

PHASE CHANGE MATERIALS, HEAT EXCHANGERS AND ASSOCIATED THERMAL BATTERIES

TECHNICAL FIELD

Embodiments of the present invention relate to the design and manufacture of thermal batteries including the formulation of phase change materials (PCMs) and the design of the heat exchangers (HEXs). Embodiments of the present invention find application, though not exclusively, in the field of heating, ventilation and air conditioning (HVAC) systems.

BACKGROUND ART

Any discussion of documents, acts, materials, devices, articles or the like which has been included in this specification is solely for the purpose of providing a context for the present invention. It is not to be taken as an admission that any or all of these matters form part of the prior art base or were common general knowledge in the field relevant to the present invention as it existed in Australia or elsewhere before the priority date of this application.

PCMs that melt/freeze at various temperature ranges have been studied to identify their appropriate formulations. However, it has been appreciated by the inventors that the correct ratio for the component chemicals used to formulate the PCMs is critical to achieving the desired phase change temperatures and latent heat. Additionally, for salt-hydrate PCMs, it is challenging to determine suitable additives, and ratios of those additives, needed to address various shortcomings such as subcooling and phase separation. It has been appreciated by the inventors that it would be beneficial to develop new formulations offering the desirable thermal, physical, chemical, stability, environmental and/or economic properties and that may be suited to particular applications.

Typically, prior art HEX's are designed for the transfer of heat between stationary/moving fluids with a distinct temperature difference, which facilitates the heat transfer process. It has been appreciated by the inventors that it would be beneficial to provide HEX's that have performance characteristics that are suited to various usages, for example usage within a thermal battery involving heat transfer occurring as a result of the latent heat associated with liquid-solid phase change. In particular, it would be beneficial to

develop HEX's providing for rapid discharge and that are engineered to promote a specific amount of thermal charging/discharging.

SUMMARY OF THE INVENTION

It is an object of the present invention to overcome, or substantially ameliorate, one or more of the disadvantages of the prior art, or to provide a useful alternative.

In one aspect of the present invention there is provided a PCM having a phase change temperature of between approximately 3°C and approximately 26°C, the PCM including: 35% to 60% by weight of an inorganic salt; 1% to 9% by weight of a nucleating agent; 1% to 4% by weight of a thickening agent; and 30% to 66% by weight of water.

According to a second aspect of the invention there is provided a HEX including: a plurality of plates, each plate defining at least one fluid flow path extending across the plate, the fluid flow path being for flow of a heat transfer fluid; the plurality of plates being disposed in a regular array and being spaced from each other so as to define a volume intermediate adjacent plates for receipt of a PCM; wherein, when disposed in the regular array, a first flow path extending across a first plate is offset relative to a second flow path extending across a second plate adjacent to the first plate.

Preferably, the fluid flow paths are configured such that, in use, a flow of the heat transfer fluid through a fluid flow path at a target in-use flow rate results in turbulence in the heat transfer fluid having a Reynolds number of between 4000 and 7500.

According to another aspect of the invention there is provided a thermal battery including: a tank; a HEX housed within the tank; and a PCM housed within the tank in thermal exchange with the HEX.

Preferably, the PCM utilised in the thermal battery is as described above. Additionally, or alternatively, the PCM may be formulated in accordance with the method as described above.

In one embodiment of the thermal battery, the HEX is as described above.

The features and advantages of the present invention will become further apparent

from the following detailed description of preferred embodiments, provided by way of example only, together with the accompanying drawings.

BRIEF DESCRIPTION OF THE ACCOMPANYING DRAWINGS

Figure 1 is a graph of energy storage vs temperature for a first embodiment of a PCM;

Figure 2 is a graph of energy storage vs temperature for a second embodiment of a PCM;

Figure 3 is a graph of energy storage vs temperature for a third embodiment of a PCM;

Figure 4 is an isometric view of an embodiment of a HEX according to an aspect of the invention;

Figure 5 is an isometric view of an embodiment of a plate as used in the HEX of figure 4;

Figure 6 is a front side view of the plate of figure 5 including some exemplary dimensions (in mm);

Figure 7 is a plan view of the plate of figure 5 including some exemplary dimensions (in mm);

Figure 8 is a plan view of the region labelled B in figure 7 showing a close-up of an inlet of a plate including some exemplary dimensions (in mm);

Figure 9 is a right side view of the plate of figure 5 including some exemplary dimensions (in mm);

Figure 10 is a cross sectional view of a thermal battery having the HEX housed therein, with the cross section taken along a horizontal centreline of the thermal battery extending orthogonal to each of the plates and including some exemplary dimensions (in mm);

Figure 11 is a close-up view extracted from figure 10 showing the horizontal cross section of some of the fluid flow paths of some plates in more detail including some exemplary dimensions (in mm);

Figure 12 is a isometric cross sectional view of a plate with the cross section being

taken through a horizontal centre line of the plate;

Figure 13 is an isometric view of an embodiment of a tank for use as part of a thermal battery, the tank being configured to house a PCM and another embodiment of a HEX;

Figure 14 is an isometric view of another embodiment of a tank for use as part of a thermal battery, the tank being ready to receive the HEX illustrated in figures 4 to 12, along with the PCM;

Figure 15 is an isometric view of the embodiment of a thermal battery using the tank shown in figure 14, with the HEX installed therein and without a lid;

Figure 16 is an isometric view of a thermal battery identical to that of figure 15, but with hidden detail being shown;

Figure 17 is a graph showing simulated results for water output temperature vs time and PCM melt fraction vs time for an embodiment of a thermal battery according to an aspect of the invention making use of the ISO+5 PCM (water mass flow rate = 2400 kg/h, water inlet temperature = 15 °C, ISO+5 initial temperature = -3 °C);

Figure 18 is a graph showing simulated results for power discharge rate vs time for the embodiment of a thermal battery making use of the ISO+5 PCM (water mass flow rate = 2400 kg/h, water inlet temperature = 15 °C, ISO+5 initial temperature = -3 °C);

Figure 19 is a graph showing simulated results for water output temperature vs time and PCM melt fraction vs time for an embodiment of a thermal battery according to an aspect of the invention making use of the ISO+12 PCM (water mass flow rate = 2400 kg/h, water inlet temperature = 22 °C, ISO+12 initial temperature = 3 °C);

Figure 20 is a graph showing simulated results for power discharge rate vs time for the embodiment of a thermal battery making use of the ISO+12 PCM (water mass flow rate = 2400 kg/h, water inlet temperature = 22 °C, ISO+12 initial temperature = 3 °C);

Figure 21 is a graph showing simulated results for water output temperature vs time and PCM melt fraction vs time for an embodiment of a thermal battery according to an aspect of the invention making use of the ISO+25 PCM (water mass flow rate = 2400 kg/h, water inlet temperature = 35 °C, ISO+25 initial temperature = 17 °C); and

Figure 22 is a graph showing simulated results for power discharge rate vs time for the embodiment of a thermal battery making use of the ISO+25 PCM (water mass flow rate =

2400 kg/h, water inlet temperature = 35 °C, ISO+25 initial temperature = 17 °C).

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

Embodiments of the PCM can have a phase change temperature ranging between approximately 3°C and approximately 27°C. In general, at least one inorganic salt comprises 35% to 60% by weight of the PCM. At least one nucleating agent comprises 1% to 9% by weight of the PCM. At least one thickening agent comprises 1% to 4% by weight of the PCM. Typically, water makes up 30% to 66% of the PCM.

One preferred formulation of the PCM has a phase change temperature of between approximately 3°C and approximately 6°C. This formulation of the PCM includes 51% to 60% by weight of an inorganic salt, which is made up of 38% to 43% by weight of dipotassium hydrogen phosphate and 13% to 17% by weight of potassium fluoride. Nucleating agents comprise 3% to 9% by weight of this formulation of PCM, including 1% to 3% by weight of dicalcium phosphate, 1% to 3% by weight of aluminium oxide and 1% to 3% by weight of sodium chloride. This formulation of the PCM includes 1% to 4% by weight of a thickening agent, which in the preferred embodiment is a superabsorbent polymer such as sodium polyacrylate and/or a carbomer. Finally, this formulation includes approximately 30% to 40% by weight of water.

A preferred embodiment of the PCM, referred to herein as ISO+5, has a phase change temperature of between approximately 4°C and approximately 5°C. An energy storage vs temperature graph for this embodiment is shown in figure 1. Dipotassium hydrogen phosphate comprises approximately 40.3% (preferably 40.33%) by weight of the ISO+5 and potassium fluoride comprises approximately 15.0% (preferably 14.95%) by weight of the ISO+5. Dicalcium phosphate comprises approximately 2.3% (preferably 2.26%) by weight of the ISO+5. Aluminium oxide comprises approximately 2.3% (preferably 2.26%) by weight of the ISO+5. Sodium chloride comprises approximately 2.3% (preferably 2.26%) by weight of the ISO+5. The ISO+5 formulation includes approximately 2.7% (preferably 2.71%) by weight of sodium polyacrylate and/or a carbomer. Finally, the ISO+5 formulation has 35.2% (preferably 35.22%) by weight of water.

Testing using thermal cycling testing equipment and differential scanning calorimetry

(DSC) has shown the ISO+5 embodiment of the formulation to exhibit the following properties:

- a phase change temperature range of approximately 4°C to approximately 5°C;
- a latent heat of at least approximately 190 kJ/kg to 200 kJ/kg;
- a thermal conductivity in a solid phase of at least approximately 0.9 W/m·K and more specifically 1.0 W/m·K;
- a thermal conductivity in a liquid phase of at least approximately 0.5 W/m·K and more specifically 0.52 W/m·K;
- a specific heat capacity in a solid phase of at least approximately 1.4 kJ/kg·K and more specifically 1.5 kJ/kg·K;
- a specific heat capacity in a liquid phase of at least approximately 2.0 kJ/kg·K and more specifically 2.1 kJ/kg·K;
- a density in a solid phase of at least approximately 1700 kg/m³ and more specifically 1750 kg/m³; and
- a density in a liquid phase of at least approximately 1600 kg/m³ and more specifically 1650 kg/m³.

Another preferred formulation of the PCM has a phase change temperature of between approximately 9°C and approximately 13°C. This formulation of the PCM includes 48% to 58% by weight of an inorganic salt, which is made up of 30% to 36% by weight of sodium sulfate and 18% to 22% by weight of ammonium chloride. A nucleating agent, in the form of sodium tetraborate, comprises 1% to 3% by weight of this formulation of PCM. This formulation of the PCM includes 1% to 3% by weight of a thickening agent, which in the preferred embodiment is a superabsorbent polymer such as sodium polyacrylate and/or a carbomer. Finally, this formulation includes approximately 40% to 45% by weight of water.

A preferred embodiment of the PCM, referred to herein as ISO+12, has a phase change temperature of between approximately 10°C and approximately 12°C. An energy storage vs temperature graph for this embodiment is shown in figure 2. Sodium sulfate comprises approximately 33.6% (preferably 33.61%) by weight of the ISO+12. Ammonium chloride comprises 19.8% (preferably 19.80%) by weight of the ISO+12. Sodium tetraborate comprises approximately 2.0% (preferably 1.98%) by weight of the ISO+12. The ISO+12 formulation includes approximately 2.0% (preferably 1.98%) by weight of sodium polyacrylate and/or a carbomer. Finally, the ISO+12 formulation has 42.6% (preferably

42.62%) by weight of water.

Testing using thermal cycling testing equipment and DSC has shown the ISO+12 embodiment of the formulation to exhibit the following properties:

- a phase change temperature range of approximately 10°C to approximately 12°C;
- a latent heat of at least approximately 160 kJ/kg to 170 kJ/kg;
- a thermal conductivity in a solid phase of at least approximately 1.0 W/m·K and more specifically 1.05 W/m·K;
- a thermal conductivity in a liquid phase of at least approximately 0.5 W/m·K and more specifically 0.54 W/m·K;
- a specific heat capacity in a solid phase of at least approximately 1.4 kJ/kg·K and more specifically 1.5 kJ/kg·K;
- a specific heat capacity in a liquid phase of at least approximately 2.0 kJ/kg·K and more specifically 2.1 kJ/kg·K;
- a density in a solid phase of at least approximately 1500 kg/m³ and more specifically 1550 kg/m³; and
- a density in a liquid phase of at least approximately 1400 kg/m³ and more specifically 1450 kg/m³.

Another preferred formulation of the PCM has a phase change temperature of between approximately 23°C and approximately 27°C. This formulation of the PCM includes 35% to 43% by weight of an inorganic salt, which is made up of 20% to 24% by weight of disodium phosphate and 15% to 19% by weight of sodium carbonate. A nucleating agent, in the form of sodium tetraborate, comprises 1% to 3% by weight of this formulation of PCM. This formulation of the PCM includes 1% to 3% by weight of a thickening agent, which in the preferred embodiment is a superabsorbent polymer such as sodium polyacrylate and/or a carbomer. Finally, this formulation includes approximately 57% to 66% by weight of water.

A preferred embodiment of the PCM, referred to herein as ISO+25, has a phase change temperature of between approximately 24°C and approximately 26°C. An energy storage vs temperature graph for this embodiment is shown in figure 3. Disodium sulfate comprises approximately 21.8% (preferably 21.80%) by weight of the ISO+25. Sodium carbonate comprises 16.7% (preferably 16.67%) by weight of the ISO+25. Sodium tetraborate

comprises approximately 2.0% (preferably 2.00%) by weight of the ISO+25. The ISO+25 formulation includes approximately 2.0% (preferably 2.00%) by weight of sodium polyacrylate and/or a carbomer. Finally, the ISO+25 formulation has 61.5% (preferably 61.53%) by weight of water.

Testing using thermal cycling testing equipment and DSC has shown the ISO+25 embodiment of the formulation to exhibit the following properties:

- a phase change temperature range of approximately 24°C to approximately 26°C;
- a latent heat of at least approximately 190 kJ/kg to 200 kJ/kg;
- a thermal conductivity in a solid phase of at least approximately 1.0 W/m·K and more specifically 1.04 W/m·K;
- a thermal conductivity in a liquid phase of at least approximately 0.5 W/m·K and more specifically 0.52 W/m·K;
- a specific heat capacity in a solid phase of at least approximately 1.4 kJ/kg·K and more specifically 1.5 kJ/kg·K;
- a specific heat capacity in a liquid phase of at least approximately 2.0 kJ/kg·K and more specifically 2.1 kJ/kg·K;
- a density in a solid phase of at least approximately 1500 kg/m³ and more specifically 1550 kg/m³; and
- a density in a liquid phase of at least approximately 1400 kg/m³ and more specifically 1450 kg/m³.

It will be appreciated by those skilled in the art that some embodiments of the present invention provide PCMs exhibiting high latent heat capacity per unit volume or mass. In practice, this helps to minimize the size of the thermal storage systems that make use of the embodiments of the PCMs. Some embodiments also exhibit high thermal conductivity at both solid and liquid phases to enable heat transfer to/from the PCMs at a desirable rate during phase change. Specifically, some embodiments exhibit higher thermal conductivity and density compared to most prior art organic PCMs, as well as offering a narrow and well-defined melting temperature range. Some embodiments also exhibit small volume change during phase change at the typical operating temperatures, which can reduce the requirements for mechanical stability and PCM storage volume. Some embodiments also exhibit favourable phase stability, which eases the heat storage setting. Some embodiments also exhibit

congruent melting (i.e. in this context ‘congruent’ means without any significant changes of composition, enthalpy or phase change temperature during repeated phase change processes and without phase separation), which helps ensure that the PCM provides reliable and predictable performance and excellent long term stability throughout its projected operational lifespan. Hence, some embodiments avoid the low latent heat and phase separation issues that have been observed in some prior art inorganic PCMs operating within this temperature range. Some embodiments also exhibit high density, which helps reduce the overall sizing of the thermal storage systems making use of the PCM. Some embodiments also exhibit minimal sub-cooling. For improved safety, some embodiments of the PCM are non-toxic, non-flammable, not corrosive and non-explosive. Importantly, some embodiments exhibit low cost because their raw materials are readily commercially available at affordable price points.

It is believed by the inventors that the favorable characteristics listed in the preceding paragraph give some embodiments of this PCM the potential to outperform prior art PCMs. These favorable characteristics also make some embodiments of this PCM promising candidates for various thermal energy storage applications requiring precise temperature control. Examples of new opportunities for thermal energy storage that are potentially opened up by embodiments of the PCM include applications such as temperature-controlled shipping and storage of temperature-sensitive products, such as medical devices, pharmaceuticals, vaccines, and biologics. Other potential applications include temperature control in food and beverage storage and transportation, particularly for products that require a specific temperature range to maintain their quality and safety. Other potential applications include thermal energy storage in buildings to regulate indoor temperature, improve energy efficiency and reduce heating and cooling load for air conditioners and chillers. Yet other potential applications include temperature-controlled packaging for products that require specific temperature ranges during transportation, such as blood samples or medical devices. Further potential applications include cooling vests or blankets for medical applications, such as post-operative recovery, fever reduction, and emergency medical response.

The thermal battery 1 shown in figures 15 and 16 includes a tank 2, which is configured to house a PCM. In some embodiments the PCM used within the thermal battery 1 is selected from amongst those described above. The tank 2 is made from a suitably strong, liquid impervious material. More specifically, the tank 2 of some embodiments is made from stainless steel, such as SS304, and in other embodiments the tank 2 is made from a

thermoplastic polymer, such as polypropylene, or the like. Some embodiments of the tank 2 also include a thermally insulative outer shroud (not illustrated) surrounding the tank 2. The embodiment of the tank 2 illustrated in figure 13 includes externally disposed buttressing members 3 to help resist the outward mechanical stresses exerted by the PCM housed within the tank 2.

In one embodiment, the external dimensions of the thermal battery 1 are sized to allow it to pass through an average sized doorway. This allows the embodiment of the thermal battery 1 to be easily brought into a typical air conditioning plant room.

A HEX 4 is also housed within the tank 2. In some embodiments the HEX used within the thermal battery 1 is the HEX 4 illustrated in figure 4, which is discussed in more detail below. However, in other embodiments, such as that shown in figure 13, another embodiment of a HEX 6 may be utilised, which in the illustrated example is a shell-and-tube HEX with a series of serpentine tubes.

The HEX 4 includes a plurality of plates 5, each of which defines at least one fluid flow path 7 extending across the plate 5. As illustrated in figures 5, 6 and 7, for example, the fluid flow path 7 extends on each side of each of the plates 5 between an inlet 8 and an outlet 9 in a serpentine manner. An example of an inlet 8 (which is identical to an outlet 9) is illustrated in figure 8. The fluid flow paths 7 on each of the plates 5 are for flow of a heat transfer fluid, which in the preferred embodiment is typically water, although in other embodiments the heat transfer fluid could take other forms such as glycol, for example. In use, the heat transfer water flows into the inlet 8 that is disposed at a first edge 11 of the plate 5, along a straight section 10 of the fluid flow path 7 that spans a majority of the length between edge 11 and opposite edge 12 of the plate 5. This leads to a curved section 13 of the fluid flow path 7, which turns the heat transfer water through 180° and leads into another straight section 14 that extends back towards the first edge 11. The fluid flow path 7 continues in this manner through a plurality of straight sections and curved sections until the path 7 has extended in a serpentine manner across a majority of the face of the plate 5, after which the heat transfer water exits through the outlet 9.

Each of the serpentine fluid flow paths 7 preferably includes between fourteen and eighteen of the straight sections 14, with the illustrated preferred embodiment having a total of sixteen straight sections 14 of 686mm length each that are interlinked by a total of fifteen

curved sections 13 having an inner radius of 8mm and an outer radius of 26mm. Each of the curved sections 13 is disposed adjacent one of the edges 11 or 12 of the plate 5.

In some embodiments the cross-sectional shape of the fluid flow path is polygonal. In the illustrated embodiment, each of the fluid flow paths 7 has a 4-sided diamond cross-sectional shape 31. In some embodiments the 4-sided diamond cross-sectional shape has a pair of equal opposite internal angles of between 46° and 89° and in the illustrated embodiment this angle is 60° . In some embodiments the 4-sided diamond cross-sectional shape 31 has a minor diagonal length of between 15mm and 20mm and in the illustrated embodiment this length is 18mm. In some embodiments the 4-sided diamond cross-sectional shape 31 has a major diagonal length of between 22mm and 31mm and in the illustrated embodiment this length is 27.2mm. The outer two vertices of the diamond cross-sectional shape 31 are rounded, with a radius of approximately 2mm. These dimensions are best illustrated in figure 11.

In another embodiment, each of the fluid flow paths 7 has a circular cross-sectional shape having a diameter of between 12mm and 20mm. In yet another embodiment, each of the fluid flow paths 7 has an elliptical cross-sectional shape.

The distance between the centres of two adjacent straight sections 14 is preferably between 30mm and 38mm and in the illustrated embodiment this distance is 34mm, as best shown in figure 11. The length of each serpentine fluid flow path 7 as defined on each of the plates 5 is preferably between 10.4m and 13.1m and in the illustrated embodiment this length is 11.8m.

In one embodiment, each of the plates 5 is initially formed from a pair of pieces of stainless steel sheeting. In one manufacturing method, each of the sheets is stamped to form either a left half or a right half of the plate including half of the fluid flow path. The two sheets are then joined together along the plate centre line such that the two halves of the fluid flow path are in opposing alignment with each other. This is done using a connection method such as welding, adhesive, or the like. In another manufacturing method, each of the sheets is formed from a blow moulding process in which the whole plate is formed without a need to join separate pieces. The final step in the manufacture of a plate 5 is attachment of an inlet 8 and an outlet 9 to either end of the fluid flow path 7.

As shown for example in figure 16, the plurality of plates 5 are disposed within the tank 2 in a regular array in which the plates 5 are parallel to each other and each plate 5 extends across the width of the tank 2 between the tank rear wall 17 and tank front wall 18. As best shown in figures 5 and 6, the third edge 15 of each of the plates 5 includes a planar projection 19 and the fourth edge 16 of each of the plates 5 includes a planar projection 20. The width of planar projection 19 is 42mm; whereas the width of planar projection 20 is 25mm. Hence, on each plate 5, the entire fluid flow path 7 is offset towards the fourth edge 16 relative to the outer perimeter of the plate 5. As best shown in figures 14 and 16, a slot assembly 21 having a plurality of slots 22 is disposed on the internal side of the tank rear wall 17. An identical slot assembly 21 is disposed on the internal side of the tank front wall 18. The slots 22 of the two slot assemblies 21 are in alignment with each other across the width of the tank 2, with the open ends of the slots 22 facing towards the centre of the tank 2. This allows the projections 19 and 20 of each plate 5 to be disposable within the slots 22 so as to mount the plate 5 within the tank 2 with the fluid flow path 7 in one of two possible offset options. In the first offset option, projection 19, which has a 42 mm width, is mounted in a slot 22 of the slot assembly 21 that is on the tank rear wall 17 and projection 20, which has a 25 mm width, is mounted in a slot 22 of the slot assembly 21 that is on the tank front wall 18. This results in the fluid flow path 7 being offset towards the tank front wall 18. In the second offset option, wider projection 19 is mounted in a slot 22 of the slot assembly 21 that is on the tank front wall 18 and narrower projection 20 is mounted in a slot 22 of the slot assembly 21 that is on the tank rear wall 17. This results in the fluid flow path 7 being offset towards the tank rear wall 17. Each plate 5 is disposed within the tank 2 in alternating offset options relative to the adjacent plates. Hence, the fluid flow path 7 of each plate 5 is offset relative to the fluid flow paths 7 of the adjacent plates 5. This results in the overall cross sectional flow path arrangement shown for example in figure 10, with the cross section being taken in a horizontal plane passing through the middle of the HEX 4.

More particularly, as shown in figure 10, the fluid flow path of the left-most plate 26, for example, when considered in cross section, is defined by the sixteen diamond-shaped passageways 31 on that plate 26. The fluid flow path of the adjacent plate 27 is defined by the sixteen diamond-shaped passageways 31 on adjacent plate 27. It can be seen that the sixteen diamond-shaped passageways 31 of the flow path of the left-most plate 26 are offset relative to the sixteen diamond-shaped passageways 31 of the flow path of the adjacent plate 27. This alternating offset pattern continues across all forty plates 5 of the HEX 4.

The centre line of each of the plates 5 is spaced from the centre line of an adjacent plate 5 with a separation distance of 29mm, which defines a volume 23 intermediate adjacent plates 5. It is within this volume 23 that the PCM is housed. Some PCM is also housed in the volume 24 between the left end plate 26 and the left sidewall 29 of the tank 4 and between right end plate 28 and the right sidewall 30 of the tank 4. Hence, the PCM housed in volume 23, and the heat transfer water that is housed within the diamond-shaped passageways 31, are in thermal exchange with each other. More specifically, in use, heat passes from the heat transfer water, through the 1mm thick thermally conductive walls 25 that form the fluid flow paths 7, and into the PCM, or vice versa.

It has been appreciated by the inventors that the turbulence experience by the heat transfer fluid as it flows through the flow paths 7 impacts upon the effectiveness of the HEX 4. Too little turbulence detracts from the heat exchange performance of the HEX. Too much turbulence can choke the flow of the heat transfer fluid as it flows through the inlet 8 or outlet 9 or through the flow paths 7. The details of the fluid flow paths 7, such as shape and dimensions, are configured such that, in use, a flow of the heat transfer fluid through the fluid flow path at a target in-use flow rate results in turbulence in the heat transfer fluid having a Reynolds number of between 4000 and 7500 and more preferably between 4500 and 7000. The target in-use flow rate used for the turbulence modelling is the median flow rate that is anticipated to be used during a typical heat exchange cycle. For a typical usage, the median flow rate is between about 1000 kg/hour and about 5000 kg/hour. For the illustrated preferred embodiment, the median flow rate is approximately 2400 kg of water flowing through the HEX 4 per hour.

As can be seen in figures 4 and 16, the HEX 4 includes an inlet manifold 32 that supplies the heat transfer water to the inlet 8 of a first plate 5. The heat transfer water then flows through the flow path 7 of the first plate, out the outlet 8 of the first plate 5, through a connector tube 33, and into the inlet of an adjacent plate 5. This continues until the heat transfer water has flowed through a total of five plates 5. At this point the heat transfer water exits from the outlet 9 of the fifth plate 5 and into an exhaust manifold 34. This collection of five plates 5 is referred to as a channel and the illustrated embodiment has a total of eight channels.

In a typical implementation, the thermal battery 1 is charged by being cooled at night or when low cost electricity is accessible until the PCM freezes. This occurs either solely due to the low nightly ambient temperature, or with the assistance of cooling machinery, such as an air conditioning system that is preferably being powered at off-peak energy rates. The thermal insulation of the thermal battery 1 keeps the PCM frozen as the temperature rises during the following day. Once the ambient temperatures are high, it is beneficial to discharge the thermal battery 1 to assist an external system that needs to lose heat, such as an air conditioning system running on a hot day, for example. At this point, hot heat transfer water from the external system is pumped into the inlet manifold 32. This results in flow of the hot water through the channels of the HEX 4, which cools the water. The cooled water then returns to the external system via exhaust manifold 34. This type of arrangement can help reduce the energy usage of the external system during the peak energy periods that are typically applicable during the daytime. It will be appreciated that this has the potential to contribute to substantial energy cost savings.

In another embodiment, the thermal battery is charged by being cooled during a period in which excess on-site electricity is generated or when low cost renewable energy is available. Once charged, the thermal battery 1 is subsequently available for discharge during peak cooling demand/ high electricity tariff periods.

The types of PCMs likely to be used within the HEX 4 typically have low thermal conductivity, usually below 1 W/(mK) , which hinders the heat transfer rate into and out of the PCM. The heat transfer rate can be enhanced by minimizing the thermal resistance in the PCM regime by increasing the heat transfer area that is available between the PCM and the HEX 4. However, an increase in heat transfer area will generally result in a more costly HEX 4. Therefore, the design of the HEX 4 entails a compromise between the thermal performance of the thermal battery 1 and the cost. The design of the HEX 4 aims to achieve a low thermal resistance of the PCM to be on a similar scale to the thermal resistance of the heat transfer fluid.

Figures 17 and 18 illustrate simulated results for the discharge of a thermal battery making use of the ISO+5 PCM and making use of the illustrated HEX 4. In this simulation, the initial temperature of the PCM is -3°C , the water inlet temperature is 15°C and the water flow rate is 2400 kg/hr. This simulation revealed the following performance metrics.

Simulation results for ISO+5

Average water outlet temperature during the period 0 - 0.2 h (°C)	-0.6
Average water outlet temperature during the period 0.2 - 1 h (°C)	5.7
Average water outlet temperature during the period 1 - 1.5 h (°C)	12.4
Average cooling discharge rate during the period 0 - 0.2h (kW)	45.2
Average cooling discharge rate during the period 0.2 - 1h (kW)	25.8
Average cooling discharge rate during the period 1 - 1.5h (kW)	7.1
Total cooling energy: 0 - 1.5 h (kWh)	33.3

Figures 19 and 20 illustrate simulated results for the discharge of a thermal battery making use of the ISO+12 PCM and making use of the illustrated HEX 4. In this simulation, the initial temperature of the PCM is 3°C, the water inlet temperature is 22°C and the water flow rate is 2400 kg/hr. This simulation revealed the following performance metrics.

Simulation results for ISO+12

Average water outlet temperature during the period 0 - 0.2 h (°C)	5.6
Average water outlet temperature during the period 0.2 - 1 h (°C)	12.0
Average water outlet temperature during the period 1 - 1.5 h (°C)	18.3
Average cooling discharge rate during the period 0 - 0.2h (kW)	44.8
Average cooling discharge rate during the period 0.2 - 1h (kW)	25.0
Average cooling discharge rate during the period 1 - 1.5h (kW)	7.6
Total cooling energy: 0 - 1.5 h (kWh)	31.2

Figures 21 and 22 illustrate simulated results for the discharge of a thermal battery making use of the ISO+25 PCM and making use of the illustrated HEX 4. In this simulation,

the initial temperature of the PCM is 17°C, the water inlet temperature is 35°C and the water flow rate is 2400 kg/hr. This simulation revealed the following performance metrics.

Simulation results for ISO+25

Average water outlet temperature during the period 0 - 0.2 h (°C)	19.5
Average water outlet temperature during the period 0.2 - 1 h (°C)	25.5
Average water outlet temperature during the period 1 - 1.5 h (°C)	31.4
Average cooling discharge rate during the period 0 - 0.2h (kW)	44.9
Average cooling discharge rate during the period 0.2 - 1h (kW)	26.4
Average cooling discharge rate during the period 1 - 1.5h (kW)	10.0
Total cooling energy: 0 - 1.5 h (kWh)	35.1

While a number of preferred embodiments have been described, it will be appreciated by persons skilled in the art that specific operational requirements will necessitate numerous variations and/or modifications to the invention without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A phase change material (PCM) having a phase change temperature of between approximately 3°C and approximately 27°C, the PCM including:
 - 35% to 60% by weight of an inorganic salt;
 - 1% to 9% by weight of a nucleating agent;
 - 1% to 4% by weight of a thickening agent; and
 - 30% to 66% by weight of water.
2. A PCM according to claim 1, wherein the phase change temperature is between approximately 3°C and approximately 6°C and wherein the PCM includes:
 - 51% to 60% by weight of an inorganic salt;
 - 3% to 9% by weight of a nucleating agent;
 - 1% to 4% by weight of a thickening agent; and
 - 30% to 40% by weight of water.
3. A PCM according to claim 2, wherein the inorganic salt includes:
 - 38% to 43% by weight of dipotassium hydrogen phosphate; and
 - 13% to 17% by weight of potassium fluoride.
4. A PCM according to claim 2 or 3, wherein the nucleating agent includes:
 - 1% to 3% by weight of dicalcium phosphate;
 - 1% to 3% by weight of aluminium oxide; and
 - 1% to 3% by weight of sodium chloride.
5. A PCM according to any one of claims 2 to 4, wherein the thickening agent is a superabsorbent polymer.
6. A PCM according to claim 5 wherein the superabsorbent polymer is sodium polyacrylate and/or a carbomer.
7. A PCM according to claim 1, wherein the phase change temperature is between approximately 4°C and approximately 5°C and wherein the PCM includes:

approximately 40.3% by weight of dipotassium hydrogen phosphate;
approximately 15.0% by weight of potassium fluoride;
approximately 2.3% by weight of dicalcium phosphate;
approximately 2.3% by weight of aluminium oxide;
approximately 2.3% by weight of sodium chloride;
approximately 2.7% by weight of sodium polyacrylate and/or a carbomer; and
approximately 35.2% by weight of water.

8. A PCM according to claim 7, wherein the PCM has at least one of the following properties:

a latent heat of at least approximately 190 kJ/kg;
a thermal conductivity in a solid phase of at least approximately 0.9 W/m·K;
a thermal conductivity in a liquid phase of at least approximately 0.5 W/m·K;
a specific heat capacity in a solid phase of at least approximately 1.4 kJ/kg·K;
a specific heat capacity in a liquid phase of at least approximately 2.0 kJ/kg·K;
a density in a solid phase of at least approximately 1700 kg/m³; and/or
a density in a liquid phase of at least approximately 1600 kg/m³.

9. A PCM according to claim 1, wherein the phase change temperature is between approximately 9°C and approximately 13°C and wherein the PCM includes:

48% to 58% by weight of an inorganic salt;
1% to 3% by weight of a nucleating agent;
1% to 3% by weight of a thickening agent; and
40% to 45% by weight of water.

10. A PCM according to claim 9, wherein the inorganic salt includes:

30% to 36% by weight of sodium sulfate; and
18% to 22% by weight of ammonium chloride.

11. A PCM according to claim 9 or 10, wherein the nucleating agent includes 1% to 3% by weight of sodium tetraborate.

12. A PCM according to any one of claims 9 to 11, wherein the thickening agent is a superabsorbent polymer.
13. A PCM according to claim 12 wherein the superabsorbent polymer is sodium polyacrylate and/or a carbomer.
14. A PCM according to claim 1, wherein the phase change temperature is between approximately 10°C and approximately 12°C and wherein the PCM includes:
approximately 33.6% by weight of sodium sulfate;
approximately 19.8% by weight of ammonium chloride;
approximately 2.0% by weight of sodium tetraborate;
approximately 2.0% by weight of sodium polyacrylate and/or a carbomer; and
approximately 42.6% by weight of water.
15. A PCM according to claim 14, wherein the PCM has at least one of the following properties:
a latent heat of at least approximately 160 kJ/kg;
a thermal conductivity in a solid phase of at least approximately 1.0 W/m·K;
a thermal conductivity in a liquid phase of at least approximately 0.5 W/m·K;
a specific heat capacity in a solid phase of at least approximately 1.4 kJ/kg·K;
a specific heat capacity in a liquid phase of at least approximately 2.0 kJ/kg·K;
a density in a solid phase of at least approximately 1500 kg/m³; and/or
a density in a liquid phase of at least approximately 1400 kg/m³.
16. A PCM according to claim 1, wherein the phase change temperature is between approximately 23°C and approximately 27°C and wherein the PCM includes:
35% to 43% by weight of an inorganic salt;
1% to 3% by weight of a nucleating agent;
1% to 3% by weight of a thickening agent; and
57% to 66% by weight of water.
17. A PCM according to claim 16, wherein the inorganic salt includes:
20% to 24% by weight of disodium phosphate; and

15% to 19% by weight of sodium carbonate.

18. A PCM according to claim 16 or 17, wherein the nucleating agent includes 1% to 3% by weight of sodium tetraborate.

19. A PCM according to any one of claims 16 to 18, wherein the thickening agent is a superabsorbent polymer.

20. A PCM according to claim 19, wherein the superabsorbent polymer is sodium polyacrylate and/or a carbomer.

21. A PCM according to claim 1, wherein the phase change temperature is between approximately 24°C and approximately 26°C and wherein the PCM includes:

- approximately 21.8% by weight of disodium phosphate;
- approximately 16.7% by weight of sodium carbonate;
- approximately 2.0% by weight of sodium tetraborate;
- approximately 2.0% by weight of sodium polyacrylate and/or a carbomer; and
- approximately 61.5% by weight of water.

22. A PCM according to claim 21, wherein the PCM has at least one of the following properties:

- a latent heat of at least approximately 190 kJ/kg;
- a thermal conductivity in a solid phase of at least approximately 1.0 W/m·K;
- a thermal conductivity in a liquid phase of at least approximately 0.5 W/m·K;
- a specific heat capacity in a solid phase of at least approximately 1.4 kJ/kg·K;
- a specific heat capacity in a liquid phase of at least approximately 2.0 kJ/kg·K;
- a density in a solid phase of at least approximately 1500 kg/m³; and/or
- a density in a liquid phase of at least approximately 1400 kg/m³.

23. A heat exchanger (HEX) including:

- a plurality of plates, each plate defining at least one fluid flow path extending across the plate, the fluid flow path being for flow of a heat transfer fluid;

the plurality of plates being disposed in a regular array and being spaced from each other so as to define a volume intermediate adjacent plates for receipt of a PCM;

wherein, when disposed in the regular array, a first flow path extending across a first plate is offset relative to a second flow path extending across a second plate adjacent to the first plate.

24. A HEX according to claim 23, wherein the fluid flow paths are configured such that, in use, a flow of the heat transfer fluid through a fluid flow path at a target in-use flow rate results in turbulence in the heat transfer fluid having a Reynolds number of between 4000 and 7500.

25. A HEX according to claim 24, wherein the Reynolds number is between 4500 and 7000.

26. A HEX according to any one of claims 23 to 25, wherein each of the fluid flow paths has a polygonal cross-sectional shape.

27. A HEX according to any one of claims 23 to 26, wherein each of the fluid flow paths has a 4-sided diamond cross-sectional shape.

28. A HEX according to claim 27 wherein the 4-sided diamond cross-sectional shape has a pair of equal opposite internal angles of between 46° and 89° .

29. A HEX according to claim 27 or 28 wherein the 4-sided diamond cross-sectional shape has a minor diagonal length of between 15mm and 20mm and a major diagonal length of between 22mm and 31mm.

30. A HEX according to any one of claims 23 to 25, wherein each of the fluid flow paths has a circular or elliptical cross-sectional shape.

31. A HEX according to claim 30 wherein the circular cross-sectional shape has a diameter of between 12mm and 20mm.

32. A HEX according to any one of claims 23 to 31, wherein the fluid flow path extending across each plate is offset relative to an outer perimeter of the plate such that each plate is disposable within the HEX with the fluid flow path in one of two possible offset options.
33. A HEX according to claim 32 wherein each plate is disposed within the HEX in alternating offset options relative to an adjacent plate such that the fluid flow paths of each plate are offset relative to the fluid flow path of an adjacent plate.
34. A HEX according to any one of claims 23 to 33, wherein each fluid flow path extends between an inlet and an outlet.
35. A HEX according to claim 34 including an inlet manifold configured, in use, to supply heat transfer fluid to at least some of the inlets and an exhaust manifold configured, in use, to receive heat transfer fluid from at least some of the outlets.
36. A HEX according to any one of claims 23 to 35, wherein each of the fluid flow paths includes between 14 and 18 straight sections spanning a majority of a length between opposite edges of the plate, the straight sections being interlinked by a plurality of curved sections disposed adjacent the opposite edges of the plate.
37. A HEX according to claim 36 wherein a distance between the centres of two adjacent straight sections is between 30mm and 38mm.
38. A HEX according to any one of claims 23 to 37, wherein a length of each fluid flow path as defined on each of the plates is between 10.4m and 13.1m.
39. A HEX according to claim 24, wherein the target in-use flow rate is between 1000 kg/hour and 5000 kg/hour.
40. A HEX according to any one of claims 23 to 39, wherein the fluid flow path is serpentine.
41. A thermal battery including:

a tank;
a HEX housed within the tank; and
a PCM housed within the tank in thermal exchange with the HEX.

42. A thermal battery according to claim 41 wherein the PCM is as defined in any one of claims 1 to 22.

43. A thermal battery according to claim 41 or 42 wherein the HEX is as defined in any one of claims 23 to 40.