temperatures of the bed.

[0033] Incorporating encapsulated Phase Change Materials (PCMs) into the packing may provide further benefits, such as increasing the energy density. The low conductivity of PCMs is currently a challenge that may be overcome by enhancing heat transfer by mixing the PCM with the higher conductivity packing material or using encapsulated PCMs with very small particle diameters (<<1 cm). Encapsulation of PCMs prevents the PCM material from melting and mixing into the heat transfer fluid system. In exemplary embodiments, encapsulated PCM's particles are non-rock constituents included as part of the aggregate blend. In exemplary embodiments, encapsulated PCM's may consist of up to 50% of the mass or volume of the aggregate materials in the packed bed. The cost of encapsulated phase change materials is typically more expensive per unit of energy stored than rock. Therefore, in a very low-cost bed design that incorporates encapsulated PCMs, typically the PCMs would be confined to helping buffer and control output temperatures versus providing the primary mechanism for bulk thermal energy storage.

[0034] In exemplary embodiments, the overall bed porosity and particle size distributions are designed to minimize the axial thermal conductivity of the bed. Typically, the heat transfer fluid has a thermal conductivity less than about 10% of the rock constituent. By working with a higher surface area per unit volume rock bed, the heat flow path through the bed may be further disrupted and the bulk thermal conductivity of the overall bed may be reduced. In some implementations, this type of bed design may help minimize variations in the temporal evolution of the thermocline in the bed due to heat redistribution inside the bed itself.

[0035] In some implementations, this type of bed design may increase the roundtrip efficiency of the thermal battery over a charge/discharge cycle. In exemplary embodiments, a majority of the stored energy can be extracted in a relatively short period of time. In some cases, over 85% of the stored energy can be extracted in a charge/discharge cycle in less than twelve hours and in some instances, less than six hours. In exemplary embodiments, the surface area of rock per unit volume is approximately 215 m^2/m^3. In another implementation, the surface area of rock per unit volume is higher. In yet another implementation, the surface area of rock per unit volume is lower.

[0036] For sizing a solar thermal battery recharge rate, daily recharge rates will follow the solar cycle and will typically vary between 4-8 hrs depending on site and season. For sizing a solar thermal battery discharge rate, utility power discharge rates typically require discharge in as short as four hours to meet utility peaking power demands. Commercial operations may tend to spread the accumulated solar heat over a 24/7 operations cycle and therefore have even longer storage requirements that can approach 18 hours in some cases. The energy storage size and corresponding rates of recharge/discharge are dependent on the scale of the solar field. For an approximately one acre system, the peak rates of solar thermal battery charging/discharging will be of order 1 MW and the storage capacity would be up to ~10 MWhr. Larger solar fields would require larger individual thermal batteries (~GW rate of charge/discharge for 10 GWhr storage) or banks of the smaller **10** MWhr thermal batteries.

[0037] The container or bed **12** could be designed in various ways to improve reliability and performance of the thermal energy storage system. Processed metals (e.g. steel, aluminum) typically substantially (>500%) increase in cost per unit volume relative to pelletized rock due to the significant processing steps necessary to extract and refine these materials into their usable forms. These costs for metal increase even more when these metals are processed into usable geometric forms (e.g. pipe, pressure vessel walls, etc.). Therefore, in the design of the container for the pelletized rock bed, the bed **12** can be designed to minimize the loads and pressures that the structural elements of the thermal battery are exposed to as well as the surface area and resultant volume of structural materials that must be deployed in the bed. For example, as shown in FIG. **1**, the bed **12** may be designed as a vertical cylinder. In exemplary embodiments, the bed **12** has a height-to-diameter ratio of approximately one. In some implementations, this ratio may be greater than or less than one. In an exemplary embodiment, the bed is designed with manifolding and/or filtering to facilitate the management of rock particulate contamination that may be generated from thermal cycle stress fatigue and associated micro-fracturing of the rock bed media particularly over the charge/discharge cycles associated with a thermal battery designed for decade long or greater battery operations.

[0038] Pressure vessels to contain the packed bed and safely manage pressure inside the thermal battery can be a very large component of the cost of the overall thermal battery. To ensure the heat transfer fluid remains liquid (i.e. liquid doesn't start locally boiling), the operating pressure inside the thermal battery needs to be greater than the vapor pressure of the warmest heat transfer fluid element in the thermal store. This constraint defines a minimum pressure for the packed bed above which additional design margin should be included depending on certifying organization for the pressure vessel. The vapor pressure of heat transfer fluids is typically very sensitive to temperature also typically increasing very rapidly at temperatures at and above where the heat transfer fluid vapor pressure exceeds local atmospheric conditions. In some embodiments, the maximum operating temperature inside the thermal battery is selected such that the pressure vessel can be rated as an atmospheric pressure vessel. In other embodiments, the heat transfer fluid and the pressure vessel are optimally designed for a specified set of operating temperatures or temperature ranges in order to minimize the cost of the overall thermal battery.

[0039] In operation of exemplary systems and methods of energy storage and release, the pelletized rock bed **12** functions with a liquid heat transfer fluid **20** that percolates through the bed **12** under Darcy Flow conditions during heat transfer operations (i.e. during thermal battery charging/discharging events). This liquid heat transfer fluid **20** through the pelletized bed **12** with rock size distribution as described above provides a means for rapidly transferring heat between the liquid heat transfer fluid **20** and the blend **14** of aggregates of the pelletized rock bed while simultaneously minimizing the fluid pressure drop (in exemplary embodiments less than about 5 psid) through the bed due primarily to the very low superficial fluid velocities (e.g., less than about 1 cm/s) of the liquid heat transfer fluid **20** through the bed **12** that are factored in the overall bed design.

[0040] In exemplary embodiments, coarse media **22** is placed at the base of a cylindrical bed to provide a means of approximately uniformly manifolding fluid across the base of the bed while simultaneously supporting the weight of the bed. The manifolding is designed to minimize radial pressure drop gradient relative to the normal axial pressure gradient in the bed to help ensure the axial mass flux of fluid across the packed bed is approximately uniform. The axial pressure gradient is derived by the difference between the inlet and outlet pressure divided by the length of the bed and is represented by the equations shown in FIG. **4**. In other exemplary embodiments, this base of coarse media **22** may be separated by a screen to help ensure the porosity of the base manifold is approximately maintained over the operation of the thermal battery.

[0041] In exemplary embodiments, the top of the bed may include a fluid gap and/or coarser media in order to provide a means of approximately uniformly manifolding fluid across the top of the bed. In other exemplary embodiments, this top manifolding zone may be separated by a screen to help minimize particle contamination in the heat transfer fluid stream.

[0042] The pore velocity of the fluid may be designed sufficiently low such that coarser micro-fracture particles are retained in the bed due to the higher ballistic coefficients of these larger particles in the presence of gravity and only fine filtering is conducted at the exit at the top of the bed for scenarios where fluid flow is nominally directly vertically upward. This implementation may help facilitate the reduction in cost associated with filters and/or filter replacements over the extended life operations of a thermal battery contemplated herein.

[0043] The heat transfer fluid typically has a cost per unit volume that is greater than about at least 500% of the cost per unit volume of the pelletized rock, although other lower cost heat transfer fluids may be used. The heat transfer fluid **20** is selected with the following basic characteristics: 1) The heat transfer fluid does not freeze at temperatures above about 100° C.; 2) the heat transfer fluid has a fluid viscosity low enough to ensure the fluid pressure drop from the fluid inlet to the fluid outlet of the bed is less than about 5 psid under nominal conditions; 3) the heat transfer fluid has a fluid viscosity low enough to ensure the fluid pressure drop from the fluid inlet to the fluid outlet of the bed is less than about 100 psid under cold start-up conditions; 4) the heat transfer fluid does not chemically break down and/or alter its chemical constituency by greater than about 5% due to operations over at least 5,000 charge/discharge cycles and/or 7 years (whichever happens first) when exposed to both the temperatures and chemistry of the rock bed; 5) the heat transfer fluid has a vapor pressure of less than about 300 psia at the highest design temperature of any portion of the bed in direct contact with the heat transfer fluid. In other exemplary embodiments the heat transfer fluid vapor pressure at the highest design temperature of any portion of the bed in direct contact with the heat transfer fluid is near atmospheric pressure to allow for a very low cost pressure vessel design. In exemplary embodiments, the high density of the heat transfer fluid minimizes drops in pressure of the heat transfer fluid.

[0044] In exemplary embodiments, the heat transfer fluid **20** is a liquid comprised of carbon-based molecules, and the heat transfer fluid may be an oil. However, organic compound-based heat transfer fluids can be flammable and/or create a pressure release hazard (due to the natural vapor pressure of the fluid and/or additional gas pressure the fluid can generate if it decomposes into gas or combusts). Advantageously, disclosed systems and methods mitigate this effect and minimize this pressure release hazard such as an explosion by slowing the rate of pressure generation and associated energy release down by several orders of magnitude, e.g., from sub-10's milliseconds to sub-10's of seconds or less. Furthermore, to mitigate explosive hazard and/or inadvertent energetic releases, the heat transfer fluid and rock chemistry are jointly designed and/or selected to ensure that under worst case excessive heating conditions, less than about 1% by mass per second of either the fluid and/or rock will chemically react with one another.

[0045] Another important consideration in the design of the packed bed is the behavior of the thermocline. There is necessarily an axial temperature gradient across the packed bed. As the packed bed is charged, the thermal gradient progresses along the length of the packed bed. Eventually, it reaches the end of the fluid exit of the packed bed and the packed bed exit temperature begins to increase. Disclosed systems and methods may place a limit on the maximum amount by which this outlet temperature can increase during charging. For instance, if the exit fluid goes back into the solar field then the fluid will be heated up to higher temperatures in the solar receivers. The fluid's maximum operation temperature then sets a limit on how much the packed bed exit temperature can increase during charge. This may effectively mean that the packed bed cannot be fully charged, and therefore, in exemplary embodiments, is slightly oversized in order to provide the required energy. Incorporating PCMs (which melt at a fixed temperature) into the packed bed packing can be used to control these exit temperature variations.

[0046] There are other practical aspects that can make packed bed operation challenging. For instance, the thermal expansion and contraction of the particles can damage the particles and the containment, which is known as thermal ratcheting. These effects can be reduced to some extent by careful design of the storage container—such as by using a conical store, or by installing internal structures to support the particles and keep them in the correct place. The particles also require some treatment before they can be used. For instance, pressure losses are increased if the particles are not washed before the bed is constructed. In some embodiments, the packed bed has a variable cross-sectional geometry of particles that may have undergone some additional preparatory steps to help reduce pressure drop and bed degradation.

[0047] Furthermore, to mitigate structural damage due to storage vessel pressure related failures, the heat transfer fluid thermophysical/heat transfer properties and rock pore size distributions are jointly designed/selected to ensure that under a worst case pressure vessel casing failure that the pressure decay profile of the actual system is such that at the same point in time where P/P_0 of an ideal isentropic expansion of the just vapor component of the heat transfer fluid is 1/e (~36.7%), the pressure of the actual system at the same point in time is less than approximately 10% of the ideal isentropic expansion. In some implementations where the vapor pressure of the system is lower, this design point may be less than approximately 50%. In still other implementations where the vapor pressure of the system is not a substantial operations concern, this design point may be less than approximately 90%.

[0048] Additional beneficial mechanisms for mitigating and/or slowing the release of pressure during inadvertent pressure release under pressure vessel failure scenarios may be factored into a bed design. These include large fluid frictional losses associated with much lower density gases rapidly trying to propagate through the packed bed, the momentum transfer between low density gas and very high density particles that limits the rate of expansion of the energetic bed volume during failure, sonic velocity choking of gas/vapor trying to escape limited surface area-to-packed bed volume pore spaces that limits the volumetric generation of high velocity gases, and/or thermal quenching of runaway chemical decomposition reactions that slows and/or stop the rates of inadvertent chemical energy release.

[0049] While the apparatus, systems, and methods have been described in terms of what are presently considered to be the most practical and preferred embodiments, it is to be understood that the disclosure need not be limited to the disclosed embodiments. It is intended to cover various modifications and similar arrangements included within the spirit and scope of the claims, the scope of which should be accorded the broadest interpretation to encompass all such modifications and similar structures. The present disclosure includes any and all embodiments of the following claims.

[0050] Thus, it is seen that thermal energy storage systems and methods and solar concentrating power plants are provided. It should be understood that any of the foregoing configurations and specialized components or chemical compounds may be interchangeably used with any of the systems of the preceding embodiments. Although illustrative embodiments are described hereinabove, it will be evident to one skilled in the art that various changes and modifications may be made therein without departing from the disclosure. It is intended in the appended claims to cover all such changes and modifications that fall within the true spirit and scope of the disclosure.

What is claimed is:

1. A thermal energy storage system comprising:

a bed;

a blend of aggregates packed in the bed, the blend including rock materials; and

a high-density heat transfer fluid flowing through the blend of aggregates such that heat is transferred between the heat transfer fluid and the blend of aggregates;

wherein porosity of the aggregates increases heat transfer and the high density of the heat transfer fluid reduces the axial pressure gradient of the heat transfer fluid.

2. The system of claim **1** wherein the heat transfer fluid is a liquid with a fluid density of at least 0.4 g/cc at at least one location in the packed bed

3. The system of claim **1** wherein the blend of aggregates further includes non-rock materials.

4. The system of claim **1** wherein the porosity is less than about 30%.

5. The system of claim **4** wherein the porosity is about 10%.

6. The system of claim **1** wherein the blend of aggregates comprises one or more of: sand, pebbles, washed rock, quartz, and magnetite.

7. The system of claim **1** wherein the packed bed stores energy at temperatures less than about 325° C.

8. The system of claim **7** wherein the packed bed stores energy at temperatures less than about 250° C.

9. The system of claim **8** wherein the packed bed stores energy at temperatures less than about 150° C.

10. The system of claim **1** wherein the packed bed stores energy at temperatures less than about 425° C.

11. The system of claim **1** wherein the bed is a vertical cylinder.

12. The system of claim **1** further comprising filtering media at a base or top of the bed.

13. The system of claim **1** wherein the bed comprises means to facilitate the management of rock particulate contamination.

14. The system of claim **1** wherein the surface area of aggregate per unit volume is about 215 m^{-1}.

15. The system of claim **1** wherein the heat transfer fluid has a thermal conductivity of less than about 10% of the aggregates.

16. A thermal energy storage system comprising:

a bed including a fluid inlet and a fluid outlet;

a blend of aggregates packed in the bed, the blend including rock materials and non-rock materials; and

a heat transfer fluid flowing through the blend of aggregates such that heat is transferred between the heat transfer fluid and the blend of aggregates, the heat transfer fluid being a liquid comprised of carbon-based molecules.

17. The system of claim **16** wherein the heat transfer fluid does not freeze at temperatures above 100° C.

18. The system of claim **16** wherein the fluid viscosity of the heat transfer fluid ensures fluid pressure drop from the fluid inlet to the fluid outlet is less than about 5 psid under nominal conditions and less than about 100 psid under cold start-up conditions.

19. The system of claim **16** wherein the vapor pressure of the heat transfer fluid is less than twice atmospheric pressure at the highest design temperature of any portion of the bed in direct contact with the heat transfer fluid.

20. The system of claim **16** wherein the vapor pressure of the heat transfer fluid is less than about 300 psia at the highest design temperature of any portion of the bed in direct contact with the heat transfer fluid.

21. A method of storing and releasing energy, comprising:

packing a blend of aggregates in a bed to minimize axial thermal conductivity of the bed, the blend including rock materials and non-rock materials;

providing a liquid organic heat transfer fluid having a thermal conductivity of less than about 10% of the thermal conductivity of the blend of aggregates; and

directing the heat transfer fluid through the blend of aggregates such that heat is transferred between the heat transfer fluid and the blend of aggregates;

wherein over 85% of stored energy can be extracted in a charge/discharge cycle in less than eighteen hours.

22. The method of claim **21** wherein over 85% of stored energy can be extracted in a charge/discharge cycle in less than six hours.

23. The method of claim **21** further comprising slowing the rate of release of stored energy by at least one order of magnitude.

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