US 20140284020A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2014/0284020 A1**

Amir et al. (43) **Pub. Date: Sep. 25, 2014**

(54) **ENERGY STORAGE AND THERMAL MANAGEMENT USING PHASE CHANGE MATERIALS IN CONJUNCTION WITH HEAT PIPES AND FOILS, FOAMS OR OTHER POROUS MEDIA**

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(21) Appl. No.: **14/026,975**

(22) Filed: **Sep. 13, 2013**

Related U.S. Application Data

(63) Continuation-in-part of application No. 13/357,254, filed on Jan. 24, 2012.

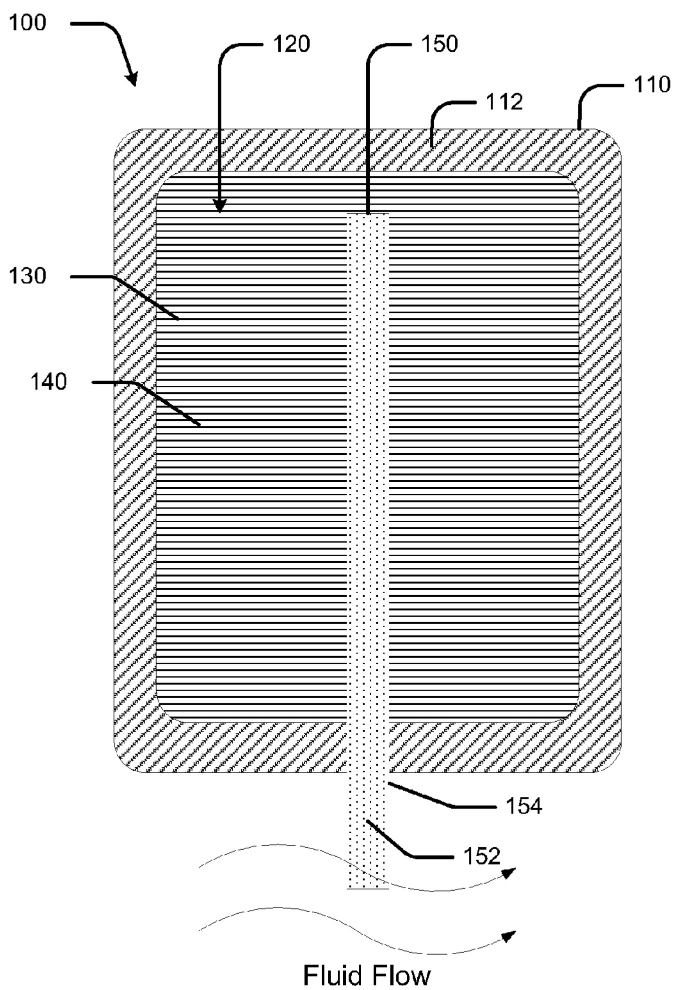
Publication Classification

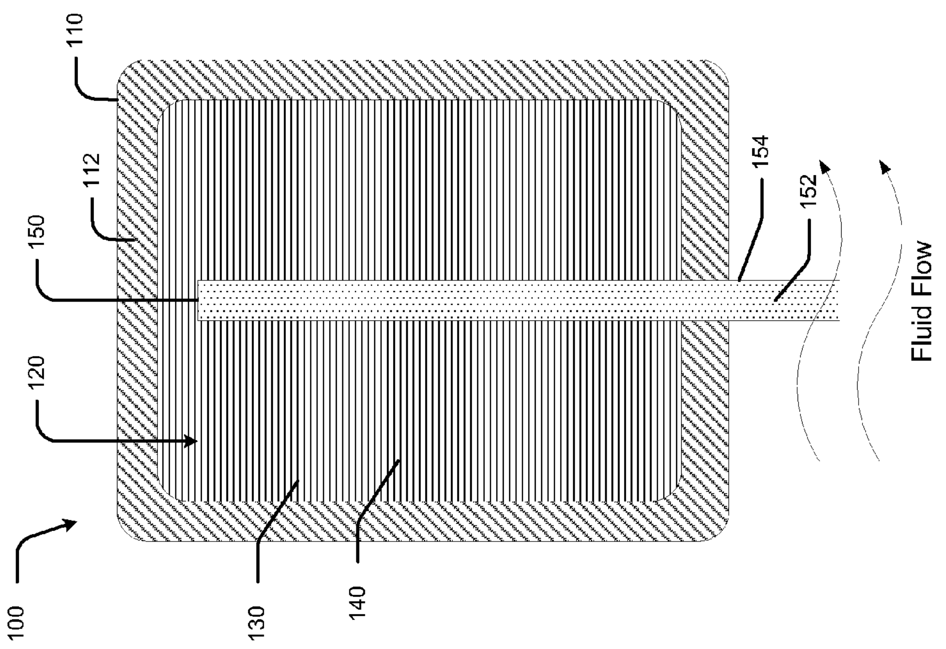
(51) **Int. Cl.**
F28D 15/04 (2006.01)

(52) **U.S. Cl.**
CPC ***F28D 15/04*** (2013.01)
USPC **165/10**

(57) **ABSTRACT**

In one aspect an apparatus to store energy comprises a housing defining an enclosed chamber, foils or foam formed from a thermally conductive material disposed in the chamber, a phase change material disposed within the chamber, and at least one heat pipe extending through the housing in thermal communication with the foam, or foil, and the phase change material. Other aspects may be described.




100
110
112
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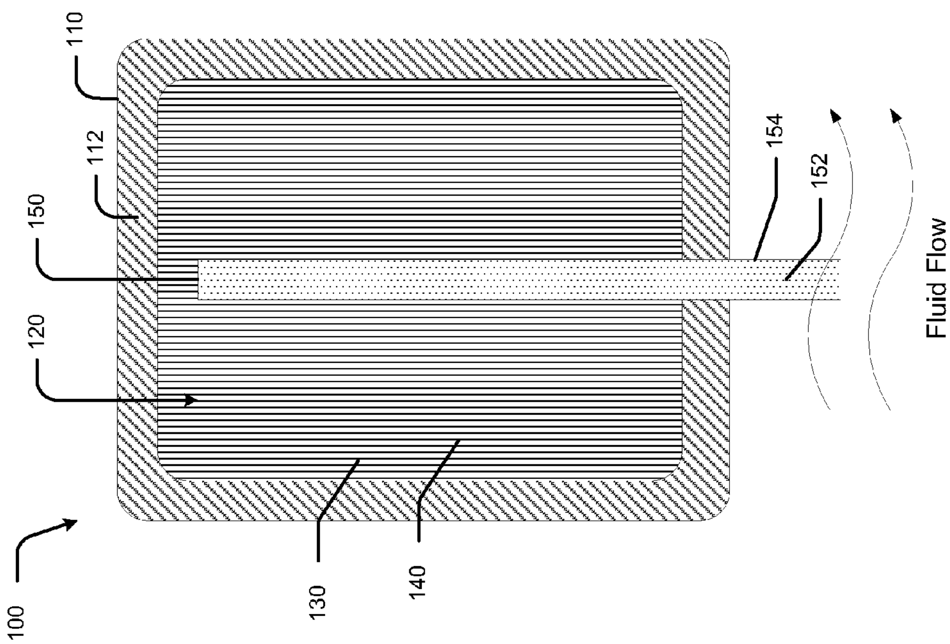
120
130
140
154
152
Fluid Flow

FIG. 1


100
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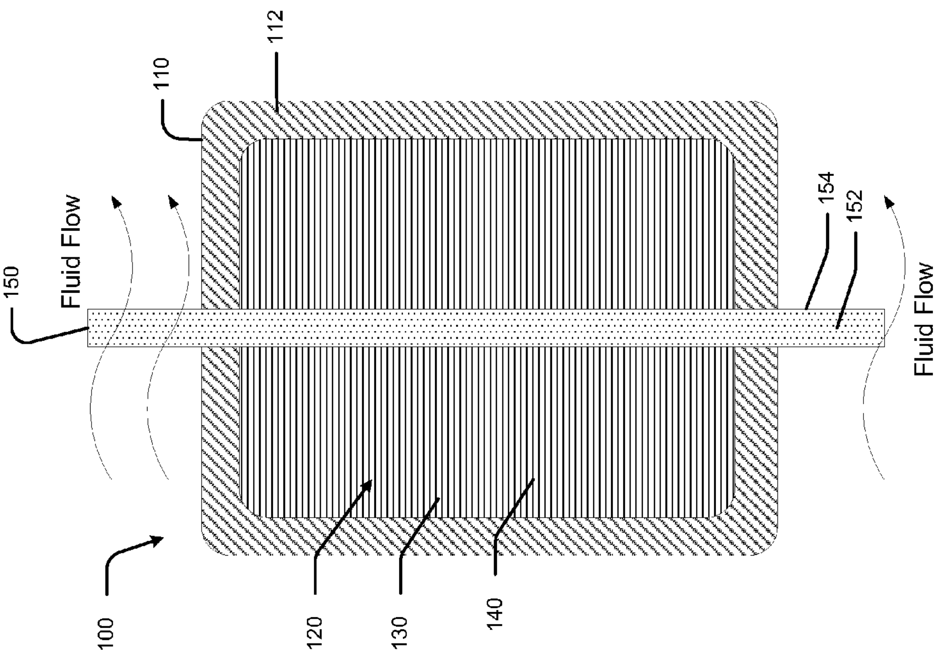
152
Fluid Flow

FIG. 2


100
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Fluid Flow
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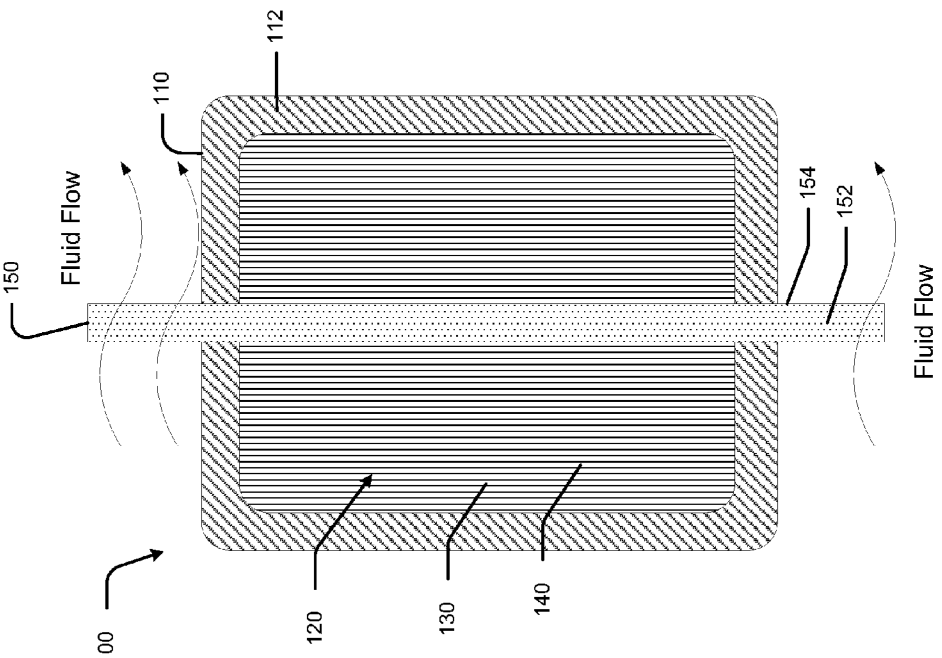
154
152
Fluid Flow

FIG. 3


100
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140
Fluid Flow
150
110
112
154
152
Fluid Flow

FIG. 4

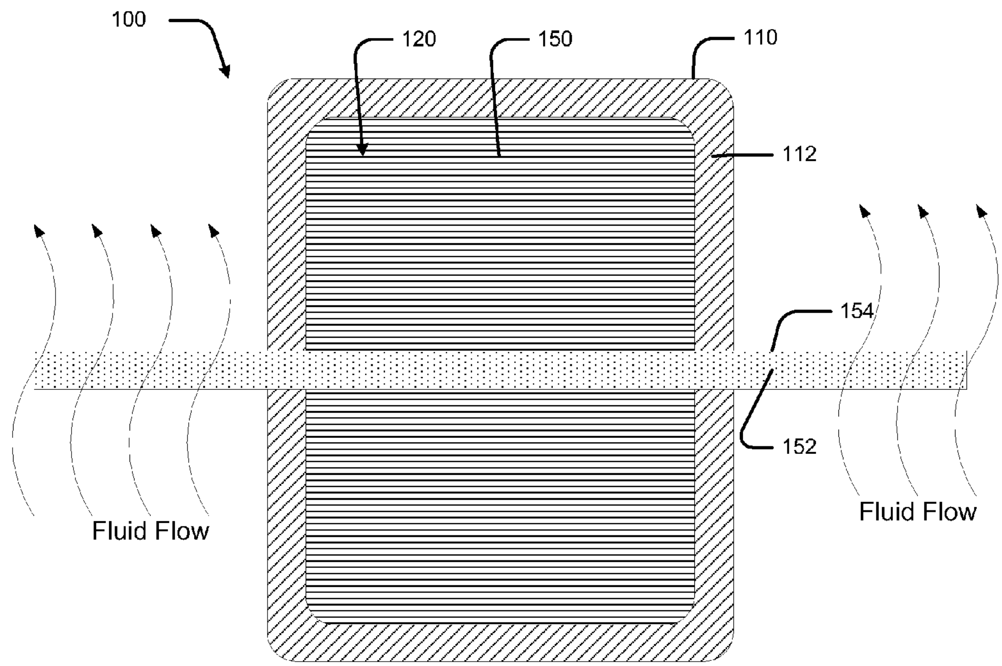

100
120
150
110
112
154
152
Fluid Flow
Fluid Flow

FIG. 5

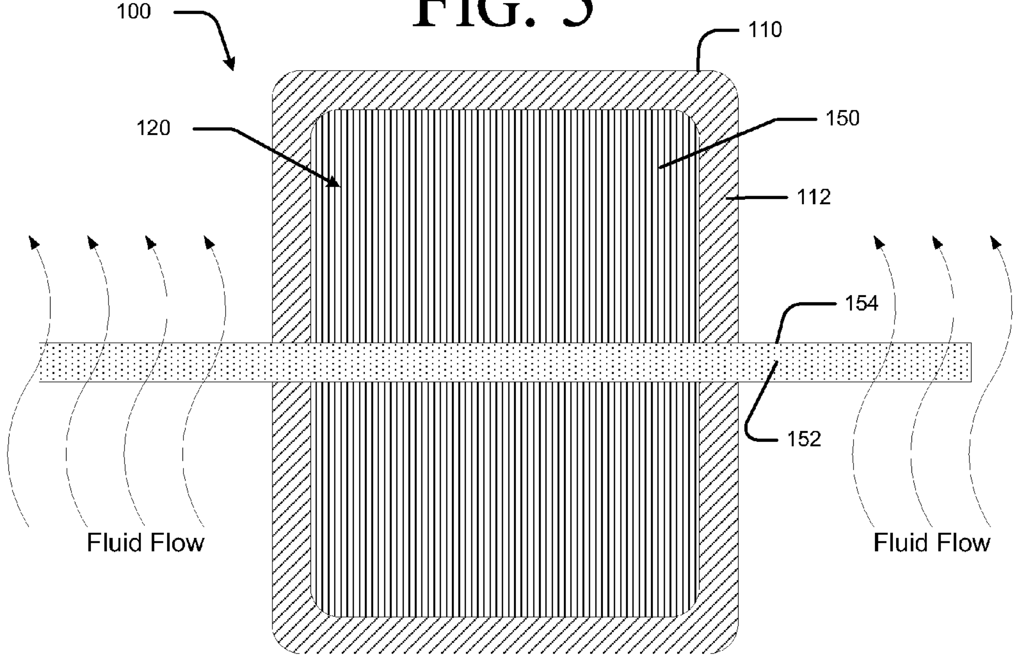

100
110
120
150
112
154
152
Fluid Flow
Fluid Flow

FIG. 6

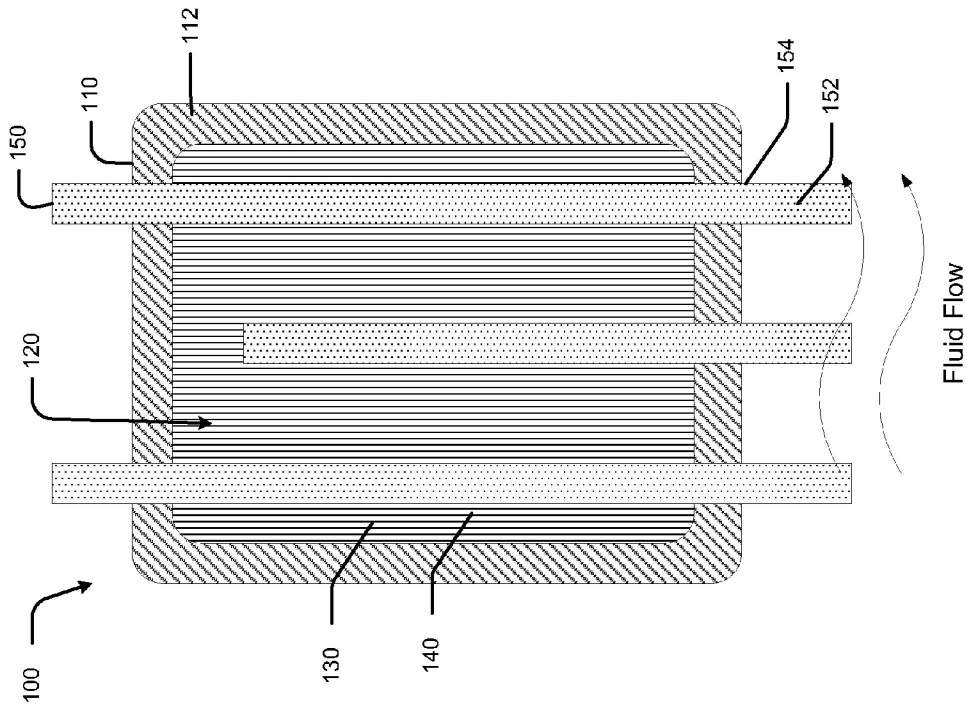
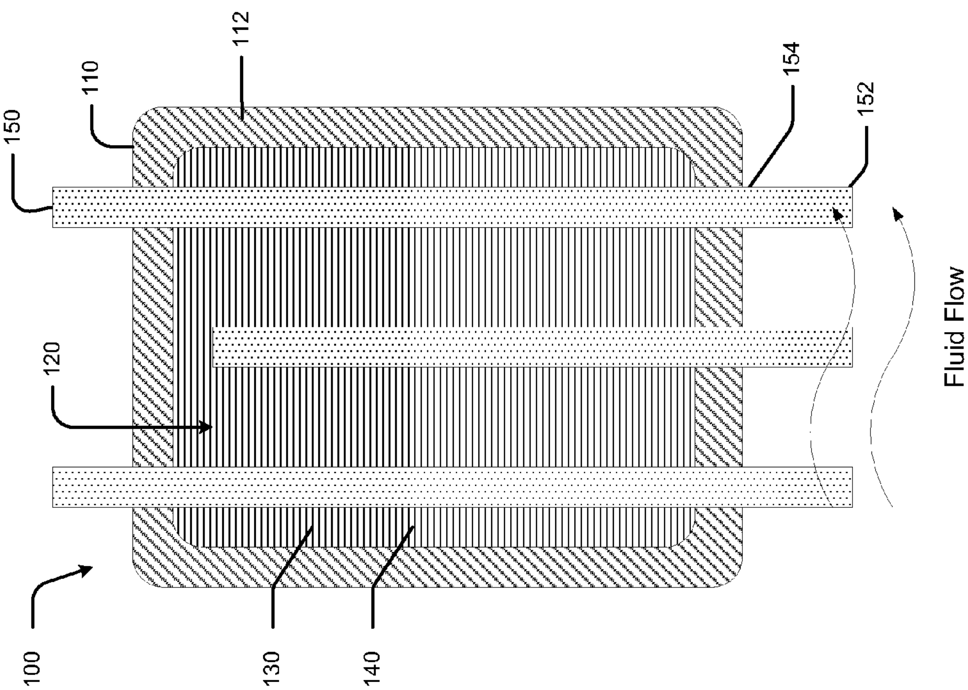

100
110
112
120
130
140
150
152
154
Fluid Flow

FIG. 8


100
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112
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130
140
150
152
154
Fluid Flow

FIG. 7

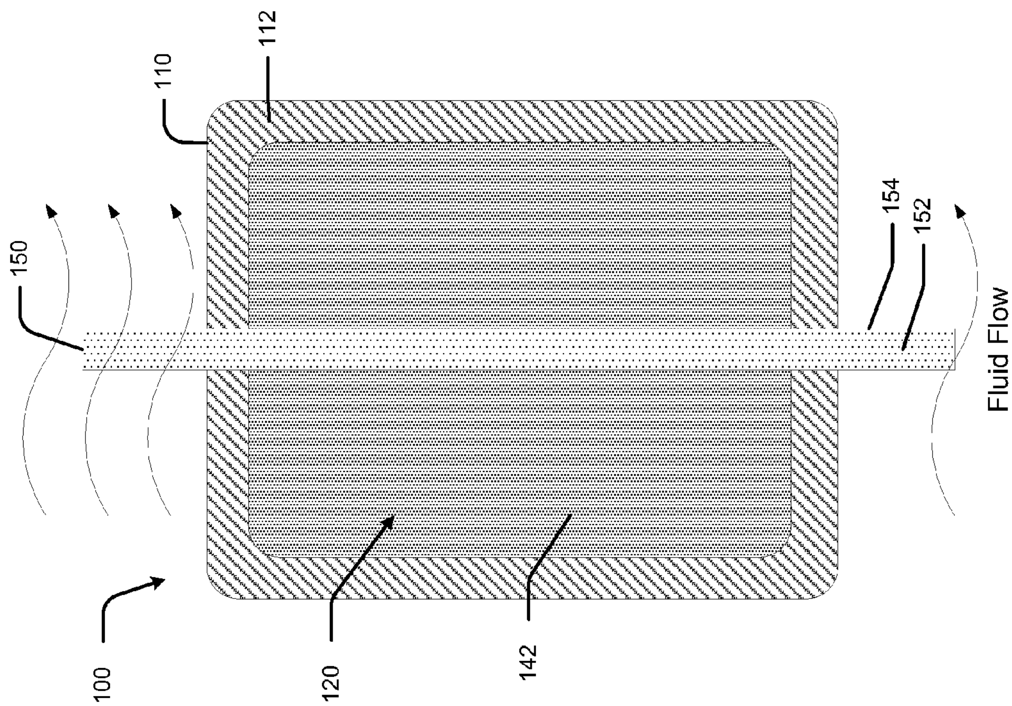
100
110
112
120
142
150
152
154
Fluid Flow

FIG. 10

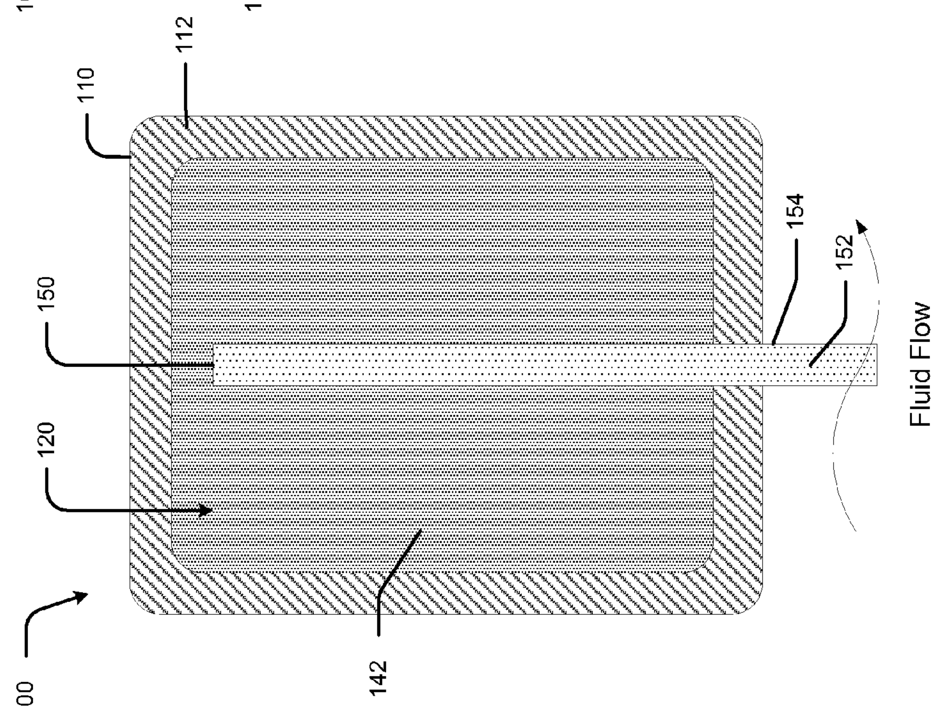
100
110
112
120
142
150
152
154
Fluid Flow

FIG. 9

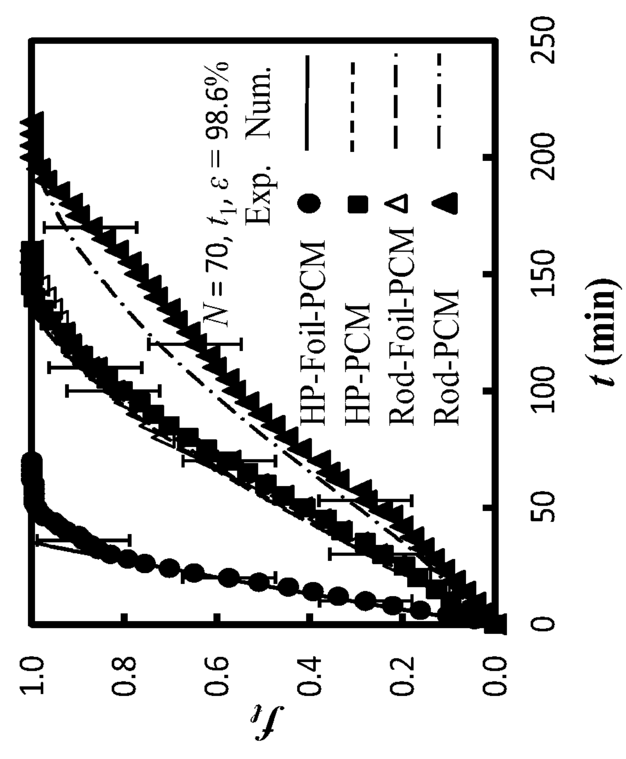
$N = 70$, t_1, $\varepsilon = 98.6\%$
Exp.
Num.
HP-Foil-PCM
HP-PCM
Rod-Foil-PCM
Rod-PCM
f_ℓ
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
t (min)

FIG. 11

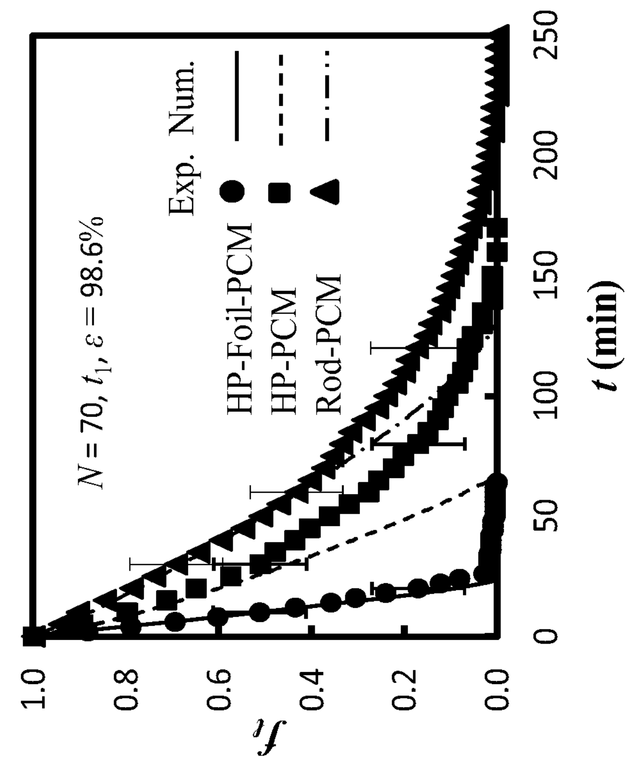
$N = 70$, t_1, $\varepsilon = 98.6\%$
Exp.
Num.
HP-Foil-PCM
HP-PCM
Rod-PCM
f_ℓ
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
t (min)

FIG. 12

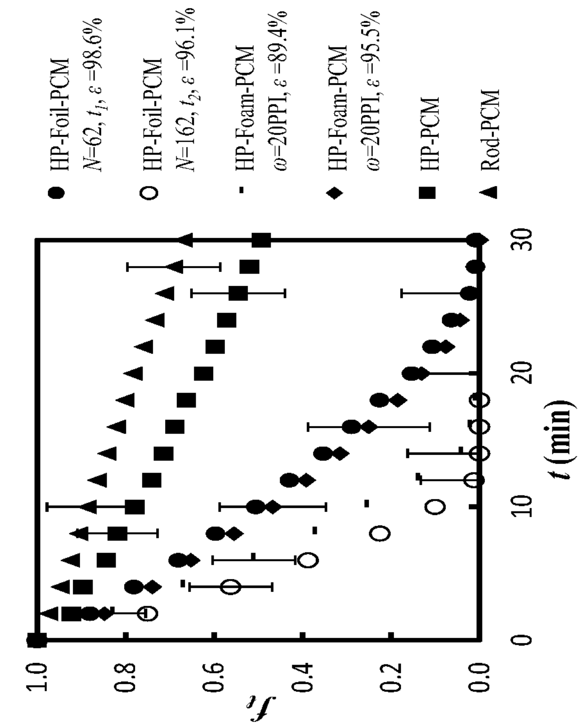
HP-Foil-PCM
N=62, t1, ε =98.6%
HP-Foil-PCM
N=162, t2, ε =96.1%
HP-Foam-PCM
ω=20PPI, ε =89.4%
HP-Foam-PCM
ω=20PPI, ε =95.5%
HP-PCM
Rod-PCM
fr
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
t (min)

FIG. 14

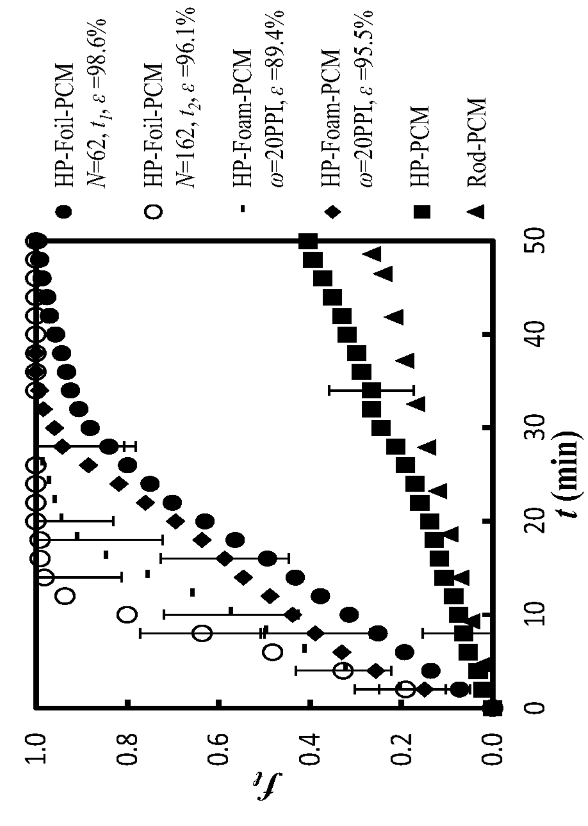
HP-Foil-PCM
N=62, t1, ε =98.6%
HP-Foil-PCM
N=162, t2, ε =96.1%
HP-Foam-PCM
ω=20PPI, ε =89.4%
HP-Foam-PCM
ω=20PPI, ε =95.5%
HP-PCM
Rod-PCM
fr
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
t (min)

FIG. 13

ENERGY STORAGE AND THERMAL MANAGEMENT USING PHASE CHANGE MATERIALS IN CONJUNCTION WITH HEAT PIPES AND FOILS, FOAMS OR OTHER POROUS MEDIA

RELATED APPLICATIONS

[0001] This application is related to U.S. patent application Ser. No. 13/357,254, to Faghri, et al., entitled UTILIZING PHANGE CHANGE MATERIAL, HEAT PIPES, AND FUEL CELLS FOR AIRCRAFT APPLICATIONS, filed Jan. 24, 2013, the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] The present disclosure relates generally to energy storage using phase change materials (PCM(s)).

[0003] Melting and solidification (including separate or simultaneous melting or solidification) of a PCM may be utilized in various applications to store and subsequently extract thermal energy in and from the PCM or to cool and heat various objects.

[0004] Phase change materials, including pure and eutectic among others, melt and freeze at a unique and known temperature (or temperature range), which provides an opportunity to precisely control the temperatures of objects being cooled or heated. Further, latent energy can be stored at a much higher energy density relative to sensible energy, resulting in reduced costs and smaller, as well as lighter, thermal management packages.

[0005] The high energy density of latent heat thermal energy storage is attractive in situations where space and weight are important such as but not limited to aerospace applications, automotive applications including thermal control of passenger cabins of electric vehicles, and waste heat recovery in automotive and aerospace applications. A more specific application is reducing the size and weight of equipment as seen in a small scale system associated with galleys or waste heat storage in commercial aircraft or for a large scale application in the field of concentrating solar power (CSP) plants.

[0006] Accordingly, systems and methods for energy storage using phase change materials may find utility in various applications.

SUMMARY

[0007] In at least one aspect, an apparatus to store energy comprises a housing defining an enclosed chamber, a foil formed from a thermally conductive metal material disposed in the chamber, a phase change material disposed within the chamber; and at least one heat pipe extending through the housing in thermal communication with the phase change material.

[0008] In another aspect, an apparatus to store energy comprises a housing defining an enclosed chamber, a phase change foam material disposed within the chamber, and at least one heat pipe extending through the housing in thermal communication with the phase change material.

[0009] The features, functions, and advantages described herein may be achieved independently in various aspects of the present disclosure or may be combined in yet other aspects, further details of which may be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Aspects of methods and systems in accordance with the teachings of the present disclosure are described in detail below with reference to the following drawings.

[0011] FIGS. **1-10** are schematic illustrations of aspects of apparatus to store energy, according to aspects.

[0012] FIG. **11** is a graph which illustrates melting rates for an apparatus to store energy, according to aspects.

[0013] FIG. **12** is a graph which illustrates solidification rates for an apparatus to store energy, according to aspects.

[0014] FIG. **13** is a graph which illustrates melting rates for an apparatus to store energy, according to aspects.

[0015] FIG. **14** is a graph which illustrates solidification rates for an apparatus to store energy, according to aspects.

[0016] Although specific features of various aspects may be shown in some drawings and not in others, this is for convenience only. Any feature of any drawing may be referenced and/or claimed in combination with any feature of any other drawing.

DETAILED DESCRIPTION

[0017] Described here are aspects of energy storage apparatus which combine heat pipes with a solid porous medium and/or an effective solid porous medium such as high thermal conductivity foams and/or foils, respectively, to increase melting and/or solidification rates of a phase change material and/or to reduce temperature differences between the hot or cold surfaces and the phase change material solid-liquid interfaces Improved thermal performance is achieved by reducing the thermal resistance between hot (or cold) surfaces or devices and the solid-liquid interface(s) of the phase change material as it undergoes phase change.

[0018] In the following description, numerous specific details are set forth to provide a thorough understanding of various aspects. However, it will be understood by those skilled in the art that the various aspects may be practiced without the specific details. In other instances, well-known methods, procedures, components, and circuits have not been illustrated or described in detail so as not to obscure the particular aspects.

[0019] FIGS. **1-10** are schematic illustrations of aspects of apparatus to store energy, according to aspects. Referring first to FIG. **1**, in some aspects an apparatus **100** to store energy comprises a housing **110** defining an enclosed chamber **120**, foils **130** formed from a thermally conductive metal material disposed in the chamber **120**, a phase change material **140** disposed within the chamber **120**, and at least one heat pipe or thermosyphon **150** extending through the housing in thermal communication with the foils **130** and the phase change material **140**.

[0020] The housing **110** can be formed from any solid material, rigid or flexible which may allow for PCM volume expansion. In some aspects the housing **110** may comprise a thermally insulative material **112** which may be formed from a suitable polymeric material, e.g., a plastic or the like, and may be formed into a three-dimensional shape, e.g., a cylinder or a rectangular prism. In other aspects, the housing **110** may comprise a material of high thermal conductivity such as copper **112**, such as for electronic cooling applications, or any combination of thermally conductive and thermally insulative materials. The particular dimensions and materials of the housing **110** are not critical and may vary based on the specific application to which the apparatus is applied. In some examples, the housing may have a height that measures between 1 inch and 12 feet and others with a radius that measures between 0.5 inches and 50 feet depending on the specific application.

[0021] In some aspects the foils **130** comprise a metallic, such as aluminum, or other non-metallic high thermal conductivity foils having a thickness that measures between 0.017 millimeters to 0.024 millimeters and the phase change material **140** comprises n-octadecane interspersed among aluminum foils **130** such as the experimental system producing the results presented in FIGS. **11-14**. The number of foils and the type of phase change material within the chamber is not critical and may vary based on the specific application to which the apparatus is applied. In some examples, the number of foils in the chamber may fall into a range between 100 foils and 5000 foils.

[0022] In some aspects the thermally conductive foils **130** are disposed in a first orientation in the chamber **120** and the heat pipe **150** extends into the chamber **120** in a second orientation, different from the first orientation. In the example depicted in FIG. **1** the thermally conductive foils **130** are disposed horizontally in the chamber **120** and the heat pipe **150** extends vertically through the chamber **120**. In other aspects the thermally conductive foils **130** are disposed in a first orientation in the chamber **120** and the heat pipe **150** extends through the chamber **120** in a second orientation, substantially the same as the first orientation. In the example depicted in FIG. **2** the thermally conductive foils **130** are disposed vertically in the chamber **120** and the heat pipe **150** extends vertically through the chamber **120**.

[0023] In some aspects, the heat pipes **150** may be fabricated from, for example, copper, aluminum, and/or steel and may include a working fluid **152** operating between approximately 0° C. and approximately 200° C. More particularly, in at least some aspects, the working fluid operates between approximately 25° C. and approximately 200° C. Even more particularly, in at least some aspects, the working fluids operate between approximately 25° C. and approximately 160° C. Working fluids for use in heat pipes **150** may include, without limitation, water and/or methanol. Moreover, in at least some aspects, heat pipes **150** include a wick structure that is fabricated from, for example, sintered metal powder, metal fibers, and/or screen mesh. Alternatively, heat pipes **150** may be fabricated from any other material and/or include any other fluid that enable heat transfer system **100** to function as described herein. For example, in at least one aspect, heat pipes **150** are in a vertical orientation and are gravity assisted. Further, heat pipe **150** may be enhanced with a thermally conductive material, e.g., a thermally conductive foam **154** to enhance the thermal conductance of the heat pipe **150** and improve heat transfer with a flowing fluid.

[0024] In operation, heat is exchanged between the phase change material **140** in the apparatus **100** and a heat source or heat sink such as a fluid flowing past the heat pipe **150**. For example, if the fluid flowing past the heat pipe **150** is at a higher temperature than the phase change material **140** then heat will be transferred from the fluid to the phase change material **140**, thereby storing energy in the apparatus **100**. By contrast, if the fluid flowing past the heat pipe **150** is at a lower temperature than the phase change material **140** then heat will be transferred from the phase change material **140** to the fluid, thereby releasing energy from apparatus **100**.

[0025] In the examples depicted in FIGS. **3-4** the heat pipe **150** extends through the chamber **120** and the housing **110**. In the example depicted in FIG. **3** the thermally conductive foils **130** are disposed horizontally in the chamber **120** and the heat pipe **150** extends vertically through the chamber **120**. In the example depicted in FIG. **4** the thermally conductive foils **130** are disposed vertically in the chamber **120** and the heat pipe **150** extends vertically through the chamber **120**. The apparatus **100** of FIGS. **3** and **4** allow for heat exchange with fluid flow on two sides of the apparatus **100**. In some examples the fluid flow on one side of the apparatus may be heated fluid for the purpose of melting the phase change material **140** while the fluid flow on the other side of the apparatus **100** may be cooled fluid for the purpose of solidifying the phase change material.

[0026] In the examples depicted in FIGS. **5-6** the heat pipe extends horizontally through the chamber **120** and the housing **110**. In the example depicted in FIG. **5** the thermally conductive foils **130** are disposed horizontally in the chamber **120** and the heat pipe **150** extends horizontally through the chamber **120**. In the example depicted in FIG. **6** the thermally conductive foils **130** are disposed vertically in the chamber **120** and the heat pipe **150** extends horizontally through the chamber **120**. The apparatus **100** of FIGS. **5** and **6** allow for heat exchange with fluid flow on two sides of the apparatus **100**. It will be recognized that the heat pipe(s) **150** and foils **130** may be oriented in both horizontal and vertical orientations, or in orientations other than horizontal or vertical. For example, heat pipes **150** may extend diagonally through the chamber **120**.

[0027] In some aspects the apparatus **100** may comprise multiple heat pipes **150** which extend into or through the chamber **120** of the apparatus. In the example depicted in FIG. **7** the thermally conductive foils **130** are disposed horizontally in the chamber **120** and two heat pipes **150** extend vertically through the chamber **120**, while one heat pipe **150** extends into the chamber **120**. In the example depicted in FIG. **8** the thermally conductive foils **130** are disposed vertically in the chamber **120** and two heat pipes **150** extend vertically through the chamber **120**, while one heat pipe **150** extends into the chamber **120**. The apparatus **100** of FIGS. **7** and **8** allow for heat exchange with fluid flows on two sides of the apparatus **100**.

[0028] In some aspects the apparatus **100** may incorporate a phase change material embedded in a high thermal conductivity foam. In the examples depicted in FIGS. **9-10** the apparatus may include a housing **110** defining an enclosed chamber **120**, a phase change material-foam composite **142** disposed within the chamber, and at least one heat pipe or thermosyphon **150** extending through the housing in thermal communication with the phase change material-foam composite. By way of example, the phase change material-foam composite **142** may comprise an aluminum foam and a paraffin wax (i.e. paraffin-aluminum foam composite). One skilled in the art will recognize that the apparatus **100** of FIGS. **9** and **10** could be constructed with the heat pipes **150** oriented horizontally or in another orientation.

[0029] The apparatus **100** depicted in FIGS. **1-10** may be incorporated into heat transfer systems such as the heat transfer systems described in U.S. Patent Application Publication No. 2013/0189594, incorporated by reference here above.

[0030] Working Examples

[0031] FIG. **11** is a graph which illustrates melting rates and volumetric liquid fractions for an apparatus **100** which comprises aluminum foils **130** and a heat pipe **150**. The variable f_1 represents the volumetric liquid fraction of phase change material **140** contained in the chamber **120** that is heated from below with flowing hot water, similar to the cases shown in the FIGS. **1-2**. The variable N stands for the number of foils **130** in the chamber **120**. The thickness of aluminum foil used in this experiment is t_1=0.017 mm. The porosity, ϵ, is defined as the volume occupied by phase change material **140** compared to the total volume (summation of PCM volume and metal foil volume). The phase change material is a long chain hydrocarbon (e.g., n-octadecane) and is initially completely solid, f_1=0, and at approximately 3° C. below the PCM melting temperature. The heat pipe is copper and is water-filled.

[0032] Melting results are illustrated for (i) a solid vertical copper rod placed concentrically in a cylindrical container (Rod-PCM), (ii) a solid vertical copper rod with thin sheets of common aluminum foil (Rod-Foil-PCM) (the foils occupy very little volume, only 1.4% of the volume nominally occupied by the PCM, in other words a porosity of ϵ=98.6%), (iii) a water-filled copper heat pipe of identical external dimensions as the rod but with no foil (HP-PCM), and (iv) the heat pipe and the foils (HP-Foil-PCM) (with a similar foil volume fraction of 1.4%). FIG. **11** shows that for a similar foil volume fraction, the melting rate of the HP-Foil-PCM is about three times greater than for the Rod-Foil-PCM (which exhibits a similar melting rate to the HP-PCM).

[0033] FIG. **12** is a graph which illustrates solidification rates and volumetric liquid fractions for an apparatus **100** which comprises aluminum foils **130** and a heat pipe **150**. In the example illustrated in FIG. **12**, the phase change material **140** is initially completely liquid, f_1=1.0, at about 3° C. above the phase change material **140** melting temperature. The combination of a heat pipe with foils and a phase change material significantly outperforms other approaches.

[0034] FIG. **13** is a graph which illustrates melting rates for an apparatus **100** which comprises a aluminum foam **142** and a heat pipe **150**, analogous to the apparatus depicted in FIG. **9**.

[0035] The pore density, ω, of the metal foam is defined by the number of pores per inch (PPI). In order to make a valid comparison between HP-Foil-PCM and HP-Foam-PCM, a similar porosity (similar metal volume) must be compared. For the example illustrated in FIGS. **13** and **14** foil thickness was t_2=0.024 mm to obtain a similar liquid fraction for both melting and solidification.

[0036] FIG. **13** shows melting rates under conditions similar to those associated with FIG. **11**. The data in FIGS. **13** and **14** for HP-PCM, Rod-PCM, and HP-Foil-PCM, N=62, t_1, ϵ=98.6% are similar cases as shown in FIGS. **11** and **12**, however with a different heat pipe length in the PCM container (FIG. **11** has a heat pipe length of 90 mm while in FIGS. **13** and **14** the length is 80 mm). A comparison between HP-Foil-PCM, N=62, t_1, ϵ=98.6% (solid circles) and HP-Foil-PCM, N=162, t_2, ϵ=96.1% (open circles) shows that the melting rate is doubled by slightly decreasing the porosity by about 3% (increasing the volume of metal by 3%). The second comparison at a constant porosity is seen between HP-Foil-PCM, N=162, t_2, ϵ=96.1% (open circles) and HP-Foam-PCM, ω=20PPI, ϵ=95.5% (solid diamonds). This result shows that the HP-Foil-PCM has a higher melting rate (by about twice the value) compared to the HP-Foam-PCM cases at approximately the same porosity. It can be noted that for the HP-Foam-PCM, ω=20PPI, ϵ=95.5% case (solid diamonds) shows a similar melting rate to HP-Foil-PCM, N=62, t_1, ϵ=98.6% (solid circles; which has a higher porosity). A comparison at constant pore density between HP-Foam-PCM, ω=20PPI, ϵ=89.4% (dashes) and HP-Foam-PCM, ω=20PPI, ϵ=95.5% (solid diamonds) agrees with the results comparing HP-Foil-PCM, N=62, t_1, ϵ=98.6% (solid circles) and HP-Foil-PCM, N=162, t_2, ϵ=96.1% (open circles) concluding that a lower porosity results in a higher melting rate. Lastly HP-Foil-PCM, N=162, t_2, ϵ=96.1% (open circles) also outperforms HP-Foam-PCM, ω=20PPI, ϵ=89.4% (dashes) even with a higher porosity (lower metal mass).

[0037] FIG. **14** is a graph which illustrates solidification rates for an apparatus **100** which comprises an aluminum foam **142** or aluminum foils **130** and a heat pipe **150**. All cases of HP-Foil-PCM and HP-Foam-PCM outperform the base case of Rod-PCM as well as the HP-PCM case. The optimal configuration for both melting and solidification is HP-Foil-PCM, N=162, t_2, ϵ=96.1% (open circles) which has a melting (i.e., solidification) rate of about 14 (8) times that of the Rod-PCM, which is an extraordinary improvement using a metal volume fraction of only 3.9%.

[0038] Exemplary aspects of methods and systems as well as the concept of integrating heat pipe(s) **150** with PCM and foils/foam for transferring, storing, and/or utilizing heat in an aircraft environment are described above in detail. The methods, systems, and the described concept are not limited to the specific aspects described herein, but rather, components of systems and/or steps of the method may be utilized independently and separately from other components and/or steps described herein. Each method step and each component may also be used in combination with other method steps and/or components. Although specific features of various aspects may be shown in some drawings and not in others, this is for convenience only. Any feature of a drawing may be referenced and/or claimed in combination with any feature of any other drawing.

[0039] This written description uses examples to disclose the aspects, including the best mode, and also to enable any person skilled in the art to practice the aspects, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the disclosure is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

[0040] In the description and claims, the terms coupled and connected, along with their derivatives, may be used. In particular aspects, connected may be used to indicate that two or more elements are in direct physical or electrical contact with each other. Coupled may mean that two or more elements are in direct physical or electrical contact. However, coupled may also mean that two or more elements may not be in direct contact with each other, but yet may still cooperate or interact with each other.

[0041] Reference in the specification to "one aspect" or "some aspects" means that a particular feature, structure, or characteristic described in connection with the aspect is included in at least one implementation. The appearances of the phrase "in one aspect" in various places in the specification may or may not be all referring to the same aspect.

[0042] Although aspects have been described in language specific to structural features and/or methodological acts, it is to be understood that claimed subject matter may not be limited to the specific features or acts described. Rather, the specific features and acts are disclosed as sample forms of implementing the claimed subject matter.

What is claimed is:

1. An apparatus to store energy, comprising:

a housing defining an enclosed chamber;

a foil formed from a thermally conductive material disposed in the chamber;

a phase change material disposed within the chamber; and

at least one heat pipe extending through the housing in thermal communication with the phase change material.

2. The apparatus of claim **1**, wherein:

the housing comprises at least one of a thermally insulative or thermally conductive material.

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

the phase change material is interspersed among the foil.

4. The apparatus of claim **3**, wherein the foil comprises an aluminum foil having a thickness that measures between 0.017 millimeters to 0.024 millimeters.

5. The apparatus of claim **4**, wherein:

the metallic foil is disposed in a first orientation in the chamber; and

the heat pipe extends through the chamber in a second orientation, different from the first orientation.

6. The apparatus of claim **4**, wherein:

the metallic foil is disposed horizontally in the chamber; and

the heat pipe extends vertically through the chamber.

7. The apparatus of claim **4**, wherein:

the thermally conductive foils are disposed vertically in the chamber; and

the heat pipe extends vertically through the chamber.

8. The apparatus of claim **4**, wherein:

the thermally conductive foils are disposed horizontally in the chamber; and

the heat pipe extends horizontally through the chamber.

9. The apparatus of claim **4**, wherein:

the thermally conductive foils are disposed vertically in the chamber; and

the heat pipe extends horizontally through the chamber.

10. The apparatus of claim **1**, wherein the heat pipe is formed from a thermally conductive metal and comprises a working fluid.

11. The apparatus of claim **1**, wherein the heat pipe is enhanced with at least one of a high thermal conductivity foam or fins outside of the PCM enclosure.

12. An apparatus to store energy, comprising:

a housing defining an enclosed chamber;

a phase change material-foam composite disposed within the chamber; and

at least one heat pipe extending through the housing in thermal communication with the phase change material.

13. The apparatus of claim **12**, wherein:

the housing comprises at least one of a thermally insulative or thermally conductive material.

14. The apparatus of claim **12**, wherein:

the phase change material-foam composite comprises an aluminum foam.

15. The apparatus of claim **12**, wherein the heat pipe is formed from a thermally conductive metal and comprises a working fluid.

16. The apparatus of claim **12**, wherein the heat pipe is enhanced with at least one of a high thermal conductivity foam or fins outside of the PCM enclosure.

17. The apparatus of claim **12**, wherein:

the heat pipe extends vertically through the chamber.

18. The apparatus of claim **12**, wherein:

the heat pipe extends horizontally through the chamber.

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