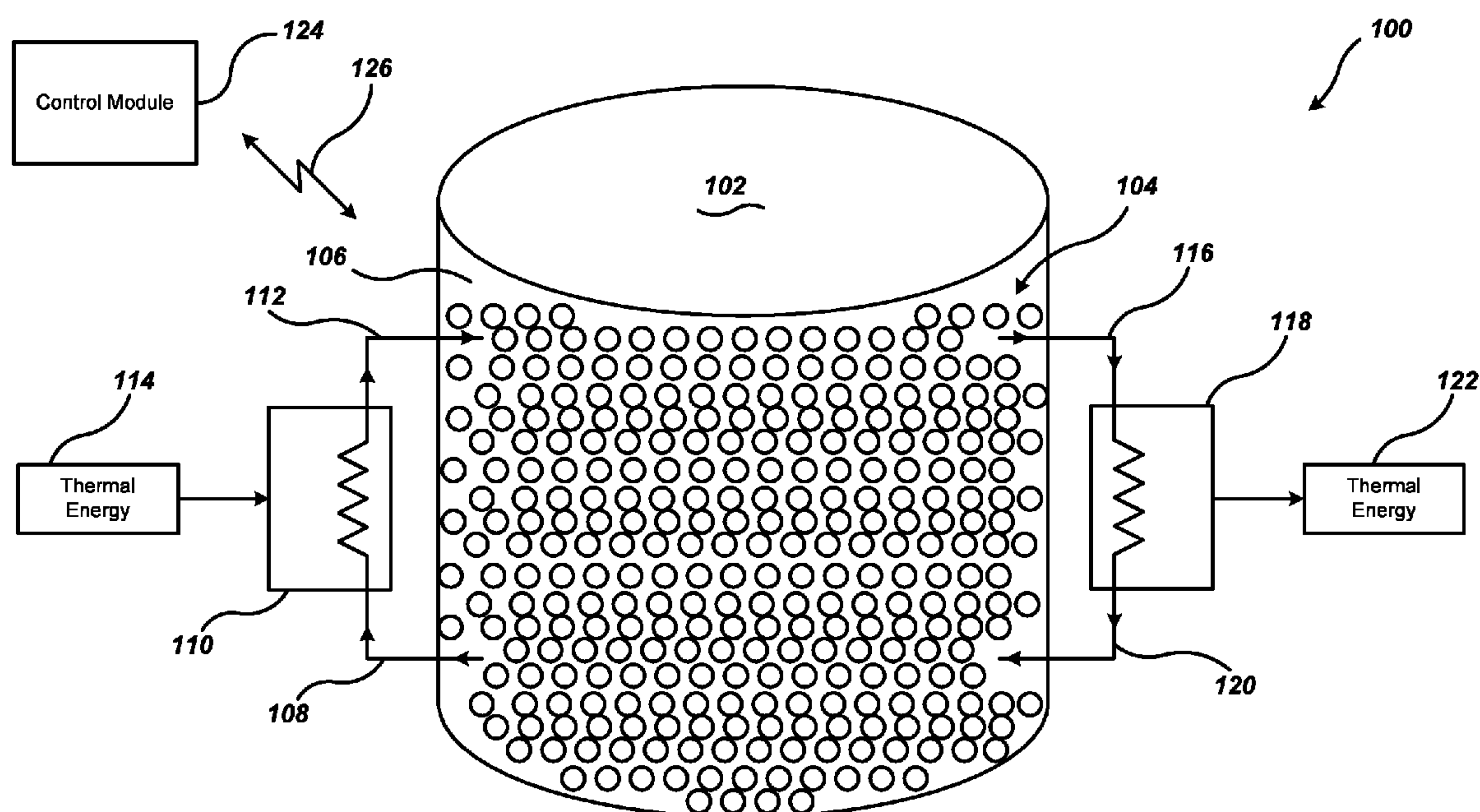


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(19) **United States**(12) **Patent Application Publication**
Mathur et al.(10) **Pub. No.: US 2012/0018116 A1**(43) **Pub. Date: Jan. 26, 2012**(54) **THERMAL ENERGY STORAGE SYSTEM
COMPRISING ENCAPSULATED PHASE
CHANGE MATERIAL****Publication Classification**(51) **Int. Cl.**
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CA (US)(57) **ABSTRACT**(21) **Appl. No.: 13/187,398**(22) **Filed: Jul. 20, 2011****Related U.S. Application Data**(60) Provisional application No. 61/366,409, filed on Jul.
21, 2010.

Systems for storing and retrieving thermal energy in encapsulated phase change material are disclosed. Thermal energy is substantially stored and/or retrieved in the form of latent heat. The capsules comprise an outer shell which is impervious to both the heat transfer fluid within which they are submerged and the phase change material encapsulated there-within. Methods for encapsulating the phase change material are also disclosed.



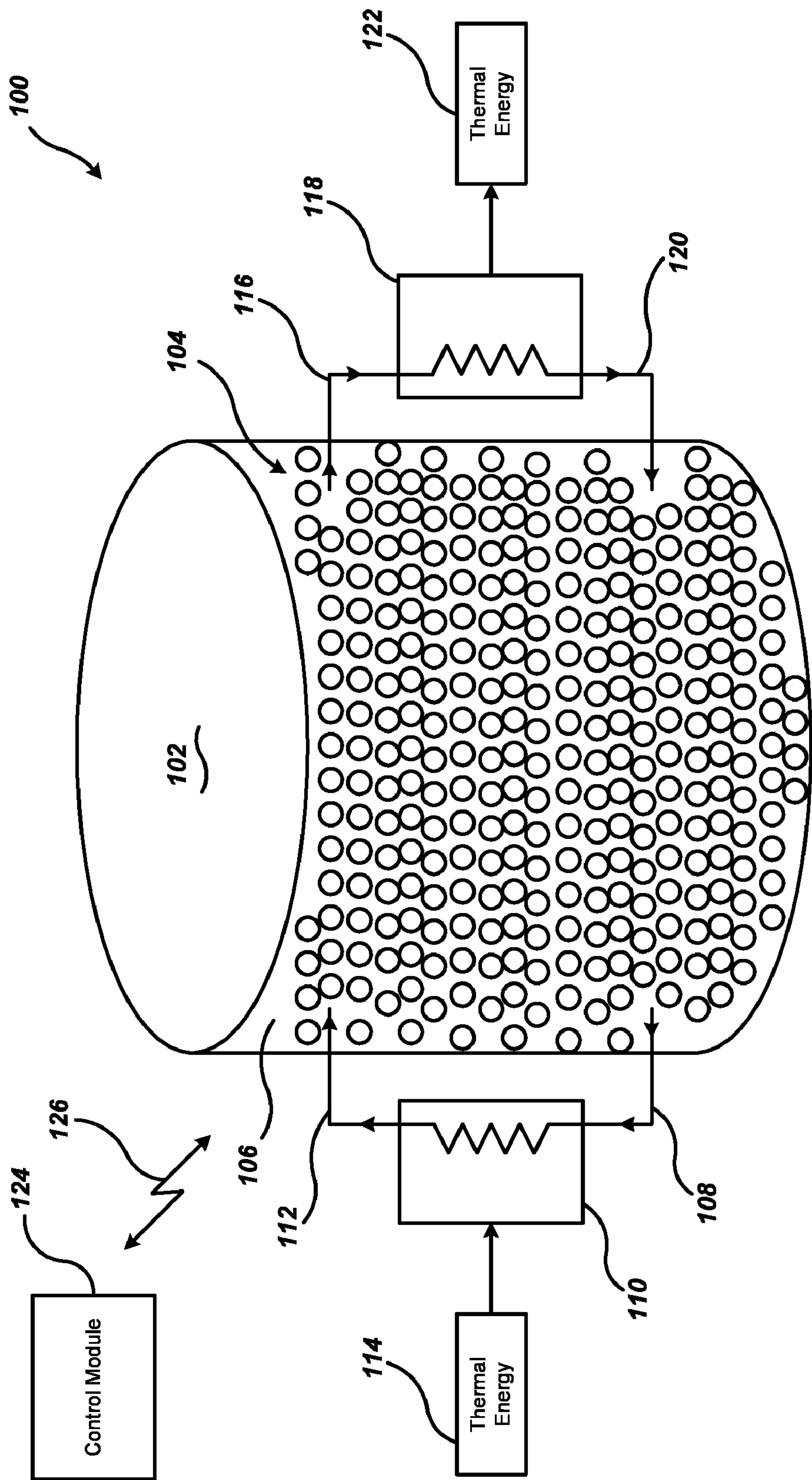


FIG. 1

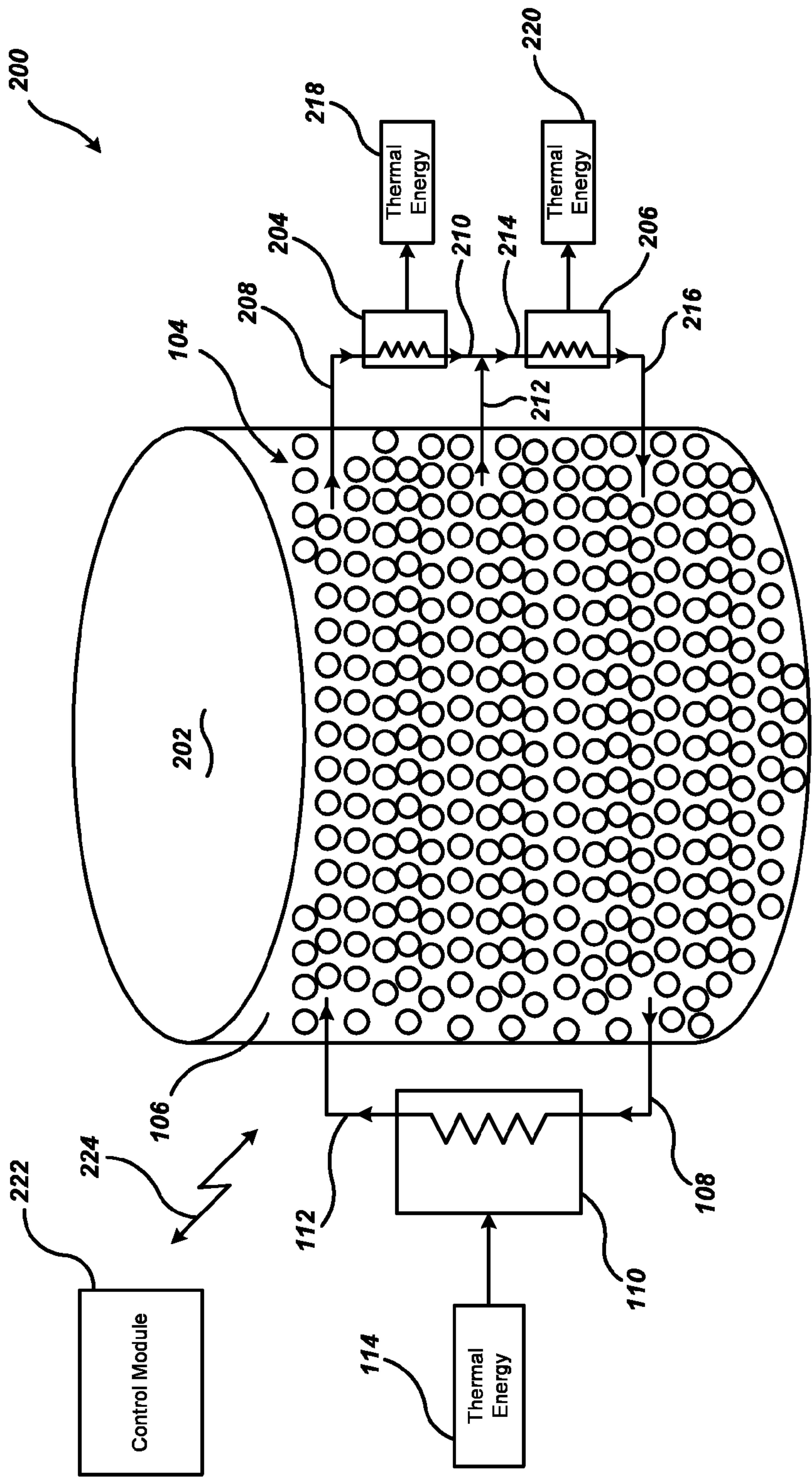


FIG. 2

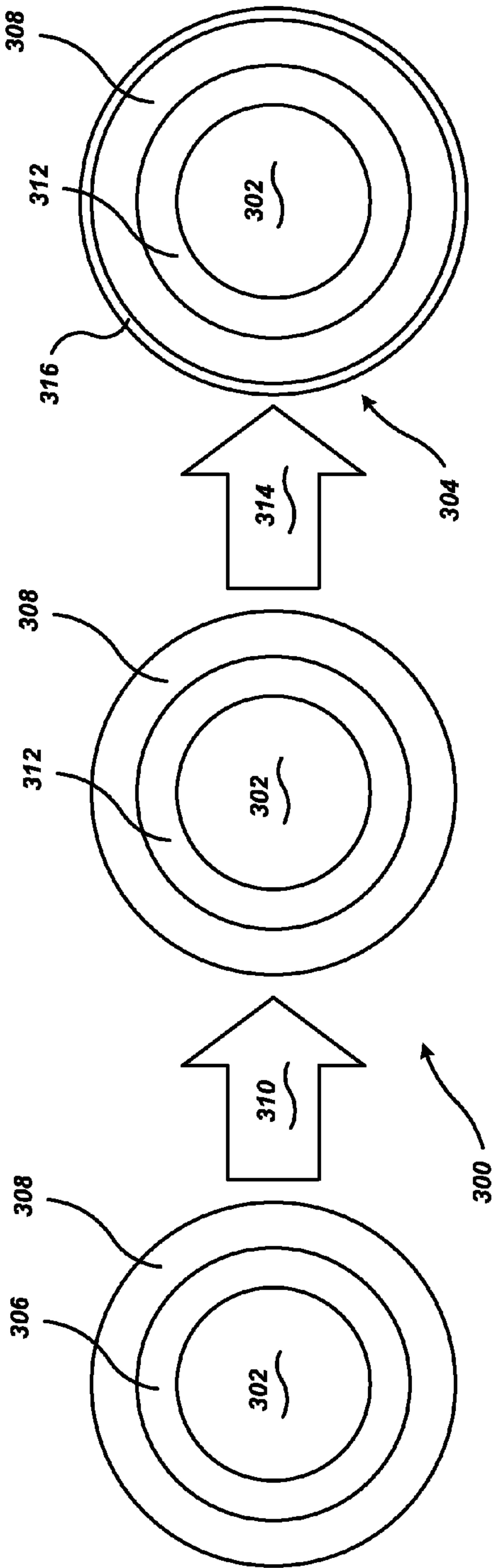


FIG. 3A

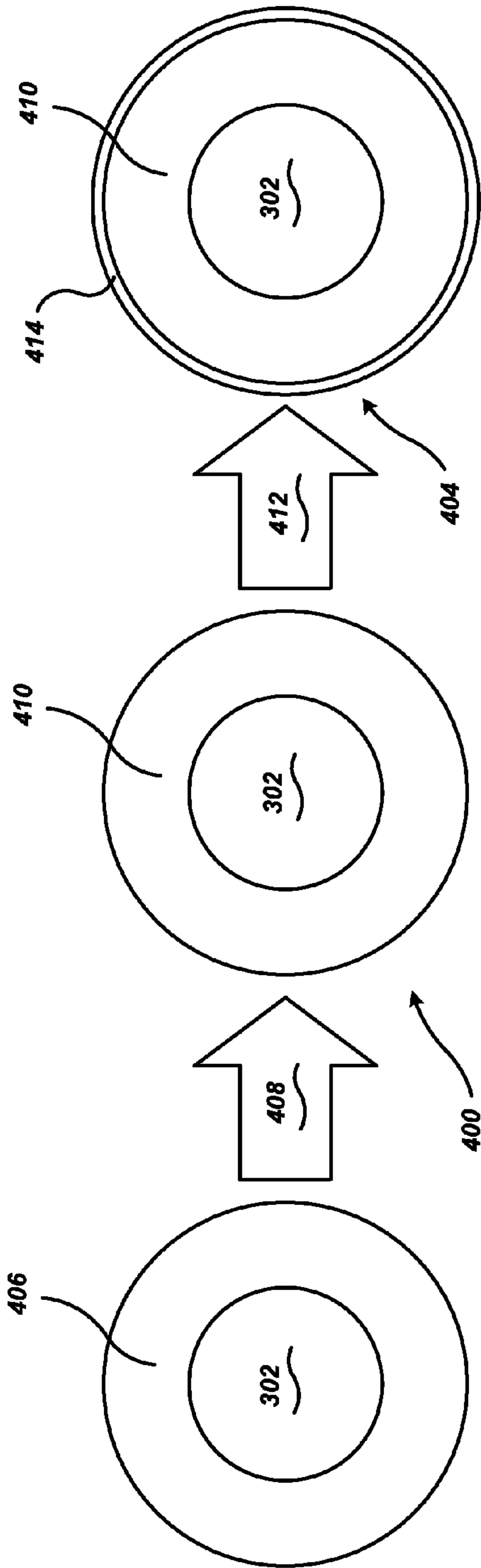


FIG. 4A

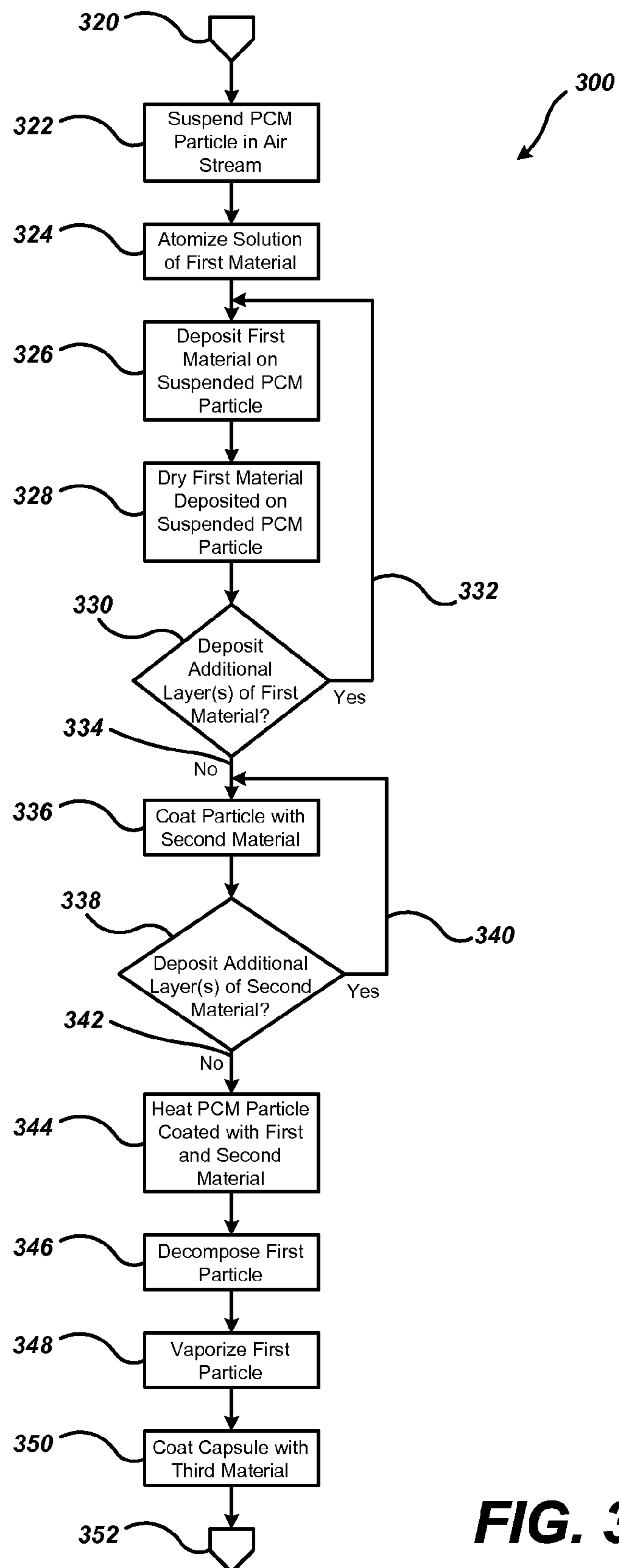


FIG. 3B

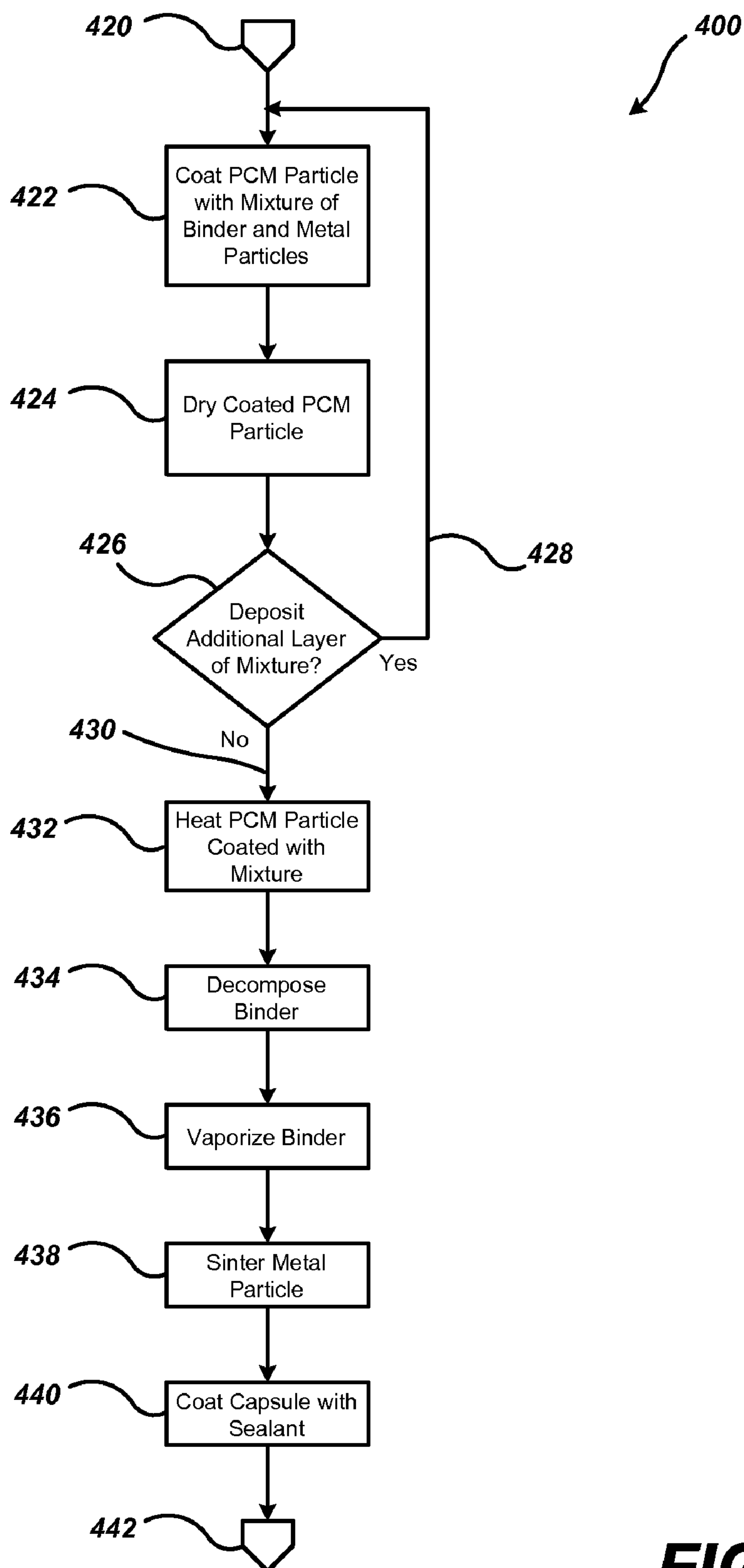


FIG. 4B

THERMAL ENERGY STORAGE SYSTEM COMPRISING ENCAPSULATED PHASE CHANGE MATERIAL

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application Ser. No. 61/366,409 filed Jul. 21, 2010 which, in its entirety, is hereby incorporated herein by reference.

TECHNICAL FIELD

[0002] The present invention relates to an apparatus for storing and retrieving thermal energy. In particular, the invention pertains to an apparatus for storing and retrieving thermal energy from an encapsulated phase change material. Methods for encapsulating said phase change material in a capsule are also provided.

BACKGROUND

[0003] Thermal energy storage systems incorporating phase change material are well known in the art. Such systems generally include a tank containing the phase change material. Thermal energy, when added to the phase change material, causes the phase change material to absorb at least some thermal energy in an amount equal to its heat of fusion and accordingly change phase from solid to liquid. Thermal energy, when removed from the phase change material, causes the phase change material to release its heat of fusion and accordingly change phase from liquid to solid.

[0004] In prior art thermal energy storage systems, generally one or more heat exchangers submerged within the phase change material are used for adding and/or removing the thermal energy. As is well known in the art, removal of thermal energy from the phase change material causes the phase change material to solidify on the heat exchanger surfaces and consequentially deteriorates the heat exchanger effectiveness.

[0005] Accordingly, there exists a need for a thermal energy storage system wherein the phase change material does not solidify on one or more heat exchangers as the phase change material releases its heat of fusion in the form of thermal energy extracted from the thermal energy storage system.

SUMMARY

[0006] An embodiment of the invention comprises an apparatus for storing and retrieving thermal energy from a phase change material encapsulated in a capsule. A plurality of such capsules are submerged in a heat transfer fluid contained within a tank. The heat transfer fluid functions as a medium for transferring thermal energy to and/or from the encapsulated phase change material. Thermal energy added to the heat transfer fluid by an external means is transferred to the phase change material within the capsules causing the phase change material to change from solid to liquid. The phase change material releases thermal energy in the process of changing from liquid to solid. The released thermal energy is added to the heat transfer fluid and transported to an external means.

[0007] The apparatus, in accordance with an embodiment of the invention, comprises a control module configured for optimizing a thermocline within the heat transfer fluid in the

tank. In one such embodiment, thermocline optimization is accomplished by changing one or more of the location along a height of the tank from whereat the heat transfer fluid is extracted, the location along a height of the tank whereat the heat transfer fluid is returned to the tank, and a flow rate of the heat transfer fluid extracted from and/or returned to the tank.

[0008] Methods are provided for encapsulating a phase change material within a capsule or a shell impervious to both the phase change material contain therewithin and the heat transfer fluid within which the capsule or shell is submerged.

[0009] In accordance with an embodiment of the invention, a particle of the phase change material is suspended in an air stream and exposed to an atomized solution of a first material. Upon drying, a coating, comprising one or more layers, of the first material is formed around the particle of the phase change material. Another coating, comprising one or more layers, of a second material is then applied around the first material encasing the phase change material. The encapsulated phase change material is then heated to a temperature sufficiently high to vaporize or thermally decompose the first material encasing the phase change material. In an embodiment of the invention, the first material is an organic polymer having a decomposition temperature less than a phase change temperature of both the phase change material and the second material. Vaporization of the first material results in a void within the capsule or shell formed by the second material within which the phase change material is encased. The void within the capsule or shell is of sufficient size to accommodate any change in the volume of the phase change material when it changes from solid to liquid.

[0010] In accordance with another embodiment of the invention, a particle of the phase change material is suspended in an air stream and exposed to a solution of a mixture comprising a binder and metal particles. Upon drying, a coating, comprising one or more layers, of the mixture is formed around the particle of the phase change material. The encapsulated phase change material is then heated to a temperature sufficiently high to both vaporize or thermally decompose the binder and sinter the metal particles. As such, the sintered metal particles form the capsule or shell encasing the phase change material therewithin. In an embodiment of the invention, the binder is an organic.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a schematic of a thermal energy storage system in accordance with an embodiment of the invention;

[0012] FIG. 2 is a schematic of a thermal energy storage system in accordance with another embodiment of the invention;

[0013] FIG. 3A illustrates a process for encapsulating a phase change material in accordance with an embodiment of the invention;

[0014] FIG. 3B is a flowchart for the process shown in FIG. 3A;

[0015] FIG. 4A illustrates a process for encapsulating a phase change material in accordance with another embodiment of the invention; and

[0016] FIG. 4B is a flowchart for the process shown in FIG. 4A.

DETAILED DESCRIPTION

[0017] While multiple embodiments of the instant invention are disclosed, alternate embodiments may become appar-

ent to those skilled in the art. The following detailed description describes only illustrative embodiments of the invention with reference to the accompanying drawings wherein like elements are designated by like numerals. It should be clearly understood that there is no intent, implied or otherwise, to limit the invention in any form or manner to that described herein. As such, all alternatives are considered as falling within the spirit, scope and intent of the instant invention.

[0018] FIG. 1 is a schematic of thermal energy storage system 100 in accordance with an embodiment of the invention. Thermal energy storage system 100 comprise storage tank 102 containing a plurality of capsules 104 submerged in heat transfer fluid 106. Each one of the plurality of capsules 104 contains a phase change material encapsulated there-within as described in detail herein below. Thermal energy is added to (or stored in) tank 102 by extracting a portion of heat transfer fluid 106 from tank 102, adding thermal energy to the extracted heat transfer fluid 106, and thereafter returning the heated heat transfer fluid 106 back to tank 102. As illustrated, heat transfer fluid 106 is extracted from tank 102 along flow path 108, heated in first heat exchanger 110, and thereafter returned to tank 102 along flow path 112. Heat transfer fluid 106 flowing through first heat exchanger 110 is heated by thermal energy 114 from an external source. In an embodiment of the invention, thermal energy 114 is supplied by a solar tower, a solar receiver, etc. Thermal energy is extracted (or removed) from tank 102 by extracting a portion of heat transfer fluid 106 from tank 102, removing the thermal energy from the extracted heat transfer fluid 106, and thereafter returning the cooled heat transfer fluid 106 back to tank 102. As illustrated, heat transfer fluid 106 is extracted from tank 102 along flow path 116, cooled in second heat exchanger 118, and thereafter returned to tank 102 along flow path 120. Heat transfer fluid 106 flowing through second heat exchanger 118 transfers thermal energy 122 to an external source. In an embodiment of the invention, thermal energy 122 is supplied to a steam generator for the purposes of operating one or more steam turbines in an electrical power plant.

[0019] Within tank 102, thermal energy is stored in the form of sensible and latent heat. In accordance with an embodiment of the invention, thermal energy within tank 102 is stored in a phase change material encapsulated in each one of the plurality of capsules 104. The heated heat transfer fluid 106 entering tank 102 along flow path 112 transfers at least a portion of its thermal energy to one or more of the plurality of capsules 104. The thermal energy transferred to capsules 104 heats the phase change material contained therewithin, and causes the phase change material to change from a solid to liquid. As such, the thermal energy is stored in the form of latent heat (also called the latent heat of fusion). Heating the phase change material while in the solid and/or the liquid phase causes thermal energy to be stored therewithin in the form of sensible heat. Thermal energy stored within the phase change material is extracted by cooling the one or more of the plurality of capsules 104. Cooling capsules 104 causes a transfer of at least a portion of thermal energy from the phase change material contained therewithin to the cooled heat transfer fluid 106 entering tank 102 along flow path 120. This extraction of thermal energy from the phase change material causes the phase change material to change from a liquid to solid. As such, the thermal energy is extracted in the form of latent heat (also called the latent heat of fusion). Cooling the

phase change material while in the solid and/or the liquid phase causes thermal energy to be extracted from therewithin in the form of sensible heat.

[0020] In an embodiment of the invention, heat transfer fluid 106 within tank 102 is of sufficient quantity to at least fully submerge the plurality of capsules 104. Accordingly, substantially all the voids between adjacent capsules 104 are substantially filled with heat transfer fluid 106.

[0021] As also shown in FIG. 1, thermal energy storage system 100 further comprises control module 124. Control module 124, via communications link 126, controls the operation and optimization of thermal energy storage system 100 and components thereof such as, and not limited to, pumps, valves, sensors, etc. In accordance with an embodiment of the invention, control module 124 optimizes the heating of heat transfer fluid 106 in first heat exchanger 110. In accordance with another embodiment of the invention, control module 124 optimizes the cooling of heat transfer fluid 106 in second heat exchanger 118. Embodiments for optimizing the heating and cooling of heat transfer fluid 106 include, and are not limited to, varying the flow rates of heat transfer fluid 106 through first and second heat exchangers 110 and 118, respectively, changing the locations along a height of tank 102 from whereat heat transfer fluid 106 is extracted from tank 102, etc. Control module 124, in alternate embodiments of the invention, further optimizes a thermocline within heat transfer fluid 106 in tank 102. Embodiments for optimizing the thermocline include, and are not limited to, changing the locations along a height of tank 102 from whereat heat transfer fluid 106 is extracted from tank 102, changing the locations along a height of tank 102 whereat heat transfer fluid 106 is returned to tank 102, varying the flow rates of heat transfer fluid 106 through first and second heat exchangers 110 and 118, respectively, etc. All variations and alternative means for optimizing the heating and cooling of heat transfer fluid 106 and/or for optimizing the thermocline within heat transfer fluid 106 in tank 102 are considered as being within the spirit, scope and intent of the present invention.

[0022] FIG. 2 is a schematic of thermal energy storage system 200 in accordance with another embodiment of the invention. As will be apparent to one skilled in the art, thermal energy storage systems 100 and 200 are similar in several aspects. Accordingly, like elements are depicted with like numerals, and only the differences between thermal energy storage systems 100 and 200 are described herein below with reference to FIG. 2.

[0023] Thermal energy storage system 200 comprise storage tank 202 containing a plurality of capsules 104 submerged in heat transfer fluid 106. Thermal energy is extracted (or removed) from tank 202 by extracting portions of heat transfer fluid 106 from a plurality of locations along a height of tank 202, removing the thermal energy from the extracted heat transfer fluid 106, and thereafter returning the cooled heat transfer fluid 106 back to tank 202. As illustrated, third and fourth heat exchanger 204 and 206, respectively, cool heat transfer fluid 106 extracted from tank 202. A first stream of heat transfer fluid 106 is extracted from tank 202 along flow path 208 and cooled in third heat exchanger 204. The cooled first stream of heat transfer fluid 106 exiting third heat exchanger 204 is mixed with a second stream of heat transfer fluid 106 extracted from tank 202 and the stream of mixed heat transfer fluid is cooled in fourth heat exchanger 206. The cooled stream of mixed fluid exiting fourth heat exchanger

206 is thereafter returned to tank **202** along flow path **216**. The first stream of heat transfer fluid **106** flowing through third heat exchanger **204** transfers thermal energy **218** to an external source, and the stream of mixed fluid flowing through fourth heat exchanger **206** transfers thermal energy **220** to the same and/or to a different external source. In an embodiment of the invention, thermal energy **220** is supplied to a steam generator and thermal energy **218** is supplied to a superheater for superheating the steam generated in the steam generator. The superheated steam, in an embodiment of the invention, operates one or more steam turbines in an electrical power plant.

[0024] Within tank **202**, the process of storing and extracting thermal energy is substantially the same as that described herein above with reference to FIG. 1.

[0025] As also shown in FIG. 2, thermal energy storage system **200** further comprises control module **222**. Control module **222**, via communications link **224**, controls the operation and optimization of thermal energy storage system **200** and components thereof such as, and not limited to, pumps, valves, sensors, etc. In several aspects, embodiments of control module **222** are similar, substantially similar, and/or the same as the embodiments of control module **124** as described herein above with reference to FIG. 1.

[0026] In an embodiment of the invention, the plurality of capsules **104** within some sections (or portions) of tanks **102** and **202** contain phase change materials having different phase change temperatures. For example, a section near a top of tanks **102** and **202** includes a layer of the plurality of capsules **104** that encapsulate a phase change material with a phase change temperature greater than a phase change temperature of a phase change material encapsulated in the plurality of capsules **104** in a layer near a bottom section of tanks **102** and **202**. In other words, the encapsulated phase change material in a section near the top of tanks **102** and **202** is different from the encapsulated phase change material in a section near the bottom of tanks **102** and **202**. In alternate embodiments of the invention, tanks **102** and **202** comprise several different types of encapsulated phase change material between the top and the bottom of tanks **102** and **202**, wherein the encapsulated phase change material have different phase change temperatures.

[0027] In accordance with an embodiment of the invention, control module **222** optimizes the cooling of heat transfer fluid **106** in third and fourth heat exchangers **204** and **206**, respectively. Embodiments for optimizing the heating and cooling of heat transfer fluid **106** include, and are not limited to, varying the flow rates of heat transfer fluid **106** through first, third and fourth heat exchangers **110**, **204** and **206**, respectively, changing the locations along a height of tank **202** from whereat heat transfer fluid **106** is extracted from tank **202**, etc. Control module **222**, in alternate embodiments of the invention, further optimizes a thermocline within heat transfer fluid **106** in tank **202**. Embodiments for optimizing the thermocline include, and are not limited to, changing the locations along a height of tank **202** from whereat the first and second streams of heat transfer fluid **106** are extracted from tank **202**, changing the locations along a height of tank **202** whereat heat transfer fluid **106** is returned to tank **202**, varying the flow rates of heat transfer fluid **106** through first, third and fourth heat exchangers **110**, **204** and **206**, respectively, varying the flow rate of the second stream of heat transfer fluid **106**, etc. All variations and alternative means for optimizing the heating and cooling of heat transfer fluid **106** and/or for

optimizing the thermocline within heat transfer fluid **106** in tank **202** are considered as being within the spirit, scope and intent of the present invention.

[0028] In accordance with an embodiment of the invention, each one of the plurality of capsules **104** comprises an outer shell with a hollow interior, wherein the hollow interior is at least partially filled with a phase change material. Accordingly, the hollow interior of the outer shell also includes a void of sufficient size to accommodate any change in the volume of the phase change material as it changes between the solid and the liquid phases. The methods, in accordance with the embodiments of the invention, for creating capsules **104** are described in detail herein below with reference to FIGS. 3A-4B.

[0029] FIG. 3A is a schematic representation of process **300** for encapsulating particle **302** of the phase change material within capsule **304** in accordance with an embodiment of the invention. Capsule **304** is one of the plurality of capsules **104**. Process **300** is described in further detail herein below with reference to FIG. 3B.

[0030] As illustrated in FIG. 3A, an entire surface of particle **302** of the phase change material is first coated with at least one layer of first material **306**. Next, an entire surface of the layer(s) of first material **306** is coated with at least one layer of second material **308**. Particle **302** coated with first and second material **306** and **308**, respectively, is then placed in environment **310** wherein it is heated to a temperature greater than a decomposition temperature of first material **306**. Accordingly, first material **306** decomposes and vaporizes. The decomposed and vaporized first material **306** outgases through the surrounding layer(s) of second material **308**. Decomposition and vaporization of first material **306** results in void **312** within the outer shell formed by second material **308**. As can be seen, particle **302** of the phase change material is encased within the outer shell formed by second material **308**. Next, the outer shell of second material **308** containing therewithin particle **302** of the phase change material and void **312** is placed in environment **314** wherein an entire surface of the outer shell of second material **308** is coated with at least one layer of third material **316**, thereby yielding capsule **304**. Capsule **304** is one of the plurality of capsules **104** submerged within heat transfer fluid **106** in tanks **102** and **202** of thermal energy storage systems **100** and **200**.

[0031] FIG. 3B is a flowchart of process **300** for encapsulating particle **302** of the phase change material in capsule **304**. In accordance with an embodiment of the invention, process **300** starts at block **320**. At block **322**, particle **302** of the phase change material is suspending in an air stream or on an air bed. A solution of first material **306** is atomized at block **324** and particle **302** of the phase change material suspended at block **322** is exposed to the atomized solution of first material **306**. At block **326**, an entire surface of particle **302** of the phase change material is coated with at least one layer of first material **306** which is then dried at block **328**. At block **330**, a determination is made whether or not additional layer(s) of first material **306** should be applied. If additional layer(s) of first material **306** are required (or desired), process **300** proceeds along path **332** and repeats with block **326**. If additional layer(s) of first material **306** are not required (or desired), process **300** proceeds along path **334** to block **336**, whereat at least one layer of second material **308** is applied to an entire surface of particle **302** of the phase change material coated with one or more layers of first material **306**. At block **338**, a

determination is made whether or not additional layer(s) of second material **308** should be applied. If additional layer(s) of second material **308** are required (or desired), process **300** proceeds along path **340** and repeats with block **336**. If additional layer(s) of second material **308** are not required (or desired), process **300** proceeds along path **342** to block **344**. At block **344**, particle **302** of the phase change material coated with layers of first and second material **306** and **308**, respectively, is heated to a temperature greater than the decomposition temperature of first material **306**, as shown at block **346**, for decomposing first material **306**. Decomposition and vaporization of first material **306** at blocks **346** and **348**, respectively, creates a void within the layer(s) of second material **308** applied at block **336**. The vapors of first material **306** produced by the decomposition and vaporization steps at blocks **346** and **348**, respectively, escape through a surface of the outer shell comprising second material **308**. In an embodiment of the invention, second material **308** is of sufficient porosity so as to not hinder the vapors of first material **306** from outgassing through the one or more layers of second material **308** forming the outer shell. Next, at block **350**, an entire outer surface of the shell formed by the one or more layers of second material **308** is coated with at least one layer of third material **316** so as to render capsule **304** impervious to both heat transfer fluid **106** within which it will be submerged and the phase change material encased therewithin. Each one of the so formed capsule **304**, which is one of the plurality of capsules **104**, comprises second material **308** as its outer shell and, as such, encases (or encapsulates) particle **302** of the phase change material. Process **300** thereafter repeats with block **322** or stops at block **352**.

[0032] In accordance with an embodiment of the invention, third material **316** substantially fills a substantial number of defects in the outer shell comprising second material **308**. Such defects include cracks, crevices, holes, voids, etc. in the outer shell. Accordingly, third material **316** renders capsule **304** impervious to both heat transfer fluid **106** within which it is submerged and the phase change material encapsulated therewithin. In an alternate embodiment of the invention second and third material **308** and **316** are the same material.

[0033] FIG. 4A is a schematic representation of process **400** for encapsulating particle **302** of the phase change material within capsule **404** in accordance with an embodiment of the invention. Capsule **404**, like capsule **304**, is one of the plurality of capsules **104**. Process **400** is described in further detail herein below with reference to FIG. 4B.

[0034] As illustrated in FIG. 4A, an entire surface of particle **302** of the phase change material is first coated with at least one layer of mixture **406** comprising metal particles and a binder. Next, particle **302** coated with mixture **406** is then placed in environment **408** wherein it is heated to a temperature greater than a decomposition temperature of the binder within mixture **406**. The binder within mixture **406** is thus decomposed and vaporized and the metal particles within mixture **406** are sintered. The sintered metal particles form shell **410** around particle **302** of the phase change material. Next, shell **410** containing therewithin particle **302** of the phase change material is placed in environment **412** wherein an entire surface of shell **410** is coated with at least one layer of material **414**, thereby yielding capsule **404**. In accordance with an embodiment of the invention, material **414** substantially fills a substantial number of defects in shell **410**. Such defects include cracks, crevices, holes, voids, etc. in shell **410**. Capsule **404**, like capsule **304**, is one of the plurality of

capsules **104** submerged within heat transfer fluid **106** in tanks **102** and **202** of thermal energy storage systems **100** and **200**.

[0035] FIG. 4B is a flowchart of process **400** for encapsulating particle **302** of the phase change material in capsule **404**. In accordance with an embodiment of the invention, process **400** starts at block **420**. At block **422**, particle **302** of the phase change material is coated with mixture **406** comprising metal particles and a binder. Mixture **406** coated on particle **302** of the phase change material is then dried at block **424**. Next, at block **426**, a determination is made whether or not additional layer(s) of mixture **406** should be applied. If additional layer(s) of mixture **406** are required (or desired), process **400** proceeds along path **428** and repeats with block **422**. If additional layer(s) of mixture **406** are not required (or desired), process **400** proceeds along path **430** to block **432**. At block **432**, particle **302** of the phase change material coated with layer(s) of mixture **406** is heated for the purpose of both decomposing the binder within mixture **406** and sintering the metal particles within mixture **406**. The binder within mixture **406** is decomposed and vaporized at blocks **434** and **436**, respectively. Furthermore, at block **438**, the metal particles within mixture **406** are sintered into forming shell **410** encasing (or encapsulating) particle **302** of the phase change material. Next, at block **440**, an entire outer surface of shell **410** formed by the sintered metal particles is coated with at least one layer of material **414** so as to render capsule **404** impervious to both heat transfer fluid **106** within which it will be submerged and the phase change material encased therewithin. Each one of the so formed capsule **404**, which is one of the plurality of capsules **104**, comprises particle **302** of the phase change material encapsulated within a shell of sintered metal particles.

[0036] In accordance with an embodiment of the invention, material **414** substantially fills a substantial number of defects in shell **410**. Such defects include cracks, crevices, holes, voids, etc. in the outer shell. Accordingly, material **414** renders capsule **404** impervious to both heat transfer fluid **106** within which it is submerged and the phase change material encapsulated therewithin.

[0037] In an embodiment of the invention, shell **410** is of sufficient elasticity to accommodate any change in the volume of the phase change material as it changes between the solid and the liquid phases. In another embodiment of the invention the encapsulated phase change material comprises a material having a phase change temperature less than a phase change temperature of the metal forming shell **410**.

[0038] In an embodiment of the invention capsule **304** encapsulates a phase change material having a phase change temperature less than a phase change temperature of second and third material **308** and **316**, respectively. In another embodiment of the invention capsule **404** encapsulates a phase change material having a phase change temperature less than a phase change temperature of shell **410** and material **414**.

[0039] The phase change material encapsulated in capsules **304** and **404** are selected from the group consisting of sodium nitrate, potassium nitrate, mixture of sodium nitrate and potassium nitrate, inorganic salts and mixtures of salts. In accordance with an embodiment of the invention, the phase change material is selected such that the phase change temperature is approximately the same as the desired temperature for storing thermal energy as latent heat. In some applications, such as a solar tower power generating system, the

encapsulated phase change material comprise a mixture of sodium nitrate and potassium nitrate having a phase change temperature approximately between 310° C. and 330° C.

[0040] As will be apparent to one skilled in the art, first material **306** is selected such that it will decompose and vaporize at a temperature less than the phase change temperatures of both the phase change material and second material **308**. As such, first material **306** is essentially a “sacrificial” material aiding in the formation of void **312**. In accordance with an embodiment of the invention, first material **306** is an organic polymer selected from the group consisting of hydroxy-propyl methyl cellulose, carboxy-methyl cellulose, ethyl cellulose, polyethylene and poly vinyl chloride.

[0041] As will be apparent to one skilled in the art, embodiments of capsules **304** and **404** comprise an outer shell having a phase change temperature greater than the phase change temperature of the encapsulated phase change material. Accordingly, second material **308** for the outer shell of capsule **304** and the material for shell **410** are selected from the group consisting of sodium chloride, bonded metal particles, sintered metal particles, clay and mixtures of clay and metal. In an embodiment of the invention, third material **316** is the same as second material **308**.

[0042] In accordance with an embodiment of the invention, the plurality of capsules **104** in tank **102** and/or **202** comprise a mixture of capsules **304** and **404**.

[0043] Although not described in detail herein, alternate methods for manufacturing capsules **304** and **404** will be apparent to one skilled in the art. All such alternatives and variations are considered as within the spirit, scope and intent of the instant invention.

[0044] For example, a method in accordance with an alternate embodiment of the invention comprises first creating a particle comprising a mixture of the phase change material and a sacrificial material such as first material **306**. This particle of the mixture is then coated with one or more layers of second material **308** or one or more layers of mixture **406** comprising metal particles and a binder. Next, the coated mixture of the phase change material and the sacrificial material is heated to a temperature greater than the decomposition temperature of the sacrificial material and/or the binder. Such heating will decompose and vaporize the sacrificial material and/or the binder. The vaporized sacrificial material will out-gas through the surrounding layer(s) of second material **308** and thereby create an outer shell of second material **308** encasing or encapsulating therewithin the phase change material and the void. If mixture **406** is used, the particle of the mixture comprising the phase change material and the sacrificial material is heated to a temperature sufficiently high to sinter the metal particles within mixture **406**. The sintered metal particles form a shell, such as shell **410**, encapsulating the phase change material therewithin. As will be appreciated, the amount of sacrificial material used will be such that the void created by the decomposition and vaporization of the sacrificial material will be of sufficient size to accommodate any change in the volume of the phase change material as it changes between the solid and the liquid phases. The outer shell comprising second material **308** or shell **410** is then coated or sealed with one or more layers of third material **316** or material **414** so as to render capsules **304** and **404** impervious to both heat transfer fluid **106** within which they will be submerged and the encapsulated phase change material.

[0045] As another example, a method in accordance with another embodiment of the invention comprises a rotating

disc atomization process for coating particle **302** of the phase change material with a sacrificial material, such as first material **306**. According to one such process, a slurry is first formed by suspending a plurality of particle **302** of the phase change material in a solution of the sacrificial material. The slurry is then poured onto a disc rotating at high speeds. Accordingly, centrifugal forces strip or pull off the excess liquid and the plurality of particle **302** of the phase change material, now coated with a thin liquid layer of the sacrificial material, roll off the rotating disc. The sacrificial material, upon drying, creates a coating encasing particle **302** of the phase change material. Thereafter, particle **302** coated with the sacrificial material is processed in accordance with the one or more embodiments of the methods described herein above.

[0046] In accordance with an embodiment of the invention, capsules **304** and **404** comprise a heat transfer surface area in the approximate range of 1,200 square meter per cubic meter of capsule volume to 3,000 square meter per cubic meter of capsule volume. In an embodiment of the invention, capsules **304** and **404** comprise a shape that is substantially similar to any one or more geometric shapes. In another embodiment of the invention, capsules **304** and **404** have a generally spherical shape with an outer diameter in the approximate range of 2 mm to 15 mm.

[0047] Various modifications and additions may be made to the exemplary embodiments described hereinabove without departing from the scope, intent and spirit of the instant invention. For example, while the disclosed embodiments refer to particular features, the scope of the instant invention is considered to also include embodiments having various combinations of features different from and/or in addition to those described hereinabove. Accordingly, the present invention embraces all such alternatives, modifications, and variations as within the scope, intent and spirit of the appended claims, including all equivalents thereof.

We claim:

1. An apparatus for storing and retrieving thermal energy, said apparatus comprising:

a tank containing

a heat transfer fluid; and

a plurality of capsules submerged in said heat transfer fluid, wherein each one of said plurality of capsules encapsulates a phase change material;

a first heat exchanger in fluid communication with said tank, said first heat exchanger configured for heating said heat transfer fluid; and

a second heat exchanger in fluid communication with said tank, said second heat exchanger configured for cooling said heat transfer fluid.

2. The apparatus of claim 1, wherein

at least a portion of thermal energy in said heat transfer fluid contained in said tank is transferred to one or more of said plurality of capsules; and

at least a portion of said encapsulated phase change material in said one or more of said plurality of capsules changes from solid to liquid.

3. The apparatus of claim 1, wherein

at least a portion of said encapsulated phase change material in one or more of said plurality of capsules changes from liquid to solid and releases thermal energy; and

at least a portion of said thermal energy released by said encapsulated phase change material is transferred from

said one or more of said plurality of capsules to said heat transfer fluid contained in said tank.

4. The apparatus of claim 1, wherein said heat transfer fluid contained in said tank is of sufficient quantity to substantially fill a substantial number of voids between said plurality of capsules.

5. The apparatus of claim 1, wherein each one of said plurality of capsules comprises an outer shell with a hollow interior, wherein said hollow is at least partially filled with said phase change material.

6. The apparatus of claim 5, wherein said outer shell is impervious to said heat transfer fluid and said phase change material.

7. The apparatus of claim 5, wherein a phase change temperature of said phase change material is less than a phase change temperature of said outer shell.

8. The apparatus of claim 5, wherein said hollow includes a void of sufficient size to accommodate a change in a volume of said phase change material when said phase change material changes from solid to liquid.

9. The apparatus of claim 5, wherein said outer shell is formed with a material selected from the group consisting of sodium chloride, bonded metal particles, sintered metal particles, clay, and mixture of clay and metal.

10. The apparatus of claim 5, wherein each one of said plurality of capsules further comprises a coating encasing said outer shell, wherein said coating substantially fills a substantial number of defects in said outer shell, said defects including cracks, crevices, holes and voids.

11. The apparatus of claim 10, wherein said coating renders said outer shell impervious to said heat transfer fluid and said phase change material.

12. The apparatus of claim 1, wherein said phase change material is selected from the group consisting of sodium nitrate, potassium nitrate, mixture of sodium nitrate and potassium nitrate, inorganic salts and mixtures of salts.

13. The apparatus of claim 1, wherein said plurality of capsules are shaped substantially like a sphere having a diameter in the range of 2 mm to 15 mm.

14. The apparatus of claim 1, wherein said heat transfer fluid heated in said first heat exchanger is

extracted from said tank at a first location proximate a bottom of said tank; and

returned to said tank at a first location proximate a top of said tank.

15. The apparatus of claim 14, wherein said first heat exchanger is a solar receiver.

16. The apparatus of claim 14, further comprising a control module configured for optimizing heating of said heat transfer fluid in said first heat exchanger.

17. The apparatus of claim 16, wherein said control module optimizes said heating by changing one or more of

said first location from whereat said heat transfer fluid is extracted from said tank; and

a flow rate of said heat transfer fluid through said first heat exchanger.

18. The apparatus of claim 17, wherein said heat transfer fluid is returned to said tank at a location along a height of said tank whereat a temperature of said fluid within said tank is approximately equal to a temperature of said heat transfer fluid exiting said first heat exchanger.

19. The apparatus of claim 16, wherein said control module is further configured for optimizing a thermocline within said heat transfer fluid within said tank.

20. The apparatus of claim 1, wherein said second heat exchanger comprises

a third heat exchanger configured for generating superheated steam; and

a fourth heat exchanger configured for generating steam.

21. The apparatus of claim 20, further comprising a control module configured for optimizing

generation of said superheated steam in said third heat exchanger; and

generation of said steam in said fourth heat exchanger.

22. The apparatus of claim 21, wherein said control module is further configured for optimizing a thermocline within said heat transfer fluid within said tank.

23. The apparatus of claim 21, wherein

a first stream of said heat transfer fluid is

extracted from said tank at a second location proximate said top of said tank; and

cooled in said third heat exchanger;

a second stream of said heat transfer fluid is

extracted from said tank at a first location between said top and said bottom of said tank; and

mixed with said cooled first stream exiting said third heat exchanger to form a stream of mixed fluid; and

said stream of mixed fluid is

cooled in said fourth heat exchanger; and

returned to said tank at a second location proximate said bottom of said tank.

24. The apparatus of claim 23, wherein said control module optimizes said generation of said superheated steam by changing one or more of

said second location from whereat said heat transfer fluid is extracted from said tank; and

a flow rate of said first stream of said heat transfer fluid through said third heat exchanger.

25. The apparatus of claim 23, wherein said control module optimizes said generation of said steam by changing one or more of

said first location between said top and said bottom of said tank from whereat said second stream of heat transfer fluid is extracted from said tank;

a flow rate of said second stream of heat transfer fluid; and

a flow rate of said stream of mixed fluid through said fourth heat exchanger.

26. The apparatus of claim 23, wherein said control module is further configured for extracting said second stream of said heat transfer fluid from a location along a height of said tank whereat a temperature of said heat transfer fluid within said tank is approximately equal to a temperature of said first stream of said heat transfer fluid exiting said third heat exchanger.

27. The apparatus of claim 23, wherein said control module is further configured for returning said stream of mixed fluid to said tank at a location along a height of said tank whereat a temperature of said heat transfer fluid within said tank is approximately equal to a temperature of said stream of mixed fluid exiting said fourth heat exchanger.

28. The apparatus of claim 1, further comprising a control module configured for optimizing a thermocline within said heat transfer fluid within said tank.

29. The apparatus of claim 28, wherein

heat transfer fluid exiting said first heat exchanger is returned to said tank at a location along a height of said tank whereat a temperature of said heat transfer fluid

within said tank is approximately equal to a temperature of said heat transfer fluid exiting said first heat exchanger; and

heat transfer fluid exiting said second heat exchanger is returned to said tank at a location along a height of said tank whereat a temperature of said heat transfer fluid within said tank is approximately equal to a temperature of said heat transfer fluid exiting said second heat exchanger.

30. The apparatus of claim **28**, wherein said control module is further configured for

heating said heat transfer fluid in said first heat exchanger; and

cooling said heat transfer fluid in said second heat exchanger.

31. The apparatus of claim **1**, wherein said heat transfer fluid cooled in said second heat exchanger is

extracted from said tank at a first location proximate a top of said tank; and

returned to said tank at a first location proximate a bottom of said tank.

32. The apparatus of claim **31**, further comprising a control module configured for optimizing cooling of said heat transfer fluid in said second heat exchanger.

33. The apparatus of claim **32**, wherein said control module optimizes said cooling by changing one or more of

said first location from whereat said heat transfer fluid is extracted from said tank; and

a flow rate of said heat transfer fluid through said second heat exchanger.

34. The apparatus of claim **33**, wherein said heat transfer fluid is returned to said tank at a location along a height of said tank whereat a temperature of said fluid within said tank is approximately equal to a temperature of said heat transfer fluid exiting said second heat exchanger.

35. The apparatus of claim **32**, wherein said control module is further configured for optimizing a thermocline within said heat transfer fluid within said tank.

36. The apparatus of claim **1**, wherein a phase change temperature of said phase change material encapsulated in said plurality of capsules in a top portion of said tank is greater than a phase change temperature of said phase change material encapsulated in said plurality of capsules in a bottom portion of said tank.

37. A method of encapsulating a phase change material in a capsule, said method comprising suspending a particle of said phase change material in an air stream;

coating an entire surface of said suspended particle with at least one layer of a first material, said step of coating comprising

atomizing a solution of said first material;

depositing said atomized first material onto said surface of said suspended particle; and

drying said first material deposited on said suspended particle;

coating an entire surface of said layer of said first material with at least one layer of a second material; and

encapsulating said phase change material within a shell formed by said second material, said step of encapsulating comprising

heating said particle coated with said first material and said second material;

decomposing said first material; and

vaporizing said first material.

38. The method of claim **37**, wherein said capsule is shaped substantially like a sphere having a diameter in the range of 2 mm to 15 mm.

39. The method of claim **37**, wherein said step of encapsulating renders said second material impervious.

40. The method of claim **37**, further comprising rendering said second material impervious by coating an entire surface of said layer of said second material with one or more layers of a third material after said step of encapsulation.

41. The method of claim **40**, wherein said second material and said third material are same.

42. The method of claim **37**, further comprising substantially filling a substantial number of defects in said layer of said second material by applying one or more layers of a third material after the step of encapsulating, wherein said defects include cracks, crevices, holes and voids.

43. The method of claim **42**, wherein said second material and said third material are same.

44. The method of claim **37**, wherein said phase change material is selected from the group consisting of sodium nitrate, potassium nitrate, mixture of sodium nitrate and potassium nitrate, and inorganic salts.

45. The method of claim **37**, wherein said first material is a sacrificial compound having a decomposition temperature generally less than a phase change temperature of said phase change material and a phase change temperature of said second material, and wherein the step of encapsulating generally comprises thermally decomposing said first material.

46. The method of claim **45**, wherein said sacrificial compound is selected from the group consisting of an organic polymer, hydroxy-propyl methyl cellulose, carboxy-methyl cellulose, ethyl cellulose, polyethelene and poly vinyl chloride.

47. The method of claim **37**, wherein said second material is selected from the group consisting of sodium chloride, bonded metal particles, sintered metal particles, clay, and mixture of clay and metal.

48. The method of claim **37**, further comprising applying one or more additional layers of said first material before coating with said second material.

49. The method of claim **48**, further comprising rendering said second material impervious by coating an entire surface of said layer of said second material with one or more layers of a third material after said step of encapsulation.

50. The method of claim **48**, further comprising substantially filling a substantial number of defects in said layer of said second material by applying one or more layers of a third material after the step of encapsulating, wherein said defects include cracks, crevices, holes and voids.

51. The method of claim **48**, further comprising applying one or more additional layers of said second material before the step of encapsulating.

52. The method of claim **51**, wherein said step of encapsulating renders said second material impervious.

53. The method of claim **51**, further comprising rendering said second material impervious by coating an entire surface of said layer of said second material with one or more layers of a third material after said step of encapsulation.

54. The method of claim **51**, further comprising substantially filling a substantial number of defects in said layer of said second material by applying one or more layers of a third material after the step of encapsulating, wherein said defects include cracks, crevices, holes and voids.

55. The method of claim **37**, further comprising applying one or more additional layers of said second material before the step of encapsulating.

56. The method of claim **55**, wherein said step of encapsulating renders said second material impervious.

57. The method of claim **55**, further comprising rendering said second material impervious by coating an entire surface of said layer of said second material with one or more layers of a third material after said step of encapsulation.

58. The method of claim **55**, further comprising substantially filling a substantial number of defects in said layer of said second material by applying one or more layers of a third material after the step of encapsulating, wherein said defects include cracks, crevices, holes and voids.

59. The method of claim **37**, further comprising submerging a plurality of capsules in a heat transfer fluid, wherein each one of said plurality of capsules encapsulates said phase change material;

transferring at least a portion of thermal energy in said heat transfer fluid to one or more of said plurality of capsules; and

subjecting at least a portion of said phase change material encapsulated in said one or more of said plurality of capsules to change from solid to liquid.

60. The method of claim **59**, further comprising transferring thermal energy to said heat transfer fluid from a means other than said phase change material.

61. The method of claim **59**, further comprising submerging a plurality of capsules in a heat transfer fluid, wherein each one of said plurality of capsules encapsulates said phase change material;

subjecting at least a portion of said phase change material encapsulated in one or more of said plurality of capsules to change from liquid to solid and release thermal energy; and

transferring at least a portion of said thermal energy release by said phase change material from one or more of said plurality of capsules to said heat transfer fluid.

62. The method of claim **61**, further comprising transferring thermal energy to said heat transfer fluid from a first means other than said phase change material; and transferring thermal energy from said heat transfer fluid to a second means other than said phase change material.

63. The method of claim **37**, further comprising submerging a plurality of capsules in a heat transfer fluid, wherein each one of said plurality of capsules encapsulates said phase change material;

subjecting at least a portion of said phase change material encapsulated in one or more of said plurality of capsules to change from liquid to solid and release thermal energy; and

transferring at least a portion of said thermal energy release by said phase change material from one or more of said plurality of capsules to said heat transfer fluid.

64. The method of claim **63**, further comprising transferring thermal energy from said heat transfer fluid to a means other than said phase change material.

65. A method of encapsulating a phase change material in a capsule, said method comprising
suspending a particle of said phase change material in an air stream;
coating an entire surface of said suspended particle with at least one layer of a mixture of

a binder and metal particles, said step of coating comprising

depositing said mixture onto said surface of said suspended particle; and

drying said mixture deposited on said suspended particle;

encapsulating said phase change material within said capsule, said step of encapsulating comprising
heating said particle coated with said mixture;
vaporizing said binder; and
sintering said metal particles to form a shell encapsulating said phase change material.

66. The method of claim **65**, wherein said shell is shaped substantially like a sphere having a diameter in the range of 2 mm to 15 mm.

67. The method of claim **65**, wherein said step of encapsulating renders said shell impervious.

68. The method of claim **65**, further comprising rendering said shell impervious by coating an entire surface of said shell with a sealant after said step of encapsulating.

69. The method of claim **65**, further comprising substantially filling a substantial number of defects in said shell by applying one or more layers of a sealant after the step of encapsulating, wherein said defects include cracks, crevices, holes and voids.

70. The method of claim **65**, wherein said phase change material is selected from the group consisting of sodium nitrate, potassium nitrate, mixture of sodium nitrate and potassium nitrate, and inorganic salts.

71. The method of claim **65**, wherein said binder is a sacrificial compound having a decomposition temperature generally less than a phase change temperature of said phase change material, and wherein the step of encapsulating generally comprises thermally decomposing said binder.

72. The method of claim **71**, wherein said sacrificial compound is selected from the group consisting of an organic polymer, clay, and mixture of clay and metal.

73. The method of claim **65**, further comprising applying one or more additional layers of said mixture before said step of encapsulating.

74. The method of claim **65**, further comprising sequentially repeating said steps of coating and encapsulating in an alternating manner until a pre-determined number of shells have been formed, wherein encapsulating is a final step.

75. The method of claim **74**, further comprising applying a sealant after encapsulating and before coating.

76. The method of claim **74**, comprising rendering said capsule impervious by coating an entire surface of said capsule with a sealant after said final step of encapsulating.

77. The method of claim **74**, further comprising substantially filling a substantial number of defects in said shell by applying one or more layers of a sealant after the step of encapsulating, wherein said defects include cracks, crevices, holes and voids.

78. The method of claim **65**, further comprising submerging a plurality of capsules in a heat transfer fluid, wherein each one of said plurality of capsules encapsulates said phase change material;

transferring at least a portion of thermal energy in said heat transfer fluid to one or more of said plurality of capsules; and

subjecting at least a portion of said phase change material encapsulated in said one or more of said plurality of capsules to change from solid to liquid.

79. The method of claim **78**, further comprising transferring thermal energy to said heat transfer fluid from a means other than said phase change material.

80. The method of claim **78**, further comprising submerging a plurality of capsules in a heat transfer fluid, wherein each one of said plurality of capsules encapsulates said phase change material;

subjecting at least a portion of said phase change material encapsulated in one or more of said plurality of capsules to change from liquid to solid and release thermal energy; and

transferring at least a portion of said thermal energy release by said phase change material from one or more of said plurality of capsules to said heat transfer fluid.

81. The method of claim **80**, further comprising transferring thermal energy to said heat transfer fluid from a first means other than said phase change material; and

transferring thermal energy from said heat transfer fluid to a second means other than said phase change material.

82. The method of claim **65**, further comprising submerging a plurality of capsules in a heat transfer fluid, wherein each one of said plurality of capsules encapsulates said phase change material;

subjecting at least a portion of said phase change material encapsulated in one or more of said plurality of capsules to change from liquid to solid and release thermal energy; and

transferring at least a portion of said thermal energy release by said phase change material from one or more of said plurality of capsules to said heat transfer fluid.

83. The method of claim **82**, further comprising transferring thermal energy from said heat transfer fluid to a means other than said phase change material.

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