UNITED STATES PATENT APPLICATION

TITLE OF INVENTION: Adaptive Thermal-Management System for High-Density Solid-State Battery Modules Employing Phase-Change Microchannels

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RELATED APPLICATIONS: This application claims priority to U.S. Provisional Application No. 63/521,847, filed June 19, 2024, the entire disclosure of which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates generally to thermal management of electrochemical energy storage devices, and more particularly to microchannel-based heat-exchange systems incorporating phase-change materials (PCMs) for regulating operating temperatures of high-density solid-state battery modules used in electric vehicles and grid-storage applications.

BACKGROUND OF THE INVENTION

High-density solid-state battery modules generate substantial heat during rapid charge and discharge cycles. Conventional thermal-management approaches relying on liquid cooling plates or air-cooled fins have proven inadequate as cell-level power densities exceed 500 W/kg. Excessive thermal gradients across a module degrade ionic conductivity in solid electrolyte layers, accelerate lithium dendrite nucleation at grain boundaries, and reduce cycle life by as much as 40% (see, e.g., Smith et al., *J. Power Sources*, vol. 511, 2024, pp. 1–18).

Prior art phase-change systems (U.S. Pat. No. 10,847,223 to Chen; U.S. Pat. No. 11,201,366 to Nakamura et al.) disclose encapsulated PCM slurries in macro-scale channels. These designs suffer from non-uniform PCM distribution, high pumping parasitic losses, and inability to dynamically redirect coolant flow in response to localised hot spots.

There remains a need for a thermally adaptive system that (a) achieves uniform temperature distribution within $\pm 1\,^{\circ}\mathrm{C}$ across a 48-cell module, (b) operates without external pumping power during Phase I of the thermal cycle, and (c) supports in-situ PCM re-solidification without module disassembly.

SUMMARY OF THE INVENTION

In one aspect, the invention provides an adaptive thermal-management assembly comprising: a plurality of microchannel plates (**100**) interleaved between solid-state battery cells (**102**); a network of microchannels (**104**) formed within each plate, each microchannel having a hydraulic diameter in the range of 200–800 μm; a phase-change material (**106**) disposed within a sealed reservoir (**108**) fluidly coupled to the microchannel network; and an adaptive valve array (**110**) operable by shape-memory alloy actuators (**112**) to selectively direct PCM flow toward regions of elevated thermal load.

In another aspect, the invention provides a method of thermally managing a solid-state battery module, comprising: sensing a temperature differential exceeding a threshold of $2\,^{\circ}\mathrm{C}$ between any two battery cells (**102**); actuating at least one shape-memory alloy valve (**112**) to redirect molten PCM (**106**) from a cooler microchannel region to the hotter region; and passively re-solidifying the PCM upon cessation of the thermal load without external actuation.

These and other features of the invention are set forth more particularly in the Detailed Description that follows.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective, partially exploded view of a solid-state battery module incorporating the adaptive thermal-management assembly (**100**) of the invention.

FIG. 2 is a cross-sectional view taken along line 2–2 of FIG. 1, showing the microchannel plate (**100**) in relation to adjacent battery cells (**102**) and the sealed PCM reservoir (**108**).

FIG. 3 is an enlarged schematic of the adaptive valve array (**110**) in the closed configuration (FIG. 3A) and the open configuration (FIG. 3B).

FIG. 4 is a graph illustrating module temperature uniformity ($\pm\,^{\circ}\mathrm{C}$) versus cycle number for the invention compared with a prior-art cooling plate.

FIG. 5 is a flow diagram of the thermal-management method according to an embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Reference is now made to the drawings in which like reference numerals designate like or corresponding parts throughout the several views.

I. Microchannel Plate Assembly (100)

As shown in FIG. 1 and FIG. 2, the microchannel plate (**100**) is fabricated from thermally conductive aluminium alloy 6061-T6 having a bulk thermal conductivity of 167 W/m K. The plate (**100**) is 1.5 mm thick and is dimensioned to match the footprint of each prismatic battery cell (**102**), nominally 148 mm × 98 mm. A serpentine array of microchannels (**104**) is formed by photochemical etching to a depth of 400 µm and a width of 300 µm, yielding a hydraulic diameter $D_h = 343$ µm. The channel walls (**114**) are coated with a 30 nm-thick layer of titanium nitride (TiN) by physical vapour deposition to prevent corrosion from the PCM (**106**).

II. Phase-Change Material (106) and Reservoir (108)

The PCM (**106**) in the preferred embodiment is a binary paraffin eutectic (n-eicosane/n-octadecane, 60:40 wt.%) exhibiting a melting onset temperature of $33.5\,^{\circ}\mathrm{C}$ and a latent heat of 218 kJ/kg. The sealed reservoir (**108**) is housed within an anodised aluminium enclosure (**116**) mounted to one lateral edge of the module, providing a PCM charge of 85 g per 12-cell tier. A flexible graphite membrane (**118**) at the reservoir outlet accommodates volumetric expansion of up to 12% upon PCM melting without mechanical stress on seals.

III. Adaptive Valve Array (110) and SMA Actuators (112)

The adaptive valve array (**110**), detailed in FIG. 3, comprises a set of binary-position microvalves (**120**) disposed at each microchannel branch junction. Each microvalve (**120**) is actuated by a shape-memory alloy (Nitinol, 50.8 at.% Ni) wire actuator (**112**) of diameter 100 µm. The Nitinol actuator (**112**) has a transformation temperature of $35\,^{\circ}\mathrm{C}$; when the local cell surface temperature exceeds this threshold, the actuator (**112**) contracts by 4% of its 20 mm free length, rotating the valve disc (**122**) by 90° to the open position and admitting molten PCM (**106**) flow through the adjacent microchannel (**104**).

Temperature sensors (**124**) – NTC thermistors with sensitivity of $-4.4\,\%\,^{\circ}\mathrm{C}^{-1}$ – are embedded in each cell-facing surface of the plate (**100**) and connected to a battery management controller (**126**) via a flexible printed circuit (**128**). The controller (**126**) executes a proportional-integral control law with a 50 ms sampling interval, commanding individual SMA actuators (**112**) through pulse-width-modulated drive signals.

IV. Performance and Re-Solidification

During a 3C discharge cycle at an ambient temperature of 25 °C, prototype testing demonstrated that the assembly maintained cell temperatures within ±0.8 °C across all 48 cells for 95% of the discharge duration (FIG. 4), compared with ±4.3 °C for a conventional aluminium cooling plate of equivalent mass. Upon completion of the discharge cycle, the PCM (**106**) re-solidifies passively within 12 minutes, driven by conduction to ambient through the module housing, without any external pumping power or heater intervention.

V. Alternative Embodiments

In an alternative embodiment, the PCM (**106**) may be replaced by a microencapsulated PCM slurry (**130**) dispersed in a dielectric carrier fluid (perfluorocarbon, 3M Novec™ 7500), enabling active pumped-loop operation at power densities exceeding 800 W/kg while retaining the latent-heat buffering benefit. In yet another embodiment, the microchannel plate (**100**) may be formed from a carbon-fibre-reinforced polymer composite (**132**) for weight-critical aerospace applications.

The foregoing description of the preferred embodiments is presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Modifications and variations are possible in light of the above teachings.

CLAIMS

1. An adaptive thermal-management assembly for a solid-state battery module, comprising:

a plurality of microchannel plates interleaved between a corresponding plurality of solid-state battery cells, each microchannel plate comprising a network of microchannels having a hydraulic diameter in the range of 200 µm to 800 µm;

a phase-change material disposed within a sealed reservoir fluidly coupled to the microchannel network, the phase-change material having a melting onset temperature between 30 °C and 45 °C; and

an adaptive valve array comprising a plurality of microvalves, each microvalve being operable to selectively direct flow of the phase-change material within the microchannel network in response to a local temperature signal.

2. The assembly of claim 1, wherein each microvalve of the adaptive valve array is actuated by a shape-memory alloy wire having a transformation temperature that corresponds to the melting onset temperature of the phase-change material.

3. The assembly of claim 2, wherein the shape-memory alloy wire comprises Nitinol having a nickel content of 50.8 atomic percent and a free length of between 10 mm and 40 mm.

4. The assembly of claim 1, wherein the phase-change material comprises a binary paraffin eutectic of n-eicosane and n-octadecane in a weight ratio of between 55:45 and 65:35.

5. The assembly of claim 1, wherein each microchannel plate is fabricated from an aluminium alloy having a bulk thermal conductivity of at least 150 W/m K, and wherein the microchannel walls are coated with a corrosion-resistant layer comprising titanium nitride having a thickness of between 20 nm and 50 nm.

6. The assembly of claim 1, further comprising a battery management controller operatively connected to a plurality of temperature sensors embedded in respective microchannel plates, the controller being configured to execute a proportional-integral control law to command individual microvalves of the adaptive valve array.

7. The assembly of claim 6, wherein the temperature sensors comprise negative-temperature-coefficient thermistors having a sensitivity of at least $-3\,\%\,°C^{-1}$, and wherein the controller samples the temperature sensors at an interval of 100 ms or less.

8. The assembly of claim 1, wherein the sealed reservoir further comprises a flexible membrane configured to accommodate volumetric expansion of the phase-change material upon melting of at least 10% without mechanical stress on seals of the reservoir.

9. A method of thermally managing a solid-state battery module, comprising:
sensing, by a plurality of temperature sensors, a temperature differential between at least two solid-state battery cells exceeding a predetermined threshold;
actuating, in response to the sensed temperature differential, at least one microvalve of an adaptive valve array to redirect flow of a phase-change material within a microchannel network toward a battery cell exhibiting the higher temperature; and
passively re-solidifying the phase-change material within the microchannel network upon reduction of the thermal load below the predetermined threshold.

10. The method of claim 9, wherein the predetermined threshold is 2 °C, and wherein the passively re-solidifying step occurs without application of external pumping power or external heaters.

11. The method of claim 9, further comprising embedding a flexible printed circuit within each microchannel plate, the flexible printed circuit electrically connecting the temperature sensors to a battery management controller that commands the microvalves via pulse-width-modulated drive signals.

ABSTRACT

An adaptive thermal-management assembly for high-density solid-state battery modules comprises aluminium microchannel plates (**100**) interleaved between prismatic battery cells (**102**), a sealed reservoir (**108**) containing a binary paraffin eutectic phase-change material (PCM) (**106**) with a melting point near 33.5 °C, and an adaptive valve array (**110**) actuated by Nitinol shape-memory alloy wires (**112**). Temperature sensors (**124**) embedded in each plate report to a battery management controller (**126**), which executes a proportional-integral control law to direct molten PCM selectively toward regions of elevated thermal load. The assembly maintains temperature uniformity within ±1 °C across a 48-cell module during 3C discharge cycles without external pumping power. A flexible graphite membrane (**118**) accommodates PCM volumetric expansion, and the PCM re-solidifies passively upon cooling. The invention extends solid-state battery cycle life by reducing thermally induced electrolyte degradation and dendrite formation.

End of Patent Application — Application No. 18/472,309

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