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(54) HEAT TRANSFER SYSTEM UTILIZING THERMAL ENERGY STORAGE MATERIALS

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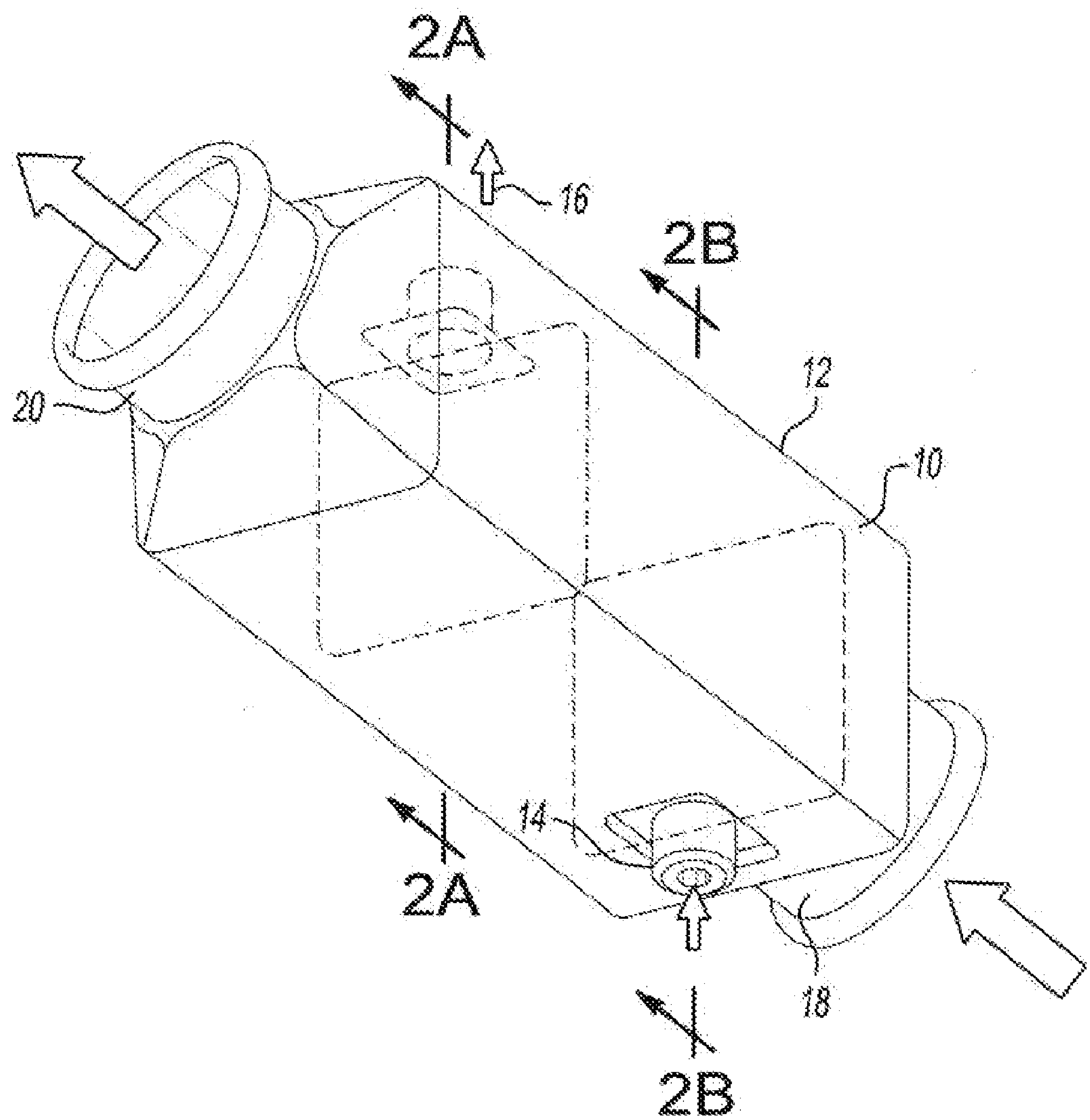
(57) **ABSTRACT**

An enhanced heat transfer between stored thermal energy and a heat recipient via a capillary pumped loop. The devices, systems and methods employ a thermal energy storage material having a solid to liquid phase transition at a temperature and a structure having a plurality of capillaries.



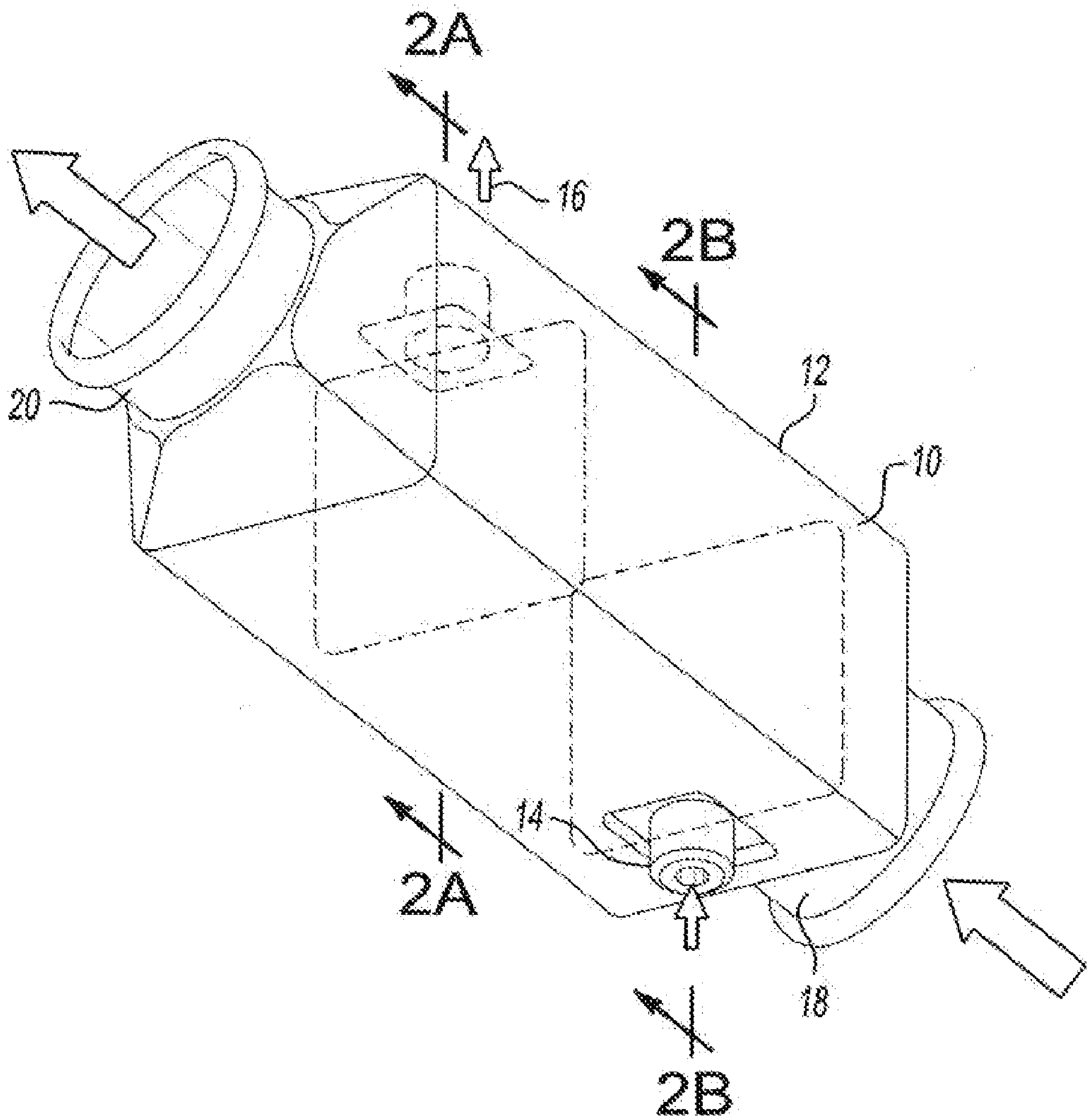


Fig-1

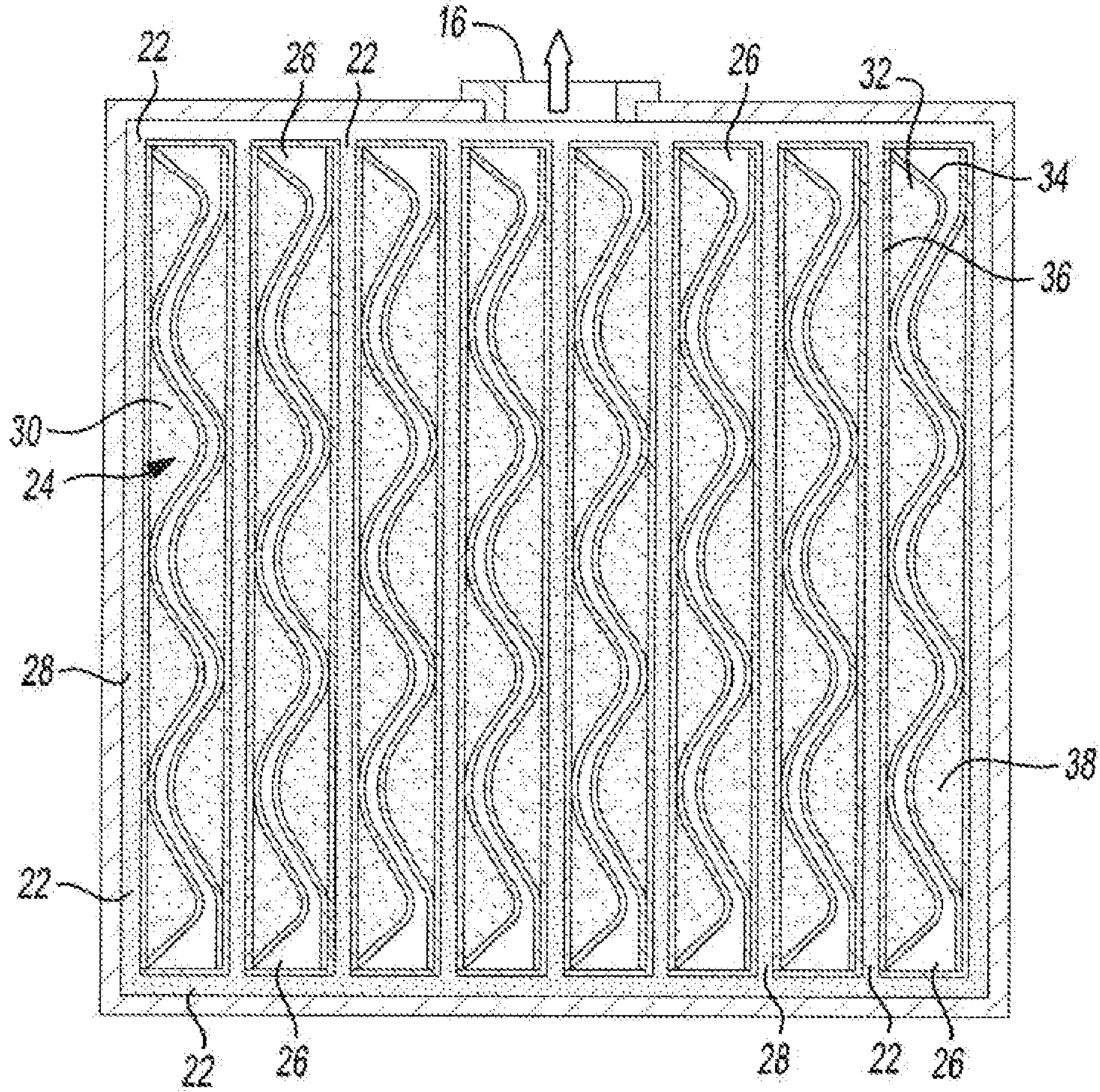


Fig-2A

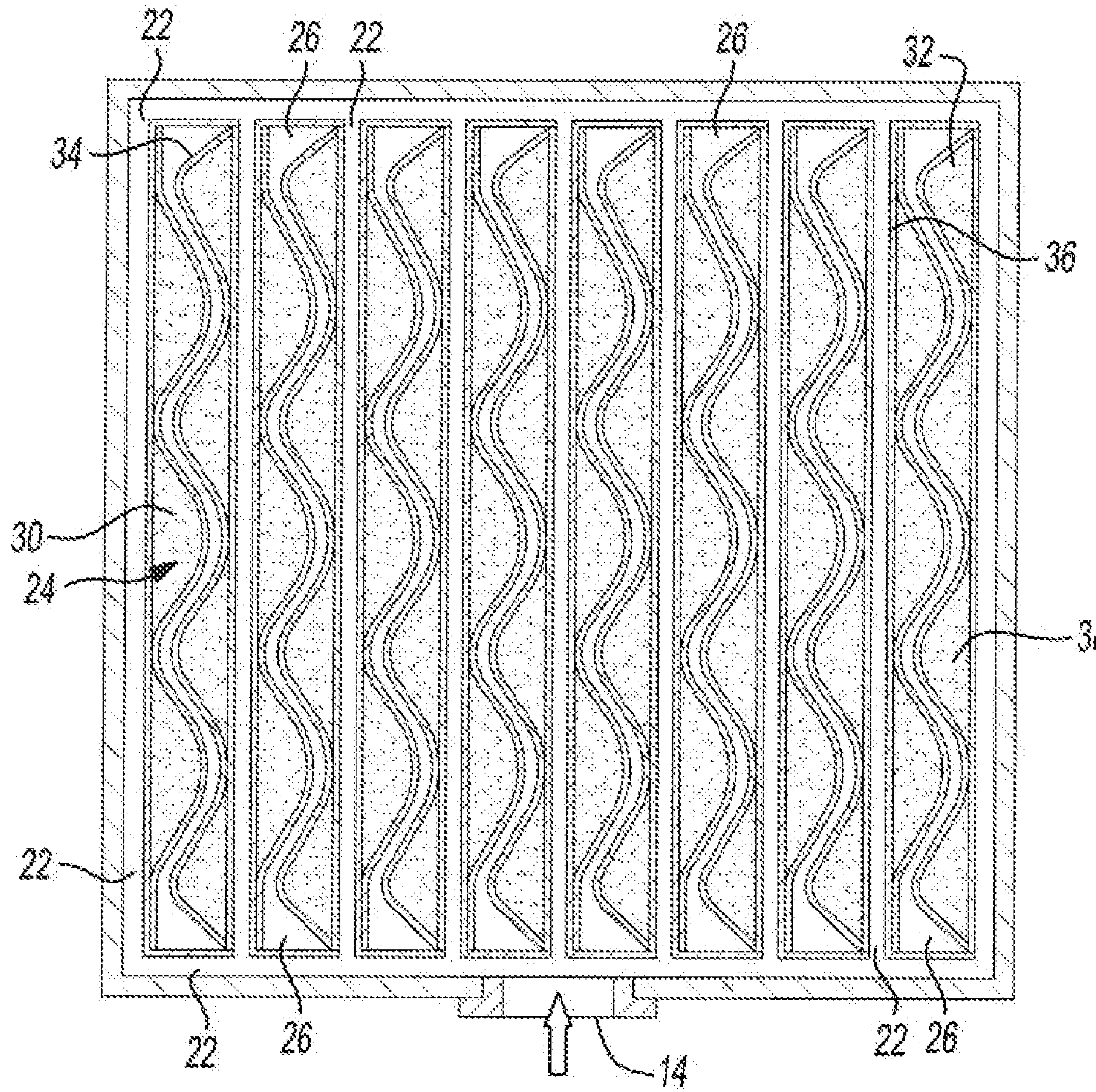


Fig-2B

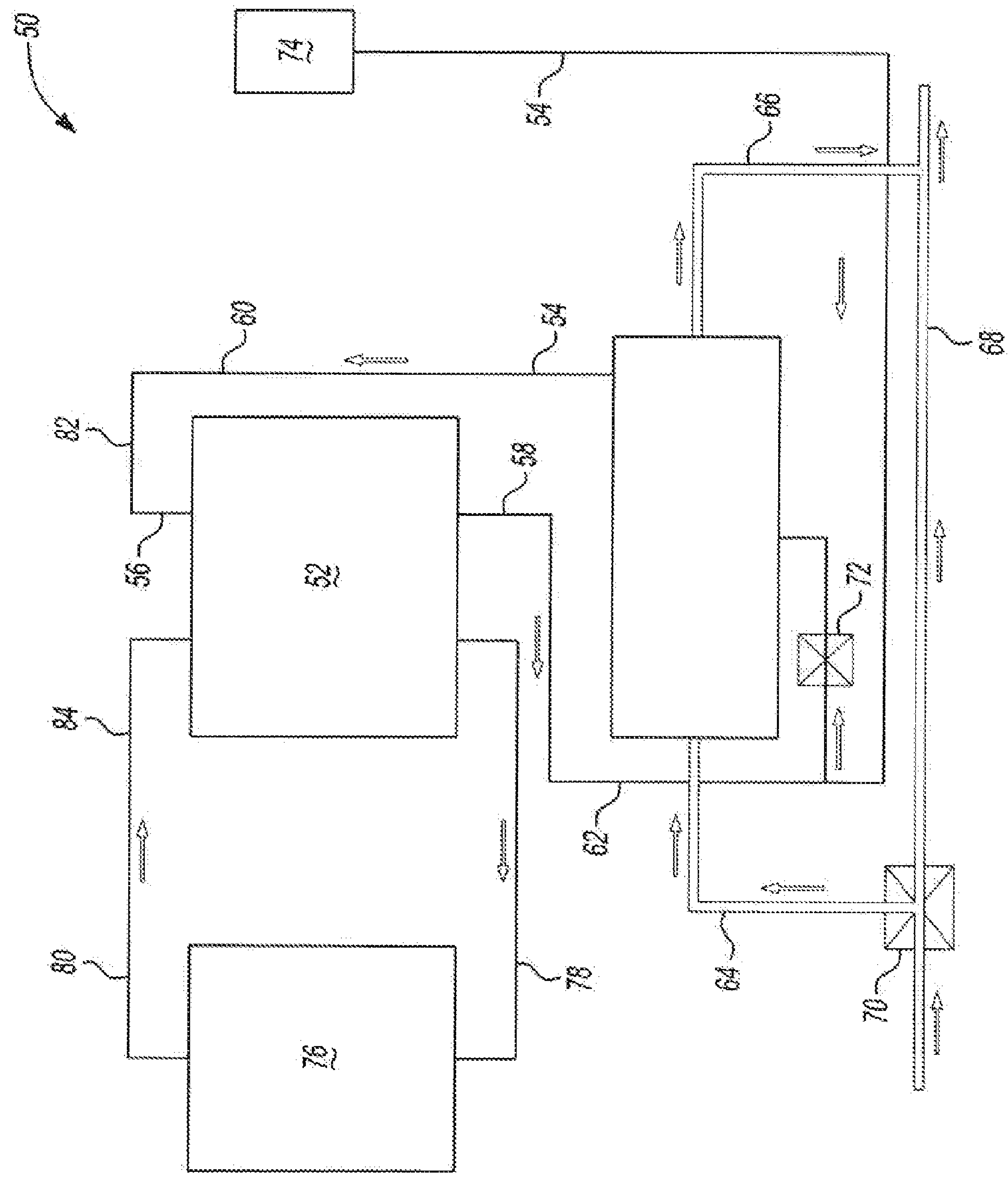


Fig-3

HEAT TRANSFER SYSTEM UTILIZING THERMAL ENERGY STORAGE MATERIALS

CLAIM OF PRIORITY

[0001] The present application claims the benefit of the filing date of US Provisional Patent Application No.: 61/245,767 (filed on Sep. 25, 2009 by Soukhojak et al.), the contents of which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] The present invention relates to enhanced heat transfer between stored thermal energy and a heat recipient via a capillary pumped loop.

BACKGROUND OF THE INVENTION

[0003] Industry in general has been actively seeking a novel approach to capture and store waste heat efficiently such that it can be utilized at a more opportune time. Further, the desire to achieve energy storage in a compact space demands the development of novel materials that are capable of storing high energy content per unit weight and unit volume. Areas of potential application of breakthrough technology include transportation, solar energy, industrial manufacturing processes as well as municipal and/or commercial building heating.

[0004] Regarding the transportation industry, it is well known that internal combustion engines operate inefficiently. Sources of this inefficiency include heat lost via exhaust, cooling, radiant heat and mechanical losses from the system. It is estimated that more than 30% of the fuel energy supplied to an internal combustion engine (internal combustion engine) is lost to the environment via engine exhaust.

[0005] It is well known that during a "cold start" internal combustion engines operate at substantially lower efficiency, generate more emissions, or both, because combustion is occurring at a non-optimum temperature and the internal combustion engine needs to perform extra work against friction due to high viscosity of cold lubricant. This problem is even more important for hybrid electric vehicles in which the internal combustion engine operates intermittently thereby prolonging the cold start conditions, and/or causing a plurality of occurrences of cold start conditions during a single period of operating the vehicle. To help solve this problem, original equipment manufacturers (OEM) are looking for a solution capable of efficient storage and release of waste heat. The basic idea is to recover and store waste heat during normal vehicle operation followed by controlled release of this heat at a later time thereby reducing or minimizing the duration and frequency of the cold start condition and ultimately improving internal combustion engine efficiency, reducing emissions, or both.

[0006] To be a practical solution, the energy density and the thermal power density requirements for a thermal energy storage system are extremely high. Applicants have previously filed 1) U.S. patent application Ser. No. 12/389,416 entitled "Thermal Energy Storage Materials" and filed on Feb. 20, 2009; and 2) U.S. patent application Ser. No. 12/389,598 entitled "Heat Storage Devices" and filed on Feb. 20, 2009. These previous applications are herein incorporated by reference in their entirety.

[0007] There are known exhaust heat recovery devices in prior art. However, they do not provide a long term (>6 hr) heat storage capability, which is desired to mitigate cold start conditions immediately after or even prior to a cold start. Therefore, there is a need for a system which can offer an unprecedented combination of high energy density, high power density, long heat retention time, and a simple mechanism of on-demand heat transfer in an automotive exhaust heat recovery system.

SUMMARY OF THE INVENTION

[0008] One aspect of the invention is a device including a thermal energy storage material having a solid to liquid phase transition at a temperature greater than about 50° C.; and a capillary structure; wherein the device is a heat storage device.

[0009] Another aspect of the invention is a device comprising one or more containers each with at least one inlet and one outlet for a working fluid, and at least one inlet and at least one outlet for a second fluid; one or more capsules containing a phase change material in the container having at least a first outer surface; a first flow path for the flow of the working fluid through the container wherein the flow path is at least partially defined by the first outer surface of the capsule; a capillary structure having a plurality of capillaries capable of pumping a working fluid through the first flow path, wherein the capillary structure partially fills the first flow path and is at least partially in contact with the first outer surface of the capsule, so that when contacted with a working fluid on one end, the working fluid is drawn into the capillary, and a second portion of the first flow path that is free of a capillary structure; a second flow path for the flow of a second fluid through the container; wherein the first flow path is in a working fluid compartment, the second flow path is in a heat transfer fluid compartment, and the phase change material is in a phase change material compartment; the phase change material is in thermal communication with the working fluid compartment and the heat transfer fluid compartment; and wherein the device is a heat storage device.

[0010] Another aspect of the invention is a system for storing and transferring heat including a heat storage device such as one described herein; a condenser having at least a first inlet and at least a first outlet and a first flow path for the working fluid; wherein the heat storage device is in fluid connection with the condenser and the system comprising a capillary pumped loop including the first flow path of the condenser and the first flow path of the heat storage device.

[0011] Yet another aspect of the invention is a method of discharging heat that includes a step of circulating a working fluid through a heat storage device described herein, such as one including a thermal energy storage material and a capillary structure.

[0012] The present invention can be used for mitigating cold start conditions in internal combustion engines and provide additional steady-state coolant heating, if needed, for occupant comfort heating and/or windshield defrosting. Other industrial applications of the present invention can also include cooling systems, other power producing applications such as Rankine cycle heat engine, thermoelectric generator or other.

[0013] In other aspects of the invention, the present invention can also be used to warm-up an electrochemical battery in a hybrid electric, plug-in hybrid electric, extended range electric vehicle or purely electric vehicle; comfort heating of vehicles capable of electric-only propulsion; automotive air conditioning using adsorption or absorption cycle refrigeration; a steady-state exhaust heat recovery using a heat engine, e.g. Rankine cycle; and industrial and residential heat storage.

BRIEF DESCRIPTION OF THE FIGURES

[0014] The present invention is further described in the detailed description which follows, in reference to the noted plurality of drawings by way of non-limiting examples of embodiments of the present invention, in which like reference numerals represent similar parts throughout the several views of the drawings, and wherein:

[0015] FIG. **1** is a schematic showing some of the main components of a heat storage device.

[0016] FIG. **2**A is a cross-section of an illustrative heat storage device. The cross-section illustrates the internal structure of a three-chamber (exhaust gas, phase change material, and working fluid) two-flow (exhaust gas and working fluid) heat storage device containing thermal energy storage material and an evaporator.

[0017] FIG. **2**B is another cross-section of an illustrative heat storage device.

[0018] FIG. **3** is a schematic showing some of the main components of a thermal energy storage system including a heat storage device and a condenser.

DETAILED DESCRIPTION OF THE PRESENT INVENTION

[0019] In the following detailed description, the specific embodiments of the present invention are described in connection with its preferred embodiments. However, to the extent that the following description is specific to a particular embodiment or a particular use of the present techniques, it is intended to be illustrative only and merely provides a concise description of the exemplary embodiments. Accordingly, the invention is not limited to the specific embodiments described below, but rather; the invention includes all alternatives, modifications, and equivalents falling within the true scope of the appended claims.

[0020] As will be seen from the teachings herein, the present invention provides a unique and unexpectedly efficient approach to the packaging and containment of thermal energy storage materials (which also includes what is commonly called "phase change materials") for heat storage and discharge applications, and particularly for applications requiring high power densities so that heat can be quickly stored, quickly removed, or both. Thermal energy storage systems herein exhibit extraordinary high power density capabilities and may be used for removing heat from a heat storage device (continuing the phase change material) in the system at a rate of at least about 10 kW per liter of the heat storage device. The teachings herein contemplate the packaging and containment of thermal energy storage materials in a relatively robust structure that will resist failure due to corrosion, due to thermally induced strains from cyclical thermal loading, or both, and will also yield a relatively high storage and discharge capacity in relation to the overall volume occupied by such structures and systems incorporating them. The teachings herein also contemplate a flow path in the heat storage device for a working fluid in which the flow path, partially includes a capillary structure having a plurality of capillaries. The capillary structure may be employed to at least partially pump the working fluid. One of the advantages of the capillary structures herein is that a relatively compact assembly is possible, which exhibits unexpectedly large and rapid heat storage and discharge capabilities. The system may be capable of pumping the working fluid without the use of a pump other than the pumping of the capillaries. As will be seen, the teachings herein contemplate a manner of packaging discrete amounts of thermal energy storage material in a plurality of capsular structures. The teachings contemplate the assembly of such capsular structures for use in a heat storage device. A number of applications made possible or more efficient as a result of such structures, devices, and/or systems are also contemplated as part of the teachings.

Heat Storage Device

[0021] As discussed above, the thermal energy storage system includes a heat storage device (i.e., a thermal energy storage device) capable of storing thermal energy. As such, the heat storage device is capable of receiving heat (such as waste heat or otherwise), storing the heat, and discharging the heat at a later time so that it may be used to heat one or more objects. Preferably, the heat storage device is capable of rapidly discharging the heat. During the discharging of the heat, the heat storage device may function as an evaporator, at least partially converting a working fluid from a liquid phase to a vapor phase. As such, the heat storage device includes a working fluid compartment for containing the working fluid (the compartment may include one or more flow paths), one or more working fluid inlets for receiving the working fluid (e.g., in a liquid state) connected to the working fluid compartment (e.g., at one side or one end of the working fluid compartment), and one or more working fluid outlets for expelling the working fluid (e.g., in a gaseous state), so that the working fluid flows into the one or more working fluid inlets, through the one or more flow paths of the working fluid compartment and out of the one or more working fluid outlets. Preferably, at least a portion of the flow path (e.g., a portion of each flow path) includes a capillary structure (such as a structure having a plurality of capillaries) capable of wicking the working fluid. The working fluid compartment of the heat storage device may be a section of a capillary pumped loop, and the capillary structure may be used to at least partially pump the working fluid through the loop.

[0022] In various aspects of the invention the heat storage device may be relatively light weight, relatively small, or both. As such, the heat storage capacity density (i.e., the maximum amount of heat that can be stored in the heat storage device divided by the volume of the heat storage device) may be relatively high, and the heat storage capacity to mass ratio (i.e., the ratio of the amount of heat that can be stored in the heat storage device and the mass of the heat storage device) may be relatively high. To achieve these efficiencies, the heat storage device may employ materials (such as thermal energy storage materials, encapsulation materials, container materials, materials for the capillary structure, and the like) that are light weight.

[0023] A large portion of the heat storage device preferably includes one or more thermal energy storage materials (preferably one or more phase change materials) capable of efficiently storing heat. The concentration of the thermal energy storage material in the heat storage device may be maximized with the proviso that the heat storage device has a working fluid compartment large enough for the working fluid to flow and quickly transfer heat from the device, and a heat transfer fluid compartment in thermal contact with the thermal energy storage material and large enough for a heat transfer fluid to flow through and efficiently transfer heat into the device. The volume of the one or more thermal energy storage materials may be greater than about 10% by volume, preferably greater than about 20% by volume, more preferably greater than about 30% by volume, even more preferably greater than about 40% by volume, and most preferably greater than about 50% by volume, based on the total volume of the container of the heat storage device.

[0024] The heat storage device may have a sufficient number of compartments so that the thermal energy storage material and one or more fluids are separated from each other. The heat storage device may have two or more (preferably three or more) compartments. The compartments may be employed to separate (e.g., substantially or entirely isolate) one, or all of i) the thermal energy storage material, ii) a first fluid (such as a heat transfer fluid) for charging (e.g., heating) the thermal energy storage material (e.g., for charging the phase change material), and iii) a second fluid (such as a working fluid) for discharging (e.g., cooling) the thermal energy storage material (e.g., the phase change material). As such, the heat storage device may include a thermal energy storage material compartment for the thermal energy storage material (e.g., a phase change material compartment for the phase change material), a compartment (e.g., a heat transfer fluid compartment) for a first fluid, and a compartment (e.g., a working fluid compartment) for a second fluid. The thermal energy storage material compartment may be in thermal communication with the heat transfer fluid compartment, the working fluid compartment, or preferably both. It will be appreciated that the thermal energy storage material compartment may share one or more walls with the heat transfer fluid compartment, with the working fluid compartment, or both. For example, the thermal energy storage material may be stored in capsules having a first surface that at least partially defines the heat transfer fluid compartment and a second surface that at least partially defines the working fluid compartment. The device may have one or more inlets and one or more outlets for the first fluid, both attached to the compartment for the first fluid, so that the first fluid (e.g., the heat transfer fluid) may flow through the inlet and enter into the device, flow into the compartment for the first fluid, and providing thermal energy to the thermal energy storage material (e.g., to the phase change material) and exit the device through an outlet. Similarly, the device may have one or more inlets and one or more outlets for the second fluid and attached to the compartment for the second fluid, so that the second fluid (e.g., the working fluid) may flow through the inlet and enter the device, flow into the compartment for the second fluid removing thermal energy from the thermal energy storage material (e.g., from the phase change material) and exit the device through an outlet.

Capillary Structure

[0025] As described above, the heat storage device includes a capillary structure that contains a plurality of capillaries. Preferably, the working fluid compartment includes a capillary structure. In general the wicking of a fluid into a capillary increases as the radius of the capillary decreases. The capillary structure may be any structure having a sufficient number of capillaries with sufficiently small radii so that the capillary structure is capable of pumping the working fluid. The capillary structure may pump the working fluid when the heat storage device (e.g., the thermal energy storage material) has a temperature at which the working fluid has a pressure greater than about 1 atmosphere; the condenser has a temperature at which the working fluid has a pressure less than about 1 atmosphere, or preferably both. The capillary structure may be employed for pumping the working fluid. Preferably, the capillary structure is employed as the only means of pumping the working fluid. As such, it is contemplated that the heat storage device may be employed in a system having a working fluid loop that is free of any pump, other than the capillary pump.

[0026] The capillary structure may of one or more objects having a porous structure, by packing together a plurality of objects so that the gaps between the objects forms the porous structure, or both. The capillary structure (e.g., the wick structure) of the heat storage device (e.g., of the evaporator of the heat storage device) may contain one or more fibers or filaments, one or more grooves, or one or more other porous structures having a generally small pore size, so that the capillary structure is capable of creating a capillary pressure on the working fluid that is great enough to overcome gravitational forces, the gas pressure difference between the evaporator and the condenser, or both. The capillary structure may be any art known capillary structure (such as those employed in heat pipes and capillary pumped loops, e.g., for cooling electronic devices). For example simple homogeneous capillary structure such as a wrapped screen, sintered metal, or axial groove may be employed. Other capillary structures that may be employed include slab, pedestal artery, spiral artery, tunnel artery, axial groove with a varying groove width, double wall artery, monogroove, channel wick, and the like. Any of the above structures may be adapted for a generally layered structure, such as may be formed between the flat surfaces of two blister packs.

[0027] The capillary structure has a pore size sufficiently small to overcome gravitational forces, to overcome the gas pressure difference between the evaporator and the condenser, or both. The capillary structure has a pore size sufficiently high so that liquid working fluid can enter the capillaries. The capillary pressure is generally inversely proportional to the pore radius. The capillary structure may have an average pore radius less than about 2 mm, preferably less than about 1 mm, more preferably less than about 400 μm, even more preferably less than about 100 μm, even more preferably less than about 30 μm, even more preferably less than about 20 μm, and most preferably less than about 10 μm.

[0028] The capillary structure located in the working fluid compartment shall fill a sufficient volume of the working fluid compartment to overcome gravitational forces, the gas pressure difference between the evaporator and the condenser, or both. The capillary structure may fill greater than 1 volume %, preferably greater than about 5 volume %, more preferably greater than about 10 volume %, and most preferably greater than about 25 volume %, of the working fluid compartment of the heat storage device. The capillary structure may fill less than about 95 volume %, preferably less than about 90 volume %, more preferably less than about 85 volume %, and most preferably less than about 75 volume % of the working fluid compartment of the heat storage device. The remaining volume of the working fluid compartment of the heat storage device is preferably free of the capillary structure.

Thermal Energy Storage Material Compartment

[0029] As described above, the thermal energy storage material preferably is isolated in one or more compartments in the heat storage device. Typically, the thermal energy storage material has a relatively low thermal diffusivity (e.g., compared with the material of the compartment in which it is provided). Preferably the shape and/or size of the one or more compartments are selected so that thermal energy can rapidly transfer into and out of the thermal energy storage material. As such, the heat storage device may employ one or means for increasing the heat transfer. For example, the one or more thermal energy storage materials may have at least one dimension that is relatively small (e.g., compared with one or more other dimensions), the thermal energy storage material may be stored in a plurality of compartments, the interior of the one or more compartments may have thermally conductive objects (e.g., fins, wire, mesh, and the like), or any combination thereof. For example, the thermal energy storage material may be stored in at least about 5, 10, 15, or 20 compartments.

[0030] The thermal energy storage material preferably is in a plurality of individually isolated cells (such as capsules), having a total surface area of the plurality of cells that is relatively high, a distance from a surface of a cell to the center of the cell that is relatively low, or both. The plurality of cells (e.g., capsules) may be arranged in one or more layers of cells. For example, the heat storage device may include a plurality of layers of cells (e.g., capsules): Each layer of cells may contain a single cell or a plurality of cells. It will be appreciated that a layer of cells (e.g., a layer of capsules) may have a relatively low thickness, a relatively high surface area to volume ratio, or both, so that heat can be rapidly removed from the interior of the cells. The cells may be in any arrangement in a layer. For example, the cells may be of the same size and shape, the cells may have varying sizes and shapes, the cells may be arranged in a repeating pattern (e.g., a pattern that contains 1, 2, or more cells) or may be arranged in a pattern that generally does not repeat. In a preferred aspect of the invention, the cells are arranged as an array of capsules (e.g., a 1-dimensional array, a 2-dimensional array, or a radial array) in each layer of capsules.

[0031] The heat storage device may include a plurality of layers of capsules with a spacing between one or more pairs of adjacent layers of capsules. A spacing may be used as a portion of the working fluid compartment or as a portion of the heat transfer fluid compartment. Layers of capsules may have a spacing on one side, have spacings on two opposing sides, have no spacing, or any combination thereof. For example, there may be a spacing between every pair of adjacent layers of capsules. Preferably, there is a spacing between every pair of adjacent layers of capsules and the spacings alternately are the working fluid compartments and the heat transfer fluid compartments.

[0032] A layer of capsules may have a surface that is arcuate and an opposing surface that is generally flat. A generally arcuate surface may be particularly attractive for a heat transfer fluid, where the arcuate path may increase the heat flow from the heat transfer fluid into the capsules. A generally flat surface may be particularly attractive for placing a capillary structure (and the thickness of the capillary structure may determine the separation between two layers of capsules on either side of a portion of the working fluid compartment). Layers having opposing surfaces that are both generally flat or both arcuate may also be employed. The heat storage device may also employ two adjacent layers of capsules that partially or substantially entirely nest together.

[0033] The size and shape of the capsules may be chosen to maximize the transfer of heat to and from the phase change material contained in the capsules. The average thickness of the capsules (e.g., the layer of capsules) may be relatively short so that the heat can quickly escape from the center of the capsule. The average thickness of the capsules may be less than about 100 mm, preferably less than about 30 mm, more preferably less than about 10 mm, even more preferably less than about 5 mm, and most preferably less than about 3 mm. The average thickness of the capsules may be greater than about 0.1 mm, preferably greater than about 0.5 mm, more preferably greater than about 0.8 mm, and most preferably greater than 1.0 mm.

[0034] The capsules preferably have a relatively high surface area to volume ratio so that the area of contact with the working fluid, the area of contact with the heat transfer fluid, or both is relatively high. For example, the capsules may have a surface that maximizes the contact with a working fluid compartment; the capsules may have a geometry that maximizes the transfer of heat between the capsule and the working fluid compartment, or both. The ratio of the total surface area of the interface between the working fluid compartment and the phase change material compartment to the total volume of the thermal energy storage material in the heat storage device may be greater than about 0.02 mm^{-1}, preferably greater than about 0.05 mm^{-1}, more preferably greater than about 0.1 mm^{-1}, even more preferably greater than about 0.2 mm^{-1}, and most preferably greater than about 0.3 mm^{-1}.

[0035] The thermal energy storage material compartment may be in the form of a blister pack or a stack of blister packs. For example, the thermal energy storage material may be encapsulated between an embossed metal layer and a flat metal layer which are sealed together to form a plurality of isolated capsules. Without limitation, the heat storage device may employ a capsule or an arrangement of capsules (e.g., a blister pack or stack of blister packs) described in U.S. patent application Ser. No. 12/389,598 entitled "Heat Storage Devices" and filed on Feb. 20, 2009.

Working Fluid Compartment And Heat Transfer Fluid Compartment

[0036] As discussed above, the heat storage device preferably includes a working fluid compartment and a heat transfer fluid compartment in thermal communication with the thermal energy storage material compartment.

[0037] The thickness of the heat transfer fluid compartment is chosen to facilitate the desired flow of the heat transfer fluid through the flow path and to maximize the transfer of heat to the phase change material. The average thickness of a layer of the heat transfer fluid compartment may be less than about 20 mm, preferably less than about 10 mm, more preferably less than about 5 mm, even more preferably less than about 3 mm, and most preferably less than about 2 mm. Higher thickness may be used when the rate at which heat is stored from the heat transfer fluid to the thermal energy storage material is not critical. The average thickness of a layer of the heat transfer fluid compartment should be high enough so that the pressure drop of the heat transfer fluid in the thermal energy storage material device is low. Preferably, the pressure drop between the heat transfer fluid inlet and the heat transfer fluid outlet of the heat storage device is less than about 95%, more preferably less than about 50%. The average thickness of a layer of the heat transfer fluid compartment may be greater than about 0.1 mm, preferably greater than about 0.2 mm, more preferably greater than about 0.4 mm, and most preferably greater than about 0.6 mm.

[0038] The thickness of the working fluid compartment is chosen to facilitate the desired flow of the working fluid through the flow path and to maximize the transfer of heat from the phase change material. The average thickness of a layer of the working fluid compartment may be less than about 20 mm, preferably less than about 10 mm, more preferably less than about 5 mm, even more preferably less than about 3 mm, and most preferably less than about 2 mm. The average thickness of a layer of the working fluid compartment may be greater than about 0.1 mm, preferably greater than about 0.2 mm, more preferably greater than about 0.4 mm, and most preferably greater than about 0.6 mm.

[0039] The spacing between adjacent layers of capsules may be used for the working fluid, the heat transfer fluid, or both. For example, at least a portion (e.g., a layer) of the heat transfer fluid compartment may be interposed between two adjacent layers of capsules. At least a portion (e.g., a layer) of the working fluid compartment may be interposed between two adjacent layers of capsules and the average thickness of the working fluid compartment may be defined by the distance (e.g., average distance) of separation of the two layers of capsules. A layer of capsules may have a layer of the working fluid compartment on one side of the capsule layer and a layer of the heat transfer fluid compartment on an opposing side.

[0040] The working fluid may be selected so that it flows into the heat storage device as a liquid, is heated by the thermal energy stored in the thermal energy storage material (e.g., the phase change material) and vaporizes, and exits the heat storage as a vapor. As such, it is preferable that the elevation of the working fluid outlet is higher than the elevation of the working fluid inlet.

[0041] As previously described, some of the working fluid compartment typically includes a region having a capillary structure for wicking the liquid into the compartment, and a region that is free of a capillary structure for the working fluid (e.g., the gaseous working fluid). For example, within a single layer of the working fluid compartment, there may be one or more regions (such as a columnar region) that contain a capillary structure and one or more regions (such as a columnar region) that are free of a capillary structure.

[0042] A surface of the thermal energy storage material compartment (e.g., an outer surface of a layer of capsules containing thermal energy storage material) may generally define at least a portion of the heat transfer fluid compartment. Similarly, a second surface of the thermal energy storage material compartment (e.g., a second outer surface of the layer of capsules containing thermal energy storage material) may generally define at least a portion of the working fluid compartment. It will be appreciated that one or more additional materials (e.g., one or more additional layers) may separate a layer of capsules from the working fluid compartment, from the heat transfer fluid compartment, or both, provided that the layer of capsules is in thermal communication with the working fluid compartment, the heat transfer compartments, or preferably both.

Thermal Energy Storage Materials

[0043] Without limitation, suitable thermal energy storage materials for the heat storage device include materials that are capable of exhibiting a relatively high density of thermal energy as sensible heat, latent heat, or preferably both. The thermal energy storage material is preferably compatible with the operating temperature range of the heat storage device. For example, the thermal energy storage material is preferably a solid at the lower operating temperature of the heat storage device, is at least partially a liquid (e.g., entirely a liquid) at the maximum operating temperature of the heat storage device, does not significantly degrade or decompose (e.g., during a time of at least about 1,000 hours, preferably of least about 10,000 hours) at the maximum operating temperature of the heat storage device, or any combination thereof. The thermal energy storage material may have a liquidus temperature e.g., a melting temperature greater than about 30° C., preferably greater than about 50° C., more preferably greater than about 80° C., even more preferably greater than about 110° C., and most preferably greater than about 140° C. The thermal energy storage material may have a liquidus temperature less than about 400° C., preferably less than about 350° C., more preferably less than about 290° C., even more preferably less than about 250° C., and most preferably less than about 200° C. The thermal energy storage material may have a heat of fusion density greater than about 0.1 MJ/liter, preferably greater than about 0.2 MJ/l, more preferably greater than about 0.4 MJ/liter, and most preferably greater than about 0.6 MJ/liter. The thermal energy storage material may have a density less than about 5 g/cm^3, preferably less than about 4 g/cm^3, more preferably less than about 3.5 g/cm^3, and most preferably less than about 3 g/cm^3.

[0044] Other examples of suitable thermal energy storage materials that may be employed in the heat transfer device include the thermal energy storage materials described in U.S. patent application Ser. No. 12/389,416 entitled "Thermal Energy Storage Materials" and filed on Feb. 20, 2009; and U.S. patent application Ser. No. 12/389,598 entitled "Heat Storage Devices" and filed on Feb. 20, 2009.

[0045] The thermal energy storage material may include (or may even consist essentially of or consist of) at least one first metal containing material, and more preferably a combination of the at least one first metal containing material and at least one second metal containing material. The first metal containing material, the second metal containing material, or both, may be a substantially pure metal, an alloy such as one including a substantially pure metal and one or more additional alloying ingredients (e.g., one or more other metals), an intermetallic, a metal compound (e.g., a salt, an oxide or otherwise), or any combination thereof. One preferred approach is to employ one or more metal containing materials as part of a metal compound; a more preferred approach is to employ a mixture of at least two metal compounds. By way of example, a suitable metal compound may be selected from oxides, hydroxides, compounds including nitrogen and oxygen (e.g., nitrates, nitrites or both), halides, or any combination thereof. One particularly preferred metal compound includes at least one nitrate compound, at least one nitrite compound or a combination thereof. It is possible that ternary, quaternary or other multiple component material systems may be employed also. The thermal energy storage materials herein may be mixtures of two or more materials that exhibit a eutectic. A particularly preferred thermal energy storage material includes a lithium containing compound, such as a lithium salt. The thermal energy storage material may be a mixture of two or more compounds (e.g., two or more salts) including at least one compound containing lithium.

[0046] A large portion of the volume of the heat storage device may be occupied by the thermal energy storage material so that the power output of the heat storage device is relatively high, the total volume of the heat storage device is relatively small, or both. For example, the ratio of the volume of the working fluid compartment to the volume of the thermal energy storage material (e.g., the phase change material) in the heat storage device may be less than about 20:1 (preferably less than about 10:1, more preferably less than about 5:1, even more preferably less than about 2:1 and most preferably less than about 1:1), the ratio of the volume of the heat transfer fluid compartment to the volume of the thermal energy storage material (e.g., the phase change material) in the heat storage device may be less than about 20:1 (preferably less than about 10:1), more preferably less than about 5:1, even more preferably less than about 2:1 and most preferably less than about 1:1), or both.

[0047] The heat storage device may contain a sufficient quantity of the thermal energy storage material so that an object to be heated (such as an internal combustion engine or a cockpit of a vehicle) can be heated to a desired temperature. For example, the heat storage device may contain sufficient quantity of thermal energy storage material to increase the temperature of an internal combustion engine by at least 10° C., preferably at least about 20° C., more preferably at least about 30° C., and most preferably at least about 40° C.

Forming Capsules

[0048] The capsules of the thermal energy storage material may be formed using any method that provides for the encapsulation of the thermal energy storage material. Without limitation, the process may employ one or any combination of the following: embossing or otherwise deforming a thin material sheet (e.g., a foil) to define a pattern in the sheet, filling depressions in the embossed sheet with the thermal energy storage material, covering an embossed sheet with a second sheet (e.g., a generally flat sheet), or attaching the two sheets. The process of forming the capsules may employ the processes described in U.S. patent application Ser. No. 12/389,598 entitled "Heat Storage Devices" and filed on Feb. 20, 2009.

[0049] Suitable sheets for encapsulating the thermal energy storage material include thin metal sheets (e.g., metal foil) that are durable, corrosion resistant, or both, so that the sheet is capable of containing the thermal energy storage material, preferably without leakage. The metal sheets may be capable of functioning in a vehicle environment with repeated thermal cycling for more than 1 year and preferably more than 5 years. Without limitation, exemplary metal sheets that may be employed include metal sheets having at least one layer of brass, copper, aluminum, nickel-iron alloy, bronze, titanium, stainless steel or the like. The sheet may be a generally noble metal or it may be one that includes a metal which has an oxide layer (e.g. a native oxide layer or an oxide layer which may be formed on a surface). The metal sheet may otherwise have a substantially inert outer surface that contacts the thermal energy storage material in operation. One exemplary metal sheet is an aluminum foil which comprises a layer of aluminum or an aluminum containing alloy (e.g. an aluminum alloy containing greater than 50 wt. % aluminum, preferably greater than 90 wt % aluminum). Another exemplary metal sheet is stainless steel. Suitable stainless steels include austenitic stainless steel, ferritic stainless steel or martensitic stainless steel. Without limitation, the stainless steel may include chromium at a concentration greater than about 10 wt. %, preferably greater than about 13 wt. %, more preferably greater than about 15 wt. %, and most preferably greater than about 17 wt. %. The stainless steel may include carbon at a concentration less than about 0.30 wt. %, preferably less than about 0.15 wt. %, more preferably less than about 0.12 wt. %, and most preferably less than about 0.10 wt. %. For example, stainless steel 304 (SAE designation) containing 19 wt. % chromium and about 0.08 wt. % carbon. Suitable stainless steels also include molybdenum containing stainless steels such as 316 (SAE designation).

[0050] The metal sheet has a thickness sufficiently high so that holes or cracks are not formed when forming the sheet, when filling the capsules with thermal energy storage material, during use of the capsules, or any combination thereof. For applications such as transportation, the metal sheet preferably is relatively thin so that the weight of the heat storage device is not greatly increased by the metal sheet. Suitable thicknesses of the metal sheet may be greater than about 10 μm, preferably greater than about 20 μm, and more preferably greater than about 50 μm. The metal foil may have a thickness less than about 3 mm, preferably less than 1 mm, and more preferably less than 0.5 mm (e.g., less than about 0.25 mm).

Thermal Energy Storage System

[0051] The heat storage device may be employed in a thermal energy storage system. The thermal energy storage material system may be used in an operational cycle containing three phases, a charge phase, a storage phase, and a discharge phase.

[0052] The thermal energy storage system preferably includes a means of heating the phase change material in the heat storage device, so that when the heat storage device is at a temperature sufficient to cause the combined vapor pressure of all components of the working fluid to exceed 1 atmosphere and the working fluid valve is opened to allow flow of the working fluid, the working fluid is a) pumped by the capillary structure; b) at least partially vaporized; c) at least partially transported to the condenser; and at least partially condenses in the condenser; so that heat is removed from the heat storage device.

[0053] The thermal energy system of the present invention may include: a heat storage device as described herein, a condenser (e.g., having an inlet for the working fluid and an outlet for the working fluid), a vapor line (e.g., a vapor tube) connecting the working fluid inlet of the condenser to the working fluid outlet of the heat storage device, and a working fluid liquid line (e.g., a liquid tube) connecting the working fluid outlet of the condenser to the working fluid inlet of the heat storage device. As described hereinbefore, the working fluid compartment preferably includes a capillary structure. As such the thermal energy storage system may contain a capillary pumped loop including the working fluid compartment in the heat storage device, a working fluid compartment in the condenser, the working fluid vapor line, and the working fluid liquid line. The condenser is capable of removing heat from the working fluid so that the working fluid partially or preferably entirely condenses. The vapor line is capable of containing the working fluid (e.g., in a vapor phase), without leaking, as it flows from the heat storage device to the condenser. The working fluid liquid line is capable of containing the working fluid (e.g., in a liquid phase), without leaking, as it flows from the condenser to the heat storage device.

[0054] The thermal energy storage system may also include a working fluid reservoir that is capable of storing excess working fluid so that when the fluid is being pumped by the capillary pump, the liquid line is filled with the working fluid. The working fluid reservoir may have a fill level that is higher in elevation than the working fluid inlet of the heat storage device, lower than the elevation of the working fluid inlet of the condenser, or both. The capillary pumped loop may have one or more valves, such as a valve in the working fluid liquid line. The valve in the working fluid liquid line may be used to prevent the working fluid from circulating in the capillary pumped loop when the heat storage device is charging, when the heat storage device is storing heat, or both. The valve may be opened when it is desired to discharge heat from the heat storage device (e.g., to heat an internal combustion engine).

[0055] The thermal energy storage system may include a heat transfer fluid inlet line (which may be a tube, a pipe, or the like) and a heat transfer fluid outlet line, respectively for flowing the heat transfer fluid into and out of the heat storage device. The heat transfer fluid inlet line and the heat transfer fluid outlet line are capable of containing the heat transfer fluid (e.g., while it flows) without leaking or cracking. For example the heat transfer fluid lines preferably do not leak or crack at the pressures of the heat transfer fluid. The thermal energy storage system may also have a heat transfer fluid bypass line capable of containing the heat transfer fluid so that it may flow unobstructed outside of the heat storage device without leaking. The heat transfer bypass line may be employed when the thermal energy storage material in the heat storage device is at or above its maximum nominal temperature, or when the temperature of the heat transfer fluid is above a critical temperature at which degradation of the thermal energy storage material may occur. The thermal energy storage system may also include a valve such as a diverter valve (e.g., a bypass valve) capable of controlling the amount of the heat transfer fluid that flows through the heat storage device and the amount of the heat transfer fluid that flows through the bypass line. The diverter valve may be employed to divert some or all of the heat transfer fluid to the bypass line (e.g., when the heat storage device is fully charged, or when the temperature of the heat transfer fluid is below a temperature of the thermal energy storage material in the heat storage device). The diverter valve may allow some or preferably all of the heat transfer fluid to flow into the heat storage device when one or any combination (e.g., all) of the following conditions are met: the temperature of the thermal energy storage material in the heat storage device is below the temperature of the heat transfer fluid, the heat storage device is not fully charged, or the temperature of the heat transfer fluid is below the maximum nominal temperature of the heat storage device.

[0056] The heat transfer fluid used to heat the heat storage device may be any liquid or gas so that the fluid flows through the heat storage device (e.g., without solidifying) when it is cold. For example, the heat transfer fluid may be a liquid or gas at a pressure of about 1 atmosphere pressure and a temperature of about 25° C., preferably about 0° C., more preferably −20° C., and most preferably at about −40° C. Without limitation, a preferred heat transfer fluid for heating the heat storage device is an exhaust gas, such as an exhaust gas from an engine (e.g., an internal combustion engine).

[0057] The condenser of the thermal energy storage system may be a heat exchanger capable of transferring thermal energy from the working fluid to another fluid. For example, the condenser may be employed for transferring heat from the working fluid to a heat transfer fluid. The heat transferred in the condenser (e.g., in the heat exchanger) preferably includes the heat of vaporization of the working fluid. The thermal energy storage system may include a cold line for providing a heat transfer fluid into the heat exchanger, and a heat line for removing heat transfer fluid from the heat exchanger. The cold line and the heat line preferably are capable of containing the heat transfer fluid of the heat exchanger without leaking as it is flows through a loop. The cold line and heat line may be part of a heat transfer fluid loop. The heat transfer fluid loop may be connected to an object to be heated. Without limitation, the object to be heated may be an internal combustion engine, a vehicle cockpit, an oil reservoir, or any combination thereof. The heat transfer fluid used in the heat transfer fluid loop may be a liquid or a gas. Preferably, the heat transfer fluid is capable of flowing at the lowest operating temperature that it may be exposed to during use (e.g., the lowest ambient temperature). Any heat transfer fluid employed in heating the heat storage device may also be employed in the heat exchanger. Preferably, the heat transfer fluid of the heat exchanger is a liquid. For example, any art known engine coolant may be employed as the heat transfer fluid. A particularly preferred heat transfer fluid is a mixture of a glycol and water.

[0058] As described above, the thermal energy storage system includes a means of heating the phase change material in the heat storage device. When the heat storage device (e.g., the phase change material in the heat storage device) is at a temperature sufficient to cause the combined vapor pressure of all components of the working fluid to exceed about 1 atmosphere and the working fluid valve is opened to allow flow of the working fluid, the working fluid is a) pumped by the capillary structure; b) at least partially vaporized; c) at least partially transported to the condenser; and d) at least partially condenses in the condenser; so that heat is removed from the heat storage device.

Working Fluids

[0059] Suitable working fluids (e.g., for the capillary pumped loop) include pure substances and mixtures having one or any combination of the following characteristics: a good chemical stability at the maximum thermal energy storage system temperature, a low viscosity (e.g., less than about 100 mPa·s), good wetting of the capillary structure (e.g., good wick wetting), chemical compatibility with (e.g., the working fluid causes low corrosion of) the materials of the capillary pumped loop (such as the container material, the materials employed to encapsulate the thermal energy storage material, the materials of the vapor and liquid lines, and the like), a temperature dependent vapor pressure that is conducive to both the evaporator and the condenser temperatures, a high volumetric latent heat of vaporization (i.e., the product of the latent heat of fusion and the density of the working fluid at about 25° C. in units of Joules per liter), or a freezing point less than or equal to the freezing point of the heat transfer fluid of the condenser (e.g., a freezing point less than or equal to the freezing point of antifreeze, a freezing point less than or equal to about −40° C., or both). For example, the equilibrium state of the working fluid may be at least 90% liquid at a temperature of −40° C. and a pressure of 1 atmosphere.

[0060] The vapor pressure of the working fluid should be high enough in the evaporator so that a vapor stream is produced that is sufficient to pump the working fluid. Preferably, the vapor pressure of the working fluid should be high enough in the evaporator so that a vapor stream is produced that is sufficient to carry the desired thermal power measured in watts from the evaporator to the condenser. The vapor pressure of the working fluid in the evaporator preferably is sufficiently low so that the capillary pumped loop does not leak and does not rupture.

[0061] The wetting of the working fluid to the capillary structure may be characterized by a contact angle of the working fluid on the material of the capillary structure. Preferably, the contact angle is less than about 80°, more preferably less than about 70°, even more preferably less than about 60°, and most preferably less than about 55°.

[0062] The working fluid preferably condenses at moderate pressures at temperatures below about 90° C. For example, the working fluid may condense at about 90° C. at a pressure less than about 2 MPa, preferably less than about 0.8 MPa, more preferably less than about 0.3 MPa, even more preferably less than about 0.2 MPa, and most preferably less than about 0.1 MPa.

[0063] The working fluid preferably can flow at very low temperatures. For example, the working fluid may be exposed to very low ambient temperatures and preferably is capable of flowing from the condenser to the heat storage device at a temperature of about 0° C., preferably about −10° C., more preferably about −25° C., even more preferably about −40° C., and most preferably about −60° C. The working fluid preferably is in a gas state when it is at a temperature of the fully charged heat storage device. For example, the working fluid may have a boiling point at 1 atmosphere less than the phase transition temperature of the thermal energy storage material in the heat storage device, preferably at least 20° C. less than the phase transition temperature of the thermal energy storage material, and more preferably at least 40° C. less than the phase transition temperature of the thermal energy storage material. In various aspects of the invention, it may be desirable for the working fluid to have a boiling point at 1 atmosphere (or the temperature at which the combined vapor pressure of all of the components of the working fluid is equal to 1 atmosphere may be) greater than about 30° C., preferably greater than about 35° C., more preferably greater than about 50° C., even more preferably greater than about 60° C., and most preferably greater than about 70° C. (e.g., so that the working fluid is a liquid at ambient conditions). In various aspects of the invention, the boiling point at 1 atmosphere of the working fluid may be (or the temperature at which the combined vapor pressure of all of the components of the working fluid is equal to 1 atmosphere may be) less than about 180° C., preferably less than about 150° C., more preferably less than about 120° C., and most preferably less than about 95° C.

[0064] The working fluids may be any fluid that can partially or completely evaporate in the heat storage device when the thermal energy storage material is at or above its liquidus temperature. Without limitation, exemplary working fluids may include or consist essentially of one or more alcohols, one or more ketones, one or more hydrocarbons, a fluorocarbon, a hydrofluorocarbon (e.g., an art known hydrofluorocarbon refrigerant, such as an art known hydrofluorocarbon automotive refrigerant), water, ammonia, or any combination thereof.

[0065] A particularly preferred working fluid includes or consists substantially of water and ammonia. For example, the combined concentration of water and ammonia in the working fluid may be at least about 80 wt. %, more preferably at least about 90 wt. %, and most preferably at least about 95 wt. % based on the total weight of the working fluid water and ammonia. The concentration of ammonia may be sufficient to keep the boiling point of the working fluid below the boiling point of water (e.g., at least 10° C. below the boiling point of water). The concentration of ammonia may be greater than about 2 wt. %, preferably greater than about 10 wt. %, more preferably greater than about 15 wt. % and most preferably greater than about 18 wt. % based on the total weight of the working fluid. The concentration of ammonia may be less than about 80 wt. %, preferably less than about 60 wt. %, more preferably less than about 40 wt. % and most preferably less than about 30 wt. % based on the total weight of the working fluid. The concentration of water in the working fluid may be greater than about 20 wt. %, preferably greater than about 40 wt. %, more preferably greater than about 60 wt. % and most preferably greater than about 70 wt. % based on the total weight of the working fluid. The concentration of water in the working fluid may be less than about 98 wt. %, preferably less than about 95 wt. %, more preferably less than about 90 wt. %, even more preferably less than about 85 wt. %, and most preferably less than about 82 wt. % based on the total weight of the working fluid. For example, a solution of about 21 wt. % ammonia and about 79 wt. % water have a liquidus point of about −40° C. and the upper limit of a boiling range at 1 atmosphere of less than about 100° C. This solution may be stored (e.g., as a liquid) in a non-pressurized container at room temperature.

[0066] Preferably, the working fluid has a combined vapor pressure of all of its components equal to 1 atmosphere at one temperature from about 0° C. to about 250° C.

[0067] The working fluid is capable of efficiently transferring thermal energy from the heat storage device so that the amount of working fluid needed to remove an amount of heat from the heat storage device is relatively small (e.g., compared to a device that uses a heat transfer fluid that is not a working fluid to remove the heat). Preferably, a large portion of the heat transferred by the working fluid is transferred in the form of heat of vaporization. The volume of working fluid, the flow rate of the working fluid, or both, may be relatively low in the thermal energy storage compared to a system that employs a heat transfer fluid that is not a working fluid and has the same initial power. The flow rate of the working fluid (i.e., the working fluid in the liquid state flowing into the heat storage device) per liter of the container of the heat storage device may be less than about 5 liters/min, preferably less than about 2 liters/min, more preferably less than about 1 liter/min, even more preferably less than about 0.5 liters/min, and most preferably less than about 0.1 liters/min. The ratio of the volume of the working fluid (e.g., in the system or in the capillary pumped loop) in the system to the total volume of the container (i.e., the volume inside the container) of the heat storage device (or even the ratio of the volume of the working fluid in the system to the volume of the thermal energy storage material in the heat storage device) may be less than about 20; preferably less than about 10, more preferably less than about 4, even more preferably less than about 2, and most preferably less than about 1.

[0068] As described above, the working fluid may transfer some of the thermal energy in the form of heat of vaporization. The working fluid preferably has a high heat of vaporization so that the amount of heat that can be transferred is high. Suitable working fluids for the heat storage device may have a heat of vaporization greater than about 200 kJ/mole, preferably greater than about 500 kJ/mole, more preferably greater than about 750 kJ/mole, even more preferably greater than about 1,000 kJ/mole, and most preferably greater than about 1,200 kJ/mole.

[0069] In applications where the temperature of the working fluid may be less than 0° C., the working fluid preferably is not water (e.g., so that the working fluid does not freeze, cause a rupture, or both).

[0070] It will be appreciated that the materials that contact with the working fluid may be resistant to corrosion from the working fluid. For example, any one or all of the surfaces of the heat storage device or thermal energy storage system that may come in contact with the working fluid (e.g., the interior of the working fluid vapor line, the interior of the working fluid liquid line, the surfaces of the working fluid compartment of the heat storage device, the interior surfaces of the working fluid valve, the surface of a working fluid compartment in the condenser, the interior surface of the working fluid reservoir, and the like) may be made of stainless steel.

[0071] It will be appreciated that any of the working fluids or heat transfer fluids employed in the thermal energy storage system described herein may include an additives package. For example, the additives package may include a stabilizer, a corrosion inhibitor, a lubricant, an extreme pressure additive, or any combination thereof.

Operation of A Thermal Energy Storage System

[0072] The thermal energy storage system has a plurality of operational phases including a charging phase where heat from outside the heat storage device is provided to the thermal energy storage material, a storing phase where at least some of the heat is stored in the thermal energy storage material, and a discharging phase where at least some of the heat is removed from the thermal energy storage material.

1. Charge Phase

[0073] The charge phase may occur when the temperature of the heat storage device (is below its maximum nominal temperature and the heat transfer fluid (e.g., exhaust gas)) has a temperature greater than the temperature of the thermal energy storage material. During the charge phase, the step of charging the thermal energy storage material (e.g., the phase change material) may include a step of transferring heat from the heat transfer fluid to the thermal energy storage material. During the charge phase, the discharge valve for the working fluid preferably is closed. Any residue of liquid working fluid in the evaporator (i.e., the working fluid compartment of the heat storage device) may boil off, enter the condenser, become liquid in the condenser and enters the reservoir. An exhaust gas bypass (such as a bypass activated by a valve shown in FIG. **1**) may be used to prevent overheating the heat storage device when the thermal energy storage system is fully charged or when the exhaust is hot enough to cause local phase change material overheating, which may result in phase change material degradation. A temperature sensor is preferably embedded in the vicinity of the phase change material to prevent overheating it by triggering the exhaust bypass valve. Other control strategies may preferably be used to prevent phase change material overheating.

2. Storage Phase

[0074] When the internal combustion engine is shut down, for example, when the vehicle is parked, the discharge valve remains closed. The heat stored in the thermal energy storage system is slowly lost to the environment. Therefore, some form of insulation is preferably used in the present invention. The better the insulation of the system is, the longer is the storage time.

[0075] Any known form of insulation which prevents loss of heat by the heat storage device may be utilized. For example, any insulation as disclosed in U.S. Pat. No. 6,889,751, incorporated herein of its entirety by reference, may be employed. The heat storage device preferably is (thermally) insulated container, such that it is insulated on one or more surfaces. Preferably, some or all surfaces that are exposed to ambient or exterior will have an adjoining insulator. The insulating material may function by reducing the convection heat loss, reducing the radiant heat loss, reducing the conductive heat loss, or any combination. Preferably, the insulation may be through the use of an insulator material or structure that preferably has relatively low thermal conduction. The insulation may be obtained through the use of a gap between opposing spaced walls. The gap may be occupied by a gaseous medium, such as an air space, or possibly may even be an evacuated space (e.g., by use of a Dewar vessel), a material or structure having low thermal conductivity, a material or structure having low heat emissivity, a material or structure having low convection, or any combination thereof. Without limitation, the insulation may contain ceramic insulation (such as quartz or glass insulation), polymeric insulation, or any combination thereof. The insulation may be in a fibrous form, a foam form, a densified layer, a coating or any combination thereof. The insulation may be in the form of a woven material, an unwoven material, or a combination thereof. The heat transfer device may be insulated using a Dewar vessel, and more specifically a vessel that includes generally opposing walls configured for defining an internal storage cavity, and a wall cavity between the opposing walls, which wall cavity is evacuated below atmospheric pressure. The walls may further utilize a reflective surface coating (e.g., a mirror surface) to minimize radiant heat losses.

[0076] Preferably, a vacuum insulation around the system is provided. More preferably, a vacuum insulation as disclosed in U.S. Pat. No. 6,889,751, incorporated herein of its entirety by reference, is provided.

3. Discharge Phase

[0077] When the heat stored in the thermal energy storage system needs to be transferred to the object to be heated, the discharge valve opens to a desired degree depending on the required discharge power (e.g., in units of Watts (W)). Liquid working fluid stored in the reservoir enters the evaporator driven by gravity, wets the wick, flows along the wick upward driven by capillary pressure and gets evaporated by heat flowing from the phase change material. The vapor flows along the gaps between the wicks and then into the condenser, where it releases its heat stored as both the latent heat of vaporization and sensible heat to coolant, which circulates between the condenser and a cold internal combustion engine and/or air heater core. During a high-power discharge the vapor pressure in the evaporator can substantially exceed that in the condenser. This pressure difference tries to push the liquid out of the evaporator along the liquid line. Without being bound by theory, it is believed that the capillary pressure formed by microscopic menisci of liquid filling the pores of the capillary structure (e.g., the wick) is what holds this pressure and keeps “pumping” liquid into the evaporator. The capillary pressure is inversely proportional to the wick’s pore size (Young-Laplace equation). The vapor has no other option to release its pressure but to flow into the condenser through the vapor line. This establishes a circular flow pattern inside a capillary pumped loop. When a desired amount of heat has been transferred by the capillary pumped loop the discharge valve closes.

[0078] During the discharge phase, the device and system of the present invention may have a relatively high power output (in units of Watts), a relatively high power output density (e.g., in units of Watts per liter of volume in the heat storage device), or both. The power output, the power output density, or both may be greater than (e.g., at least 20% greater than, more preferably at least about 100% greater than) that of an identical device or system with the exception that it does not have a capillary structure. For example, the device, system, or both may have an average power density of at least about 1 kW/liter, preferably at least about 10 kW/liter, more preferably at least about 25 kW/liter, even more preferably at least about 30 kW/liter, and most preferably at least about 50 kW/liter based on the total internal volume of the insulated volume of the heat storage device (e.g., the sum of the volumes of the thermal energy storage material compartment, the heat transfer fluid compartment and the working fluid compartment), where the power is averaged over initial discharge operation (e.g., the first 30, 60, or 120 seconds of the discharge operation), which begins for example, when a valve is opened allowing for flow of the working fluid through the first flow path of the heat storage device, and when a substantial portion (e.g., when at least 50% by volume, or at least 75% by volume) of the phase change material is in a liquid state at the start of the discharge operation (e.g. at the time the valve is opened).

[0079] It should be appreciated that the thermal energy storage system of the present invention may also be operated in a "combination" mode (e.g., as a steady-state mode) by simultaneously charging and discharging the thermal energy storage material (i.e., by simultaneously performing both the charge and the discharge phases). In the combination mode of operation, both the discharge valve of the working fluid is open and heat transfer fluid (e.g., hot exhaust gas) flows through the heat storage device. The "combination" mode of operation may establish a continuous (e.g., a constant) flow of heat from the exhaust gas to a heat recipient. An advantage of the present system over other prior art steady-state exhaust heat recovery devices is its ability to levelize the fluctuations of thermal power of the exhaust stream (which is very common in urban traffic) and deliver a more stable thermal power to the recipient by using the large heat storage capacity of the phase change material, essentially acting as a heat buffer between the exhaust gas and the heat recipient. The levelization of the heat flow can be very beneficial in ensuring optimal operation of devices powered by the exhaust heat, e.g. Rankine cycle heat engine (a.k.a. turbo-steamer), absorption or adsorption cycle refrigeration system or simply a cabin air heater.

[0080] The thermal energy storage system may employ one or more means to minimize the heat losses from the thermal energy storage system to the environment. Exemplary means of minimizing heat losses include insulating one or more components of the thermal energy storage system (e.g., the heat storage device, a line, the evaporator, or any combination thereof), use of low thermal conductivity materials, use of geometries and/or coatings that reduce radiative heat losses or heat flow distances, or any combination thereof.

[0081] Without limitation, any of the insulation means disclosed in U.S. patent application Ser. No. 12/389,598 entitled "Heat Storage Devices" and filed on Feb. 20, 2009 may be employed.

[0082] As an example, the heat storage device may employ a vacuum (e.g., a high-vacuum) jacket insulation, optionally with thin internal radiative screens to slow down radiative heat transfer between the internal and the external walls of the vacuum jacket. The rate of radiative heat transfer is roughly inversely proportional to the number of vacuum gaps between radiative screens along the heat flow path. This approach is analogous to a double Dewar flask. As such, the insulation may employ a one, two, three, or more vacuum gaps.

[0083] The heat storage device may employ one or more materials having a relatively low thermal conductivity to reduce or minimize the heat losses to the ambient. For example, the heat storage device may employ one or more materials having a thermal conductivity less than 50% of the thermal conductivity of low carbon steel (e.g., A36 grade), preferably less than 30% of the thermal conductivity of low carbon steel, more preferably less than 20% of the thermal conductivity of low carbon steel, and most preferably less than 10% of the thermal conductivity of low carbon steel. Exemplary low thermal conductivity materials that may be employed include, without limitation stainless steel, titanium alloys, silica-based glass, or any combination thereof. For example, low thermal conductivity materials may be employed for lines (e.g., tubes) that connect the inlets and outlets of the heat storage device to the condenser, to a heat source (e.g., an exhaust pipe), or both.

[0084] The heat losses may be reduced by selecting a geometry of one or more (e.g., even all) of the connecting lines (e.g., tubes or pipes) that increases the heat path distance. For example, the geometry of a line may employ thin-walled bellows instead of smooth (e.g., cylindrical) walls. The lines may be curved (e.g., have a substantially curved center line), so that direct "line-of-sight" radiative heat transfer between the heat storage device and a portion of the thermal energy storage system that is not insulated is substantially reduced or even eliminated. As such, the geometry may be selected to reduce the radiative aperture of a line without substantially increasing the hydraulic resistance of the line. Additionally, one or more sides of the line may be coated with a coating capable of reducing indirect radiative heat losses. Such coatings are generally a reflective coating such as silver.

[0085] In a preferred embodiment of the present invention, the system has the following characteristics. The encapsulant sheet thickness will be between 0.01-2 mm. The phase change material capsule size is between 0.5-100 mm. Fluid gap between capsules is between 0.1-10 mm. Dimensions of the blister pack depend on the dimensions of the heat exchanger, which will vary a lot depending on the application. It can be as small a single capsule dimension or as large as a few meters for heating and air conditioning of large buildings.

[0086] The thermal energy storage system may be employed in a transportation vehicle (e.g., an automotive vehicle) for storing energy from an engine exhaust gas. When the engine produces exhaust gas, a bypass valve may either direct the flow of the gas through the heat storage device so that the heat storage device is charged, or through a bypass line to prevent the heat storage device from overheating. When the engine is shut down, e.g., during a period when the vehicle is parked, a substantial portion of the heat stored in the heat storage device may be retained for a long time (e.g., due to vacuum insulation surrounding the heat storage device). Preferably, at least 50% of the thermal energy storage material in the heat storage device remains in a liquid state after the vehicle has been parked for 16 hours at an ambient temperature of about −40° C. If the vehicle is parked for a long enough time (e.g., at least two or three hours) for the engine to cool down substantially (e.g., so that the difference in temperature between the engine and the ambient is less than about 20° C.), the heat stored in the heat storage device may be discharged into the cold engine or other heat recipient indirectly by flowing a heat transfer fluid (such as the engine coolant) through the heat exchanger that includes the condenser for the working fluid. The working fluid is circulated in a capillary pumped loop using the capillary structure inside the heat storage device where the working fluid is vaporized. The heat from the working fluid is transferred to the engine coolant in the heat exchanger. By employing the heat storage device, heat that otherwise would be wasted may be captured during a previous trip to mitigate cold start and/or provide instant cockpit heating.

[0087] The transfer of heat using the working fluid may begin by opening the working fluid valve (i.e., the discharge valve). The sealed working fluid reservoir connected to the loop via an additional liquid line serves to accommodate changes in the working fluid liquid volume inside the loop without substantial pressure changes. Once sufficient or all useful heat is transferred from the heat storage device, the discharge valve may close. The remaining working fluid in the heat storage device may evaporate (e.g., from heat remaining in the heat storage device or when the heat storage device begins to charge) and then condenses in the condenser. As the heat storage device becomes evacuated of the working fluid, the liquid level of the working fluid level may change (e.g., rise).

[0088] The heat storage device may be a cross-flow heat exchanger (i.e., having a flow direction for the working fluid and a perpendicular flow direction for the flow of the exhaust gas). During operation, the heat storage device may include three chambers occupied by 1) exhaust gas; 2) stagnant phase change material (e.g., inside capsules, such as a blisters pack); and 3) working fluid. All three chambers are kept separate by thin walls made of an appropriate material, preferably stainless steel. Exhaust gas may flow between the surfaces (e.g., the curved surfaces) of the capsules of phase change material inside blisters, and the working fluid may flow between different surfaces (e.g., flat surfaces) of the capsules of phase change material inside blisters in a direction that is generally perpendicular to the exhaust gas flow direction. The liquid working fluid entering its chamber preferably wets a capillary structure (e.g., a metal wick) and gets transported up against the combined forces of gravity and vapor pressure by the capillary forces acting upon the working fluid liquid menisci formed inside the capillaries. This flow is sustained by continuous evaporation of the liquid using the heat drawn from the phase change material inside blisters. The vapor of working fluid leaves the capillary structure and escapes to the top of the device via vapor channels which may be interdigitated between columns of the capillary structure squeezed between the surfaces (e.g., the flat surfaces) of the capsules of phase change material inside blisters. The vapor of working fluid flows into the condenser where it transfers its heat of vaporization and sensible heat to the cold coolant and becomes liquid again to return to the heat storage device and continue its circulation in the loop, being pumped only by the capillary forces existing inside the capillary structure (e.g., metal wick) that is partially impregnated by liquid working fluid. All columns of the capillary structure may be connected to a common porous base. Such a porous base may be employed to distribute the liquid working fluid entering from the bottom of the device to the different columns.

[0089] Furthermore, the present invention may be used in combination with additional elements/components/steps. For example, absorption or adsorption cycle refrigeration system for air conditioning may be used as the heat recipient instead of or in addition to the cold coolant (e.g., the condenser may serve also as an evaporator for the refrigerant circulating inside an air conditioner's fluid loop). In another application, a steady-state waste heat recovery system using a heat engine, e.g., a Rankine cycle, can be constructed so that it uses the same or different capillary pumped loop working fluid and adds a mechanical power generating turbine to'the vapor line between the heat storage device and the condenser, (e.g., to overcome high vapor pressure upstream from the turbine), and/or adds a liquid pump to the liquid line between the condenser and heat storage device. The above turbine can convert a part of the captured from the exhaust gas waste heat into useful mechanical or electrical work and thus improve the overall fuel efficiency of the vehicle.

[0090] While the present invention may be susceptible to various modifications and alternative forms, the exemplary embodiments discussed above have been shown by way of example. However, it should again be understood that the invention is not intended to be limited to the particular embodiments disclosed herein. Indeed, the present techniques of the invention are to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the following appended claims.

[0091] FIG. **1** is a thermal energy storage heat storage device of the present invention including an inventive heat storage device. As illustrated in FIG. **1**, the heat storage device **10** may include a container **12** having a working fluid inlet **14**, a working fluid outlet **16**, a heat transfer fluid inlets **18** and a heat transfer fluid outlets **20**. The volume of the heat storage device is about 1 liter and the thermal energy storage material fills more than about 60 volume % of the heat storage device.

[0092] FIG. **2**A is an illustrative cross-section (i.e., the cross-section as shown in FIG. **1**) of the heat storage device **10** of FIG. **1**. The heat storage device includes layers of capsules **32**, with spacing between each adjacent layer of capsules. The layers of capsules **32** each have a surface that is arcuate **34** and an opposing surface that is generally flat **36**. At least a portion (e.g., a layer) of the heat transfer fluid compartment **26** is interposed between two layers of capsules. A portion (e.g., a layer) of the working fluid compartment **22** is interposed between two adjacent layers of capsules and the average thickness of the working fluid compartment, defined by the distance (e.g., average distance) of separation of the two layers of capsules, is about 1 mm. The layers of capsules generally have a layer of the working fluid compartment **22** on one side of the capsule layer and a layer of the heat transfer fluid compartment **26** on an opposing side. The average thickness of a layer of the heat transfer fluid compartment is about 1 mm.

[0093] As shown in FIGS. **1**, **2**A and **2**B, the heat storage device has an inlet **14** for flowing a working fluid into the working fluid compartment of the heat storage device and an outlet **16** for flowing the working fluid out of the heat storage device. The outlet is at a higher elevation than the inlet, so that the flow of the working fluid includes a generally vertical component. The working fluid is a mixture of about 79 wt. % water and about 21 wt. % ammonia. The working fluid is in thermal contact with the thermal energy storage material **30**. At least some of the working fluid compartment includes 5 mm strips of a metal wick that forms a capillary structure. The cross-section of FIG. **2**A shows a region of the working fluid compartment **22** in which all of the layers of the working fluid compartments have the metal wick. Between the 5 mm strips of wick are 10 mm wide sections that are free of metal wick, as shown in the cross-section FIG. **2**B. As illustrated in FIG. **2**A, the capillary structure (i.e., metal wick) may extend the length of the working fluid compartment. A portion of the capillary structure is in thermal contact with each of the capsules containing the phase change material (e.g., the capillary structure is in contact with a portion of the generally flat outer surface next to each capsule).

[0094] The thermal energy system of the present invention is shown in FIG. **3**. The thermal energy storage system **50** includes the heat storage device, a condenser **52** having an inlet **56** for the working fluid **54** and an outlet **58** for the working fluid, a vapor tube **60** connecting the working fluid inlet **56** of the tube connecting the working fluid outlet **58** of the condenser **52** to the working fluid inlet of the heat storage device. The thermal energy storage system contains a capillary pumped loop including the working fluid compartment in the heat storage device, a working fluid compartment in the condenser, the working fluid vapor tube, and the working fluid liquid tube. The thermal energy storage system also includes a working fluid reservoir **74**. The working fluid reservoir has a fill level that is higher in elevation than the working fluid inlet of the heat storage device and lower than the elevation of the working fluid inlet of the condenser **58**. The capillary pumped loop may have a valve **72** in the working fluid liquid tube **62**. The valve is used to prevent the working fluid from circulating in the capillary pumped loop when the heat storage device is charging and when the heat storage device is storing heat. The valve is opened when it is desired to discharge heat from the heat storage device.

[0095] Referring again to FIG. **3**, the thermal energy storage system includes a heat transfer fluid inlet line **64** and a heat transfer fluid outlet line **66**, for flowing the heat transfer fluid into and out of the heat storage device. The thermal energy storage system also has a heat transfer fluid bypass line **68**. The thermal energy storage system also includes a diverter valve (e.g., a bypass valve) **70** to divert some or all of the heat transfer fluid to the bypass line **68** (e.g., when the heat storage device is fully charged, or when the temperature of the heat transfer fluid is below a temperature of the thermal energy storage material in the heat storage device).

[0096] The condenser **52** of the thermal energy storage system is a heat exchanger The thermal energy storage system includes a cold line **80** for providing a heat transfer fluid into the heat exchanger, and a heat line **78** for removing heat transfer fluid from the heat exchanger. The cold line **80** and heat line **78** are part of a heat transfer fluid loop **84**. The heat transfer fluid loop contains an engine coolant, is connected to an internal combustion engine **76** and is used to heat the internal combustion engine with the energy stored in the heat storage device.

What is claimed is:

1. A device including

i) one or more thermal energy storage material compartments:

ii) a thermal energy storage material encapsulated in one or more thermal energy storage material compartments, wherein the thermal energy storage material has having a solid to liquid phase transition at a temperature;

iii) one or more working fluid compartments in thermal contact with the thermal energy storage material; and

iv) and a capillary structure having a plurality of capillaries in the working fluid compartment;

wherein the device is a heat storage device.

2. The device of claim **1**, wherein the thermal energy storage material has a solid to liquid phase transition at a temperature greater than about 50° C.

3. The device of claim **2**, wherein the thermal energy storage material has a solid to liquid phase transition at a temperature from about 90° C. to about 300° C.

4. (canceled)

5. The device of claim **2**, wherein the thermal energy storage material is encapsulated in a plurality of capsules.

6. (canceled)

7. (canceled)

8. The device of claim **2**, comprising:

i) one or more containers each with at least one inlet and one outlet for a working fluid, and at least one inlet and at least one outlet for a second fluid;

ii) one or more capsules containing the thermal energy storage material in the container having at least a first outer surface, wherein the thermal energy storage material is a phase change material;

iii) a first flow path for the flow of the working fluid through the container wherein the flow path is at least partially defined by the first outer surface of the capsule;

iv) a capillary structure having a plurality of capillaries capable of pumping a working fluid through the first flow path, wherein the capillary structure partially fills the first flow path and is at least partially in contact with the first outer surface of the capsule, so that when contacted with a working fluid on one end, the working fluid is drawn into the capillary, and a second portion of the first flow path that is free of a capillary;

v) a second flow path for the flow of a second fluid through the container;

wherein the first flow path is in a working fluid compartment, the second flow path is in a heat transfer fluid compartment, and the phase change material is in a phase change material compartment;

the phase change material is in thermal communication with the working fluid compartment and the heat transfer fluid compartment; and

wherein the device is a heat storage device.

9. The device of claim **8**, wherein the plurality of capillaries includes capillaries having a pore diameter of less than about 200 μm.

10. The device of claim **9**, wherein the capsule includes a second outer surface wherein the second outer surface at least partially defines the second flow path.

11. (canceled)

12. (canceled)

13. (canceled)

14. The device of claim **9**, wherein the container is at least partially insulated.

15. (canceled)

16. A system for storing and transferring heat including:

a. the heat storage device of claim **2**;

b. a condenser having at least a first inlet and at least a first outlet and a first flow path for a working fluid;

wherein the heat storage device is in fluid connection with the condenser and the system comprises a capillary pumped loop including the first flow path of the condenser and the first flow path of the heat storage device.

17. The system of claim **16**, wherein the system includes the working fluid and the working fluid has a combined vapor pressure of all of its components equal to 1 atmosphere at a temperature from about 0° C. to about 250° C.

18. (canceled)

19. The system of claim **16**, wherein the working fluid includes one or more alcohols, one or more ketones, one or more hydrocarbons, a fluorocarbon, a hydrofluorocarbon, water, ammonia, or any combination thereof.

20. The system of claim **19**, wherein the working fluid includes a solution of ammonia and water.

21. (canceled)

22. The system of claim **17**, wherein the system includes a working fluid valve to control the flow of the working fluid from the heat storage device to the condenser.

23. The system of claim **16**, wherein the system includes a vapor tube connecting the outlet of the heat storage device and the inlet of the condenser; a liquid tube connecting the outlet of the condenser and the inlet of the heat storage device; and a working fluid at least partially filling the condenser.

24. (canceled)

25. (canceled)

26. (canceled)

27. The system of claim **16**, wherein the system includes a means of heating the phase change material in the heat storage device, so that when the heat storage device is at a temperature sufficient to cause the combined vapor pressure of all components of the working fluid to exceed 1 atmosphere and the valve is opened to allow flow of the working fluid, the working fluid is

a) pumped by the capillary structure;

b) at least partially vaporized; and

c) at least partially transported to the condenser; and

d) at least partially condenses in the condenser; so that heat is removed from the heat storage device.

28. (canceled)

29. (canceled)

30. The system of claim **16**, wherein the system is free of a pump for pumping the working fluid other than the capillary pump.

31. The system of claim **16**, wherein the condenser includes a second flow path, a second inlet and a second outlet for transporting a heat transfer fluid through the condenser so that the condenser can transfer heat from the working fluid to the heat transfer fluid.

32. (canceled)

33. (canceled)

34. The system of claim **16**, wherein the system includes a working fluid, and the ratio of the volume of the working fluid to the volume of the phase change material is less than about 20:1.

35. (canceled)

36. The system of claim **16**, wherein the second fluid is an exhaust gas, and the system includes a valve for controlling the flow of the exhaust gas through the second flow path of the heat storage device.

37. The system of claim **16**, wherein the system has an average power density of at least about 1 kW per liter of the insulated (internal) volume of the device averaged over the first 30 seconds of operation, which begins when a valve is opened allowing for flow of the working fluid through the first flow path of the heat storage device, wherein at least 50% by volume of the phase change material is in a liquid state at the time the valve is opened.

38. (canceled)

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