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Battery Modules Comprising Immersion-Cooled Prismatic Battery Cells and Methods of Fabricating Thereof

Abstract

Described herein are battery modules comprising immersion-cooled prismatic battery cells and methods of fabricating thereof. A battery module comprises prismatic battery cells that are stacked along the primary module axis. The module also comprises top, bottom, and side covers and two end plates, collectively enclosing these battery cells. Each cover forms two fluid channels, both fluidically open to the prismatic battery cells. Furthermore, the module comprises bus bars that interconnect the cell terminals and protrude into the fluid channels formed by the top cover. One end plate comprises two fluid ports for connecting to a thermal management system. Each port is fluidically coupled to one fluid channel, formed by the top cover, and one fluid channel, formed by the bottom cover. The other end plate fluidically couples the two fluid channels, formed by the top cover, and, separately, the two fluid channels, formed by the bottom cover.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation-in-part of PCT/US2024/012274 filed on 2024 Jan. 19, which claims the benefit under 35 U.S.C. § 119(e) of U.S. Provisional Patent Application 63/480,710, filed on 2023 Jan. 20, which is incorporated herein by reference in its entirety for all purposes.

BACKGROUND
[0002] Electric vehicles are propelled using electric motors powered by battery packs. Each battery pack can include one or more battery modules, each comprising one or more battery cells. These cells can be connected in series and/or parallel and controlled by a battery management system. While the operating temperature of battery cells depends on various materials used to fabricate these cells (e.g., electrolyte solvents), most battery cells are designed to operate in the 0-60° C. range. It should be noted that battery cells can be very sensitive to their operating temperatures. For example, the power rating of battery cells can drop quickly with the temperature (caused by lower ionic mobility). At the same time, battery cells degrade faster and can potentially enter unsafe conditions when operated at high temperatures.
[0003] In addition to various environmental conditions that can change cells' operating temperature, battery cells can generate considerable heat while charging and discharging, especially at high rates (that can be desirable for many applications). For example, Joule heating caused by cells' internal resistance is one of the largest contributors. Other contributors include but are not limited to electrode reactions and entropic heat generation caused by the insertion and de-insertion of lithium ions in and out of the electrodes. To maintain optimum operating temperatures, the heat must be removed from the battery cells as this heat is being generated within the cells. It should be noted that other components of battery packs (e.g., bus bars that interconnect battery cells) can also cause heating and should be also cooled whenever possible.
[0004] Liquid cooling or, more generally, liquid-based thermal management of battery cells is beneficial in comparison to, e.g., air cooling because of the large heat capacities and heat transfer coefficient of many liquids in comparison to air. However, controlling the distribution of liquid within battery packs can be challenging. For example, most liquid-cooled battery packs have battery cells isolated from liquid passages thereby preventing any direct contact between the cells and thermal liquid and relying on various heat-transferring components positioned in between. Furthermore, many liquid-cooled battery packs utilize cylindrical cells (e.g., 18650 cells) because of their small factor and ease of cooling (e.g., by thermal coupling to cell bottoms). However, battery packs with cylindrical cells tend to have lower energy density because of their inherent packing density limitations. Finally, most battery cooling systems focus on cooling batteries and ignore bus bar cooling.
[0005] What is needed are new battery modules comprising immersion-cooled prismatic battery cells and methods of fabricating thereof.
SUMMARY
[0006] Described herein are battery modules comprising immersion-cooled prismatic battery cells and methods of fabricating thereof. A battery module comprises prismatic battery cells that are stacked along the primary module axis. The module also comprises top, bottom, and side covers

and two end plates, collectively enclosing these battery cells. Each cover forms two fluid channels, both fluidically open to the prismatic battery cells. Furthermore, the module comprises bus bars that interconnect the cell terminals and protrude into the fluid channels formed by the top cover. One end plate comprises two fluid ports for connecting to a thermal management system. Each port is fluidically coupled to one fluid channel, formed by the top cover, and one fluid channel, formed by the bottom cover. The other end plate fluidically couples the two fluid channels, formed by the top cover, and, separately, the two fluid channels, formed by the bottom cover.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. **1** is a block diagram of an electric vehicle comprising a battery pack having one or more battery modules with immersion-cooled battery cells, in accordance with some examples.

[0008] FIG. **2** is a schematic illustration of a battery module comprising immersion-cooled battery cells, in accordance with some examples.

[0009] FIG. **3**A is a schematic perspective view of a stack of prismatic battery cells, in accordance with some examples.

[0010] FIG. **3**B is a schematic side view of the stack of prismatic battery cells in FIG. **3**A, in accordance with some examples.

[0011] FIG. **3**C is a schematic side view of two cells in the stack of prismatic battery cells in FIG. **3**A, in accordance with some examples.

[0012] FIG. **4**A is a schematic perspective view of a stack of prismatic battery cells and bus bars, in accordance with some examples.

[0013] FIGS. **4**B and **4**C are schematic cross-sectional side views of two types of connection between a bus bar and a cell terminal, in accordance with some examples.

[0014] FIG. **5**A is a schematic perspective view of a stack of prismatic battery cells partially enclosed with top, bottom, and side covers, in accordance with some examples.

[0015] FIG. **5**B is a schematic expanded view of a corner of the stack of prismatic battery cells in FIG. **5**A.

[0016] FIG. **5**C is a schematic front view of the stack of prismatic battery cells in FIG. **5**A.

[0017] FIG. **6**A is a schematic perspective view of a battery module illustrating a first cover attached to the top, bottom, and side covers, in accordance with some examples.

[0018] FIG. **6**B is a schematic perspective view of the battery module in FIG. **6**A, with an exploded view of the first cover.

[0019] FIGS. **7**A and **7**B are perspective front and back views of a first cover, in accordance with some examples.

[0020] FIGS. **7**C and **7**D are front and back views of the first cover in FIG. **7**A.

[0021] FIG. **7**E is a side view of the first cover in FIG. **7**A.

[0022] FIG. **7**F is a cross-sectional view of the first cover in FIG. **7**A.

[0023] FIGS. **7**G and **7**H are front and cross-sectional views of a second-cover center portion, in accordance with some examples.

[0024] FIG. **7**I is a schematic representation of thermal modeling in a battery module, in accordance with some examples.

[0025] FIG. **8**A is a schematic front view of a battery pack comprising 12 interconnected battery modules, in accordance with some examples.

[0026] FIG. **8**B is a schematic expanded view of an interconnecting plate used in the battery pack in FIG. **8**A.

[0027] FIG. **9** is a process flowchart of a method for fabricating a battery module comprising immersion-cooled battery cells, in accordance with some examples.

[0028] FIG. **10**A is a schematic perspective view of a battery pack comprising 13 interconnected battery modules, in accordance with some examples.

[0029] FIGS. **10**B-**10**D are schematic perspective and front views of the battery pack in FIG. **10**A with end covers removed to illustrate interconnecting units used for supporting the battery modules relative to each other, in accordance with some examples.

[0030] FIG. **11**A is a schematic perspective view of a portion of the battery pack in FIG. **10**A, illustrating an interconnecting unit attached to four battery modules, in accordance with some examples.

[0031] FIG. **11**B is a schematic perspective view of the four battery modules in FIG. **11**A with the interconnecting unit removed, illustrating the engagement units of the four battery modules to which the interconnecting unit is configured to attach, in accordance with some examples.

[0032] FIG. **11**C is a schematic cross-sectional view of two battery modules and interconnecting unit attached to the engagement units of these battery modules, in accordance with some examples.

[0033] FIG. **11**D is an expanded view of the portion of the two battery modules and interconnecting unit in FIG. **11**C.

[0034] FIG. **11**E is an expanded view of the two battery modules and interconnecting unit in FIG. **11**D prior to inserting the protrusion of the interconnecting unit into the unit opening, in accordance with some examples.

[0035] FIGS. **11**F and **11**G are schematic perspective views of a circular interconnecting unit configured to interconnect four engagement units of different battery modules, in accordance with some examples.

[0036] FIGS. **11**H and **11**I are schematic perspective views of a three-quarter circular interconnecting unit configured to interconnect three engagement units of different battery modules, in accordance with some examples.

[0037] FIGS. **11**J and **11**K are schematic perspective views of a semi-circular interconnecting unit configured to interconnect two engagement units of different battery modules, in accordance with some examples.

[0038] FIGS. **11**L and **11**M are schematic perspective views of a quarter-circular interconnecting unit configured to connect to the engagement units of a single battery module and provide support to an end cover, in accordance with some examples.

[0039] FIGS. **12**A and **12**B are schematic perspective views of first and second end plates illustrating four engagement units of each end plate, in accordance with some examples.

[0040] FIG. **12**C is a side view of two battery modules, illustrating the first end plates of these modules contacting each other while forming a gap between the top cover of one module and the bottom cover of the other module, in accordance with some examples.

[0041] FIGS. **13**A and **13**B are exploded and assembled/cross-sectional view of a first end plate, in accordance with some examples.

[0042] FIGS. **14**A and **14**B are exploded and assembled/cross-sectional view of a second end plate, in accordance with some examples.

DETAILED DESCRIPTION

[0043] In the following description, numerous specific details are outlined to provide a thorough understanding of the present invention. The present invention may be practiced without some or all of these specific details. In other instances, well-known process operations have not been described in detail to avoid obscuring the present invention. While the invention will be described in conjunction with the specific examples, it will be understood that it is not intended to limit the invention to the examples.

Introduction

[0044] As noted above, battery cells can be very sensitive to operating temperatures. At the same time, these temperatures can be influenced by the environment and by the cells' operation (e.g., self-heating). Liquid-based thermal management provides efficient ways of controlling the temperature of battery cells. However, the thermal coupling of battery cells and thermal liquids can be challenging. The immersion cooling of battery cells brings battery cells in direct contact with thermal liquids, which is beneficial for thermal transfer. The key challenges include controlling the distribution and flow of thermal liquids around battery cells and other components (e.g., bus bars).

[0045] Described herein are battery modules comprising immersion-cooled prismatic battery cells and methods of fabricating thereof. Specifically, each battery cell comes in direct contact with a thermal liquid (e.g., mineral oil such as transformer oil) at two locations on the top surfaces and two additional locations on the bottom surface. The thermal-liquid immersion cooling should be distinguished from other cooling methods where cooled elements do not come in contact with the cooling liquid (e.g., separated by other components) and/or gas-phase materials (e.g., air) are used for cooling. Immersion cooling involves the submersion of various battery module components into a thermal liquid (which may be also referred to as a dielectric liquid) to dissipate heat. The benefits of immersion cooling include but are not limited to (1) efficient heat dissipation and cooling uniformity (e.g., the liquid surrounding the submerged components absorbs heat more effectively, relative to air cooling, preventing overheating and ensuring optimal performance), (2) energy efficiency (e.g., requiring less power to flow the thermal liquid in comparison to flowing air to achieve the same level of cooling), (3) higher operating capabilities of battery module/higher heat dissipation rates (e.g., the thermal liquid coolant being a more efficient heat conductor than air), (4) silent operation (e.g., air cooling systems that involve fans and other mechanical components producing noise, immersion cooling is generally quieter), (5) space savings, (e.g., a higher hardware density and reduced need for extensive air cooling infrastructure can result in space savings). This is especially valuable in situations where physical space is limited or costly.

[0046] A battery module comprises at least a top cover and a bottom cover. Each cover is attached (e.g., glued) to the respective sides of the battery cells and forms two fluid channels, both fluidically open to the prismatic battery cells. Specifically, parts of the cells' top surfaces form one side of each top fluid channel. Similarly, parts of the cells' bottom surfaces form one side of each bottom fluid channel. It should be noted that the top and bottom are used in this description solely for differentiating purposes and not to indicate or limit the orientation of battery modules or each component. For example, depending on the orientation of battery modules, the bottom cover can be positioned above the top cover when a gravitational force is used as a reference. Furthermore, the module comprises bus bars that interconnect the cell terminals and protrude into the fluid channels formed by the top cover. As such, the thermal liquid comes in direct contact with the battery cells, bus bars, and any connections between the battery cells and bus bars (e.g., weld nuggets) thereby providing direct cooling of these components through the direct conduction between these elements and the thermal liquid. It should be noted that the thermal liquid experiences extensive convection within these channels, which further enhances the heat transfer.

[0047] Furthermore, a battery module comprises end plates such that the battery cells are stacked between the two end plates. One end plate comprises two fluid ports for connecting to a thermal management system. Each port is fluidically coupled to one fluid channel, formed by the top cover, and one fluid channel, formed by the bottom cover. The other end plate fluidically couples the two fluid channels, formed by the top cover, and, separately, the two fluid channels, formed by the bottom cover.

[0048] In some examples, battery cells are glued together for the structural integrity of the resulting battery module. The adhesive layers provided between the cells can also be used for the electrical isolation of battery cells and, to some extent, for the thermal isolation of the cells (both of which are safety measures). Furthermore, the direct attachment of the battery cells effectively provides some internal structural support (e.g., a module skeleton) and reduces the structural requirements from the external components, thereby reducing the weight/size of these components (and increasing the gravimetric/volumetric capacity of the module). The external support is provided by a combination of top, bottom, and side covers as well as end plates. These external components can be independently glued to the battery cells and also glued to each other. Furthermore, the end plates may have a dual-component configuration, e.g., operable as both a cover and a reinforcement element. The reinforcement element can be used for attaching the module to other components (e.g., other modules, anchor points in a battery pack, and the like), as described below with reference to FIGS. **8**A-**8**B.

Examples of Electric Vehicles

[0049] Battery modules described herein can be used in battery packs of electric vehicles. FIG. **1** is a block diagram of electric vehicle **100** comprising battery pack **110** having one or more battery modules **120** with prismatic battery cells **130**, in accordance with some examples. Prismatic battery cells **130** can be also referred to as immersion-cooled battery cells or, more specifically, liquid immersion-cooled battery cells because of their direct contact with thermal liquid **105** (e.g., with at least the top surfaces **131** and the bottom surfaces **132** of the prismatic battery cells **130**). Likewise, battery modules **120** may be referred to as immersion-cooled battery module or, more specifically, liquid-immersion-cooled battery module. Specifically, thermal liquid **105** is pumped between thermal management system **104** and battery modules **120**. Thermal management system **104** may include pumping means (e.g., a hydraulic pump) and means for thermally conditioning thermal liquid **105** (e.g., a radiator for releasing the heat from thermal liquid **105** to the environment, a heat pump, a heater, and the like). Various fluid connectors **114** (e.g., pipes, hoses) can be used for connecting thermal management system **104** and battery modules **120**. In some examples, this connection can be flexible, allowing to move battery modules **120** or, more generally, to move battery pack **110** relative to thermal management system **104**. For example, battery pack **110** can move relative to thermal management system **104** to change the center of gravity of electric vehicle **100** (for stability).

[0050] Electric vehicle **100** can comprise electric motor **106** that can be electrically coupled (e.g., through an inverter and control circuitry) to battery pack **110**. Electric vehicle **100** can also comprise electric vehicle controller **108**, which can be coupled to various other components of electric vehicle **100**. In some examples, battery pack **110** has its own controller, e.g., battery management system **112**, which can be communicatively coupled to electric vehicle controller **108**. In some examples, electric motor **106** is also immersion-cooled, e.g., using the same thermal management system **104** that is used for cooling the battery module **120**.

[0051] As noted above, battery module **120** comprises prismatic battery cells **130**, top cover **150**, bottom cover **160**, side covers **170**, first end plate **121**, and second end plate **122**, collectively enclosing these battery cells. Top cover **150** and bottom cover **160** form fluid channels to bring thermal liquid **105** in direct contact with prismatic battery cells **130**. Thermal liquid **105** can be introduced to battery module **120** through first end plate **121**, and first end plate **121** can distribute thermal liquid **105** among these fluid channels, formed by top cover **150** and bottom cover **160**. Second end plate **122** interconnects each pair of these channels thereby providing a return path for thermal liquid **105**. Additional aspects of battery module **120** will now be described with references to FIG. **2**-**8**B.

Examples of Battery Modules

[0052] FIG. **2** is a schematic illustration of battery module **120** comprising immersion-cooled battery cells **130**, in accordance with some examples. Specifically, in the view of FIG. **2**, prismatic battery cells **130** are hidden by other components such as top cover **150**, bottom cover **160**, side covers **170**, first end plate **121**, and second end plate **122**. A combination of top cover **150**, bottom cover **160**, side covers **170**, first end plate **121**, and second end plate **122** enclose prismatic battery cells **130** and isolate prismatic battery cells **130** from the environment. The combination of top cover **150**, bottom cover **160**, first end plate **121**, and second end plate **122** helps to provide immersion cooling to prismatic battery cells **130** as further described below.

[0053] FIG. **3**A is a schematic perspective view of a stack of prismatic battery cells **130**, in accordance with some examples. Specifically, top cover **150**, bottom cover **160**, side covers **170**, first end plate **121**, and second end plate **122** are not shown in FIG. **3**A. FIG. **3**B illustrates a corresponding side view of that stack. While FIGS. **3**A and **3**B illustrate thirty (30) battery cells **130**, one having ordinary skill in the art would understand that any number of cells can be used in one battery module **120**.

[0054] Battery cells **130** used in battery module **120** are prismatic, rather than cylindrical. As noted above, prismatic battery cells **130** can be packed more compactly (with fewer spaces in between cells) within battery module **120** resulting in a higher density of battery module **120**. For purposes of this description, a prismatic battery cell is defined as a cell having a shape of a rectangular prism (as opposed to a cylinder). As such, a prismatic battery cell has three distinct dimensions: (a) height, (b) width, and (c) thickness. In some examples, the height of prismatic battery cell **130** (used in battery module **120**) is between 50 millimeters and 200 millimeters or, more specifically, between 75 millimeters and 125 millimeters. In the same or other examples, the width of prismatic battery cell **130** (used in battery module **120**) is between 50 millimeters and 200 millimeters or, more specifically, between 75 millimeters and 125 millimeters. In some examples, the thickness of prismatic battery cell **130** (used in battery module **120**) is between 5 millimeters and 50 millimeters or, more specifically, between 10 millimeters and 30 millimeters.

[0055] Prismatic battery cells **130** can be of various chemistry types, e.g., nickel-manganese-cobalt (NMC), lithium iron phosphate (LFP), and lithium titanate (LTO), at least based on the composition of positive electrodes. For example, lithium titanate (LTO) cells can support high charge-discharge rates, which may be particularly useful for industrial applications such as electric tractors, loaders, and the like.

[0056] Referring to FIGS. **3**A and **3**B, prismatic battery cells **130** are stacked along primary axis **129** of battery module **120**. While FIG. **3**A illustrates a single stack, the same battery module **120** may include multiple different stacks (e.g., positioned next to each other). Prismatic battery cells **130** comprise top surfaces **131**, bottom surfaces **132** opposite to top surfaces **131**, and side surfaces **133** extending between top surfaces **131** and bottom surfaces **132**. For example, each top surface **131**, bottom surface **132**, and side surface **133** can be substantially parallel to primary axis **129**. In some examples, each of prismatic battery cells **130** has a height, length, and thickness such that the thickness is less than the height and less than the length and such that the thickness is parallel to primary axis **129** of battery module **120**. Prismatic battery cells **130** can be stacked along their thicknesses.

[0057] Prismatic battery cells **130** also comprise cell terminals **134** positioned on top surfaces **131**. Cell terminals **134** are used to form electrical connections to prismatic battery cells **130**. In some examples, cell terminals **134** are isolated from the other external components (e.g., the case, lid) of prismatic battery cells **130** such that these components are neutral. In some examples, prismatic battery cells **130** comprise pressure-release burst valves **136** configured to release gases from the interior of prismatic battery cells **130** when the pressure inside prismatic battery cells **130** exceeds a set threshold. In more specific examples, pressure-release burst valve **136** of each prismatic battery cell **130** is positioned between cell terminals **134** of that cell.

[0058] Referring to FIG. **3**C, in some examples, two adjacent prismatic battery cells **130** are mechanically interconnected by adhesive layer **138** extending between prismatic battery cells **130** in each adjacent pair. Some examples of adhesive layer **138** include but are not limited to epoxy and polyurethane. The thickness of adhesive layer **138** can be used to accommodate variations in the cell thicknesses. For example, a pair of thin cells may have a thicker adhesive layer, while a pair of thick cells may have a thinner adhesive layer, such that the combined thickness is the same regardless of the cell thicknesses. Furthermore, flexible adhesives can be used to accommodate cell swelling (if any) during the operation of battery module **120**. In some examples, adhesive layers **138** also provide electrical insulations between adjacent cells (e.g., even though the sides of battery cells **130** can be substantially neutral).

[0059] Adhesive layers **138** provide attachment/bonding between prismatic battery cells **130** in the set adding to the overall structural integrity of battery module **120**. In other words, a combination of prismatic battery cells **130** and adhesive layers **138** is operable as an internal structural element (which can be referred to as a “skeleton”) of battery module **120**. Other components of battery module **120**, e.g., top cover **150**, bottom cover **160**, and side covers **170** are operable as an internal structural element (“exoskeleton”). Furthermore, adhesive layers **138** provide electrical isolation and, in some examples, thermal isolation of adjacent prismatic battery cells **130**. While the cases of prismatic battery cells **130** can be neutral, the electrical isolation can help to improve the overall module safety (e.g., when internal shorts develop in one or more prismatic battery cells **130**).

[0060] Referring to FIG. **4**A, battery module **120** comprises bus bars **140** interconnecting cell terminals **134**. Bus bars **140** can be made from copper, aluminum, nickel, and other suitable conductive materials. While FIG. **4**A illustrates one example of cell connections (i.e., 6p-5s connection scheme, in which each 6 prismatic battery cells **130** have parallel connections forming a set, and 5 such sets are interconnected in series), other examples are also within the scope. The connection scheme depends on the required voltage output of battery module **120** and other like factors.

[0061] FIGS. **4**B and **4**C are schematic cross-sectional side views of two types of connection between bus bar **140** and cell terminal **134**, in accordance with some examples. In FIG. **4**B, the main portion of bus bar **140** is offset (along the Y-axis) relative to cell terminal **134** such that this main portion of bus bar **140** and cell terminal **134** are positioned next to each other. Bus bar **140** may comprise connecting link **145** for each cell terminal **134**, extending from the main portion of bus bar **140**. In some examples, this connecting link **145** is operable as a fusible link. The thickness or, more specifically, the cross-sectional area of connecting link **145** can be less than that of the main portion of bus bar **140** since, in some examples, connecting link **145** needs to support lower current ratings than the main portion of bus bar **140** (e.g., with parallel cell connections). In some examples, the thickness of connecting link **145** is selected to enable the welding of connecting link **145** to cell terminal **134**. Connecting link **145** can be welded to or can be monolithic with the main portion of bus bar **140**.

[0062] Referring to FIG. **4**C, in some examples, bus bar **140** is positioned on the top of cell terminal **134**. In this example, bus bar **140** can have bus bar opening **146** (e.g., a through opening or a blunt opening shown in FIG. **4**C) that enables the welding of bus bar **140** to cell terminal **134**. For example, the blunt opening may be used to form a portion of bus bar **140** that has a reduced thickness suitable for welding this portion to cell terminal **134**. The rest of bus bar **140** can have a thickness suitable for current carrying. When a through opening is used, the welding can be performed around the circumference of this opening.

[0063] In some examples, bus bars **140** comprise a plurality of disjoined components, forming first bus-bar row **141** and second bus-bar row **142**. In more specific examples, bus bars **140** in first bus-bar row **141** are connected to cell terminals **134** having one polarity (e.g., positive cell terminals), while bus bars **140** in second bus-bar row **142** are connected to cell terminals **134** having the other polarity (e.g., negative cell terminals). Since cell terminals **134** are positioned on top surfaces **131** (in the example shown in FIG. **4**A), bus bars **140** are also positioned next to top surfaces **131**. Furthermore, the interconnecting parts of first bus-bar row **141** and second bus-bar row **142** extend parallel to primary axis **129** of battery module **120**.

[0064] FIG. **4**A illustrates each first bus-bar row **141** and second bus-bar row **142** is formed by three separate bus-bar components. One of these bus-bar components comprises contact plate **143** to form an external electrical connection to these components. Contact plate **143** protrudes away from the interconnecting parts in a direction substantially perpendicular to primary axis **129**. FIG. **4**A illustrates an example where contact plates **143** are positioned on opposite sides of the stack formed by prismatic battery cells **130**. However, an example where contact plates **143** are positioned on the same side of the stack is also within the scope. In some examples, contact plates **143** comprises opening **144** for protruding an electrical connector that forms the electrical connection.

[0065] It should be noted that during the operation of battery module **120**, bus bars **140** are immersion-cooled as further described below. As such, the cross-section of bus bars **140** can be reduced in comparison to bus bars that are not cooled thereby allowing some resistive heating within bus bars **140**. For example, the temperature coefficient of copper is about 0.00404 C.sup.−1. Therefore, increasing the temperature of copper bus bars by 50° C. will cause the resistivity to increase by about 20%. Without the temperature control of bus bars **140**, the dimensions of bus bars **140** need to accommodate the highest operating temperature. It should be noted that the heating of bus bars **140** can be caused by receiving the heat from battery cells **130** and also from the internal resistive heating. However, increasing the size of bus bars **140** (to accommodate for higher operating temperatures) is highly undesirable since this increases the weight and size of bus bars **140** (and as a result of battery module **120**). Furthermore, bus bars **140** can be used (in addition to thermal liquid **105**) for transferring the heat between battery cells **130**.

[0066] Referring to FIGS. 5A-5C, battery module **120** comprises top cover **150** and bottom cover **160**. In some examples, battery module **120** also comprises side covers **170**, which can be optional. Top cover **150** and bottom cover **160** can be formed from various suitable insulating materials, such as plastic.

[0067] As shown in FIG. 5C, top cover **150** is attached to prismatic battery cells **130**, facing top surfaces **131**. For example, top cover **150** can be glued directly to top surfaces **131** of prismatic battery cells **130**. For example, epoxy, polyurethane, and other types of adhesives can be used for these purposes.

[0068] When side covers **170** are present, top cover **150** may overlap and be glued (e.g., epoxy, polyurethane) to side covers **170**, e.g., as shown in FIG. 5C. In some examples, top cover **150** can be glued to both top surfaces **131** and side surfaces **133** of prismatic battery cells **130**. For example, top cover **150** can extend side lips that overlap with side surfaces **133** and can be glued to side surfaces **133**. Top cover **150** also forms first top fluid channel **151** and second top fluid channel **152**, each fluidically open to prismatic battery cells **130**. Specifically, each first top fluid channel **151** and second top fluid channel **152** are enclosed. In some examples, each first top fluid channel **151** and second top fluid channel **152** has a rectangular cross-sectional profile such that three sides are formed by top cover **150** while the remaining fourth side is formed by top surfaces **131** of prismatic battery cells **130**.

[0069] In a similar manner, bottom cover **160** is attached to prismatic battery cells **130**, facing bottom surfaces **132**, and forms first bottom fluid channel **161** and second bottom fluid channel **162**, each fluidically open to prismatic battery cells **130**. For example, bottom cover **160** can be glued directly to bottom surfaces **132** of prismatic battery cells **130**. When side covers **170** are present, bottom cover **160** may overlap and may be glued to side covers **170**, e.g., as shown in FIG. 5C.

[0070] Overall, each prismatic battery cell **130** is immersed/comes in contact with the thermal liquid provided in all four fluid channels, i.e., first top fluid channel **151**, second top fluid channel **152**, first bottom fluid channel **161**, and second bottom fluid channel **162**. Each prismatic battery cell **130** is cooled or, more generally, thermally managed from top surface **131** and bottom surface **132** thereby ensuring more a uniform temperature profile within prismatic battery cell **130** (e.g., in comparison to one-sided cooling of battery cells). Furthermore, first top fluid channel **151** and second top fluid channel **152** are also used for cooling bus bars **140**. For example, first bus-bar row **141** protrudes into first top fluid channel **151** while second bus-bar row **142** protrudes into second top fluid channel **152**.

[0071] In general, the width of these fluid channels is determined by the width of battery cells **130**. The fluid channels can be as wide as possible considering that top cover **150** and bottom cover **160** need to be supported relative to battery cells **130** (e.g., at least around edges) and also considering that both top channels need to be separated from each other (and only fluidically interconnected by second end plate **122**). Otherwise, the width of these fluid channels can be maximized to provide maximum contact and heat transfer with battery cells **130**. In other words, the fluid channels are designed to expose as much of top surfaces **131** and bottom surfaces **132** of battery cells **130** as possible. On other hands, the height of these fluid channels can be minimal to reduce the thickness of top cover **150** and bottom cover **160** and the total height of battery module **120**.

[0072] Referring to FIG. **5**C, in some examples, top cover **150** forms gas-venting channel **153** fluidically open to pressure-release burst valves **136**. In case one or more prismatic battery cells **130** experience internal over-pressurization, the corresponding pressure-release burst valves **136** open and release internal gases (and possibly other matter) from these cells into gas-venting channel **153** thereby allowing to depressurize the cells. In some examples, gas-venting channel **153** is fluidically isolated from other components, e.g., bus bars **140**, thereby preventing further propagation of unsafe conditions and even potentially continuing the operation of battery module **120**. In some examples, one or both of first end plate **121** and second end plate **122** comprises burst valves to vent gases from battery module **120** (e.g., when the pressure inside gas-venting channel **153** exceeds a set threshold).

[0073] In some examples, battery module **120** further comprises side covers **170**, facing side surfaces **133** of prismatic battery cells **130**. Each side cover **170** is attached to top cover **150** and to bottom cover **160**. For example, FIG. **5**B illustrates bottom cover **160** comprising side lips **169** that overlaps with and glued to side covers **170**. Top cover **150** can have a similar lip that overlaps with side covers **170**. In some examples, side covers **170** are also attached to first end plate **121** and second end plate **122**. For example, side covers **170** comprises first lip **171** and second lip **172** extending perpendicular to primary axis **129**. For example, FIG. **6**A illustrates first lip **171**. First lip **171** overlaps with and is attached to first end plate **121** such that a portion of first end plate **121** extends between first lip **171** and prismatic battery cells **130**. Similarly, second lip **172** overlaps with and is attached to second end plate **122** such that a portion of second end plate **122** extends between second lip **172** and prismatic battery cells **130**.

[0074] Side covers **170** can be formed from aluminum and are used to provide the structural integrity to battery module **120**. In some examples, a side of side covers **170** facing prismatic battery cells **130** is made from an electrically insulating material such as rubber or polymer (e.g., sprayed on battery cells **130** and/or side covers **170**) to insulate the metal base of side covers **170** from prismatic battery cells **130**. Even though the cases of prismatic battery cells **130** can be neutral, the electrical isolation can help to improve the overall module safety. In some examples, side covers **170** are formed from an insulating material (e.g., carbon fiber, glass fiber). Side covers **170** also provide structural support within battery module **120**.

[0075] Referring to FIGS. **6**A and **6**B, battery module **120** comprises first end plate **121**, which is attached (e.g., glued or, more specifically, sealed to) to both top cover **150** and bottom cover **160**. When side covers **170** are present, first end plate **121** is also attached (e.g., glued) to side covers **170**. Second end plate **122** is attached to both top cover **150** and bottom cover **160** and fluidically interconnecting first top fluid channel **151** and first bottom fluid channel **161** and, separately, fluidically interconnecting second top fluid channel **152** and second bottom fluid channel **162**.

[0076] Referring to FIGS. **6**A and **6**B, in some examples, first end plate **121** comprises first fluid port **251** and second fluid port **252**, used for fluidic connection of battery module **120** to other components of electric vehicle **100**, e.g., thermal management system **104**. Specifically, first fluid port **251** and second fluid port **252** allow for thermal liquid **105** to flow into and out of battery module **120** and can be referred to as inlet and outlet ports. First end plate **121** also help to fluidically couple these ports to other fluid channels within battery module **120** thereby controlling the distribution of thermal liquid **105** within battery module **120**. Specifically, first fluid port **251** is fluidically coupled to both first top fluid channel **151** and first bottom fluid channel **161**. Separately, second fluid port **252** is fluidically coupled to both second top fluid channel **152** and second bottom fluid channel **162**. It should be noted that a combination of first fluid port **251**, first top fluid channel **151**, and first bottom fluid channel **161** are fluidically isolated from second fluid port **252**, second top fluid channel **152**, and second bottom fluid channel **162** at first end plate **121**. However, first top fluid channel **151** and second top fluid channel **152** and, separately, second top fluid channel **152** and second bottom fluid channel **162** are fluidically interconnected by second end plate **122** as further described below. As such, a combination of first end plate **121** and second end plate **122** provides both distribution and looping of thermal liquid **105** within battery module **120**. In this example, both first fluid port **251** and second fluid port **252** are positioned on the same side of battery module **120**, i.e., first end plate **121**, which helps with routing fluid connectors **114** (e.g., pipes, hoses) to the same side of battery module **120**. However, examples, where first fluid port **251** and second fluid port **252** are different sides of battery module **120**, are also within the scope.

[0077] Referring to FIGS. **7**A and **7**C, In some examples, first end plate **121** comprises first contact opening **253** overlapping with first contact plate **143**. First contact opening **253** can be used to form an electrical connection to first contact plate **143**, e.g., by protruding a conductive terminal (not shown). It should be noted that this protruding terminal is sealed against first end plate **121** since first contact plate **143** is positioned on the thermal liquid side and this seal prevents the thermal liquid from leaking outside of battery module **120**.

[0078] In some examples, first end plate **121** comprises signal-trace opening **255**, which can be used to protrude various wires/voltage leads through first end plate **121**. These wires/voltage leads can also be sealed against first end plate **121** to prevent the thermal liquid from leaking outside of battery module **120**.

[0079] Referring to FIGS. **6**A and **6**B, in some examples, first end plate **121** comprises first reinforcement element **200** and first cover **210** formed from different materials. For example, first reinforcement element **200** can be formed from metal, such as aluminum, steel, and the like. First cover **210** can be formed from plastic. The material of first cover **210** can be selected such that first cover **210** provides electric isolation of battery cells **130** from the environment and other conductive components. Furthermore, the material of first cover **210** can simplify the fabrication of first cover **210** such as forming various internal channels for the distribution of thermal liquid **105**. At the same time, first reinforcement element **200** provides structural support to first cover **210** and enables battery module **120** to connect to other battery modules as further described below. First cover **210** is inserted into the cavity formed by top cover **150**, bottom cover **160**, and side covers **170** and is sealed against each of these components. Furthermore, first reinforcement element **200** can be glued or otherwise attached to one or more (e.g., all) of top cover **150**, bottom cover **160**, and side covers **170**. In some examples, side covers **170** bend around the edge of first reinforcement element **200** forming a lip, e.g., as shown in FIG. **6**A. In the same or other examples, first cover **210** is at least partially positioned between first reinforcement element **200** and prismatic battery cells **130**.

[0080] Referring to FIG. **6**B, in some examples, first cover **210** comprises first-cover center portion **220** and first-cover outer protrusion **230**, monolithic with and extending from first-cover center portion **220** away from prismatic battery cells **130**. First-cover outer protrusion **230** comprises multiple pieces separated by first-cover channels **231**, extending through first-cover outer protrusion **230** to first-cover center portion **220**. First reinforcement element **200** comprises first reinforcement frame **202** and first reinforcement cross-member **204** such that first reinforcement frame **202** surrounds first-cover outer protrusion **230** while first reinforcement cross-member **204** protrudes into first-cover channels **231**. This overlap (and the increased contact area) between first reinforcement element **200** and first cover **210**, provide greater support to first cover **210** by first reinforcement element **200**.

[0081] Referring to FIG. **6**B, in some examples, first cover **210** further comprises first-cover inner protrusion **240**, monolithic with and extending from first-cover center portion **220** toward prismatic battery cells **130**. First-cover inner protrusion **240** extends into an opening formed by top cover **150** and bottom cover **160** and is attached to each of top cover **150** and bottom cover **160**.

[0082] Referring to FIG. **7**B, in some examples, first-cover inner protrusion **240** comprises cutout **242** such that a portion of first bus-bar row **141** extends into cutout **242**.

[0083] Referring to FIGS. **7**B, **7**D, and **7**E, in some examples, first-cover inner protrusion **240** comprises sealing extensions **244** protruding into and sealing first top fluid channel **151**, second top fluid channel **152**, first bottom fluid channel **161**, and second bottom fluid channel **162**.

[0084] Referring to FIG. **7**F, in some examples, first-cover inner protrusion **240** comprises first set of internal fluid channels **246** fluidically coupling first fluid port **251** with both first top fluid channel **151** and first bottom fluid channel **161**. First-cover inner protrusion **240** comprises second set of internal fluid channels **248** fluidically coupling second fluid port **252** with both second top fluid channel **152** and second bottom fluid channel **162**.

[0085] First end plate **121** and second end plate **122** may have many similar features. For example, reinforcement elements of first end plate **121** and second end plate **122** may be substantially similar or even the same (and interchangeable). On other hand, first cover **210** and second cover **260** can have different designs. For example, first cover **210** comprises fluid port **251** and second fluid port **252** (operable as an inlet and outlet and described above), while second cover **260** may not have any such ports, e.g., as schematically shown in FIGS. **7**G and **7**H. It should be noted that positioning both inlet and outlet on the same side of battery module **120** is used to achieve uniform heat transfer from different battery cells as will now be described with reference to battery module cooling and FIG. **7**I in the context of first top fluid channel **151** and second top fluid channel **152**. One having ordinary skill in the art would understand that the same approach applies to battery module heating as well as first bottom fluid channel **161** and second bottom fluid channel **162**.

[0086] Referring to FIG. **7**I, as the thermal liquid having an inlet temperature (T.sub.in) enters battery module **120**, the thermal liquid receives the heat (H.sub.1) and increases the fluid temperature as the fluid continues to flow through the module. For example, upon reaching the last cell in this series, the fluid temperature (T.sub.x) will be higher that the inlet temperature (T.sub.x>T.sub.in). Assuming that all battery cells have the same temperature (T.sub.cell), the first cell that comes in contact with the immediately incoming (colder) fluid will lose more heat than any subsequent cell in this series since the heat transfer is proportional to the temperature gradient between the cell and the fluid. For example, the heat transfer from the last cell in this series (H.sub.x∝T.sub.cell−T.sub.x) will be smaller than the heat transfer from the first cell in this series (H.sub.1∝T.sub.cell−T.sub.in) due to the thermal liquid heating and the thermal gradient reduction (T.sub.in<T.sub.x.fwdarw.H.sub.1>H.sub.x). If the thermal liquid is not looped and allowed to exit on the other side of the battery module, then the first cell will be cooled more than the last cell. However, when the thermal liquid is looped and has both first top fluid channel **151** and second top fluid channel **152** (both providing fluidic contact to each cell), there is additional heat transfer occurs from each cell. Specifically, the heat transfer provided by first top fluid channel **151** is described above resulting in the first cell will be cooled more than the last cell. However, as the thermal liquid is directed from first top fluid channel **151** to second top fluid channel **152**, the order of the cell experiencing the flow is flipped while the thermal liquid continues to heat. The last cell sees this return flow first and experiences additional heat transfer (H′.sub.x∝T.sub.cell−T′.sub.x). The first cell sees this return flow last and also experiences additional heat transfer (H′.sub.1∝T.sub.cell−T.sub.out). Since the thermal liquid continues to heat (T.sub.out>T′.sub.x), the last cell is now cooled more (H′.sub.x>H′.sub.1). Combining the two heat transfers (provided by first top fluid channel **151** to second top fluid channel **152**), the total heat transfer is more balanced (H.sub.x+H′.sub.x{tilde over ( )}H.sub.1+H′.sub.1) than the heat transfer provided by each of the channels individually.

[0087] Returning to FIGS. **7**G and **7**H, second cover **260** comprises second contact opening **263**, which is used for connecting to one of bus bars **140**. In other words, one connection to bus bars **140** is formed through first contact opening **253** in first cover **210**, while the other connection to bus bars **140** is formed through second contact opening **263** in second cover **260**. Having such connections on the opposite sides of battery module **120** allows forming various connections among modules. Alternatively, both contact openings are positioned on the same cover (e.g., the cover that also includes fluid ports or the cover that does not include any fluid ports).

[0088] Similar to first cover **210**, second cover **260** comprises second-cover center portion **265** as well as second-cover outer protrusion **261** and second-cover inner protrusion **262**, extending in opposite sides from second-cover center portion **265**. Second-cover inner protrusion **262** faces battery cells **130** and extends into the cavity formed by top cover **150**, bottom cover **160**, and side covers **170**. In some examples, second-cover inner protrusion **262** is glued to each of top cover **150**, bottom cover **160**, and side covers **170**. Furthermore, in some examples, second-cover inner protrusion **262** comprises additional sealing extensions **264** protruding into and sealing first top fluid channel **151**, second top fluid channel **152**, first bottom fluid channel **161**, and second bottom fluid channel **162**. Finally, second-cover inner protrusion **262** comprises inner channels that fluidically couple first top fluid channel **151** and second top fluid channel **152** and, separately, fluidically couple first bottom fluid channel **161** and second bottom fluid channel **162**, e.g., as schematically shown in FIG. **7**H.

[0089] Referring to FIGS. **6**A and **6**B, in some examples, first reinforcement frame **202** comprises four openings **275**, each positioned in a different corner of first reinforcement frame **202**. Openings **275** can be used for connecting battery module **120** to other modules as will now be described with reference to FIGS. **8**A and **8**B. Specifically, FIG. **8**A illustrates twelve battery modules **120** arranged into a battery pack **110** and interconnected using interconnecting units **118**. FIG. **8**B is an expanded view of an interconnecting unit **118** interconnecting four battery modules **120**. Specifically, the interconnecting unit **118** is bolted to each of the four battery modules **120** using a fastener **119**. A portion of a battery module **120** connected to an interconnecting unit **118** may be referred to as an engagement unit (further described below).

Examples of Methods of Fabricating Battery Modules

[0090] FIG. **9** is a process flowchart corresponding to method **900** of fabricating battery module **120**, in accordance with some examples. Method **900** may commence with (block **910**) adhering prismatic battery cells **130** stacked along primary axis **129** of battery module **120** and comprising top surfaces **131**, bottom surfaces **132** opposite to top surfaces **131**, side surfaces **133** extending between top surfaces **131** and bottom surfaces **132**, and cell terminals **134** positioned on top surfaces **131**.

[0091] Method **900** may proceed with (block **920**) attaching bus bars **140** to cell terminals **134**. Bus bars **140** form first bus-bar row **141** and second bus-bar row **142** and interconnecting cell terminals **134**. In some examples, method **900** comprises (block **925**) attaching side covers **170**.

[0092] Method **900** may proceed with (block **930**) attaching top cover **150** to prismatic battery cells **130** and (block **935**) attaching bottom cover **160**. Specifically, after these attaching operations, top cover **150** faces top surfaces **131** and forms first top fluid channel **151** and second top fluid channel **152**, each fluidically open to prismatic battery cells **130**. Similarly, bottom cover **160** faces bottom surfaces **132** and forms first bottom fluid channel **161** and second bottom fluid channel **162**, each fluidically open to prismatic battery cells **130**.

[0093] Method **900** may proceed with (block **940**) attaching first end plate **121** and (block **945**) attaching second end plate **122**. Specifically, first end plate **121** is attached to both top cover **150** and bottom cover **160** and comprises first fluid port **251** and second fluid port **252**. As described above, first fluid port **251** is fluidically coupled to both first top fluid channel **151** and first bottom fluid channel **161**. Second fluid port **252** is fluidically coupled to both second top fluid channel **152** and second bottom fluid channel **162**. Second end plate **122** fluidically interconnects first top fluid channel **151** and first bottom fluid channel **161** and, separately, fluidically interconnects second top fluid channel **152** and second bottom fluid channel **162**.

[0094] In some examples, method **900** proceed with (block **960**) interconnecting battery modules

120, e.g., using interconnecting units **118** and fasteners **119** as shown in FIGS. **8**A-**8**B and further described below. For example, battery modules **120** may be stacked together such that their engagement units **270** (positioned at the corners of each battery module **120**) contact each other. The engagement units **270** that contact each other may be referred to as an engagement unit set **279**. There could be two, three, or four engagement units **270** in each engagement unit set **279**. An interconnecting unit **118** may be positioned over each engagement unit set **279** such that the engagement units **270** in this engagement unit set **279** are compressed against each other. Various features of the engagement units **270** and interconnecting units **118** that enable this compression are described below. Fasteners **119** may protrude through the engagement units **270** and bolted to the corresponding engagement units **270**.

Examples of Interconnecting Battery Modules

[0095] FIGS. **10**A-**10**D are schematic perspective and front views of a battery pack **110** comprising thirteen interconnected battery modules **120**, in accordance with some examples. The boundary of each battery module **120** is identified with dashed lines as these boundaries are obscured by end covers **111** in FIG. **10**A and by battery-pack busbars **113** in FIGS. **10**B-**10**D. Furthermore, it should be noted that FIGS. **10**B-**10**D illustrate one side of the battery pack **110**, i.e., the side with the first end plate **121** each comprising a first fluid port **251** and a second fluid port **252** in addition to an electric contact **254** connected to one of the battery-pack busbars **113**). In some examples, a battery pack **110** also comprises mounting rails **116**, one on each side of the battery pack **110** (e.g., as shown in FIG. **10**A). These mounting rails **116** may be integrated into interconnecting units **118**, e.g., along the bottom side of the battery module **120** in the bottom row. For example, FIG. **10**B illustrates a front mounting rail **116** comprising five interconnecting units **118**, i.e., two quarter-circular interconnecting units **118** (each positioned along the sides of the battery pack **110** and connected to only one battery module **120**) and three semicircular interconnecting units **118** (each connected to a pair of battery modules **120**). Other interconnecting units **118** may be standalone structures and further described below with reference to FIG. **11**F-**11**M.

[0096] In general, a battery pack **110** may comprise any number of battery modules **120**. The number and arrangement of the battery modules **120** in battery pack **110** depends on the available space, voltage/current/power/energy requirements, and other factors. Each battery module **120** in a battery pack **110** may be mechanically connected to at least one other battery module **120** using interconnecting units **118**, e.g., as shown in FIGS. **10**B-**10**D. Each interconnecting unit **118** may interconnect two, three, or four battery modules **120**. Similarly, depending on the location of the battery module **120** in a battery pack **110**, this battery module **120** may be connected to two other modules (e.g., referring to the top battery module **120** in FIGS. **10**B-**10**C), three other battery modules (e.g., referring to each corner battery module **120** in FIGS. **10**B-**10**C), five other battery modules (e.g., referring to each battery module **120** in the middle along the edges in FIGS. **10**B-**10**C), six other battery modules (e.g., referring to a battery module **120** right under the top battery module **120** in FIGS. **10**B-**10**C), eight other battery modules (e.g., referring to any interior battery module **120** in FIGS. **10**B-**10**C), or some other number of battery modules. Furthermore, in addition to being mechanically interconnected, the battery modules **120** may be interconnected electrically (e.g., using battery-pack busbars **113** shown in FIG. **10**B-**10**D) and/or fluidically. The electrical connections depend on the voltage/current requirements, while fluidic may depend on cooling requirements. These connections may be covered with and protected by end covers **111** (e.g., as shown in FIG. **10**A).

[0097] Referring to FIG. **10**D, a battery pack **110** comprises at least a first battery module **120***a* and a second battery module **120***b*. As noted above, each battery module **120** comprises a first end plate **121**, a second end plate **122**, prismatic battery cells **130** stacked between the first end plate **121** and the second end plate **122**, a top cover **150** attached to the prismatic battery cells **130**, and a bottom cover **160** attached to the prismatic battery cells **130**. The top cover **150** forms one or more top fluid channels open to each of the prismatic battery cells **130** thereby allowing a thermal liquid to directly contact each of the prismatic battery cells **130**. The bottom cover **160** forms one or more bottom fluid channels open to each of the prismatic battery cells **130** thereby allowing the thermal liquid to directly contact each of the prismatic battery cells **130**. The first end plate **121** is attached to both the top cover **150** and the bottom cover **160** and comprises a first fluid port **251** and a second fluid port **252** fluidically coupled to one or more top fluid channels and one or more bottom fluid channels. The second end plate **122** is attached to both the top cover **150** and the bottom cover **160** and fluidically interconnects one or more top fluid channels and one or more bottom fluid channels.

[0098] Referring to FIG. **10**D, each of the first end plate **121** and the second end plate **122** comprises four engagement units **270** located at corners of the first end plate **121** and the second end plate **122**. It should be noted that FIG. **10**D illustrates the first end plate **121** of each of the first battery module **120***a* and the second battery module **120***b*. The second end plate **122** has a similar arrangement of the engagement units **270** and is further explained below with reference to FIGS. **12**B and **14**A-**14**B. Furthermore, the engagement units **270** (in FIG. **10**D) are hidden behind interconnecting units **118** and identified with dashed lines.

[0099] Referring to FIG. **10**D, the first end plate **121** of the first battery module **120***a* comprises a first-module engagement unit **270***a*, being a part of the four engagement units **270** of the first end plate **121** of the first battery module **120***a*. The first end plate **121** of the second battery module **120***b* comprises a second-module engagement unit **270***b*, forming at least a part of an engagement unit set **279** together with the first-module engagement unit **270***a* and being a part of the four engagement units **270** of the first end plate **121** of the second battery module **120***b*. An interconnecting unit **118** is attached to the engagement unit set **279** and compresses the first-module engagement unit **270***a* against the second-module engagement unit **270***b*. Specifically, the interconnecting unit **118** compresses the first-module engagement unit **270***a* against the second-module engagement unit **270***b* along the Y axis, thereby supporting the first battery module **120***a* and the second battery module **120***b* relative to each other.

[0100] FIG. **11**A is a schematic perspective view of a portion of the battery pack in FIG. **10**B, illustrating an interconnecting unit **118** attached to four battery modules **120**, in accordance with some examples. Specifically, the 2 bolted to each battery module **120** or, more specifically, its engagement unit **270** using a fastener **119**. FIG. **11**B is a schematic perspective view of the same four battery modules **120** with the interconnecting unit removed **118**, illustrating the engagement units **270** of these battery modules **120**. Specifically, these engagement units **270** form an engagement unit set **279**. While in this example, the engagement unit set **279** is formed by four engagement units **270**, in other examples, the engagement unit set **279** can be formed by only two engagement units **270** or only three engagement units **270**. Furthermore, each engagement unit **270** comprises a threaded opening **275** such that a fastener **119** can be threaded and supported in this threaded opening **275**.

[0101] FIG. **11**C is a schematic cross-sectional view of two battery modules **120** (i.e., a first battery module **120***a* and a second battery module **120***b*) and interconnecting unit **118** attached to the engagement units **270** of these battery modules **120** (i.e., a first-module engagement unit **270***a* and a second-module engagement unit **270***b*) using fasteners **119**. Specifically, a fastener **119** protrudes through each of the first-module engagement unit **270***a* and the second-module engagement unit **270***b* and is threaded into the threaded opening **275** of each of the first-module engagement unit **270***a* and the second-module engagement unit **270***b*. The interconnecting unit **118** or, more specifically, the base **300** of the interconnecting unit **118** comprises a base opening **305** such that a fastener **119** protrudes through the base opening **305** and is threaded into one of the first-module engagement unit **270***a* and the second-module engagement unit **270***b*.

[0102] FIG. **11**D is an expanded view of the portion of the two battery modules **120** and interconnecting unit **118** in FIG. **11**C. Specifically, the interconnecting unit **118** comprises a base **300** and a protrusion **310**. The engagement units **270** comprise a unit inner surface **331** and a unit outer surface **332** opposite of the unit inner surface **331**. An engagement-unit opening **335** extends from the unit outer surface **332** toward the unit inner surface **331**. When the interconnecting unit **118** is attached to the four engagement units **270**, the protrusion **310** of the interconnecting unit **118** extends into the engagement-unit opening **335**.

[0103] FIG. **11**E is a corresponding view prior to inserting the protrusion **310** of the interconnecting unit into the engagement-unit opening **335**, in accordance with some examples. The protrusion **310** comprises a first protrusion surface **311** and a second protrusion surface **312** opposite of the first protrusion surface **311**. The first protrusion surface **311** forms an angle (α) with the base inner surface **301** that is greater than 90° C. In some examples, this angle (α) is 95-120° C. or, more specifically, 100-110°. This angle (α) ensures that the first-module engagement unit **270***a* is compressed against the second-module engagement unit **270***b* as the interconnecting unit **118** is attached to both the first-module engagement unit **270***a* and second-module engagement unit **270***b* or, more specifically, as the protrusion **310** of the interconnecting unit **118** is being inserted into the engagement-unit openings **335** of the first-module engagement unit **270***a* and second-module engagement unit **270***b*. Referring to FIG. **11**E, the first protrusion surface **311** directly interfaces each of the first-module engagement unit **270***a* and the second-module engagement unit **270***b* or, more specifically, with the first unit-opening surface **341** of these units causing the compression.

[0104] Further referring to FIG. **11**E, in some examples, the protrusion **310** comprises a third protrusion surface **313** extending parallel to the base inner surface **301**. At least one of the base inner surface **301** or the third protrusion surface **313** directly interfaces each of the first-module engagement unit **270***a* and the second-module engagement unit **270***b*. This provides a positive stop (along the X-axis) for the interconnecting unit **118** while the interconnecting unit **118** is being attached to the first-module engagement unit **270***a* and the second-module engagement unit **270***b*.

[0105] Further referring to FIG. **11**E, in some examples, the engagement-unit opening **335** is defined by a first unit-opening surface **341**, a second unit-opening surface **342**, and a third unit-opening surface **343**. The first unit-opening surface **341** directly interfaces the first protrusion surface **311** thereby compressing the first-module engagement unit **270***a* against the second-module engagement unit **270***b*. The first unit-opening surface **341** forms an angle (β) with the unit outer surface **332** that is greater than 90°. In some examples, this angle (β) is the same as the angle (α), between the first protrusion surface **311** and the base inner surface **301**, described above.

[0106] Referring to FIGS. **12**A and **12**B, each engagement-unit opening **335** forms a quarter-circle channel, extending between two orthogonal surfaces of the battery module **120** (e.g., one surface defined by a corresponding side cover **170** and another surface defined by one of the top cover **150** or the bottom cover **160**).

[0107] In some examples, the four engagement units **270** of each of the first end plate **121** and the second end plate **122** are monolithically connected. For example, each of the first end plate **121** and the second end plate **122** comprises a reinforcement element **200** such that the four engagement units **270** are parts of the reinforcement element **200**. In some examples, the reinforcement element **200** may be formed from aluminum.

[0108] Referring to FIGS. **13**A and **13**B, in some examples, the first end plate **121** further comprises a first cover **210**, positioned between the reinforcement element **200** and the prismatic battery cells **130** and electrically isolating the reinforcement element **200** from the prismatic battery cells **130**. The first fluid port **251** and the second fluid port **252** protrude through each of the first cover **210** and the reinforcement element **200**. Furthermore, a first contact opening **253** may protrude through each of the first cover **210** and the reinforcement element **200**. In some examples, the first cover **210** is glued to each of the reinforcement element **200** and the prismatic battery cells **130**.

[0109] Referring to FIGS. **14**A and **14**B, in some examples, the second end plate **122** further comprises a second cover **260**, positioned between the reinforcement element **200** and the prismatic battery cells **130** and electrically isolating the reinforcement element **200** from the prismatic battery cells **130**. It should be noted that the reinforcement element **200** of the first end plate **121** may be different from that of the second end plate **122**. However, each reinforcement element **200** comprises four engagement units **270** that can provide up to **8** connections to each battery module **120**. The design of all engagement units **270** may be the same. Furthermore, referring to FIGS. **14**A and **14**B, a second contact opening **263** may protrude through each of the second cover **260** and the reinforcement element **200**. In some examples, the second cover **260** is glued to each of the reinforcement element **200** and the prismatic battery cells **130**.

[0110] Referring to FIG. **11**B, in some examples, the engagement unit set **279** consists of the first-module engagement unit **270***a*, the second-module engagement unit **270***b*, and two additional engagement units. In these examples, the interconnecting unit **118** has a circular shape, e.g., as shown in FIGS. **11**F-**11**G. Alternatively, the engagement unit set **279** consists of the first-module engagement unit **270***a*, the second-module engagement unit **270***b*, and one additional engagement unit. In these examples, the interconnecting unit **118** has a three-quarter-circular shape, e.g., as shown in FIGS. **11**H-**11**I. Furthermore, the engagement unit set **279** may consist of only the first-module engagement unit **270***a* and the second-module engagement unit **270***b*. In this case, the interconnecting unit **118** has a semi-circular shape, e.g., as shown in FIGS. **11**J-**11**K.

[0111] FIGS. **11**L-**11**M illustrate another example of an interconnecting unit **118** that connects only to one engagement unit **270**, e.g. at the outer corner of the battery pack **110**. The purpose of this interconnecting unit **118** is to connect the battery module **120** to an end cover **111** (e.g., as shown in FIG. **10**A) or other covers. For example, an interconnecting unit **118** may comprise one or more supporting portions **320**, which may extend orthogonal to the base outer surface **302**. When two supporting portions **320** are provided, these supporting portions **320** may be orthogonal to each other, e.g., to attach to different battery pack covers. Each supporting portion **320** may comprise a supporting-portion opening **325** (e.g., a threaded opening) for securing a fastener.

[0112] Referring to FIG. **12**C, in some examples, compressing the first-module engagement unit **270***a* against the second-module engagement unit **270***b* also compresses the first end plate **121** of the first battery module **120***a* against the first end plate **121** of the second battery module **120***b*. At the same time, the bottom cover **160** of the first battery module **120***a* faces and is spaced away from the top cover **150** of the second battery module **120***b* when the first end plate **121** of the first battery module **120***a* against the first end plate **121** of the second battery module **120***b*. As such, the first end plate **121** (and the second end plate **122**) or, more specifically, their reinforcement element **200** may be used to transfer loads between different battery modules **120** in a battery pack **110**.

Conclusion

[0113] Although the foregoing concepts have been described in some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications may be practiced within the scope of the appended claims. It should be noted that there are many alternative ways of implementing processes, systems, and apparatuses. Accordingly, the present embodiments are to be considered illustrative and not restrictive.

Claims

1. A battery pack comprising: a first battery module and a second battery module, each comprising a first end plate, a second end plate, prismatic battery cells stacked between the first end plate and the second end plate, a top cover attached to the prismatic battery cells, and a bottom cover attached to the prismatic battery cells, wherein: the top cover forms one or more top fluid channels open to each of the prismatic battery cells thereby allowing a thermal liquid to directly contact each of the prismatic battery cells, the bottom cover forms one or more bottom fluid channels open to each of the prismatic battery cells thereby allowing the thermal liquid to directly contact each of the prismatic battery cells, the first end plate is attached to both the top cover and the bottom cover and comprises a first fluid port and a second fluid port fluidically coupled to the one or more top fluid

channels and the one or more bottom fluid channels, the second end plate is attached to both the top cover and the bottom cover and fluidically interconnects the one or more top fluid channels and the one or more bottom fluid channels, each of the first end plate and the second end plate comprises four engagement units located at the corners of the first end plate and the second end plate, the first end plate of the first battery module comprises a first-module engagement unit, being a part of the four engagement units of the first end plate of the first battery module, and the first end plate of the second battery module comprises a second-module engagement unit, forming at least a part of an engagement unit set together with the first-module engagement unit and being a part of the four engagement units of the first end plate of the second battery module; and an interconnecting unit is attached to the engagement unit set and compresses the first-module engagement unit against the second-module engagement unit.
2. The battery pack of claim 1, wherein: each of the four engagement units comprises a threaded opening, and the interconnecting unit is attached to each of the first-module engagement unit and the second-module engagement unit using a fastener protruding through each of the first-module engagement unit and the second-module engagement unit and threaded into the threaded opening of each of the first-module engagement unit and the second-module engagement unit.
3. The battery pack of claim 1, wherein: the interconnecting units comprises a base and a protrusion, the base comprises a base inner surface and a base outer surface opposite of the base inner surface, the protrusion extends from the base inner surface in a direction away from the base outer surface, the protrusion comprises a first protrusion surface and a second protrusion surface opposite of the first protrusion surface, and the first protrusion surface forms an angle greater than 90° with the base inner surface and directly interfaces each of the first-module engagement unit and the second-module engagement unit thereby compressing the first-module engagement unit against the second-module engagement unit.
4. The battery pack of claim 3, wherein: the protrusion comprises a third protrusion surface extending parallel to the base inner surface, and at least one of the base inner surface or the third protrusion surface directly interfaces each of the first-module engagement unit and the second-module engagement unit.
5. The battery pack of claim 3, wherein the base further comprises a base opening such that a fastener protrudes through the base opening and is threaded into one of the first-module engagement unit and the second-module engagement unit.
6. The battery pack of claim 3, wherein: each of the four engagement units comprising a unit inner surface and a unit outer surface opposite of the unit inner surface, an engagement-unit opening extending from the unit outer surface toward the unit inner surface, and the protrusion of the interconnecting unit extends into the engagement-unit opening.
7. The battery pack of claim 6, wherein: the engagement-unit opening is defined by a first unit-opening surface, a second unit-opening surface, and a third unit-opening surface, and the first unit-opening surface directly interfaces the first protrusion surface thereby compressing the first-module engagement unit against the second-module engagement unit.
8. The battery pack of claim 7, wherein the first unit-opening surface forms an angle greater than 90° with the unit outer surface.
9. The battery pack of claim 8, wherein the angle between the first unit-opening surface and the unit outer surface is the same as the angle between the first protrusion surface and the base inner surface.
10. The battery pack of claim 6, wherein the engagement-unit opening forms a quarter-circle channel.
11. The battery pack of claim 1, wherein the four engagement units of each of the first end plate and the second end plate are monolithically connected.
12. The battery pack of claim 1, wherein each of the first end plate and the second end plate comprises a reinforcement element such that the four engagement units are parts of the

reinforcement element.

13. The battery pack of claim 12, wherein: the first end plate further comprises a first cover, positioned between the reinforcement element and the prismatic battery cells and electrically isolating the reinforcement element from the prismatic battery cells, and the first fluid port and the second fluid port protrude through each of the first cover and the reinforcement element.

14. The battery pack of claim 13, wherein the first cover is glued to each of the reinforcement element and the prismatic battery cells.

15. The battery pack of claim 1, wherein: the first end plate and the second end plate comprises an electric contact, the electric contact on the first end plate of the first battery module has a different polarity from the electric contact on the first end plate of the second battery module.

16. The battery pack of claim 1, wherein: the engagement unit set consists of only the first-module engagement unit and the second-module engagement unit, and the interconnecting unit has a semi-circular shape.

17. The battery pack of claim 1, wherein: the engagement unit set consists of the first-module engagement unit, the second-module engagement unit, and one additional engagement unit, and the interconnecting unit has a three-quarter-circular shape.

18. The battery pack of claim 1, wherein: the engagement unit set consists of the first-module engagement unit, the second-module engagement unit, and two additional engagement units, and the interconnecting unit has a circular shape.

19. The battery pack of claim 1, further comprising an end cover enclosing the first end plate of each of the first battery module and the second battery module and connected to the interconnecting unit.

20. The battery pack of claim 1, wherein: compressing the first-module engagement unit against the second-module engagement unit also compresses the first end plate of the first battery module against the first end plate of the second battery module, and the bottom cover of the first battery module faces and spaced away from the top cover of the second battery module when the first end plate of the first battery module against the first end plate of the second battery module.