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

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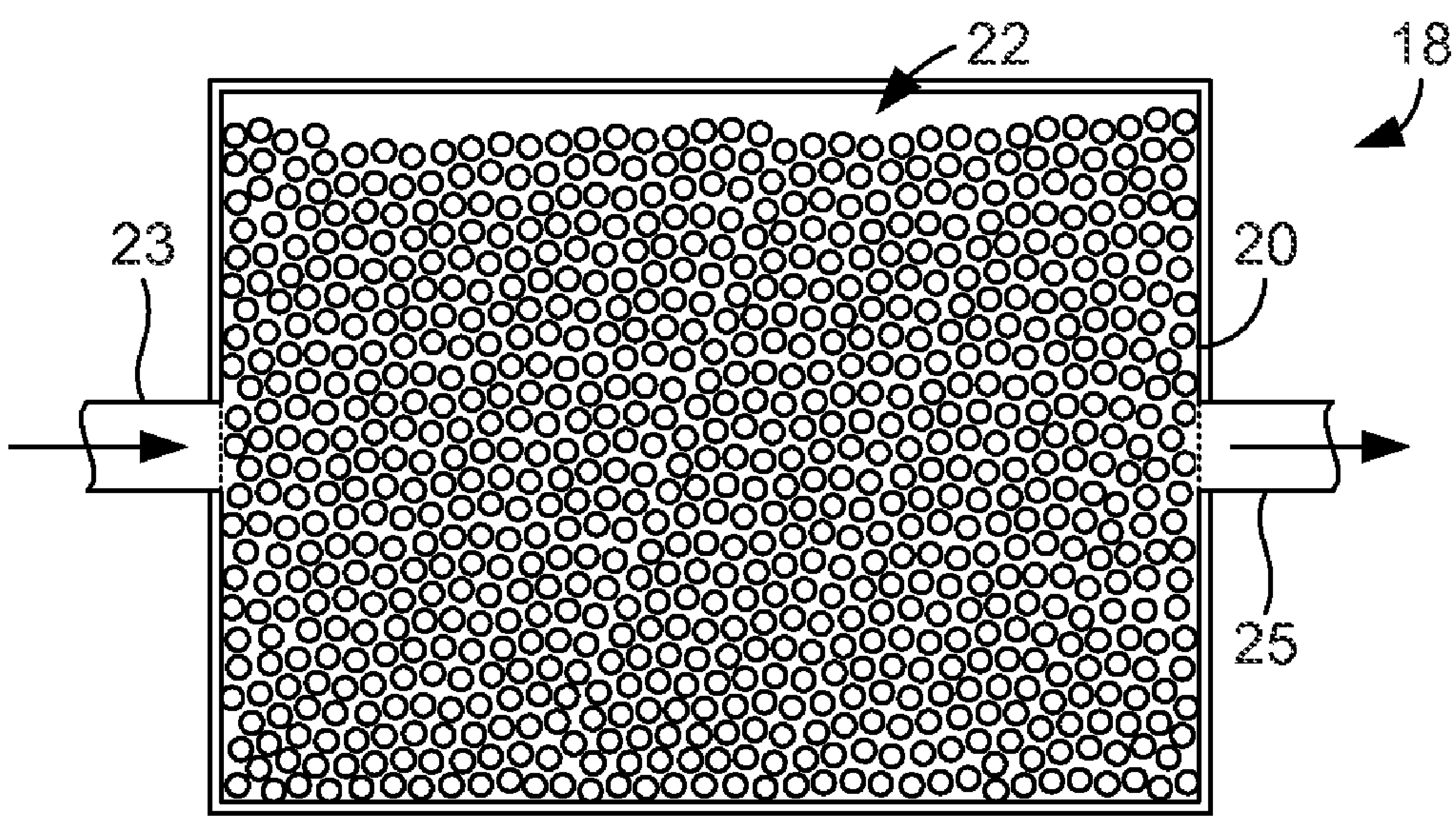
(57) **ABSTRACT**

In one embodiment, a thermal energy storage system includes a first cascade containing a first phase change material and a second cascade containing a second phase change material, wherein the melting point of the first phase change material is different than the melting point of the second phase material.



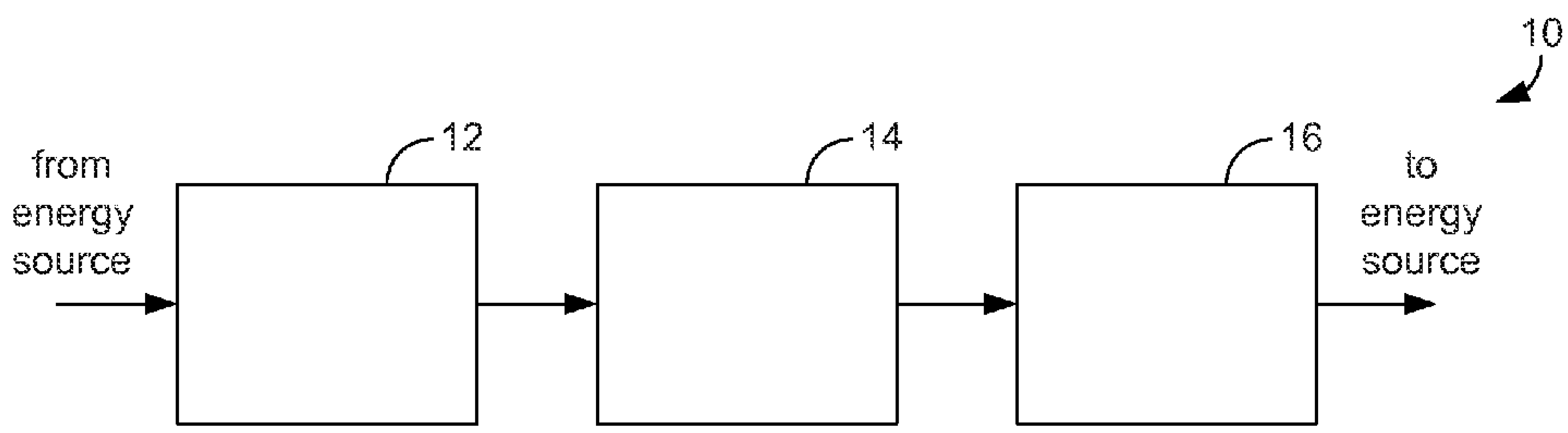


FIG. 1

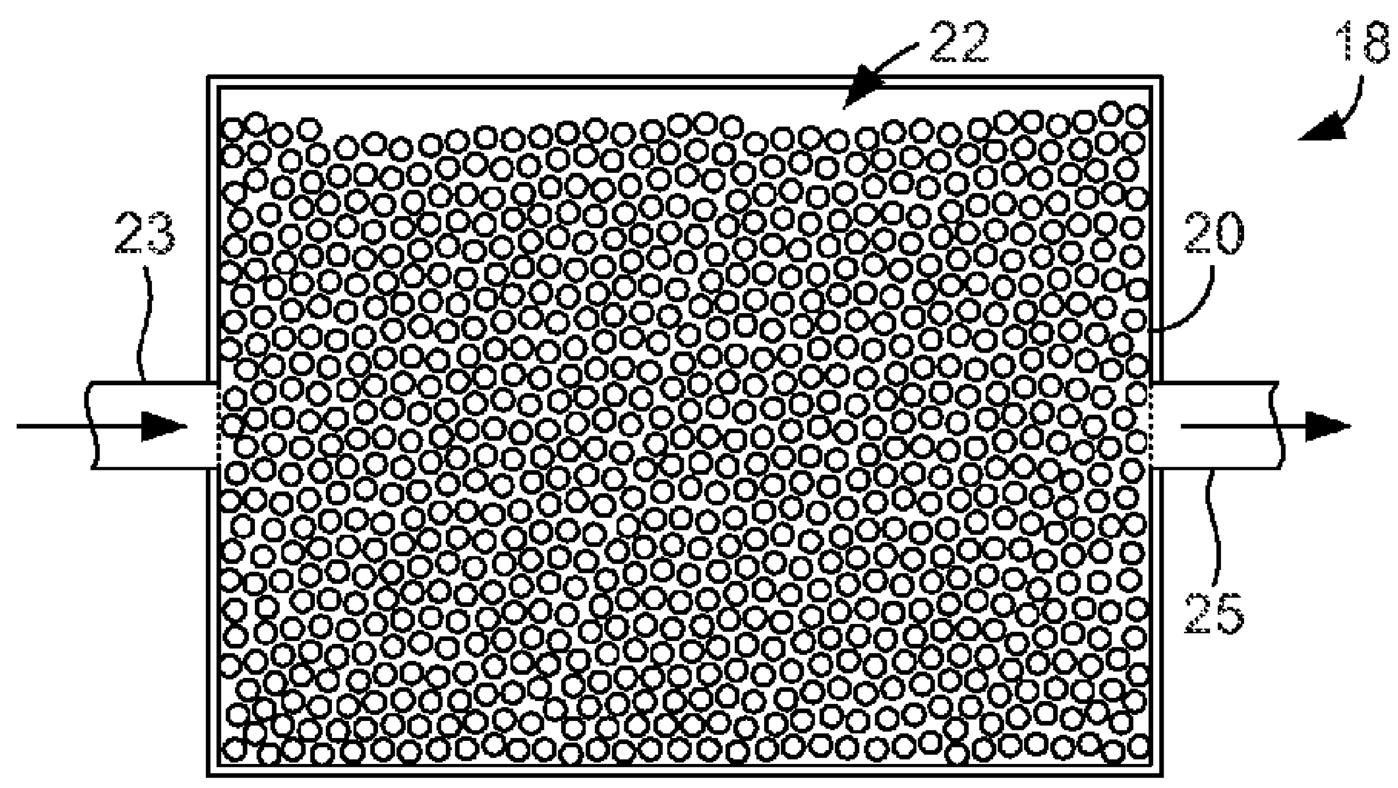


FIG. 2

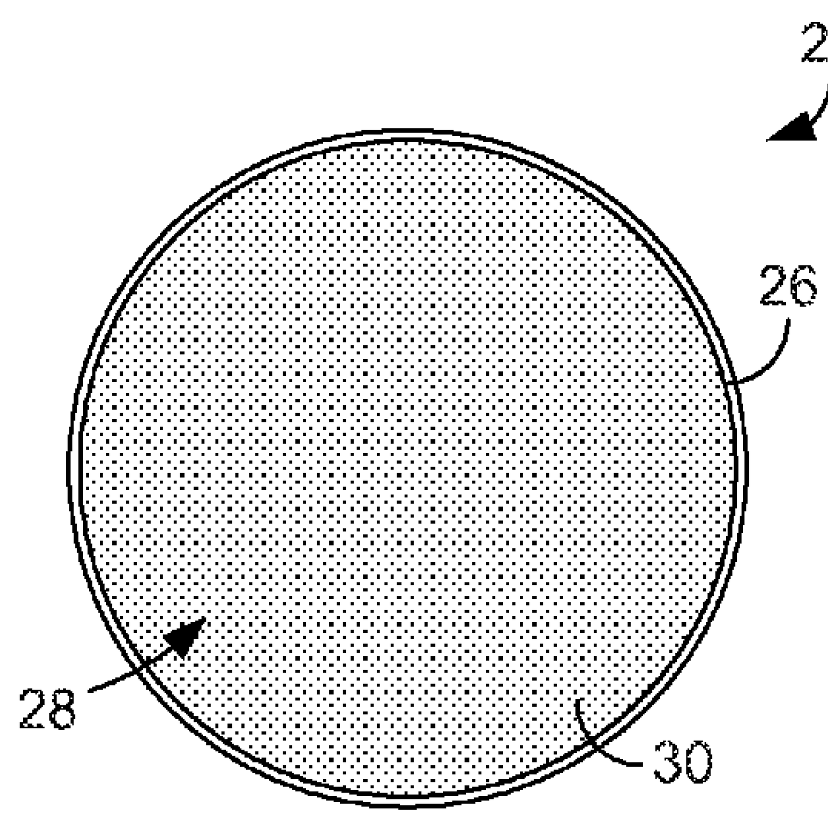


FIG. 3A

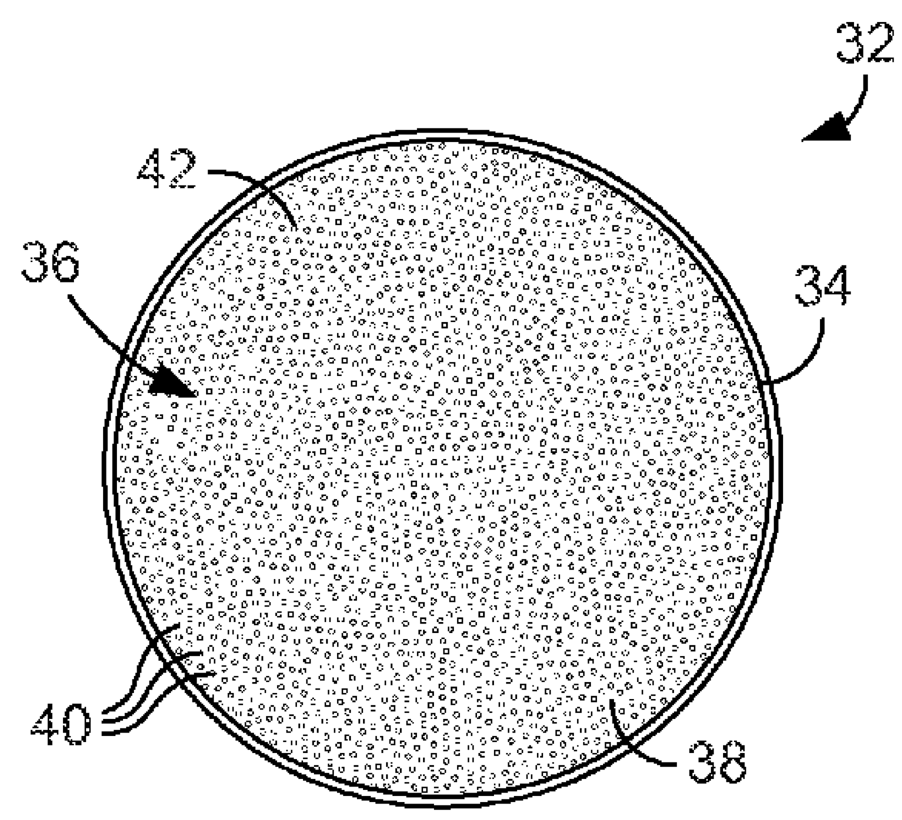


FIG. 3B

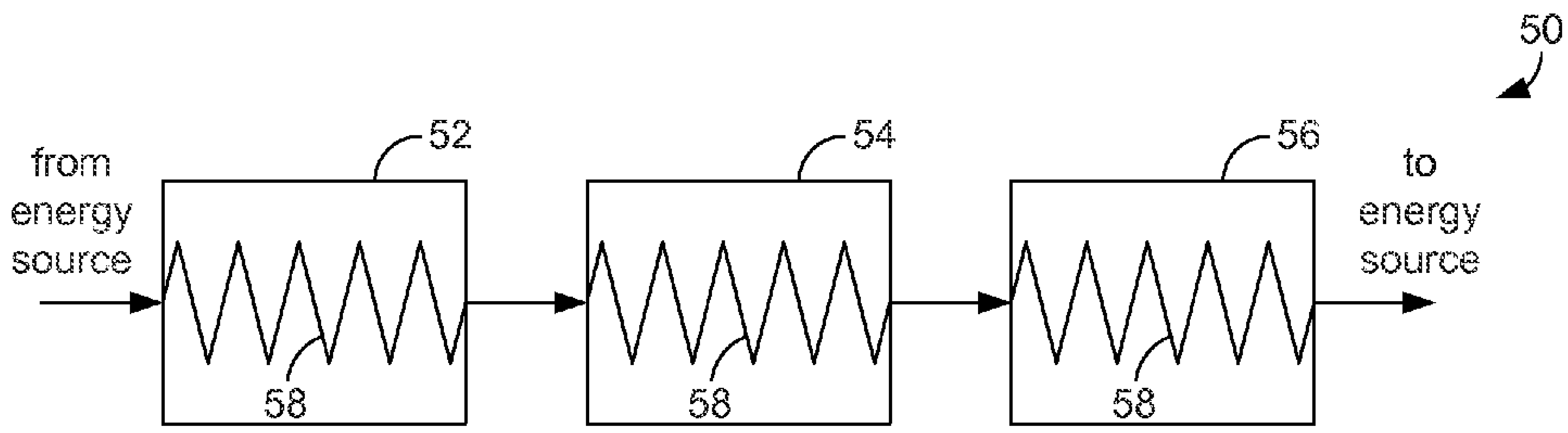


FIG. 4

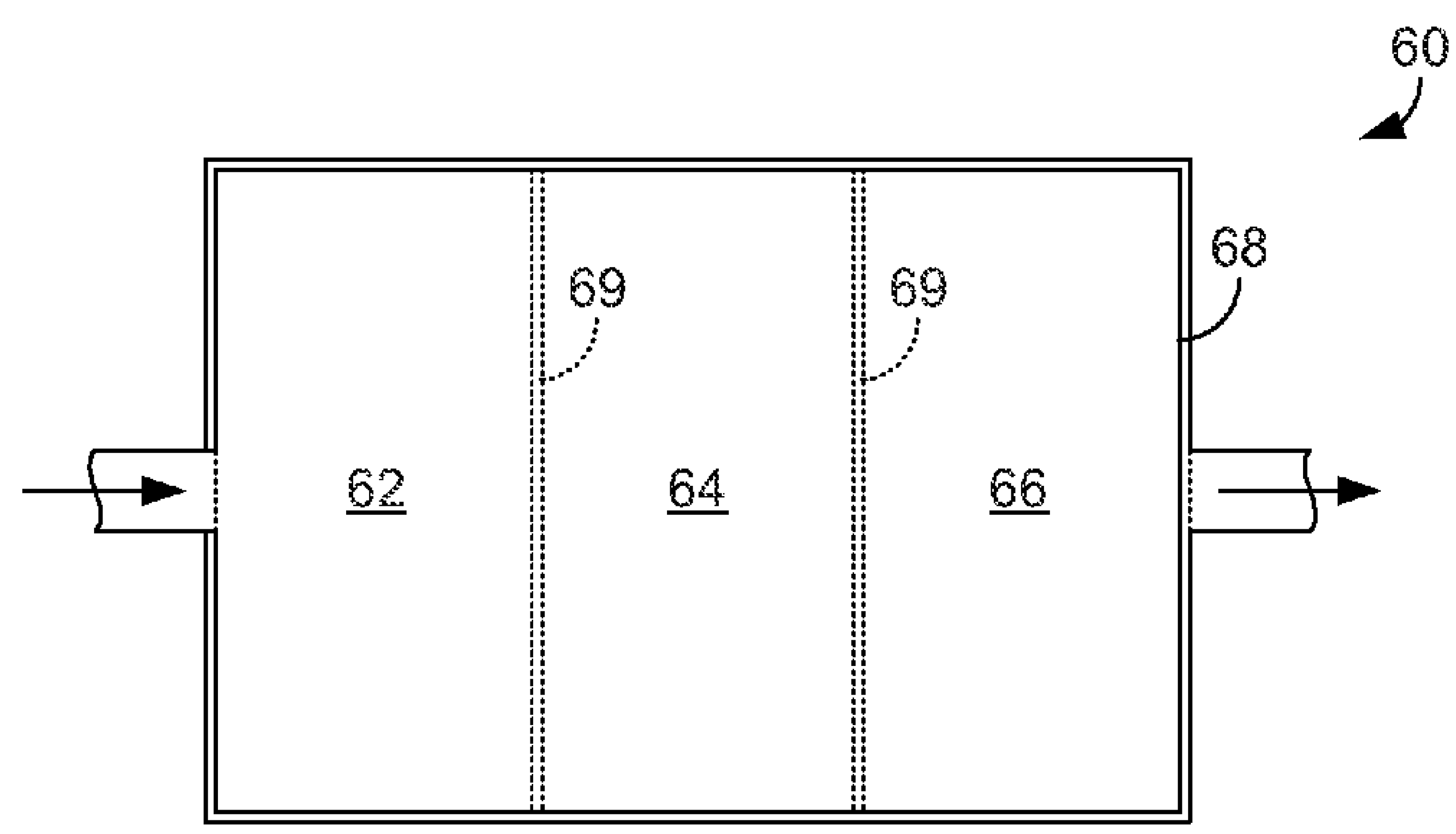


FIG. 5

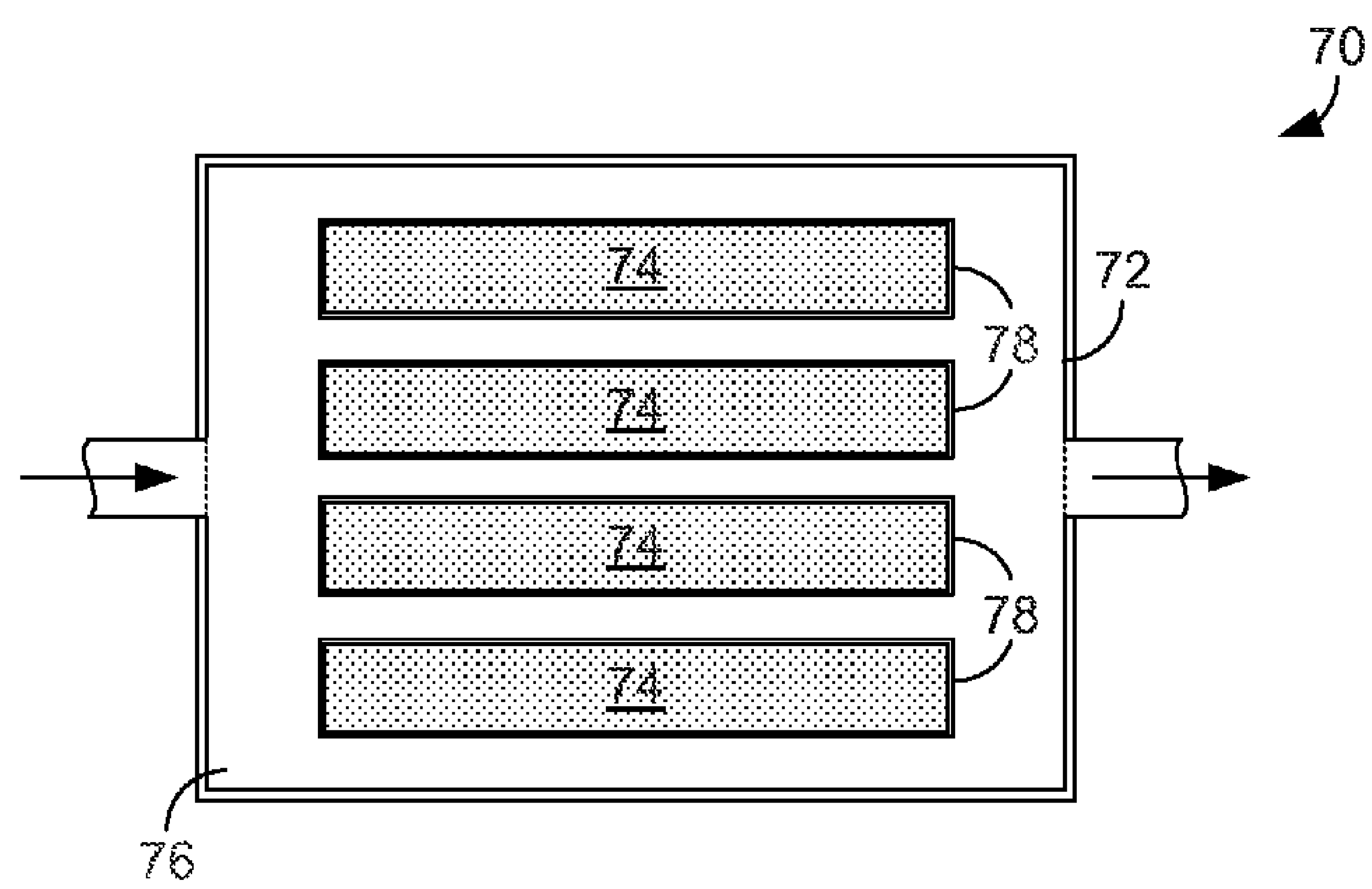


FIG. 6

SYSTEMS AND METHODS FOR THERMAL ENERGY STORAGE

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to co-pending U.S. Provisional Application Ser. No. 61/553,598 filed Oct. 31, 2011, which is hereby incorporated by reference herein in its entirety.

BACKGROUND

[0002] Thermal energy storage will be essential for solar thermal power plants to feed into the power grid in the future. At present, synthetic oils or molten salts are used for thermal energy storage. Both of these materials store energy as sensible heat, which requires a large amount of the material. Recently, phase change materials (PCMs) that store heat as latent heat have been suggested for use in thermal energy storage. PCMs can store a great deal more heat per unit mass, and therefore require much less material. However, PCMs store latent heat at only one unique temperature for that material, while heat is often needed across a range of temperatures. Although cascaded PCM storage has been suggested, such systems still do not match the needed storage/discharge characteristics. Furthermore, PCM heat conductivities are very small, which creates an obstacle that must be overcome to make full use of them in thermal energy storage applications.

[0003] In view of the foregoing discussion, it can be appreciated that it would be desirable to have an improved system and method for thermal energy storage.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] The present disclosure may be better understood with reference to the following figures. Matching reference numerals designate corresponding parts throughout the figures, which are not necessarily drawn to scale.

[0005] FIG. **1** is a schematic diagram of a first embodiment of a thermal energy storage system.

[0006] FIG. **2** is a block diagram of an embodiment of a cascade of the thermal energy storage system of FIG. **1**.

[0007] FIG. **3**A is a first embodiment of a thermal energy storage capsule that can be used in the cascade of FIG. **2**.

[0008] FIG. **3**B is a second embodiment of a thermal energy storage capsule that can be used in the cascade of FIG. **2**.

[0009] FIG. **4** is a schematic diagram of a second embodiment of a thermal energy storage system.

[0010] FIG. **5** is a schematic diagram of a third embodiment of a thermal energy storage system.

[0011] FIG. **6** is a block diagram of a further cascade that can be used in a thermal energy storage system.

DETAILED DESCRIPTION

[0012] As described above, it would be desirable to have an improved system and method for thermal energy storage, which could be used in solar thermal power plants. More particularly, it would be desirable to have such a system and method that utilizes the desirable properties of phase change materials (PCMs). Disclosed herein are examples of such systems and methods.

[0013] In the following disclosure, various embodiments are described. It is to be understood that those embodiments are example implementations of the disclosed inventions and that alternative embodiments are possible. All such embodiments are intended to fall within the scope of this disclosure.

[0014] FIG. **1** illustrates a first embodiment of a thermal energy storage system **10** that can be used with a solar thermal power plant (not shown). The system **10** includes multiple cascades **12**, **14**, and **16** arranged in series. Each cascade can comprise a storage tank or other container that holds thermal energy storage material that is used to store and release heat as needed. As is suggested by FIG. **1**, a heat transfer fluid (e.g., oil) that is heated by an energy source, such as a solar collector of a solar thermal power plant, can flow through the first cascade **12**, through the second cascade **14**, through the third cascade **16**, and back to the energy source. The first cascade **12** can be a relatively high temperature cascade (e.g., 370° C. to 410° C.), the second cascade **14** can be a medium temperature cascade (e.g., 340° C. to 370° C.), and the third cascade **16** can be a relatively low temperature cascade (e.g., 300° C. to 340° C.). Of course, these temperature ranges are only examples. The concept can be applied to any temperatures and ranges as long as suitable PCMs are available. In addition, greater or fewer cascades can be used. Regardless of the number of cascades, the heat transfer fluid can sequentially travel from relatively hot to relatively cool cascades as it is circulated through the thermal energy storage system **10**.

[0015] FIG. **2** illustrates an example cascade **18** that can be used in a thermal energy storage system, such as the system **10**. As is shown in FIG. **2**, the cascade **18** comprises a storage tank **20** that holds a plurality of thermal energy storage capsules **22** that each contain a thermal energy storage material. FIGS. **3**A and **3**B illustrate example capsules **24** and **32**, respectively. Beginning with FIG. **3**A, the capsule **24** is configured as a sphere that is defined by a rigid spherical capsule wall **26**. The material used to construct the wall **26** depends upon the temperatures that the capsule **24** must withstand. Example materials include polymer, metal, or ceramic materials. In some embodiments, the capsule **24** is a macro-capsule and has a diameter of approximately 1 to 2 inches. Of course, the dimensions of the capsule can be greater or smaller.

[0016] The capsule wall **26** defines an interior space **28** that is filled with a thermal energy storage material **30**. In some embodiments, the thermal energy storage material **30** comprises a single PCM. In other embodiments, the thermal energy storage material **30** can comprise a mixture of two or more different PCMs that have different phase change temperatures. The PCMs can, for example, comprise one or more salts, such as sodium nitrate. Preferably, the mixture of PCMs is non-eutectic so that the mixture will not behave as a single material. In some embodiments, the phase change temperatures of the PCMs in the mixture fall within a relatively narrow range. For example, the capsule **24** could contain three different PCMs, a first PCM having a phase change temperature of approximately 300° C., a second PCM having a phase change temperature of approximately 305° C., and a third PCM having a phase change temperature of approximately 310° C. In such a case, the PCMs would sequentially change from solid to liquid as they are heated and their respective phase change temperatures are crossed, and would likewise sequentially change from liquid to solid as they are cooled and the phase change temperatures are again crossed. Capsule shapes other than spherical, such as egg shapes, ellipsoids, rectangular, conical, or even odd shapes are also possible.

[0017] FIG. 3B illustrates a second example capsule **32**. The capsule **32** also has a spherical capsule wall **34**, which can, for example, be made of polymer, metal, or ceramic material. In some embodiments, the capsule **32** is also a macro-capsule and has a diameter of approximately 1 to 2 inches. Again the dimensions can be greater or smaller. The capsule wall **34** defines an interior space **36** that is filled with a thermal energy storage material **38**. In this embodiment, however, the thermal energy storage material **38** comprises a plurality of PCM particles **40** that are suspended in a fluid **42**, such as an oil. The particles **40** can all be made from the same PCM or can be made from two or more different PCMs having different phase change temperatures, for example, that fall within a relatively small range of temperatures. In some embodiments, the fluid **42** comprises at least 5% of the volume within the capsule **32**, such that each PCM particle **40** is separated from the other capsules by a fluid layer, thereby enabling the fluid to move inside the capsule. The viscosity of the fluid **42** is such that at least a layer of the fluid is maintained between the PCM particles **40** and the fluid is able to move at the prevailing temperature.

[0018] When the thermal energy storage system **10** includes cascades containing PCM capsules, such as capsules **24** or **32**, the heat transfer liquid can flow through the cascades and between the capsules, making direct contact with those capsules. With reference to FIG. **2**, the heat transfer liquid can enter the tank **20** through an inlet pipe **23** and exit the tank through an outlet pipe **25**. Therefore, heat from the liquid can be transferred to the capsules and their thermal energy storage material. In some embodiments, the heat transfer fluid comprises at least 5% of the volume of each cascade, such that each capsule is separated from the other capsules by a fluid layer, thereby enabling the fluid to move around the capsules and therefore enhancing the heat transfer in the cascade. The viscosity of the heat transfer fluid is selected so that such movement is possible. When the capsules are relatively large, they will remain in their cascade and will not travel on to the next cascade along with the heat transfer liquid. In other embodiments, a screen or grate can be provided at the cascade inlet and outlet to prevent capsule migration.

[0019] In some embodiments, each cascade contains capsules that each contain a same single PCM. For example, the first cascade **12** could comprise capsules containing a single PCM that changes phase at a temperature of approximately 300° C., the second cascade **14** could comprise capsules containing a single PCM that changes phase at a temperature of approximately 350° C., and the third cascade **16** could comprise capsules containing a single PCM that changes phase at a temperature of approximately 400° C.

[0020] In other embodiments, each cascade contains capsules containing different single PCMs, wherein each PCM changes phase within a relatively narrow range of temperatures. For example, the first cascade **12** could contain three different types of capsules, a first type of capsule that contains a single PCM that changes phase at approximately 300° C., a second type of capsule that contains a single PCM that changes phase at approximately 305° C., and third type of capsule that contains a single PCM that changes phase at approximately 310° C., such that a range of approximately 300° C. to 310° C. is covered. Each of the second and the third cascades **14** and **16** could likewise contain multiple types of capsules that together cover a different range of temperature.

[0021] In still other embodiments, each cascade can contain capsules that each contain multiple PCMs, wherein each PCM changes phase within a relatively narrow range of temperatures. For example, the first cascade **12** could contain capsules that contain multiple PCMs that each changes phase within the range of approximately 300° C. to 310° C., the second cascade **14** could contain capsules that contain multiple PCMs that each changes phase with the range of approximately 350° C. to approximately 360° C., and the third cascade **16** could contain capsules that contain multiple PCMs that each changes phase with the range of approximately 400° C. to 410° C.

[0022] In yet other embodiments, combinations of the above-described embodiments could also be used.

[0023] FIG. **4** illustrates a further thermal energy storage system **50**. Like the system **10**, the system **50** includes multiple cascades **52**, **54**, and **56** arranged in series. Each cascade holds thermal energy storage material that is used to store and release heat as needed. As is suggested by FIG. **4**, a heat transfer fluid (e.g., oil) that is heated by an energy source such as a solar thermal plant can flow through the first cascade **52**, through the second cascade **54**, through the third cascade **56**, and back to the energy source. In the embodiment of FIG. **4**, however, the heat transfer fluid is separated from the thermal energy storage material by the walls of coils **58** that pass through the thermal energy storage material. Therefore, the cascades **52**, **54**, and **56** function as heat exchangers.

[0024] The thermal energy storage material within the cascades **52**, **54**, and **56** comprises PCMs. In some embodiments, the PCMs are in bulk form, meaning that they are not encapsulated in capsules or other discrete elements. A single different PCM can be contained within each cascade **52**, **54**, and **56**. For example, the first cascade **52** can contain a first PCM that changes phases a relatively high temperature (e.g., 370° C. to 410° C.), the second cascade **54** can contain a second PCM that changes phases a medium temperature (e.g., 340° C. to 370° C.), and the third cascade **56** can contain a third PCM that changes phases a relatively low temperature (e.g., 300° C. to 340° C.). In general, other temperatures and temperature ranges can be used. In other embodiments, each cascade can contain a non-eutectic mixture of multiple PCMs, each of which changes phase within a relatively narrow range of temperatures. For example, the first cascade **52** could contain a mixture of multiple PCMs that each changes phase within the range of approximately 300° C. to 310° C., the second cascade **54** could contain a mixture of multiple PCMs that each changes phase with the range of approximately 350° C. to 360° C., and the third cascade **56** could contain a mixture of multiple PCMs that each changes phase with the range of approximately 400° C. to 410° C.

[0025] FIG. **5** illustrates a further thermal energy storage system **60**. Like the system **50**, the system **60** includes multiple cascades **62**, **64**, and **66** arranged in series that contain PCMs in bulk form. However, in the embodiment of FIG. **5**, each cascade is a separate compartment of a single storage tank **68**, which are separated by divider walls **69**. The cascades **62**, **64**, **66** can function and contain contents similar to those described above in relation to the systems **10** and **50**. The compartments **62**, **64**, and **66** can alternatively be arranged in a vertical orientation (not shown) with the higher temperatures on top, or they can be arranged in other orientations.

[0026] FIG. **6** illustrates a further cascade **70**. The cascade **70** comprises a storage tank **72** that contains one or more pieces of foam **74** that are suspended within a heat transfer fluid **76**. The foam pieces **74** can be composed of a heat conducting material, such as metal. Regardless of their composition, the foam pieces **74** each comprise a plurality of pores that contain one or more PCMs. In some embodiments, each foam piece contains a single PCM. In other embodiments, each foam piece **74** contains a non-eutectic mixture of multiple PCMs. Each foam piece **74** can be covered with an impermeable outer cover or layer **78** that prevents the PCMs from migrating from the foam when in liquid form.

[0027] In the above-described systems, each cascade comprised one or more PCMs. It is noted, however, that one or more of the cascades could include sensible heat storage material. For instance, if the system included three cascades, the highest and lowest temperature cascades could comprise one or more PCMs, and the intermediate temperature cascade could comprise sensible heat storage material.

1. A thermal energy storage system comprising:
first cascade containing a first phase change material; and
a second cascade containing a second phase change material;
wherein the melting point of the first phase change material is different than the melting point of the second phase material.

2. The system of claim **1**, wherein the first and second cascades comprise first and second storage tanks and further comprising pipes that enable a heat transfer liquid to flow from one tank to the other tank.

3. The system of claim **1**, wherein the first and second cascades comprise first and second compartments of a single storage tank.

4. The system of claim **1**, wherein at least one of the phase change materials is contained within thermal energy storage capsules.

5. The system of claim **4**, wherein the thermal energy storage capsules comprise rigid capsule walls.

6. The system of claim **5**, wherein the capsule walls are spherical.

7. The system of claim **4**, wherein the thermal energy storage capsules contain a single phase change material.

8. The system of claim **4**, wherein the thermal energy storage capsules contain a non-eutectic mixture of multiple phase change materials.

9. The system of claim **4**, wherein the thermal energy storage capsules contain phase change material particles suspended within a liquid.

10. The system of claim **4**, wherein at least one of the cascades contains multiple types of thermal energy storage capsules, each type of capsule containing a different phase change material.

11. The system of claim **1**, wherein at least one of the cascades comprises a single phase change material in bulk.

12. The system of claim **1**, wherein at least one of the cascades comprises a non-eutectic mixture of multiple phase change materials in bulk.

13. The system of claim **1**, wherein at least one of the cascades comprises a piece of foam that contains a phase change material.

14. The system of claim **13**, wherein the piece of foam contains a single phase change material.

15. The system of claim **13**, wherein the piece of foam contains a non-eutectic mixture of multiple phase change materials.

16. A thermal energy storage capsule comprising:
a capsule wall that defines an interior space; and
a phase change material contained within the interior space.

17. The capsule of claim **16**, wherein the capsule wall is spherical.

18. The capsule of claim **17**, wherein the capsule has an outer diameter of approximately 1 to 2 inches.

19. The capsule of claim **16**, wherein the capsule contains a single phase change material.

20. The capsule of claim **16**, wherein the capsule contains a non-eutectic mixture of multiple phase change materials.

21. The capsule of claim **16**, wherein the capsule contains phase change material particles suspended within a liquid.

* * * * *