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(54) HIGH-TEMPERATURE LATENT HEAT STORAGE SYSTEM USING TRANSPORTABLE HEAT PIPES FOR VERSATILE INTEGRATION WITH EMERGING MICROREACTORS

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(57) **ABSTRACT**

A heat pipe integrated thermal battery ("HITB") is provided that may include a storage tank, a thermal storage medium within the storage tank, a guide tube extending within the storage tank and through at least one end of the storage tank, and a heat pipe configured to be movable within the guide tube. The heat pipe may be configured to discharge heat to and absorb heat from the thermal storage medium within the storage tank.

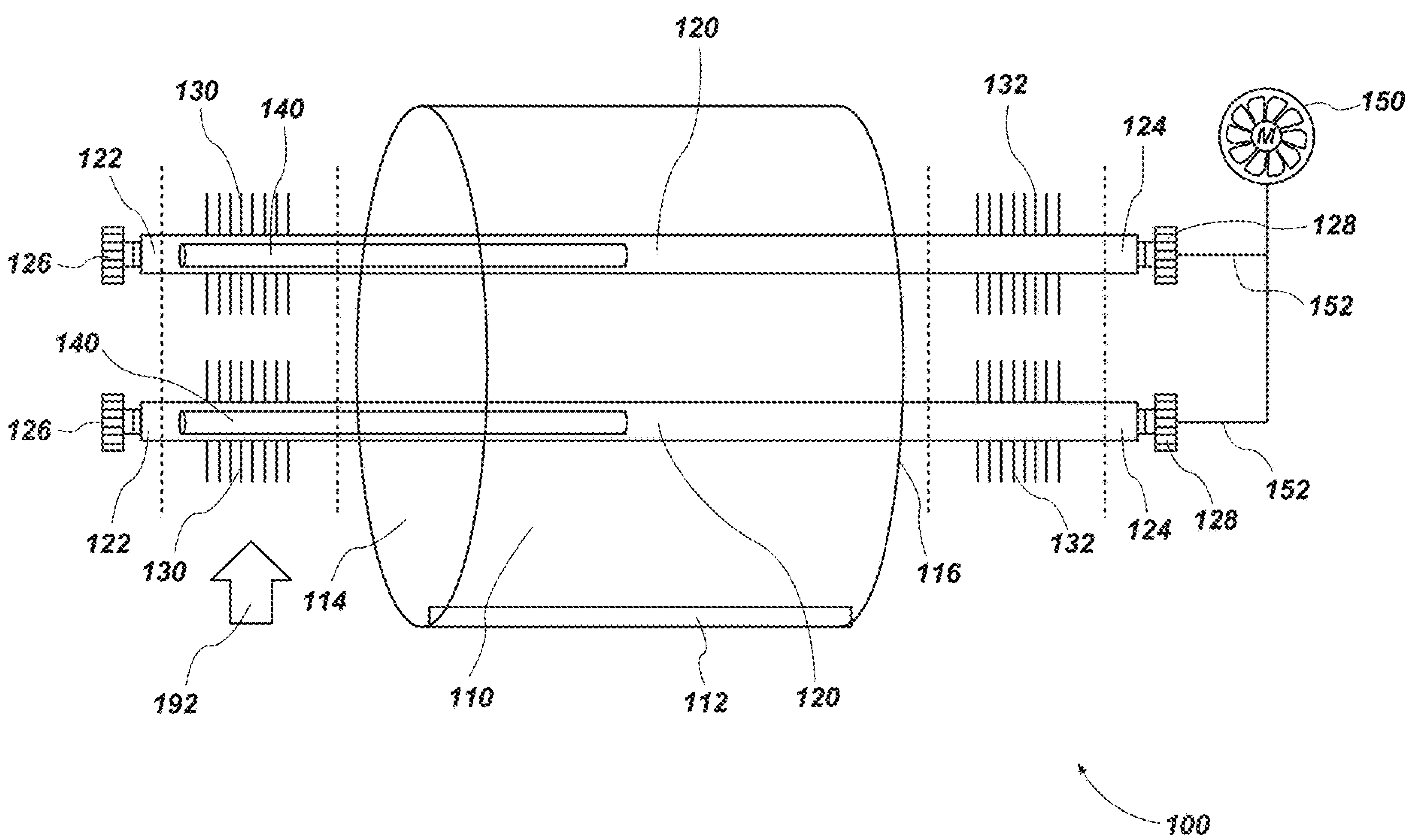


FIG. 1A

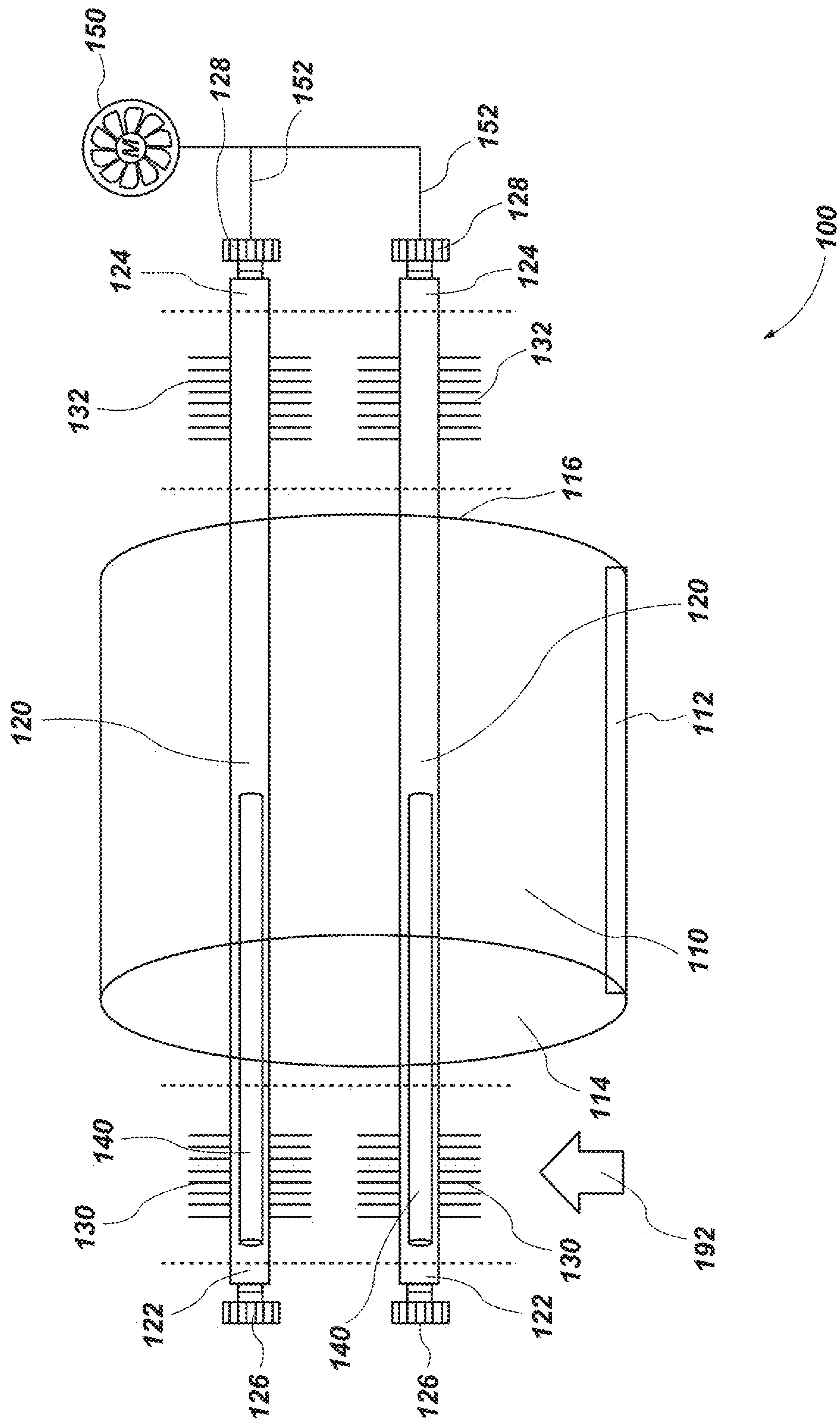
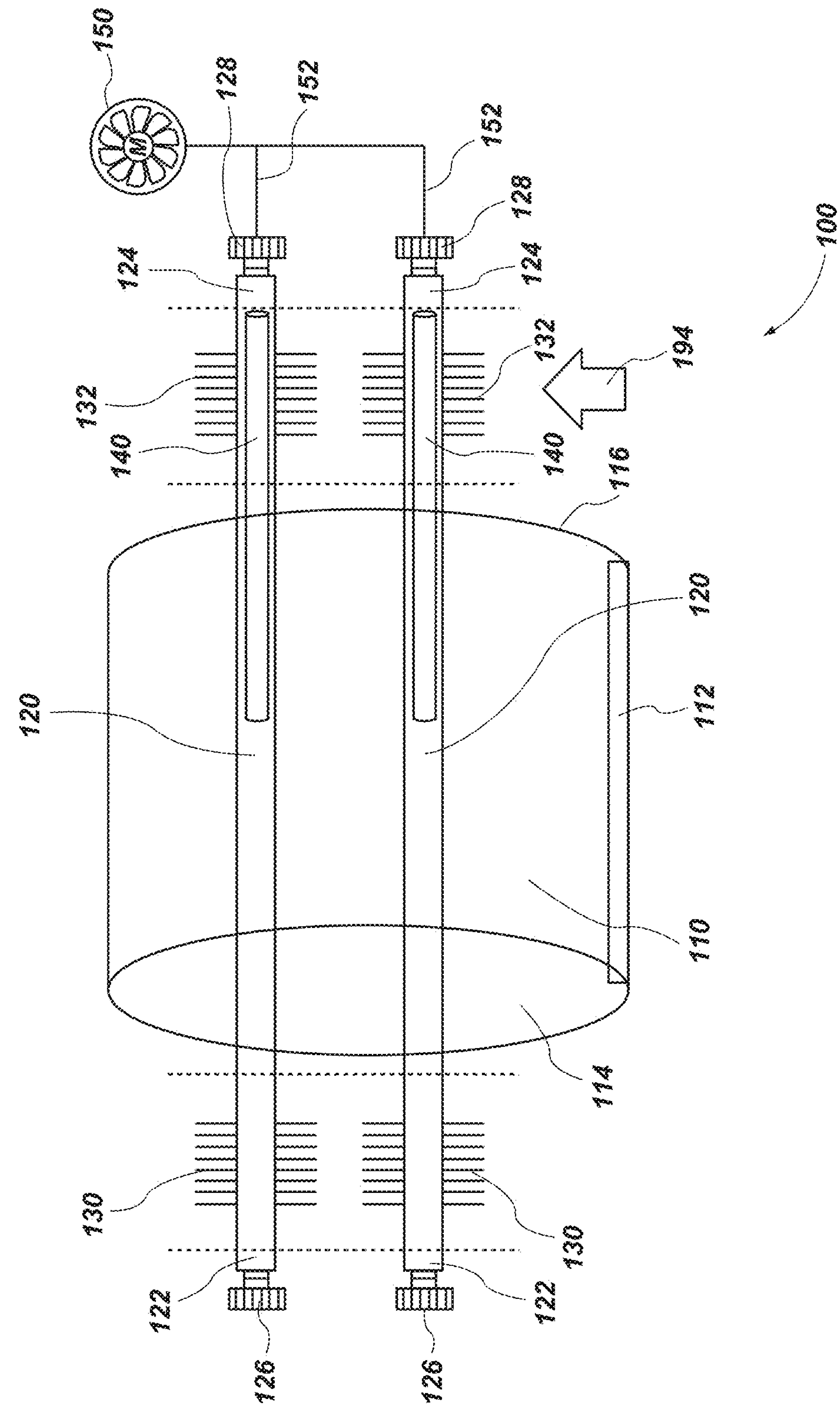

150
128
152
152
128
100
124
124
132
132
116
120
120
112
110
114
140
130
192
122
140
122
130
126
126

FIG. 1A


150
128
152
152
128
124
124
100
132
132
194
140
140
116
120
120
112
110
114
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130
122
122
126
126

FIG. 1B

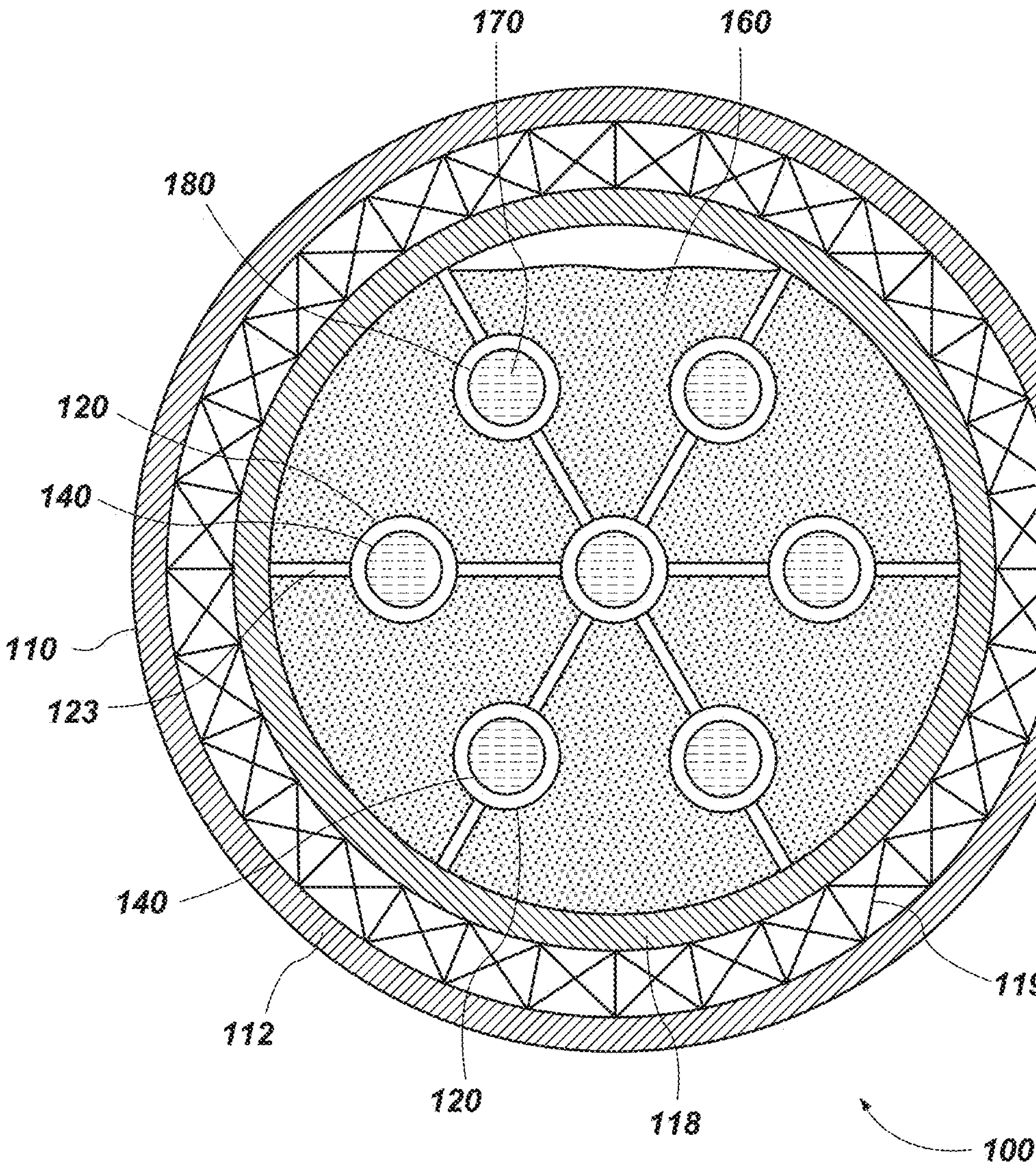


FIG. 2

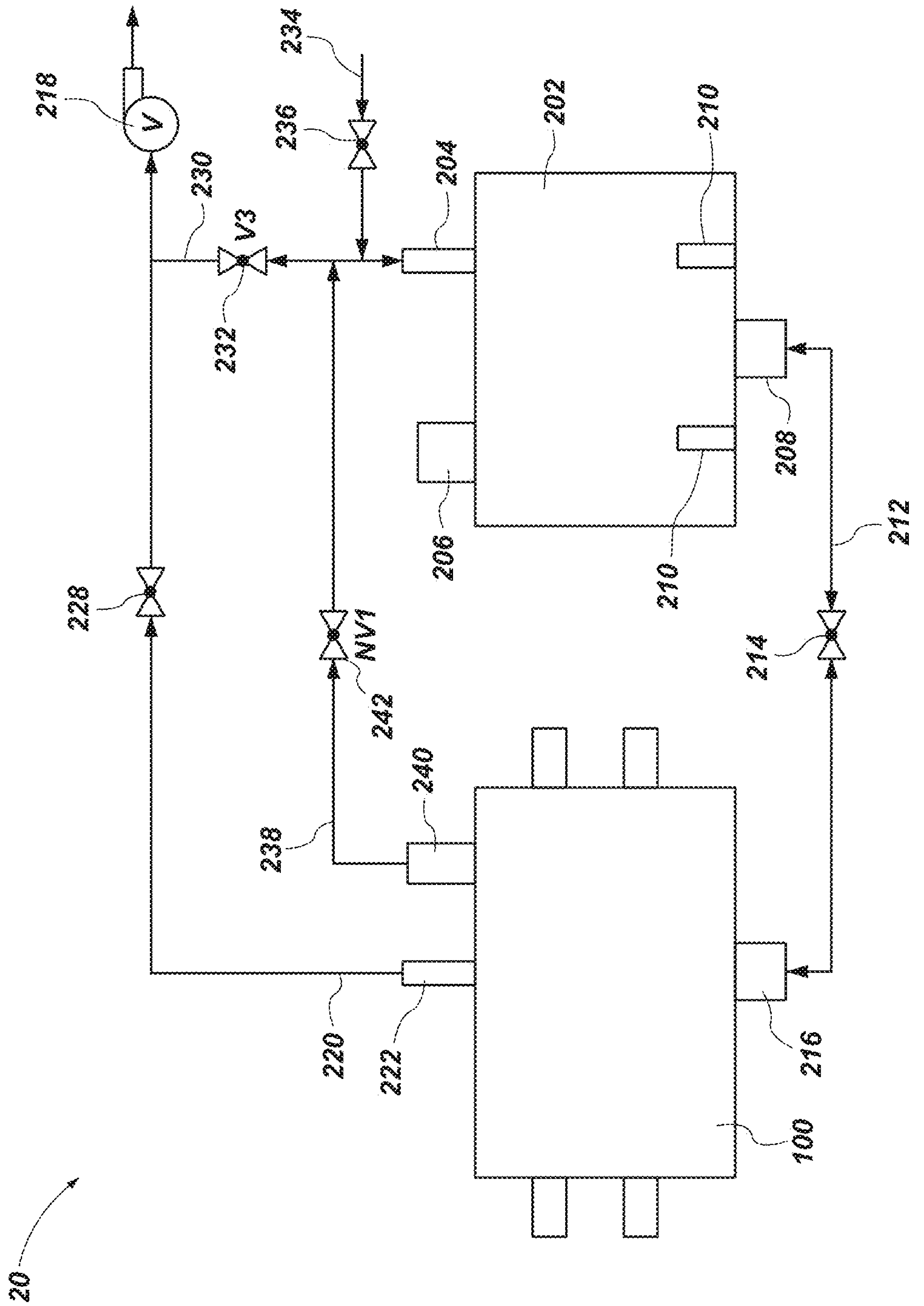
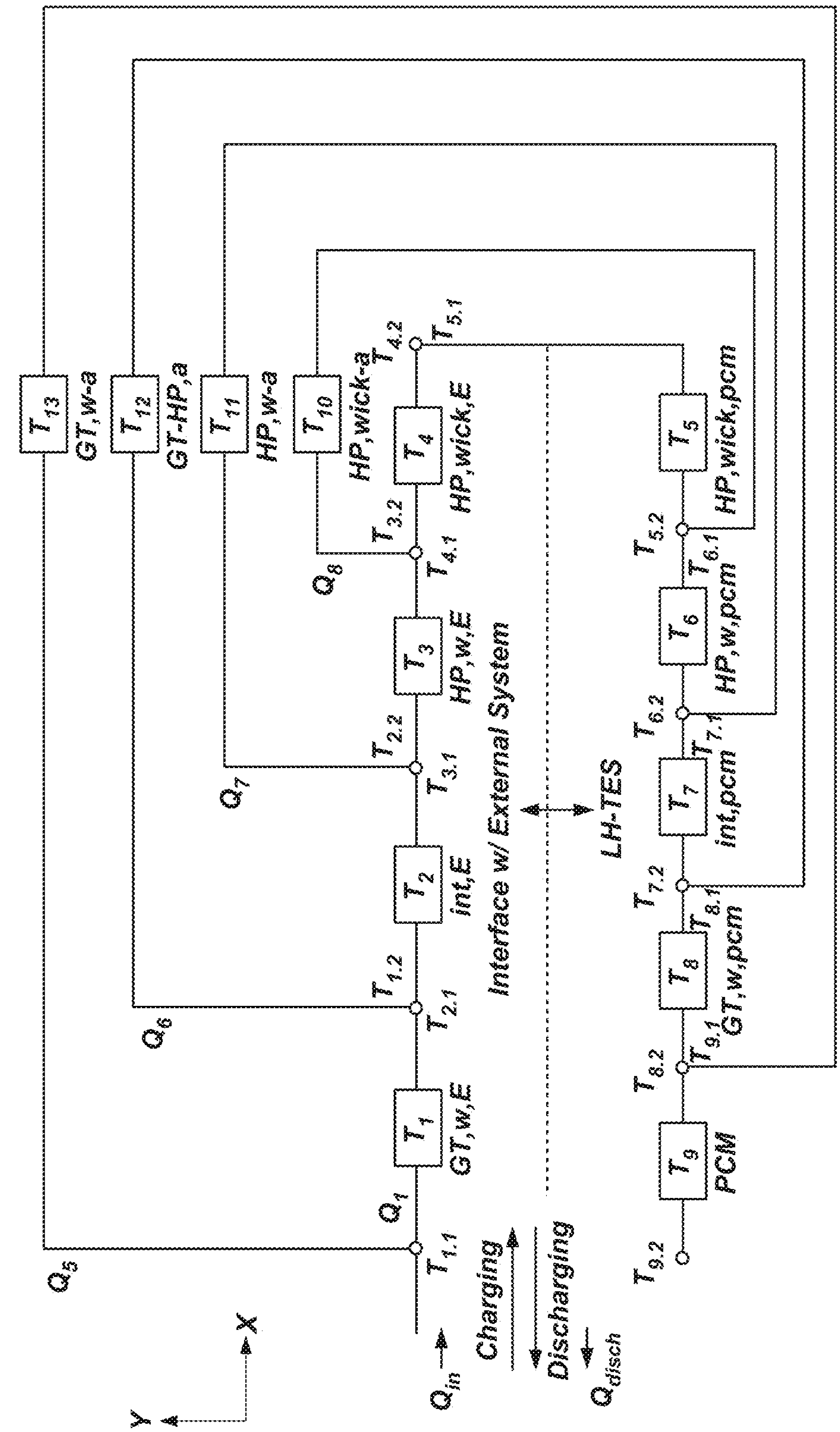

20
218
V
234
236
230
V3
232
204
202
210
208
206
210
212
228
NV1
242
214
240
238
220
222
216
100

FIG. 3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T12
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T10
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T6
HP,w,pcm
T3
HP,w,E
T7
int,pcm
T2
int,E
T8
GT,w,pcm
T1
GT,w,E
T9
PCM
Interface w/ External System
LH-TES
Charging
Discharging
Q5
Q6
Q7
Q8
Q1
Qin
Qdisch
X
Y

FIG. 4

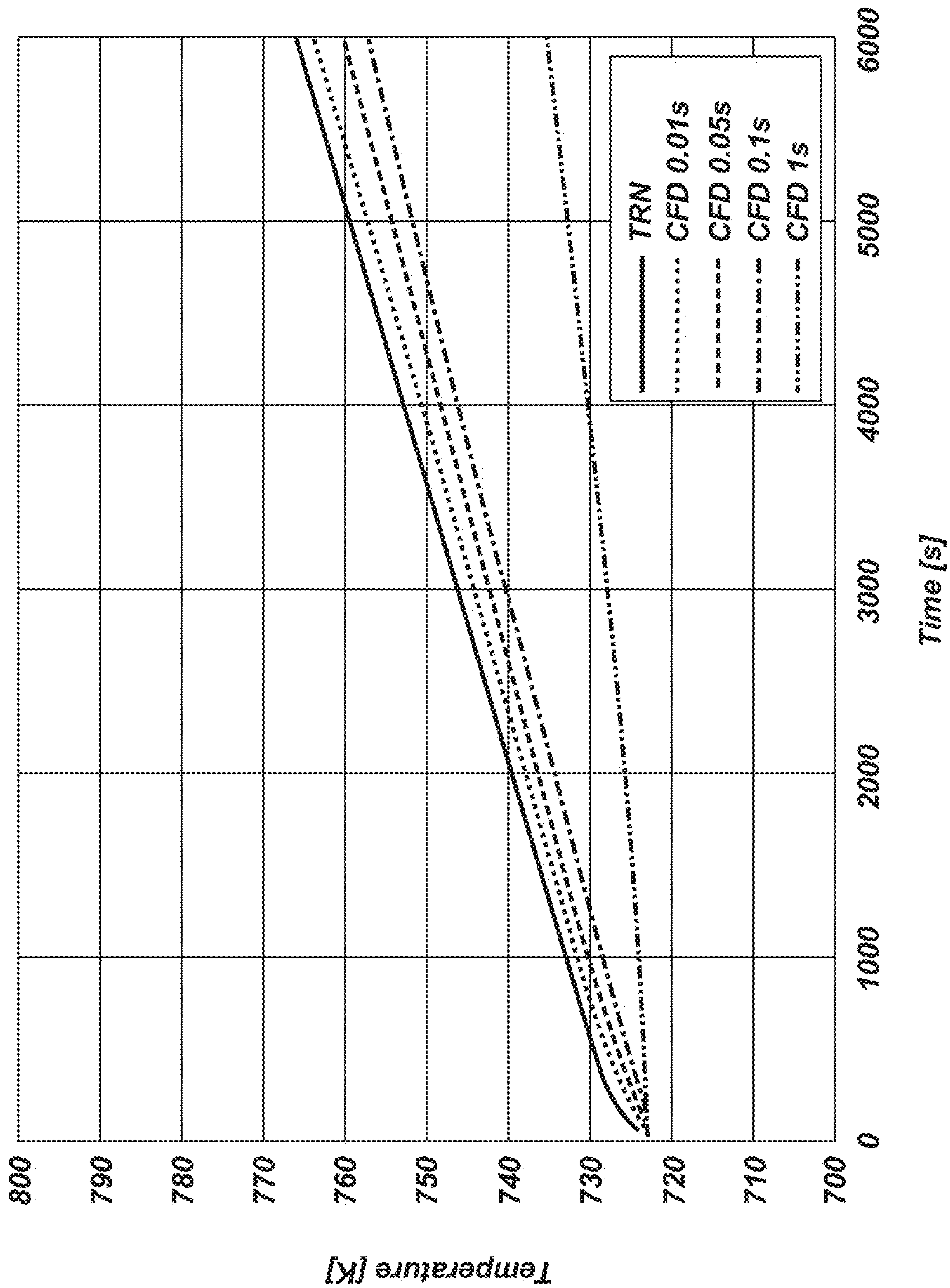
Temperature [K]
800
790
780
770
760
750
740
730
720
710
700
Time [s]
0
1000
2000
3000
4000
5000
6000
TRN
CFD 0.01s
CFD 0.05s
CFD 0.1s
CFD 1s

FIG. 5

HIGH-TEMPERATURE LATENT HEAT STORAGE SYSTEM USING TRANSPORTABLE HEAT PIPES FOR VERSATILE INTEGRATION WITH EMERGING MICROREACTORS

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit under 35 U.S.C. §119(e) of U.S. Provisional Patent Application Ser. No. 63/379,926, filed Oct. 18, 2022, the disclosure of which is hereby incorporated herein in its entirety by this reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under Contract Number DE-AC07-051D14517 awarded by the United States Department of Energy. The government has certain rights in the invention.

TECHNICAL FIELD

[0003] Thermal energy storage systems are disclosed. More particularly, latent heat storage systems including a heat pipe integrated thermal battery and methods of using the heat pipe integrated thermal battery are disclosed.

BACKGROUND

[0004] With growing interest in the development of micro nuclear reactors and their application to microgrids, high-temperature thermal energy storage ("TES") has received growing attention as a technology to reinforce the energy utilization and profitability of such reactors. TES offers the benefit of making heat a dispatchable energy asset. With an increasing interest/demand to connect micro nuclear reactors to microgrid(s), TES may help to maximize the energy utilization and profit of this class of new reactors. However, commercial-scale deployment of high temperature TES in the energy sector is difficult. Such challenges in deployment include the ability to interface the TES with other systems. This challenge also applies when combining high-temperature TES with advanced nuclear energy systems.

BRIEF SUMMARY

[0005] According to some embodiments, a heat pipe integrated thermal battery ("HITB") may include a storage tank, a thermal storage medium within the storage tank, a guide tube extending within the storage tank and through at least one end of the storage tank, and a heat pipe configured to be movable within the guide tube. The heat pipe may be configured to discharge heat to and absorb heat from the thermal storage medium within the storage tank.

[0006] In some embodiments, a thermal energy storage system is provided. The thermal energy storage system may include a feed and drain tank comprising a heating element operable to melt a thermal storage medium to a molten state and a heat pipe integrated thermal battery ("HITB") comprising a storage tank. The storage tank may be operable to hold the thermal storage medium such that latent heat of the thermal storage medium may be stored in the HITB. The thermal energy storage system may further include a thermal storage medium transport line connecting the feed and drain tank to the HITB and a pump configured to move the thermal storage medium from the feed and drain tank to the HITB and from the HITB to the feed and drain tank.

[0007] In some embodiments, a method for operating a heat pipe integrated thermal battery ("HITB") is provided. The method may include charging the HITB and discharging the HITB. To charge the HITB a heat pipe may be moved through a guide tube to of the HITB to a charging position. Heat may be absorbed into the heat pipe from a first external system and transferred from the heat pipe to a thermal storage medium in a storage tank of the HITB.

[0008] To discharge the HITB, the heat pipe may be moved through the guide tube to a discharging position. Heat may be absorbed into the heat pipe from the thermal storage medium in the storage tank of the HITB and discharged from the heat pipe to a second external system.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The disclosure is illustrated and described herein with reference to the various drawings, in which like reference numbers are used to denote like system components/method steps, as appropriate, and in which:

[0010] FIG. **1**A shows a schematic view of a heat pipe integrated thermal battery in a first operating state and FIG. **1**B shows the heat pipe integrated thermal battery of FIG. **1**A in a second operating state, according to embodiments of the disclosure;

[0011] FIG. **2** shows a schematic section view of the heat pipe integrated thermal battery;

[0012] FIG. **3** shows a schematic view of a thermal energy storage system incorporating the heat pipe integrated thermal battery;

[0013] FIG. **4** shows thermal resistance pathways involved in the heat transfer between a heat source or heat sink and the thermal storage medium of the heat pipe integrated thermal battery; and

[0014] FIG. **5** is a graph showing comparisons between a thermal resistant network model and Computational Fluid Dynamics ("CFD") simulations that were performed for verifying the accuracy of a TRN model.

DETAILED DESCRIPTION

[0015] High temperature thermal energy storage (TES) systems that include a heat pipe integrated thermal battery (HITB) are disclosed. The HITB is configured to store latent heat by moving heat pipes within the HITB. The high temperature TES system may be coupled to an external thermal system that produces heat and operates at a temperature above about 150° C. The high temperature TES system may be easily coupled to the external thermal system without using complex interfacing mechanisms and without creating additional safety issues.

[0016] The high temperature TES system including the HITB may be a latent heat storage system that enables flexible and robust integration with the external thermal system. The HITB may incorporate so called "transportable heat pipes" within the HITB to adjust the degree of thermal connection between a TES medium of the HITB and the external thermal system during use and operation of the high temperature TES system. The transportable heat pipes may be embedded heat pipes that provide a passive and flexible thermal connection between the TES medium and the external thermal system. The transportable heat pipes are configured to exchange heat between the TES medium of the

HITB and the external thermal system. The transportable heat pipes are configured to be moved within (e.g., displaced within) guide tubes of the HITB, which provide a barrier between a fluid (e.g., a working fluid) of the external system and the TES medium surrounding the heat pipes.

[0017] The thermal connection between the HITB and the external thermal system may result in no separate heat exchanger or pump being required for thermal integration, providing a significant cost benefit. Safety issues that may arise from interconnecting disparate systems may also be reduced or eliminated. Also, there is no single failure of the high temperature TES system because individual heat pipes operate independent of each other. The high temperature TES system may be easily scaled up to include multiple modules.

[0018] FIG. **1**A shows a schematic view of a HITB **100** in a first operating state and FIG. **1**B shows the HITB **100** of FIG. **1**A in a second operating state, according to embodiments of the disclosure. FIG. **2** shows a schematic section view of the HITB **100**. Referring to FIGS. **1A-2**, the HITB **100** may comprise a storage tank **110**. The storage tank **110** shown in FIGS. **1A-2** comprises a cylindrical shape having a cylindrical outer wall **112**, a planar first end **114** and a planar second end **116**. The storage tank **110** may be insulated to retain thermal energy within the HITB **100**. To this end, the storage tank **110** may further comprise an inner wall **118** and an insulating liner **119** between the inner wall **118** and the outer wall **112**. In some embodiments, the walls, including the inner wall **118** and the outer wall **112**, of the storage tank **110** may be formed from stainless steel, such as stainless steel **316**. However, other materials may also be used depending on a particular application of the HITB **100**. The insulating liner **119** may comprise a boron nitride ceramic coating.

[0019] The storage tank **110** may be configured to house (e.g., contain) a thermal storage medium **160**. The thermal storage medium **160** may be formulated to exhibit a high heat capacity, high conductivity, high diffusivity, and high latent heat of fusion at an operating temperature of the HITB **100**. The thermal storage medium **160** may also exhibit a solid-to-liquid phase change at a temperature around the operating temperature. By way of example only, the thermal storage medium **160** may comprise a metal alloy. The thermal storage medium **160** may include, but is not limited to, an aluminum alloy such as an aluminum-magnesium-zinc alloy. Other materials may also be used as a thermal storage medium **160** of the HITB **100**. Such materials may be considered a "phase change material" ("PCM") in that the material may undergo a solid-liquid phase change through a melting-solidification cycle at temperatures within a desired operating range for the HITB **100**. For example, in addition to an aluminum-magnesium-zinc alloy discussed above, the thermal storage medium **160** may comprise molten salts, such as $MgCl_2$-NaCl, FLiNaK, or $CaCl_2$-NaCl. The thermal storage medium **160** may be formulated such that thermal energy is stored as latent heat of the PCM. Accordingly, the PCM used as the thermal storage medium **160** may be selected based on a target operating temperature for a given application.

[0020] The storage tank **110** may be formed of any suitable size for a particular thermal storage capacity. In some embodiments, the storage tank **110** may comprise a 30 kw-hour thermal storage capacity. For instance, the storage tank **110** may comprise a 60-cm diameter and a 60-cm length to provide the 30 kw-hour thermal storage capacity. However, this is merely exemplary and other dimensions of the storage tank **110** may be utilized based on a desired thermal storage capacity and a particular application.

[0021] The HITB **100** may further comprise a plurality of guide tubes **120** that are embedded within and extend through the storage tank **110**. The guide tubes **120** may be oriented so as to be parallel with a longitudinal axis of the storage tank **110**. The guide tubes **120** may have a length that is longer than a length of the storage tank **110** from the first end **114** to the second end **116**. The guide tubes **120** may thus protrude out from at least one of the first end **114** or the second end **116** of the storage tank **110**. In some embodiments, first ends **122** of the guide tubes **120** extend from the first end **114** of the storage tank **110** and second ends **124** of the guide tubes **120** extend from the second end **116** of the storage tank **110**. The guide tubes **120** may be centered relative to the length of the storage tank **110** such that the lengths of the portions of the guide tubes **120** protruding from each end **114**, **116** of the storage tank are substantially equal to one another. That is, a length of the portion of a guide tube **120** extending from the first end **122** of the guide tube **120** to the first end **114** of the storage tank is equal to a length of the portion of the guide tube **120** extending from the second end **116** of the storage tank **110** to the second end of the guide tube **120**. However, the guide tubes **120** may be positioned at any desired location relative to the storage tank **110**.

[0022] The guide tubes **120** may be supported by the storage tank **110** via a plurality of support members **123**. The support members **123** may comprise a plurality of rods or struts that extend from the inner wall **118** of the storage tank **110**. The support members **123**, the guide tubes **120**, and the storage tank **110** may be formed integrally (e.g., together) such as via an additive manufacturing process, casting, or other suitable manufacturing methods. Alternatively, the support members **123**, the guide tubes **120**, and the storage tank **110** may be formed separately and may be joined together using any suitable joining process such as welding or joining via one or more fasteners.

[0023] The guide tubes **120** may comprise a first end cap **126** disposed at a first end **122** of the guide tube and a second end cap **128** disposed at the second end **124** of the guide tube **120**. The end caps **126**, **128** may be configured to seal an inside of the guide tubes **120** from an external environment (e.g., an operating environment). In some embodiments, the end caps **126**, **128** may be selectively removeable from the ends **122**, **124** of the guide tubes **120** to provide access to the inside of the guide tubes **120**.

[0024] The guide tubes **120** may comprise first fins **130** disposed adjacent to the first end **122** of the guide tubes **120** and may comprise second fins **132** disposed adjacent to the second end **124** of the guide tubes **120**. The first fins **130** may be configured to facilitate heat transfer between the guide tubes **120** and fluid from the external thermal system providing a hot fluid supply source. The second fins **132** may be configured to facilitate heat transfer between the guide tubes **120** and another external thermal system, such as an industrial system providing a cold fluid supply source to be heated by the guide tubes **120**.

[0025] The guide tubes **120** may be configured to support transportable heat pipes **140** within the guide tubes **120**. The transportable heat pipe **140** within each guide tube **120** is configured and operable to receive heat from the external thermal system and to discharge heat to another external thermal system via the guide tubes **120**. The transportable heat pipe **140** within each guide tube **120** is further configured and operable to receive heat from and discharge heat to the thermal storage medium **160** within the storage tank **110**.

[0026] The transportable heat pipe **140** may include a working medium **170** within the transportable heat pipe **140**. The working medium **170** with the transportable heat pipe **140** may be a liquid metal, such as sodium. However, other liquid metals may be used. By way of example only, the transportable heat pipe **140** may be a sodium heat pipe. The transportable heat pipe **140** may function as a passive heat transfer device. In some embodiments, the transportable heat pipe **140** may have a working temperature range of from about 400° C. to about 1000° C. The transportable heat pipe **140** may be configured to be replaceable, such as to be removable from the guide tubes **120** via the caps **126**, **128**, and to be placed into the guide tubes **120** via the caps **126**, **128**. Since the thermal storage medium **160** is separated from other fluids, no fluid exchange occurs between the working medium **170** and the thermal storage medium **160** or between the thermal storage medium **160** and fluids from external systems.

[0027] The HITB may comprise a heat pipe drive mechanism **150** that is configured and operable to move the transportable heat pipes **140** within respective guide tubes **120**. The transportable heat pipe **140** may be moved between the first operating state (e.g., a charging position within the guide tubes **120**) and the second operating state (e.g., a discharging position within the guide tubes **120**) by the heat pipe drive mechanism **150**. The heat pipe drive mechanism **150** may comprise a linear actuator **152** associated with each heat pipe **140**. For example, the linear actuator **152** may comprise a worm gear stepper motor or other suitable linear actuator. Each linear actuator **152** may be configured and operable to move a respective heat pipe **140** within a respective guide tube **120**. In some embodiments, each linear actuator **152** may be operated independent from other linear actuators **152**. In some embodiments, the linear actuators **152** are controlled collectively. The linear actuators **152** may be any suitable linear actuator such as a hydraulic actuator, a pneumatic actuator, a mechanical actuator, or the like.

[0028] The heat pipe drive mechanism **150** may be configured to move the transportable heat pipes **140** through the guide tubes **120** to various positions within the guide tubes. In FIG. **1**A, the HITB **100** is shown where the heat pipe drive mechanism **150** has driven the heat pipes **140** within the guide tubes **120** to a position adjacent to the first end **122** of the guide tubes **120** (e.g., the first operating state or charging position). In this position, at least a portion of the heat pipe **140** is adjacent to the fins **130** of the guide tube **120** and at least a portion of the heat pipes **140** extends beyond the first end **114** of the storage tank **110**. Thus, the heat pipe **140** may be configured and operable to receive thermal energy from a hot fluid supply source **192** from an external thermal system via the interface between the heat pipe **140** and the guide tube **120** to transfer the heat to the thermal storage medium **160** in the storage tank **110** of the HITB **100**. In some embodiments, the heat pipes **140** may facilitate heat transfer from the hot fluid supply source **192** via the working medium **170** while in the first operating state as shown in FIG. **1**A. In some embodiments, the transportable heat pipes **140** may be moved to be within the thermal storage tank **110** (e.g., moved to a position within the guide tube **120** between the first end **114** and the second end **116** of the thermal storage tank **110**) such that heat stored in the transportable heat pipe **140** from the hot fluid supply source **192** of the external thermal system may be transferred to the thermal storage medium **160**. In this manner, heat may be transferred from the external thermal system to the thermal storage medium **160** of the HITB **100**.

[0029] In FIG. **1**B, the HITB **100** is shown where the heat pipe drive mechanism **150** has driven the heat pipes **140** within the guide tubes **120** to a position adjacent to the second end **124** of the guide tubes **120** (e.g., the second operating state or discharging position). In this position, at least a portion of the heat pipe **140** is adjacent to the fins **132** of the guide tube **120**. The transportable heat pipes **140** may be moved out of the thermal storage tank **110** (e.g., moved to a position within the guide tube such that at least a portion of the heat pipes **140** extends beyond the second end **116** of the storage tank **110**) such that the heat pipes **140** are exposed to the external thermal system that functions as a cold fluid supply source **194**, enabling heat transfer from the thermal storage medium **160** to the external thermal system. Thus, the heat pipe **140** may be configured and operable to discharge thermal energy to the cold fluid supply source **194** from an external system via the interface between the heat pipe **140** and the guide tube **120**. In some embodiments, the heat pipes **140** may facilitate heat transfer to the cold fluid supply source **194** via the working medium **170** while in the second operating state as shown in FIG. **1**B.

[0030] In addition to the positions of the heat pipes **140** relative to the respective guide tubes **120** shown in FIGS. **1**A and **1**B, the heat pipes **140** may be moved to any desired other position within the guide tubes **120**. For example, the heat pipes **140** may be moved to a position at least partially or fully within the storage tank **110** to discharge heat to or absorb heat from the thermal storage medium **160**.

[0031] A portion of the heat pipe drive mechanism **150** may be configured to extend through the caps **128** of the guide tubes **120** to interface with and move the transportable heat pipes **140**. The caps **128** may provide a dynamic seal with the heat pipe drive mechanism **150** to maintain a predetermined environment within the guide tubes **120**. For example, an inert gas may be provided in the guide tubes **120** to reduce contamination and corrosion within the guide tubes **120** and to the heat pipes **140**. In some embodiments, the caps **128** may be replaced with or may be incorporated into a component of the heat pipe drive mechanism that seals the second ends **124** of the heat pipes **140**.

[0032] While the heat pipe drive mechanism **150** shown in FIGS. **1**A and **1**B interfaces at the second end **124** of the guide tubes **120**, the heat pipe drive mechanism **150** is not limited to this configuration. The heat pipe drive mechanism **150** may also interface at the first end **122** of the guide tubes **120** or at both ends **122**, **124** of the guide tubes. Because the transportable heat pipes **140** are configured to move along and within the guide tubes **120**, the thermal storage medium **160** of the HITB **100** does not directly interface with a working fluid (e.g., a working medium **170**) of the transportable heat pipes **140**. The walls of the guide tubes **120** may provide a barrier between the working medium **170** of the transportable heat pipes **140** and the thermal storage medium **160** to prevent any potential safety issues that may arise in the event of a wall failure of a transportable heat pipe **140**.

[0033] To aid in the heat transfer between the guide tubes **120** and the respective transportable heat pipe **140** within each guide tube **120**, a thermal interface **180** may be provided. The thermal interface **180** may be a heat conducting sleeve disposed between an outside surface of the transportable heat pipe **140** and an inside surface of the guide tube **120**. The thermal interface **180** may be configured to remain fixed relative to one of the guide tube **120** or the transportable heat pipe **140**. A lubricant may be provided to facilitate relative movement between the thermal interface **180** and the other of the guide tube **120** or the transportable heat pipe **140**. The lubricant may include, but is not limited to, a boron nitride lubricant, a copper grease lubricant, or other suitable high temperature lubricant.

[0034] In some embodiments, the thermal interface **180** may be provided to remain fixed to an inside surface of each guide tube **120** such that the transportable heat pipe **140** is moveable through the thermal interface **180**. The thermal interface **180** may extend along an entire length of the guide tube **120** or along a portion or portions of the guide tube **120**. For example, the thermal interface **180** may be provided at portions of the guide tube at which heat transfer is to be facilitated, such as extending within the guide tube **120** along the lengths at which the fins **130** and **132** are provided. The thermal interface **180** may also be provided along the guide tube **120** at one or more portions within the storage tank **110**. In some embodiments, the thermal interface **180** may be configured so as to be absent at and adjacent to the first end **114** and the second end **116** of the storage tank. In this manner, heat transfer may be facilitated between the external systems and the transportable heat pipe while preventing inadvertent heat transfer between an external system and the thermal storage medium **160** within the storage tank **110** via the thermal interface **180** within the guide tube **120**.

[0035] In other embodiments, the thermal interface **180** may be provided to remain fixed to the transportable heat pipe **140** and is thus configured to move through the guide tube **120** with the transportable heat pipe **140**. The thermal interface **180** may extend along an entire length of the heat pipe **140** or may extend along a portion or portions of the transportable heat pipe **140**. For example, the thermal interface **180** may extend from ends of the transportable heat pipe **140** such that when the transportable heat pipe **140** is moved adjacent to one of the ends **122**, **124** of the guide tubes **120**, the thermal interface **180** is aligned to be adjacent to the one of the fins **130**, **132**. In some embodiments, the thermal interface **180** may be configured such that when the thermal interface **180** is aligned with one of the fins **130**, **132**, the thermal interface **180** does not extend through the ends **114**, **116** of the storage tank **110**. In this manner, inadvertent heat transfer between an external system and the thermal storage medium **160** within the storage tank **110** via the thermal interface **180** within the guide tube **120** may be prevented.

[0036] The thermal interface **180** may comprise a porous metal, such as a metal sheet or a metal foam. In some embodiments, the porous metal may comprise a mesh sheet of copper, bronze, stainless steel, or nickel that is formed into a sleeve to surround the transportable heat pipe **140** within the guide tube **120**. The porous metal may provide a conductive thermal contact between the guide tube **120** and the thermal interface **180** and a conductive thermal contact between the thermal interface **180** and the transportable heat pipe **140** while allowing for thermal expansion and contraction of the thermal interface **180**, the guide tubes **120**, and the transportable heat pipes **140** in changing operating temperatures.

[0037] Modifications to the HITB **100** are also possible. For example, in FIGS. **1A** and **1B**, the HITB **100** is shown with the guide tubes **120** extending from both ends **114**, **116** of the storage tank **110**. It was described above with reference to FIGS. **1A** and **1B** that when the transportable heat pipes **140** are moved to the first end **122** of the guide tubes **120**, the transportable heat pipes **140** absorb heat from a hot fluid supply source **192** from an external thermal system, and that when the transportable heat pipes **140** are moved to the second end **124** of the heat pipes **140**, the transportable heat pipes **140** discharge heat to a cold fluid supply source **194** of an external thermal system. However, this is not intended to be limiting. The HITB **100** may be configured such that the transportable heat pipes **140** discharge heat when at the first end **122** of the guide tubes **120** and absorb heat when at the second end **124** of the guide tubes. Furthermore, the HITB **100** may be configured such that the guide tubes **120** extend out of only one of the ends **114**, **116** of the storage tank **110**. For instance, a portion of the guide tubes **120** extending out of only one of the ends **114**, **116** of the storage tank **110** may facilitate both absorption of heat to and discharge of heat from the transportable heat pipes **140**, depending on with which external thermal system the HITB **100** is interfaced.

[0038] FIG. **3** shows a schematic view of a thermal energy storage system incorporating the heat pipe integrated thermal battery. In FIG. **3**, a thermal energy storage system **20** may comprise one or more HITBs, such as one or more HITBs **100** described above with reference to FIGS. **1A-2**. The thermal energy storage system **20** may comprise a feed and drain tank **202**. The feed and drain tank **202** may be configured to store a thermal storage medium (such as thermal storage medium **160** discussed above) when the HITB **100** is not in use.

[0039] The feed and drain tank **202** may comprise inlets/outlets to provide access to the feed and drain tank **202**. For example, the feed and drain tank **202** may comprise a fluid inlet/outlet **204** which may be operable to allow fluid such as a gas to enter or exit the feed and drain tank **202**. The feed and drain tank **202** may also comprise an ingot inlet **206**. The ingot inlet **206** may comprise a port through which a metallic ingot may be inserted into the feed and drain tank **202** to load the feed and drain tank **202** with the thermal storage medium (e.g., thermal storage medium **160**).

[0040] The feed and drain tank **202** may also comprise a thermal storage medium inlet/outlet **208**. The thermal storage medium inlet/outlet **208** may be configured to drain the thermal storage medium (e.g., thermal storage medium **160**) from the feed and drain tank **202** to fill the HITB **100** or to receive the thermal storage medium from the HITB **100**, as will be described in more detail below. The feed and drain tank **202** may comprise heating elements **210**. The heating elements **210** may be operable to melt the metallic ingot into a molten state for use as the thermal storage medium of the HITB **100**.

[0041] The thermal energy storage system **20** may further comprise a thermal storage medium transport line **212** that extends between the feed and drain tank **202** and the HITB **100**. The thermal storage medium transport line **212** facilitates transport of the thermal storage medium between the feed and drain tank **202** and the HITB **100**. The thermal storage medium transport line **212** may comprise a valve **214** that controls the flow of thermal storage medium between the feed and drain tank **202** and the HITB **100**. The HITB **100** may comprise an inlet/outlet **216** that connects the thermal storage medium transport line **212** to the HITB **100**, allowing the thermal storage medium to enter into and exit from the HITB **100**.

[0042] The thermal energy storage system **20** may comprise a vacuum pump **218**. The vacuum pump **218** is operable to create a pressure difference within the thermal energy storage system **20** to move the thermal storage medium between the feed and drain tank **202** and the HITB **100**. A HITB vacuum line **220** may connect the vacuum pump **218** with the HITB **100** at a vacuum inlet/outlet **222**. The HITB vacuum line **220** may comprise a valve **228** that controls the application of the vacuum to the HITB **100** via the HITB vacuum line **220**.

[0043] A feed and drain vacuum line **230** may connect the vacuum pump **218** with the feed and drain tank **202** via the fluid inlet/outlet **204**. The feed and drain vacuum line **230** may comprise a valve **232** that controls the flow through the feed and drain vacuum line **230**. An inert gas flushing line **234** may connect to the feed and drain vacuum line **230** to provide an inert gas to the feed and drain tank **202** to remove air from the system to prevent oxidation. The inert gas may comprise, for example, argon. The inert gas flushing line **234** may comprise a valve **236** to help control the flow through the inert gas flushing line **234**.

[0044] The thermal energy storage system **20** may also comprise a HITB venting line **238** that connects the HITB **100** at a venting outlet **240** to the fluid inlet/outlet **204** of the feed and drain tank **202**. The HITB venting line **238** may comprise a valve **242** to control the flow through the HITB venting line **238**. The HITB venting line **238** may protect against an overpressure condition in the HITB **100** such as during a filling operation of the HITB **100**.

[0045] As mentioned above, the thermal energy storage system **20** may facilitate filling and draining of a thermal storage medium into and out of the HITB **100**. To fill the HITB **100** with a thermal storage medium, such as thermal storage medium **160** discussed above with reference to FIGS. **1**A-**2**, one or more ingots of metallic material to be used as a source of the thermal storage medium may be loaded into the feed and drain tank **202** via the ingot inlet **206**. The heating elements **210** may heat the one or more ingots into a molten state within the heat and drain tank **202**.

[0046] In the molten state, the thermal storage medium may flow through the thermal storage medium transport line **212** from the feed and drain tank **202** to the HITB **100**. The flow may be caused by applying a vacuum via the vacuum pump **218** to the HITB **100**. For example, the valve **214** of the thermal storage medium transport line **212** may be opened to allow flow of the thermal storage medium through the thermal storage medium transport line **212**. The valve **232** of the feed and drain vacuum line **230** may be closed and the valve **228** of the HITB vacuum line **220** may be opened such that when the vacuum pump **218** is activated, a vacuum is applied to the HITB **100** at the vacuum inlet/outlet **222**. The thermal storage medium may then flow through the thermal storage medium transport line **212** from the feed and drain tank **202** to the HITB **100** to fill the HITB **100** with the thermal storage medium. During filling, gas from the HITB **100** may be vented back to the feed and drain tank **202** via the HITB venting line **238**. The valve **236** of the inert gas flushing line **234** may be opened as needed to equalize pressure in the thermal energy storage system **20**. Once filled, the HITB **100** may be separated from the thermal energy storage system **20** and moved away from the thermal energy storage system **20** to be used as described above with reference to FIGS. **1**A-**2**.

[0047] When the HITB **100** is no longer in use, it may be desirable to return the thermal storage medium to the feed and drain tank **202**. The HITB **100** may be reattached to the thermal energy storage system **20** to move the thermal energy storage medium from the HITB **100** back to the feed and drain tank **202**. To facilitate this, the valve **214** of the thermal storage medium transport line **212** may be opened to allow flow therethrough. The valve **232** of the feed and drain vacuum line **230** may be opened and the valve **228** of the HITB vacuum line **220** may be closed such that when the vacuum pump **218** is activated, a vacuum is applied to the feed and drain tank **202** at the fluid inlet/outlet **204**. The thermal storage medium may then flow through the thermal storage medium transport line **212** from the HITB **100** to the feed and drain tank **202** to drain the HITB **100** of the thermal storage medium. As needed, valves **236**, **232**, and **228** may be opened to allow inert gas to flow to the HITB **100**. The thermal storage medium may be stored in the feed and drain tank **202** for later use in the HITB **100**.

[0048] As mentioned above, the thermal energy storage system **20** including the HITB **100** may be coupled to one or more external thermal systems. For example, the HITB **100** may be coupled to external thermal systems to absorb heat from the external thermal systems for storage and later use. Such external thermal systems may be configured to produce heat at a high temperature, such as at a temperature greater than or equal to about 150° C. The external thermal system may, for example, be configured to produce heat at a temperature between about 500° C. and about 600° C. By way of example only, the external thermal system may be a nuclear reactor, such as an advanced nuclear reactor (e.g., a micro nuclear reactor), a solar power plant, or an industrial heat plant. The HITB **100** may be further coupled to other external thermal systems to discharge heat stored in the HITB **100**. Such external thermal systems may comprise power generation systems, chemical processing systems, hydrogen production systems, or other industrial applications.

[0049] To obtain a system-scale insight into the transient thermal behavior of the HITB during its cyclic operation of charge and discharge modes, a thermal resistant network (TRN) model has been developed. The TRN model was designed to evaluate the transient temperature history through each component and performance parameters such as melting completion time of a storage medium and charge/discharge periods for a given system sizing. The thermal resistance pathways involved in the heat transfer between the heat source (or heat sink) and the storage medium are presented in FIG. **4**. Here, the transient temperature at each thermal component node (i.e., T_1-T_{13}) is determined by the following transient heat conduction equation:

$$\rho_i c_{p,i} V_i \frac{dT_i}{dt} = Q_{i,1} - Q_{i,2}$$

-continued

$$= \frac{T_{i,1} - T_i}{R_{i,1}} - \frac{T_i - T_{1,2}}{R_{i,2}}$$

[0050] $Q_{i,1}$: Heat entering through the interface (I,1) to component 'i'

[0051] $Q_{i,2}$: Heat coming out through the interface (i,2) from component 'i'

[0052] $T_{i,1}$: Temperature at the interface (i,1)

[0053] $T_{i,2}$: Temperature at the interface (i,2)

[0054] FIG. **5** shows a comparison between the TRN and CFD simulations that was performed for verifying the accuracy of the TRN model. The TRN model developed is currently used to investigate the thermal performance, effect of key design parameters (e.g., heat pipe performance, thermophysical properties of storage medium), and design optimization.

[0055] The embodiments of the disclosure described above and illustrated in the accompanying drawing figures do not limit the scope of the invention, since these embodiments are merely examples of embodiments of the invention, which is defined by the appended claims and their legal equivalents. Any equivalent embodiments are intended to be within the scope of this disclosure. Indeed, various modifications of the disclosure, in addition to those shown and described herein, such as alternative useful combinations of the elements described, may become apparent to those skilled in the art from the description. Such modifications and embodiments are also intended to fall within the scope of the appended claims and their legal equivalents.

What is claimed is:

1. A heat pipe integrated thermal battery ("HITB") comprising:

a storage tank;

a thermal storage medium within the storage tank;

a guide tube extending within the storage tank and through at least one end of the storage tank; and

a heat pipe configured to be movable within the guide tube, the heat pipe being configured to discharge heat to and absorb heat from the thermal storage medium within the storage tank.

2. The HITB of claim **1**, further comprising a heat pipe drive mechanism configured to move the heat pipe within the guide tube.

3. The HITB of claim **1**, wherein the guide tube comprises fins on a portion of the guide tube that extends outside the storage tank.

4. The HITB of claim **1**, wherein the guide tube comprises an end cap allowing access within the guide tube.

5. The HITB of claim **1**, further comprising a thermal interface within the guide tube, the thermal interface being between an inner surface of the guide tube and an external surface of the heat pipe.

6. The HITB of claim **5**, wherein the thermal interface comprises a sleeve disposed against the inner surface of the guide tube.

7. The HITB of claim **6**, wherein the sleeve comprises a porous metal.

8. The HITB of claim **1**, wherein the storage tank comprises a cylindrical tank comprising an inner wall, an outer wall, and an insulating liner between the inner wall and the outer wall.

9. The HITB of claim **8**, wherein the inner wall and the outer wall comprise stainless steel and wherein the insulating liner comprises a boron nitride coating.

10. The HITB of claim **1**, wherein the thermal storage medium comprises a metal alloy and wherein heat stored in the thermal storage medium is stored as latent heat of the metal alloy.

11. The HITB of claim **10**, wherein the metal alloy comprises an aluminum alloy.

12. The HITB of claim **1**, wherein the guide tube protrudes from a first end of the storage tank and protrudes from a second end of the storage tank opposite the first end of the storage tank.

13. The HITB of claim **12**, wherein when the heat pipe is moved to a first end of the guide tube, the heat pipe is configured to absorb heat and to transfer heat to the thermal storage medium, and wherein when the heat pipe is moved to a second end of the guide tube, the heat pipe is configured to absorb heat from the thermal storage medium and release heat from the guide tube.

14. A thermal energy storage system comprising:

a feed and drain tank comprising a heating element operable to melt a thermal storage medium to a molten state;

a heat pipe integrated thermal battery ("HITB") comprising a storage tank, the storage tank operable to hold the thermal storage medium such that latent heat of the thermal storage medium may be stored in the HITB;

a thermal storage medium transport line connecting the feed and drain tank to the HITB; and

a pump configured to move the thermal storage medium from the feed and drain tank to the HITB and from the HITB to the feed and drain tank.

15. The thermal energy storage system of claim **14**, further comprising a HITB venting line connecting the HITB and the feed and drain tank, the HITB venting line being configured to vent gas from the HITB to the feed and drain tank.

16. The thermal energy storage system of claim **14**, further comprising:

a HITB vacuum line connecting the pump to the HITB, the HITB vacuum line comprising a first valve; and

a feed and drain vacuum line connecting the pump to the feed and drain tank, the feed and drain vacuum line comprising a second valve,

wherein when the first valve is opened and the second valve is closed, a vacuum is applied to the HITB to move the thermal storage medium from the feed and drain tank to the HITB via the thermal storage medium transport line, and

wherein when the first valve is closed and the second valve is opened, a vacuum is applied to the feed and drain tank to move the thermal storage medium from the HITB to the feed and drain tank.

17. A method for operating a heat pipe integrated thermal battery ("HITB") comprising:

charging the HITB, the charging comprising:

moving a heat pipe through a guide tube of the HITB to a charging position;

absorbing heat into the heat pipe from a first external system and transferring heat from the heat pipe to a thermal storage medium in a storage tank of the HITB;

discharging the HITB, the discharging comprising:
moving the heat pipe through the guide tube to a discharging position;
absorbing heat into the heat pipe from the thermal storage medium in the storage tank of the HITB and discharging heat from the heat pipe to a second external system.

18. The method of claim **17**, further comprising:
prior to charging, filling the HITB with the thermal storage medium from a feed and drain tank.

19. The method of claim **17**, further comprising:
emptying the thermal storage medium from the HITB to a feed and drain tank.

20. The method of claim **17**, wherein heat stored in the thermal storage medium is stored as latent heat of the thermal storage medium.

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