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(54) **THERMAL STORAGE SYSTEM**

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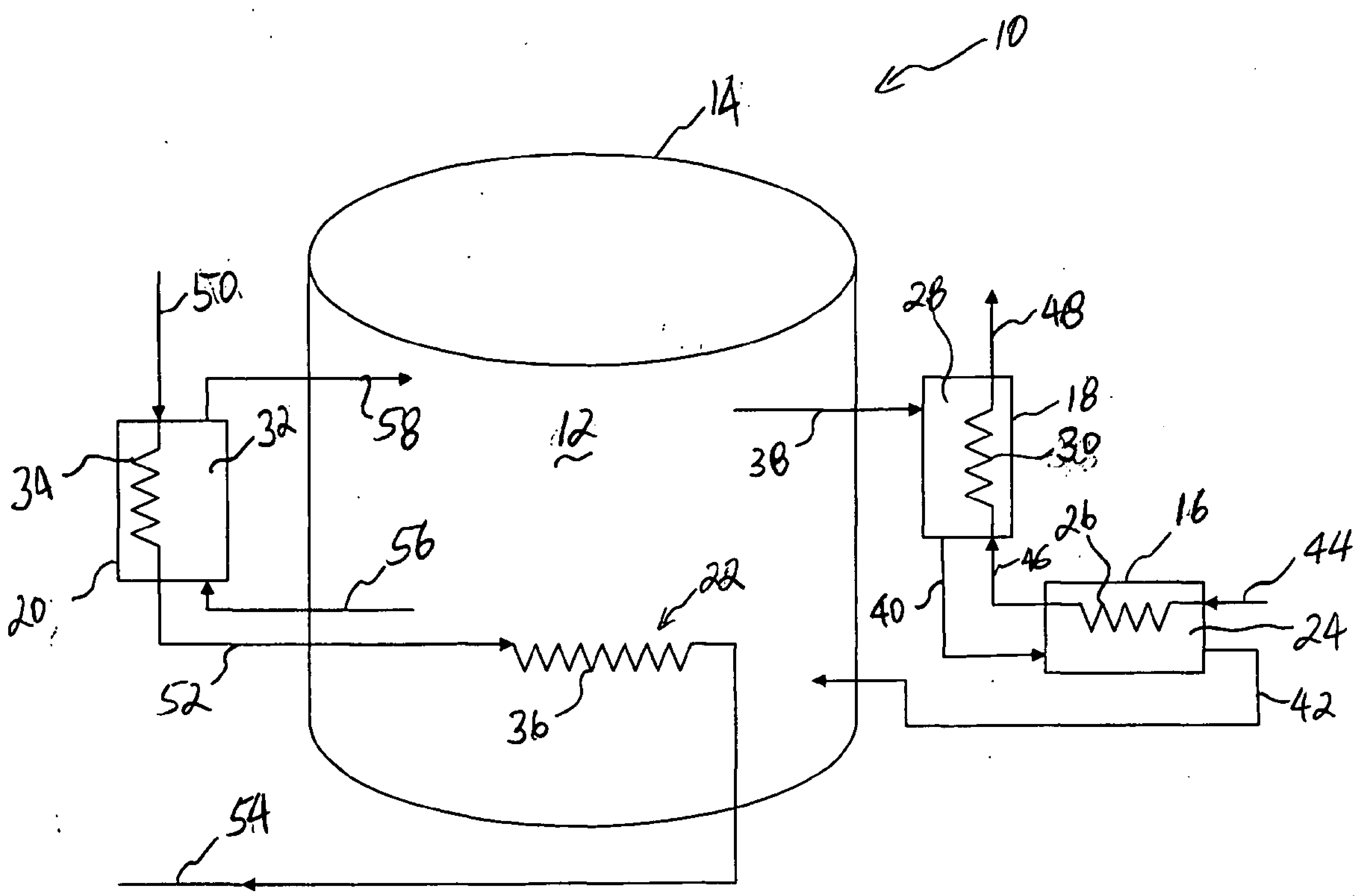
(57) **ABSTRACT**

An apparatus for storing and retrieving thermal energy from a phase change material including a plurality of heat exchangers. Each one of the plurality of heat exchangers provides the means for transferring energy between the phase change material on a primary side of the heat exchanger and a fluid on a secondary side of the heat exchanger. The phase change material is a mixture of two or more inorganic salts.



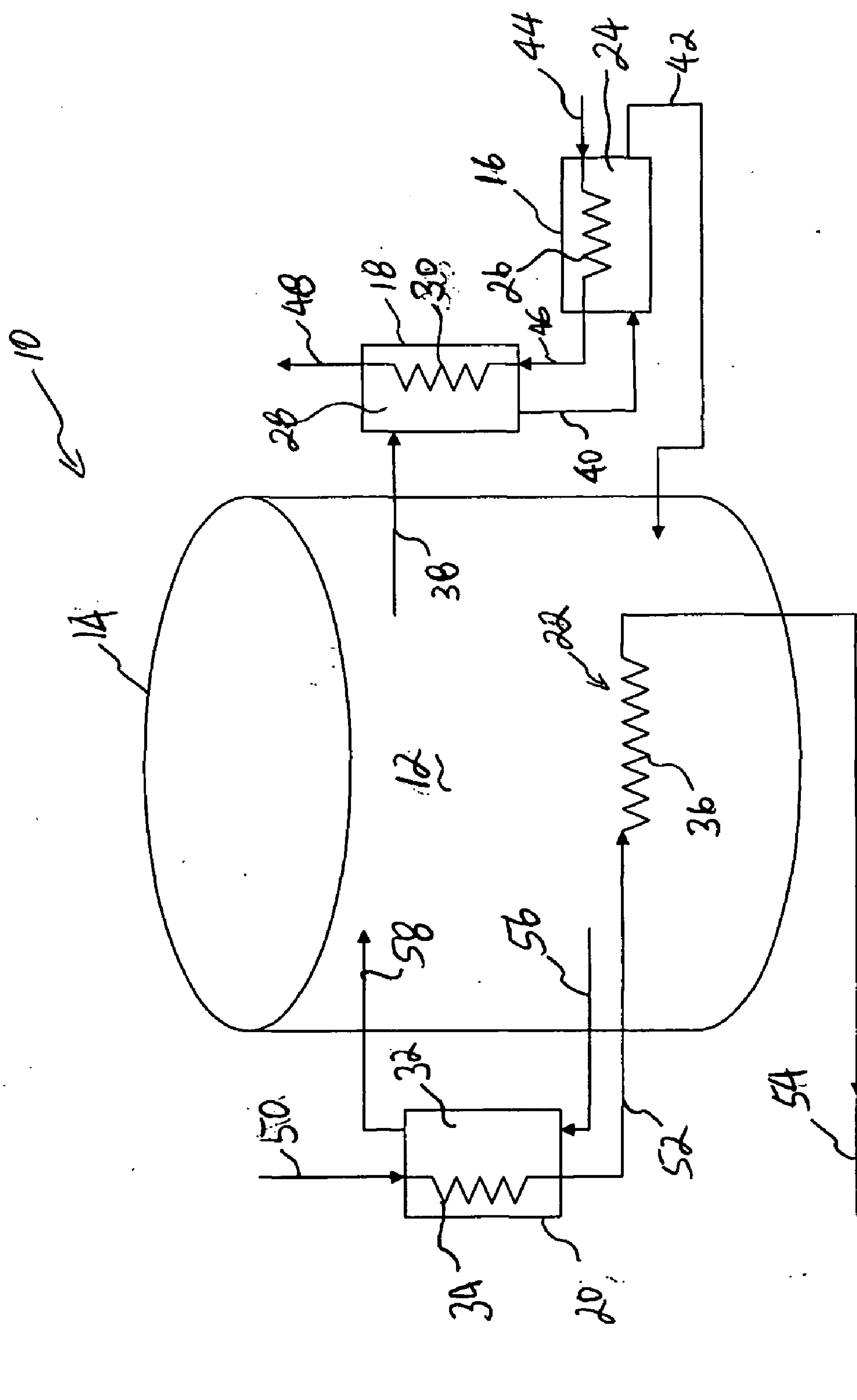

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FIG. 1

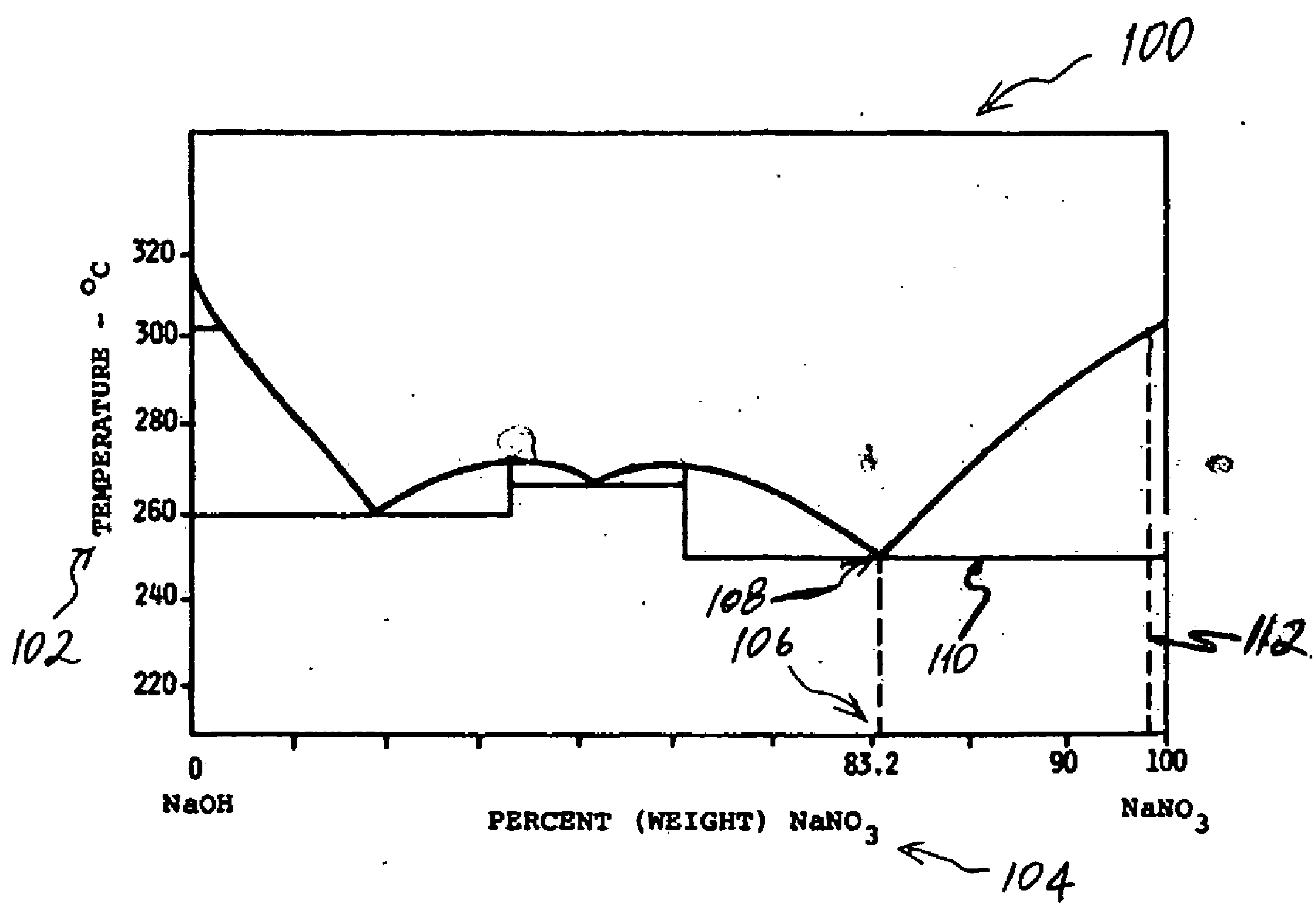
100
320
300
280
260
240
220
TEMPERATURE - °C
102
108
106
110
112
0
NaOH
83.2
90
100
NaNO3
PERCENT (WEIGHT) NaNO3
104

FIG. 2

THERMAL STORAGE SYSTEM

TECHNICAL FIELD

[0001] The instant invention relates to a thermal storage system. More specifically, the disclosure pertains to energy storage and retrieval from a phase change material.

BACKGROUND

[0002] Various types of thermal energy storage systems are well known in the art. In some systems, energy is stored and/or retrieved as sensible heat in either a solid or a liquid, or in a phase change material such as salt, or in a thermally stratified composition of a solid and a heat transfer fluid.

[0003] The storage and retrieval of sensible heat is typically accomplished by inducing a temperature difference between a hot and a cold source. As such, sensible energy storage systems are prone to large volume requirements of the liquid or solid storage media and are therefore expensive.

[0004] The transfer of energy to and from a phase change material is typically at a constant temperature and in the form of the latent heat of fusion of the material. Because the latent heat of fusion of a material is typically greater than the specific heat capacity of the same material used in a sensible storage system, the amount of the phase change material required for storing an equivalent amount of energy is typically less than the same material required for storing sensible energy. Accordingly, a phase change storage system is less costly than an equivalent sensible energy storage system and, because of their reduced size, the stand-by loses from a phase change storage system will also be less than those for a sensible heat storage system. However, retrieving the energy stored in a phase change material can be problematic in that the phase change material solidifies onto the heat exchanger surfaces when the heat of fusion is extracted from the liquid state. This build-up of the solid acts as an insulating layer, thereby reducing the heat transfer between the phase change material and the energy transport fluid.

[0005] Accordingly, there exists a need for an efficient and cost effective energy storage system comprising a phase change material.

SUMMARY

[0006] In accordance with an embodiment of the invention, a thermal energy storage system comprises a storage tank housing a phase change material. Thermal energy is stored or retrieved from the phase change material, respectively, by adding or removing energy in the form of the latent heat of fusion of the phase change material.

[0007] In an embodiment of the invention, the storage system comprises a first and a second heat exchanger fluidly connected in series such that energy from the phase change material flowing through a primary side of the first and the second heat exchangers is transferred to a first heat transfer fluid flowing through a secondary side of the first and the second heat exchangers. The storage system further comprises a third and a fourth heat exchanger fluidly connected in series such that energy from a second heat transfer fluid flowing through a secondary side of the third and the fourth heat exchangers is transferred to the phase change material on a primary side of the third and the fourth heat exchangers.

[0008] In an embodiment of the invention, the phase change material is a dilute eutectic composition comprising a mixture of two or more inorganic salts in a thermodynamic equilibrium state of solid and liquid.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** is a schematic of a thermal energy storage system in accordance with an embodiment of the invention; and

[0010] FIG. **2** is a thermodynamic phase change diagram for a phase change material in accordance with an embodiment of the invention.

DETAILED DESCRIPTION

[0011] While the present invention is subject to various modifications, embodiments illustrating the best mode contemplated by the inventors for carrying out the invention are described in detail herein below by way of examples with reference to the included drawings. However, it should be clearly understood that there is no intention to limit the invention in any form or manner to the disclosed embodiments, forms, or examples. As such, all alternatives are considered as falling within the scope, spirit and intent of the invention as defined by the appended claims.

[0012] FIG. **1** is a schematic of thermal energy storage system **10** in accordance with an embodiment of the invention. Thermal storage system **10** includes phase change material **12** contained within tank **14**, first heat exchanger **16** fluidly connected in series to second heat exchanger **18** and third heat exchanger **20** fluidly connected in series to fourth heat exchanger **22**.

[0013] In an embodiment of the invention, each one of the first, second and third heat exchangers **16**, **18** and **20**, respectively, comprise a primary side and a secondary side. As illustrated in FIG. **1**, first heat exchanger **16** comprises primary side **24** and secondary side **26**. Similarly, second heat exchanger **18** comprises primary side **28** and secondary side **30**; and third heat exchanger **20** comprises primary side **32** and secondary side **34**. Each one of first, second and third heat exchangers, **16**, **18** and **20**, respectively, are one of the various types of heat exchangers as are well known in the art, including a shell-and-tube heat exchanger. In the embodiment of thermal storage system **10**, fourth heat exchanger **22** is illustrated in FIG. **1** as comprising plurality of tubes **36** embedded in phase change material **12** within tank **14**. As such, plurality of tubes **36** include multiple tubes in a parallel arrangement connected by headers. Alternatively, plurality of tubes **36** form one or more coil of continuous tubing.

[0014] A portion of phase change material **12** extracted from tank **14** flows along path **38** and enters primary side **28** of second heat exchanger **18**. The phase change material flowing through primary side **28** exits second heat exchanger **18** along path **40** and enters primary side **24** of first heat exchanger **16**. The phase change material flowing through primary side **24** exits first heat exchanger **16** along path **42** and enters tank **14**. A first fluid flows along path **44** and enters secondary side **26** of first heat exchanger **16**. The first fluid flowing through secondary side **26** exits first heat exchanger **16** along path **46** and enters secondary side **30** of second heat exchanger **18**. The first fluid flowing through secondary side **30** exits second heat exchanger **18** along path **48**.

[0015] A second fluid flows along path **50** and enters secondary side **34** of third heat exchanger **20**. The second fluid flowing through secondary side **34** exits third heat exchanger **20** along path **52** and enters secondary side **36** of fourth heat exchanger **22**. The second fluid flowing through secondary side **36** exits fourth heat exchanger **22** along path **54**. A portion of phase change material **12** extracted from tank **14** flows along flow path **56** and enters primary side **32** of third heat exchanger **20**. The phase change material flowing through primary side **32** exits third heat exchanger **20** along flow path **58** and enters tank **14**.

[0016] As is well known to those skilled in the art, each of the first and second heat exchangers **16** and **18**, respectively, provide the means for transferring energy between the phase change material and the first fluid, respectively, flowing through the primary and the secondary sides of these heat exchangers. Similarly, third heat exchanger **20** provides the means for transferring energy between the phase change material and the second fluid, respectively, flowing through the primary and the secondary sides of this heat exchanger. Also, fourth heat exchanger **22** provides the means for transferring energy between the second fluid flowing through secondary side **36** and phase change material **12** encasing secondary side **36** of fourth heat exchanger **22**.

[0017] Whether energy is transferred to the phase change material or from the phase change material flowing through first, second and third heat exchangers **16**, **18** and **20**, respectively, is determined by the temperatures and the thermodynamic states of the fluid streams entering each primary sides **24**, **28** and **32** and secondary sides **26**, **30** and **34** of first, second and third heat exchangers **16**, **18** and **20**, respectively. Similarly, the temperature and the thermodynamic state of the second fluid entering secondary side **36** of fourth heat exchanger **22** will determine whether energy is transferred to or from phase change material **12** encasing secondary side **36**.

[0018] In accordance with an embodiment of the invention, the first fluid entering secondary side **26** of first heat exchanger **16** is feed water. Within first heat exchanger **16**, energy from the phase change material flowing through primary side **24** is transferred to the fluid flowing through secondary side **26**, converting the feed water into saturated steam. The saturated steam exits secondary side **26** along flow path **46** and enters secondary side **30** of second heat exchanger **18**. Within second heat exchanger **18**, energy from the phase change material flowing through primary side **28** is transferred to the fluid flowing through secondary side **30**, converting the saturated steam into superheated steam. The superheated steam exits secondary side **30** along flow path **48**. In an embodiment of the invention, the superheated steam flowing along flow path **48** is used for operating a steam turbine connected to a generator for generating electricity. In another embodiment, the superheated steam is used for operating a cooling apparatus such as an absorption chiller. In an alternate embodiment, the superheated steam is used for heating an enclosure. In yet another embodiment, the superheated steam is used in an industrial process. As can be seen, the superheated steam can be used in various applications.

[0019] As will be apparent to one skilled in the art, the phase change material flowing through primary sides **24** and **28** of first and second heat exchangers **16** and **18**, respectively, will undergo a change in its thermodynamic state as energy from the phase change material is transferred to the fluid flowing through secondary sides **26** and **30** of first and second heat exchangers **16** and **18**, respectively. In an embodiment of the invention, the phase change material extracted from tank **14** along path **38** is liquid. In another embodiment, the phase change material extracted from tank **14** along path **38** is a slurry comprising liquid and solid in a thermodynamic equilibrium state. Similarly, the phase change material exiting primary side **28** of second heat exchanger **18** and entering primary side **24** of first heat exchanger **16** along flow path **40** is liquid or a slurry comprising liquid and solid in a thermodynamic equilibrium state. In an embodiment of the invention wherein the phase change material entering primary side **28** of second heat exchanger **18** is a slurry, then the fraction of solid in the slurry exiting primary side **28** and entering primary side **24** of first heat exchanger **16** will be relatively more than the fraction of solid in the slurry entering primary side **28**. Similarly, if the phase change material entering primary side **24** of first heat exchanger **16** is a slurry, then the fraction of solid in the slurry exiting primary side **24** and returning to tank **14** along path **42** will be relatively more than the fraction of solid in the slurry entering primary side **24**.

[0020] In accordance with an embodiment of the invention, the second fluid entering secondary side **34** of third heat exchanger **20** is a liquid such as water or oil at a relatively high temperature. In another embodiment, the second fluid entering secondary side **34** is a gas such as saturated or superheated steam. In an alternate embodiment, the second fluid is from a heat source such as a concentrating solar collector or a solar power tower collector.

[0021] In an embodiment of the invention, a portion of phase change material **12** extracted from tank **14** flows along path **56** and enters primary side **32** of third heat exchanger **20**. The phase change material exiting third heat exchanger **20** is returned to tank **14** along flow path **58**. Within third heat exchanger **20**, energy from the second fluid flowing through secondary side **34** is transferred to the phase change material flowing through primary side **32**. In accordance with an embodiment of the invention, the phase change material enters primary side **32** as a slurry comprising liquid and solid in a thermodynamic equilibrium state and exits as a liquid. In another embodiment of the invention, the phase change material enters and exits primary side **32** as a slurry comprising liquid and solid in a thermodynamic equilibrium state. As such, the fraction of solid in the slurry exiting primary side **32** will be less than the fraction of solid in the slurry entering primary side **32**.

[0022] As previously stated, fourth heat exchanger **22** is illustrated in FIG. **1** as comprising plurality of tubes **36** embedded in phase change material **12** within tank **14**. In accordance with an embodiment of the invention, the phase change material surrounding plurality of tubes **36** is converted from solid to a slurry comprising liquid and solid in a thermodynamic equilibrium state. In another embodiment of the invention, the fraction of solid in the slurry surrounding plurality of tubes **36** is reduced. In an alternate embodiment of the invention, the slurry surrounding plurality of tubes **36** is converted into liquid.

[0023] In an embodiment of the invention, the temperature of the phase change material returned to tank **14** along path **58** is relatively higher than the temperature of the phase change material surrounding plurality of tubes **36**. Similarly, the phase change material returned to tank **14** along path **42** will be relatively cooler than the phase change material extracted from tank **14** along path **38**. As such, phase change material **12** within tank **14** will be thermally stratified. As will be apparent to one skilled in the art, the relatively warmer phase change material along path **58** does not necessarily have to be returned near the top of tank **14** for initiating and/or maintaining tank **14** in a thermally stratified state. Similarly, the relatively cooler phase change material along path **42** does not necessarily have to be returned near the bottom of tank **14** for initiating and/or maintaining tank **14** in a thermally stratified state. In a thermally stratified tank, the phase change material extracted along path **38** will be from near the top of tank **14**

[0024] In accordance with an embodiment of the invention, phase change material **12** is a mixture of two or more inorganic salts, each of which inorganic salt undergoes a thermodynamic phase change between its respective solid and liquid states. As is well known to those skilled in the art, the temperature at which one or more of the inorganic salts undergo thermodynamic phase change between its respective solid and liquid states is dictated by whether the mixture of the salts forms a eutectic composition or a dilute eutectic composition. Whether the mixture of the two or more inorganic salts forms a eutectic composition or a dilute eutectic composition is defined by one of the weight, volumetric or mole content of each of the two or more inorganic salts.

[0025] FIG. **2** shows simple phase change diagram **100** for phase change material **12** comprising a binary mixture of two inorganic salts sodium hydroxide (NaOH) and sodium nitrate ($NaNO_3$) in accordance with an embodiment of the invention. In an alternate embodiment, the phase change material comprises a mixture of three, or more, inorganic salts. For the binary mixture comprising inorganic salts NaOH and $NaNO_3$ in an embodiment of the invention, temperature **102** is a function of the weight percent of $NaNO_3$ **104**. As illustrated, the binary mixture comprising about 83.2 percent-by-weight of $NaNO_3$ and about 16.8 percent-by-weight of NaOH (numeral **106**) forms eutectic composition **108** having eutectic temperature of about 246 degrees-C. As can be seen, for the binary mixture comprising more than about 83.2 percent-by-weight of $NaNO_3$, solidus state **110** is maintained at the eutectic temperature of about 246 degrees-C. Accordingly, the NaOH will always be in the liquid state and, therefore, the binary mixture will be in the form of a slurry comprising liquid NaOH in thermodynamic equilibrium with some $NaNO_3$ in solid state. In accordance with an embodiment of the invention, phase change material **12** comprises a dilute eutectic composition in $NaNO_3$ including about 99.0 percent-by-weight of $NaNO_3$ and about 1.0 percent-by-weight of NaOH (numeral **112**).

[0026] As is well know to those skilled in the art, salt is a corrosive compound. In an embodiment of the invention, each component of thermal energy storage system **10** is manufactured from material naturally resistant to corrosion from salt. In another embodiment, each component of thermal energy storage system **10** is treated for preventing or minimizing corrosion from salt. In an alternate embodiment, each component of thermal energy storage system **10** is coated with a salt phobic compound for preventing or minimizing corrosion.

[0027] Various modifications and additions may be made to the exemplary embodiments presented hereinabove without departing from the scope and intent of the present invention. For example, while the disclosed embodiments refer to particular features, the scope of the instant invention is considered to also include embodiments having different combinations of features different from and/or in addition to those described herein. Accordingly, the scope of the present invention is intended to embrace all such alternatives, modifications, and variations as falling within the scope and intent of the appended claims, including all equivalents thereof.

What is claimed is:

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

a tank containing a phase change material;

a first heat exchanger fluidly connected in series with a second heat exchanger, wherein

the phase change material from the tank enters a primary side of the second heat exchanger;

the phase change material flows through and exits the second heat exchanger and enters a primary side of the first heat exchanger;

the phase change material flows through and exits the first heat exchanger and enters the tank;

a first fluid enters and flows through a secondary side of the first heat exchanger wherein energy is transferred between the phase change material and the first fluid; and

the first fluid exits the first heat exchanger and enters and flows through a secondary side of the second heat exchanger wherein energy is transferred between the phase change material and the first fluid; and

a third heat exchanger fluidly connected in series with a fourth heat exchanger, wherein

the fourth heat exchanger is embedded within the phase change material within the tank;

a second fluid from an energy source enters and flows through a secondary side of the third heat exchanger;

the second fluid exits the third heat exchanger and enters and flows through a secondary side of the fourth heat exchanger wherein energy is transferred between the second fluid and the phase change material surrounding the secondary side of the fourth heat exchanger;

the second fluid exits the fourth heat exchanger and returns to the energy source;

the phase change material from the tank enters and flows through a primary side of the third heat exchanger wherein energy is transferred between the phase change material and the second fluid; and

the phase change material exits the third heat exchanger and enters the tank.

2. The apparatus of claim **1**, wherein the phase change material comprises a composition in a thermodynamic equilibrium state of liquid and solid.

3. The apparatus of claim **1**, wherein

each of the first, the second and the third heat exchangers comprise shell and tube heat exchangers;

the primary side of each of the first, the second and the third heat exchangers comprises a shell; and

the secondary side of each of the first, the second and the third heat exchangers comprises a plurality of tubes.

4. The apparatus of claim **1**, wherein

the first fluid entering the first heat exchanger includes feed water;

the first fluid exiting the first heat exchanger and entering the second heat exchanger comprises saturated steam; and

the first fluid exiting the second heat exchanger comprises superheated steam.

5. The apparatus of claim **4**, wherein the superheated steam is used for generating electricity.

6. The apparatus of claim **1**, wherein
the secondary side of the fourth heat exchanger comprises a plurality of tubes embedded within the phase change material; and
the second fluid flows through the plurality of tubes.

7. The apparatus of claim **6**, wherein
the phase change material comprises a mixture of at least two or more inorganic salts.

8. The apparatus of claim **7**, wherein the mixture comprises 83.2 percent by weight sodium nitrate and 16.8 percent by weight sodium hydroxide.

9. The apparatus of claim **1**, wherein the phase change material comprises a dilute eutectic composition.

10. The apparatus of claim **9**, wherein the dilute eutectic composition comprises a mixture of at least two or more inorganic salts.

11. The apparatus of claim **10**, wherein the dilute eutectic composition comprises a dilute eutectic composition in sodium nitrate including sodium nitrate in the range of 98 to 99 percent by weight and sodium hydroxide in the corresponding range of 2 to 1 percent by weight.

12. The apparatus of claim **10**, wherein
the inside surface of the shell for each one of the first, the second and the third heat exchanger comprises a coating of a salt phobic compound; and
the outside surfaces of the plurality of tubes in each one of the first, the second, the third and the fourth heat exchanger comprise a coating of the salt phobic compound.

13. The apparatus of claim **1**, wherein the phase change material within the tank is thermally stratified.

14. The apparatus of claim **13**, wherein
the phase change material entering the second heat exchanger comprises the phase change material extracted from near a top of the tank; and
the phase change material exiting the first heat exchanger enters the tank near a bottom of the tank.

15. The apparatus of claim **14**, wherein
the phase change material entering the second heat exchanger comprises a liquid state of the phase change material; and
the phase change material entering the tank near the bottom of the tank comprises thermodynamic equilibrium state of liquid and solid.

16. The apparatus of claim **13**, wherein
the phase change material entering the third heat exchanger comprises the phase change material extracted from near the bottom of the tank; and
the phase change material exiting the third heat exchanger enters the tank near the top of the tank.

17. The apparatus of claim **16**, wherein
the phase change material entering the third heat exchanger comprises thermodynamic equilibrium state of liquid and solid; and
the phase change material exiting the third heat exchanger comprises the phase change material in the liquid state.

18. The apparatus of claim **13**, wherein
the phase change material entering the third heat exchanger comprises the phase change material in the liquid state; and
the phase change material exiting the third heat exchanger comprises the phase change material in a saturated state.

19. The apparatus of claim **18**, wherein the saturated state is a thermodynamic equilibrium state of liquid and vapor.

20. The apparatus of claim **18**, wherein the saturated state is vapor.

21. The apparatus of claim **13**, wherein
the phase change material entering the third heat exchanger comprises the phase change material in the liquid state; and
the phase change material exiting the third heat exchanger comprises the phase change material in a superheated vapor state.

22. The apparatus of claim **13**, wherein the fourth heat exchanger is positioned near the bottom of the tank.

23. The apparatus of claim **22**, wherein the phase change material near the bottom of the tank comprises thermodynamic equilibrium state of liquid and solid.

24. The apparatus of claim **1**, wherein the energy source includes a heating source.

25. The apparatus of claim **1**, wherein the energy source includes a cooling source.

26. A method for storing and retrieving thermal energy from a phase change material within a tank, the method comprising the steps of:
transferring energy from the phase change material to a first fluid; and
transferring energy from a second fluid to the phase change material.

27. The method of claim **26**, further comprising the steps of:
flowing the first fluid through a secondary side of a first heat exchanger;
flowing the first fluid exiting the first heat exchanger through a secondary side of the second heat exchanger;
extracting the phase change material from the tank;
flowing the phase change material through a primary side of the second exchanger;
transferring energy from the phase change material flowing through the second heat exchanger to the first fluid flowing through the second heat exchanger;
flowing the phase change material exiting the second heat exchanger through a primary side of the first heat exchanger;
transferring energy from the phase change material flowing through the first heat exchanger to the first fluid flowing through the first heat exchanger; and
returning the phase change material exiting the first heat exchanger to the tank.

28. The method of claim **27**, further comprising the steps of:
extracting the phase change material from the tank;
flowing the phase change material through a primary side of a third heat exchanger;
returning the phase change material from the third heat exchanger to the tank;
extracting the second fluid from an energy source and flowing the second fluid through a secondary side of the third heat exchanger;
transferring energy from the second fluid flowing through the third heat exchanger to the phase change material flowing through the third heat exchanger;
flowing the second fluid exiting the third heat exchanger through a secondary side of a fourth heat exchanger, wherein the secondary side of the fourth heat exchanger is embedded within the phase change material in the tank;

transferring energy from the second fluid flowing through the fourth heat exchanger to the phase change material surrounding the secondary side of the fourth heat exchanger; and

returning the second fluid exiting the fourth heat exchanger to the energy source.

29. The method of claim **28**, further comprising the step of maintaining the phase change material in a thermodynamic equilibrium state of liquid and solid.

30. The method of claim **29**, further comprising the step of maintaining the phase change material in a thermally stratified state.

31. The method of claim **30**, wherein

the step of flowing the phase change material through the second heat exchanger further comprises the step of extracting the phase change material from near a top of the tank; and

the step of returning the phase change material exiting the first heat exchanger to the tank further comprises the step of returning the phase change material near a bottom of the tank.

32. The method of claim **31**, wherein

the step of flowing the phase change material through the third heat exchanger further comprises the step of extracting the phase change material from near the bottom of the tank; and

the step of returning the phase change material exiting the third heat exchanger to the tank further comprises the step of returning the phase change material near the top of the tank.

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