

Comparative study of thermal management system for wide temperature safety of large-capacity energy storage batteries

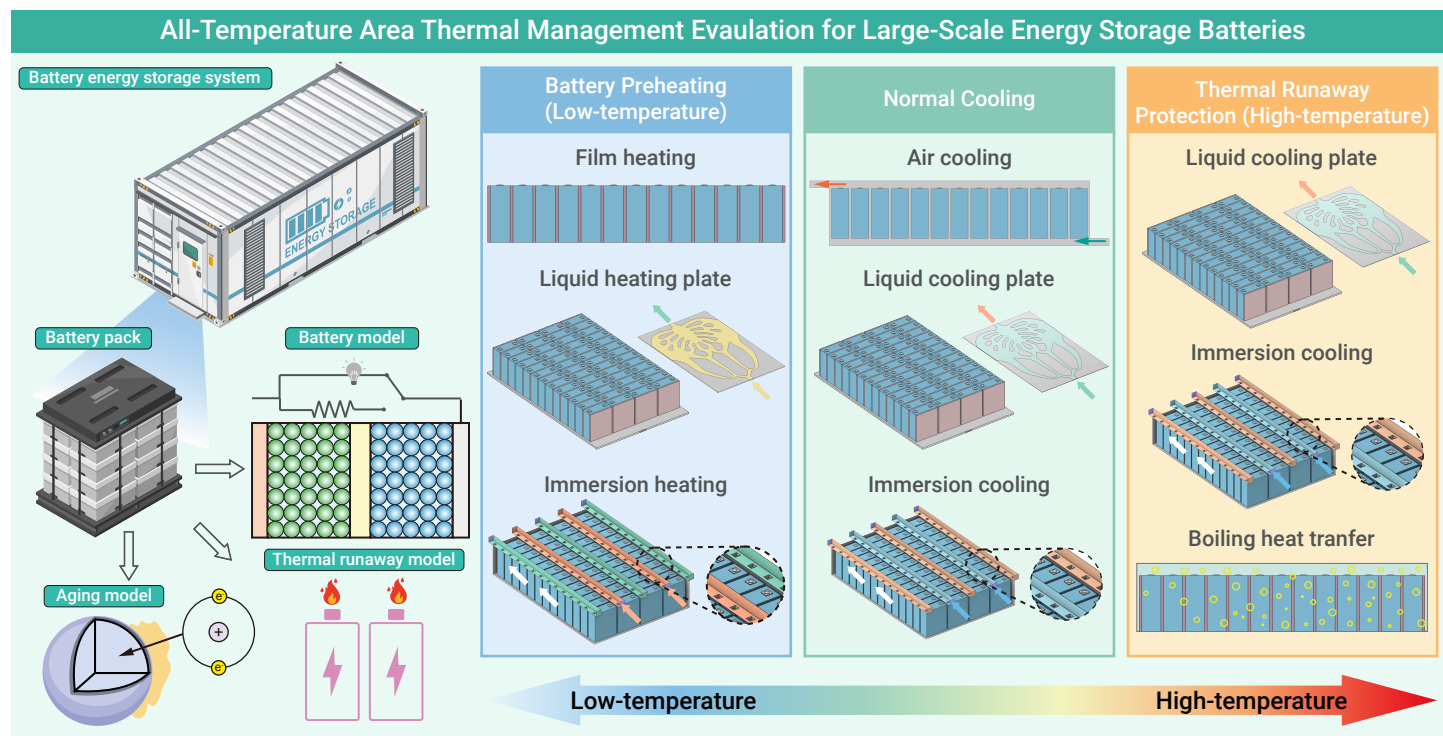
Xiangwei Lin,¹ Baijian Rong,¹ Xinyi Lin,¹ Zhijun Li,¹ Xinyu Ding,¹ Dengwei Jing,¹ Youjun Lu,¹ and Zhifu Zhou^{1,*}

*Correspondence: zfzhou@mail.xjtu.edu.cn

Received: July 9, 2025; Accepted: November 11, 2025; Published Online: January 9, 2026; <https://doi.org/10.59717/j.xinn-energy.2026.100133>

© 2026 The Author(s). This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>).

GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Immersion heating provides the fastest battery heating rate compared to other methods.
- Immersion cooling requires more power but slows down battery capacity fading.
- Liquid cooling and immersion cooling delay thermal runaway propagation.
- Boiling-based systems prevent thermal runaway through phase change cooling.
- Longer heat transfer paths lead to larger thermal inhomogeneities in some methods.

Comparative study of thermal management system for wide temperature safety of large-capacity energy storage batteries

Xiangwei Lin,¹ Baijian Rong,¹ Xinyi Lin,¹ Zhijun Li,¹ Xinyu Ding,¹ Dengwei Jing,¹ Youjun Lu,¹ and Zhifu Zhou^{1,*}

¹State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

*Correspondence: zfzhou@mail.xjtu.edu.cn

Received: July 9, 2025; Accepted: November 11, 2025; Published Online: January 9, 2026; <https://doi.org/10.59717/j.xinn-energy.2026.100133>

© 2026 The Author(s). This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>).

Citation: Lin X., Rong B., Lin X., et al. (2026). Comparative study of thermal management system for wide temperature safety of large-capacity energy storage batteries. *The Innovation Energy* 3:100133.

Even though thermal management systems have been widely developed to maintain the thermal stability and safety of lithium-ion battery, a comprehensive comparison remains insufficient for large-scale battery module, particularly across wide temperature ranges. For this purpose, a numerical framework that includes electrochemical-thermal coupled model, aging model, thermal runaway model, and hydrodynamic model is established for 46.592 kWh battery module. The aim of this study is to comprehensively assess the thermal management efficiency of different methods under low-temperature preheating, normal cooling, and thermal runaway protection scenarios. Results found that under the given configuration, battery heating rate is ordered as immersion heating > film heating > liquid heating plate, and the latter two approaches show larger thermal inhomogeneities due to battery anisotropy and longer heat transfer paths. For normal cooling condition, immersion cooling needs more power consumption to maintain the same inlet flow rate than air cooling and liquid cooling plate, but its superior cooling performance can slow down battery capacity fading after long-term cycling. Additionally, liquid cooling plate and immersion cooling allow for delaying thermal propagation after onset of thermal runaway, whereas boiling-based system can effectively prohibit thermal runaway from local overheating due to its phase change cooling effect.

INTRODUCTION

Against the worsening environment change caused by carbon emissions, achieving the sustainable development has prompted the transformation of global energy systems towards cleaner and renewable resources such as solar, wind, and tide energies.¹ With it, however, the direct integration between these resources and electricity grid may lead to working instability due to the intermittent nature in terms of weather and geography.² In this context, battery energy storage system (BESS) based on lithium-ion batteries (LIBs) has been considered as a viable solution to balance electrical storage and supply demands.³ Despite great advancements in battery technology, the practical adoptions of LIBs remain to be restricted by the several factors, e.g., thermal sensitivity, vibration, external pressure, and so on.⁴ In particular, LIBs-based system exposure to improper temperatures can give rise to significant performance deterioration, capacity aging, and even thermal failure.⁵ To mitigate the negative impacts of abnormal temperatures on LIBs' performance, developing a battery thermal management system (BTMS) that can function with preheating, cooling, and thermal runaway protection is critical for BESS applications.

In contrast to power batteries, energy storage LIBs used for BESS are usually grid-connected to renewable energy systems at high-altitude regions, which are featured by abundant wind and solar energy resources as well as extreme day-night temperature variations.⁶ From the perspective of material, when batteries are exposed to cold environments, reduced ionic diffusivity and electrical conductivity can greatly diminish the solid phase transport kinetics and increase the charge transfer resistance within LIBs, which in turn worsen the available capacity and even cause the formation of lithium dendrite.⁷⁻⁹ More importantly, liquid electrolyte may freeze and thus make the charge/discharge disabled at extremely low-temperature conditions.¹⁰ Preheating methods have become the key means to alleviate battery's performance degradation and prevent safety issues from occurring.¹¹ Based on the thermal exchange mode of heat sources, battery preheating strategies are often divided into conduction mode (e.g., self-heating, current excitation, and electrothermal element heating) and convection model (e.g., air

heating and liquid heating).¹²⁻¹⁶ Regardless of the preheating method used in BESS, the increase in battery temperature is to alleviate the material deterioration at low-temperature conditions. However, the battery preheating system also requires extra energy consumption and weight, which may result in a reduction in available energy of BESS and structural complexity. To date, most of research in this field tends to explore the heating efficiency of preheating systems for power LIBs, overlooking the additional energy demand and temperature uniformity of large-scale energy storage batteries.

On the other hand, localized hotspots within a single LIB or the entire system are another critical factor limiting the operational performance of BESSs.¹⁷ Once battery temperature exceeds the recommended threshold, a series of exothermic side reactions and solid-electrolyte interface (SEI) can be generated, leading to depletion of available lithium inventory and material decomposition.¹⁸ Moreover, LIB exposed to the high-temperature environment for a short time may suffer from the accelerated self-discharge phenomenon because of their memorized thermal history.¹⁹ To maintain the desired performance of batteries, a narrow temperature range of 15-35 °C has been commonly recommended during charging/discharging processes.²⁰ As a result, external cooling approaches are often incorporated to regulate the temperature rise and thermal gradient within batteries as soon as possible under different operating scenarios.²¹ According to heat transfer medium, existing BTMSs used for battery cooling can be classified into forced air convection, liquid cooling plate, phase change material, direct immersion, and hybrid types that integrate two or more of these schemes.²²⁻²⁶ Note that each BTMS features its unique merits and limitations in terms of different conditions. For example, forced air- and liquid cooling plate-based BTMSs are now broadly applied for commercial electric vehicle and BESS due to their easy implementation and mature design.²⁷⁻²⁹ Nevertheless, since the current battery technology is gradually evolving towards large power and energy densities, which unavoidably raises the heat generation from batteries.³⁰ Despite thermal management potential of different cooling schemes being compared, the majority of the study has been focused on power batteries,³¹⁻³³ which have significantly smaller capacities and sizes relative to energy storage LIBs.

From the above-mentioned review, battery thermal sensitivity is still an inevitable issue in the practical applications, strongly influencing the electrochemical and thermal characteristics. Currently, various BTMSs like forced air convection and liquid cooling have become the most popular measurements in battery systems. However, the majority of existing studies focuses on the thermal management performance of built BTMSs on power batteries, which often feature small in-plane area to through-plane area ratio. As a result, side-cooling design has been widely employed to enlarge thermal contact area between power LIB and heat sink.³⁴⁻³⁶ On the other hand, battery cell consisting of alternating-layer structure has great anisotropy in thermal conductivity. Bottom-cooling design enables the reduced thermal inconsistency and power consumption for energy storage batteries with large in-plane area.³⁷ Based on this, one fundamental question is ongoing about which kind of BTMS should be adopted in large-scale battery module. In addition, various thermal regulation methods at low- and high-temperature have been proposed, but each BTMS shows its own pros and cons and is primarily assessed under normal cooling condition. A direct evaluation of different kinds of methods at the wide-temperature range remains insufficient, especially in relation to preheating and thermal runaway protection, which are also the main function required for BTMSs.

To bridge these knowledge gaps, this work aims to determine thermal

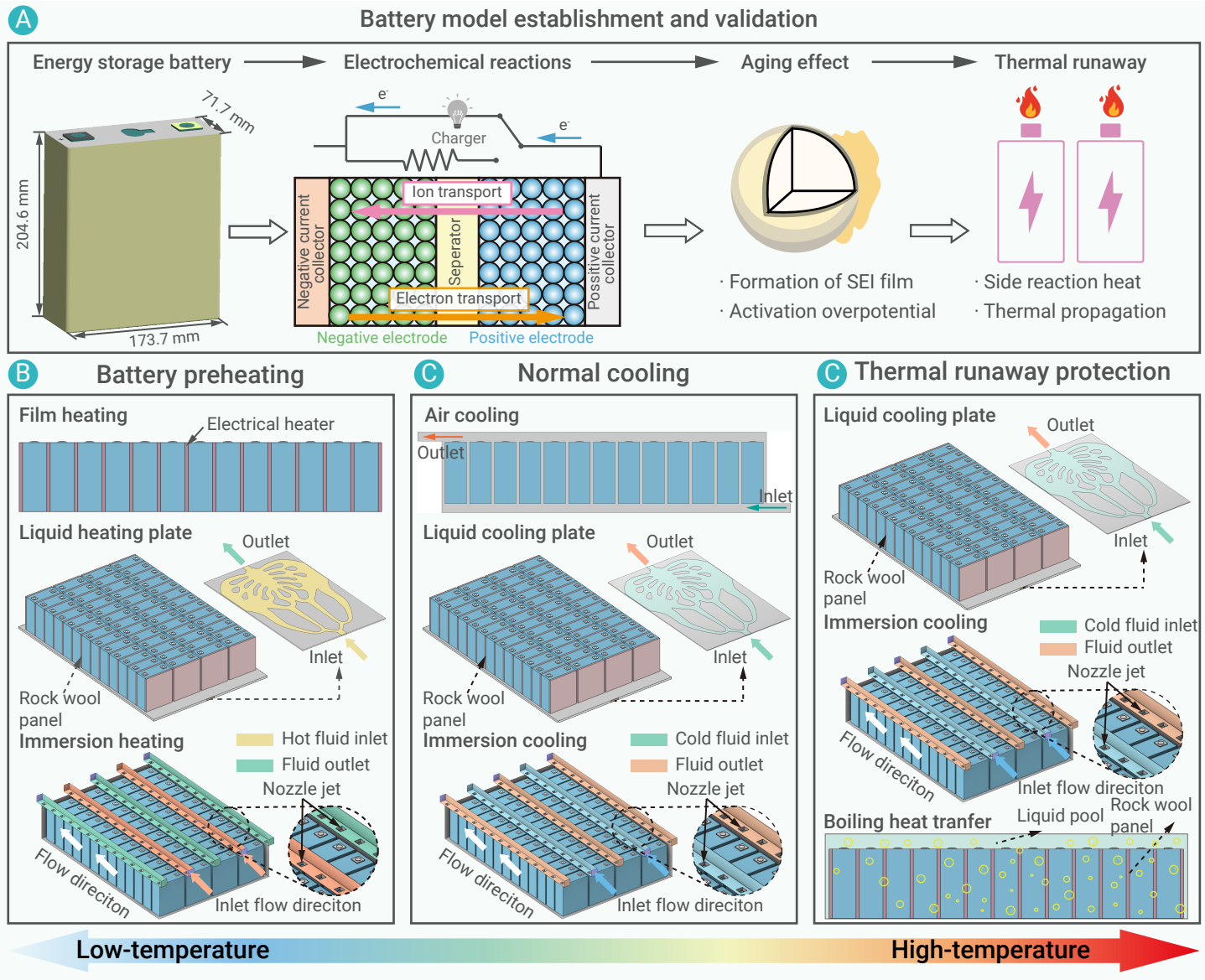


Figure 1. Illustration of the research method and technical roadmap of the present work.

management performance of different approaches for large-scale energy storage battery module at wide-temperature range. In relation to that, a framework which includes battery model, aging model, and thermal runaway model has been built to characterize electrochemical and thermal performance of energy storage LIBs under various scenarios. Meanwhile, comparative studies between battery module integrating different BTMS are discussed in terms of preheating, normal cooling, and thermal runaway protection. Based on the obtained results, a comprehensive summary about all kind of BTMSs is also examined through thermal management efficiency and system energy density. The findings of this study are expected to provide the selection guidance and to broaden the understanding of wide temperature thermal management strategies used for energy storage batteries.

MATERIALS AND METHODS

Physical description

With the increasingly growth in energy and power densities of LIBs, more efficient BTMS is required to guarantee the thermal safety of battery system under dynamic and extreme conditions. Figure 1 shows the research method and technical route of this study. In general, BESS is composed of several battery modules that are parallelly or serially interconnected to fit the power and energy capacity demands. Here, the research object focuses on an energy storage battery module which includes fifty-two 280 Ah LiFePO_4 -

graphite LIBs assembled in series with 166.4 V voltage and 46.592 kWh energy power. The arrangement of energy storage battery module can be referenced from previous work.³⁸ It is noted that battery spacing is one of the critical parameters affecting the performance of thermal management systems. For instance, smaller spacing impedes fluid convection effects, leading to heat accumulation, while larger spacing improves heat dissipation but reduces space utilization. On the other hand, excessively narrow spacing can trigger heat recovery phenomena, where heat is absorbed by adjacent cells, thereby decreasing cooling efficiency. According to previous works,^{5,39} LIBs with a size of 173.7 (x) × 71.7 (y) × 207.2 (z) mm³ are connected at the spacing of 10.3 mm in all BTMSs. To determine the thermal sensitivity effect on the energy storage battery performance, the electrochemical-thermal coupled model, aging model, and thermal runaway model are established. The first model can accurately portray the dynamic and uneven distribution of battery heat generation, while the last two models enable the prediction of the side-reactions occurred in LIBs at high-temperature environment. Additionally, the detailed specification of the studied battery is provided in Table S1.

Since each thermal management approach features its unique pros and cons, the comparative investigation for energy storage battery module should be made to provide valuable guidelines for BTMS selection. With this in mind, the battery model is further combined with hydrodynamic and heat transfer

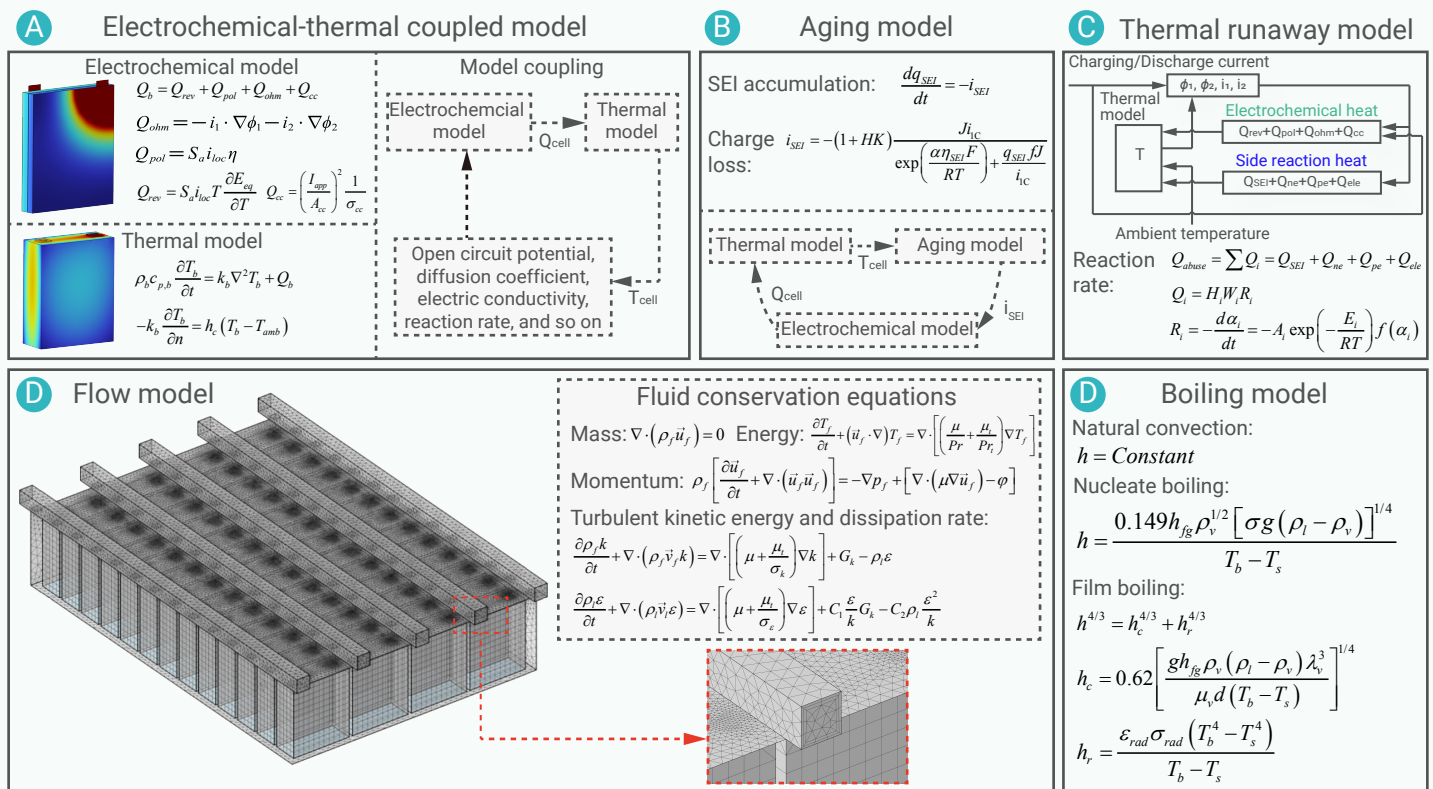


Figure 2. Framework of multi-physics model used in this work.

models to describe the battery thermal performance at module level for different BTMSs and operating conditions. As shown in Figure 1, three BTMSs including electrical heating, liquid heating plate, and immersion heating are considered for low-temperature preheating. For normal cooling, forced air convection, liquid cooling plate, and immersion cooling methods are taken into account. For thermal runaway, the suppression performance of liquid cooling plate, immersion cooling, and boiling heat transfer are compared. Except for air- and immersion-based BTMSs, rock wool panels are inserted into the battery-to-battery gap to prevent thermal propagation. The key distinction lies in the fundamental heat transfer mechanisms of each BTMS. In both air-based and single-phase immersion BTMS, inter-cell spacing is intentionally preserved to facilitate convective flow channels, thereby enhancing heat dissipation through forced convection and increasing heat transfer area. In contrast, the boiling heat transfer leverages the complex phase-change phenomena which inherently offer significantly higher heat removal capacity than single-phase convection. However, during thermal runaway propagation testing, the uncontrolled lateral heat transfer can dominate the process, potentially masking intrinsic performance difference attributable solely to the cooling mechanisms. Therefore, the adoption of rock wool in specific cases serves as a targeted isolation measure, not to equalize all physical conditions across systems, but to isolate the effect of the cooling medium's thermodynamic behavior by suppressing parasitic conductive/convective pathways that could otherwise skew the assessment of boiling-induced thermal regulation.

To reduce flow resistance caused by fluid circulation, a topological liquid plate with 12 mm thickness is implemented for liquid-based BTMS. More construction principles and details of topological liquid plate can be found in previous work.⁴⁰ Since Z-type parallel structure has widely proven to provide uniform flow rate for each channel,^{41,42} it is used to construct air-based BTMS with an inlet height of 30 mm. To prevent thermal accumulation at central region of battery module, manifold design is introduced to optimize the flow distribution of immersion-based BTMS. Referring from previous research,^{43,44} five manifold channels with two inlets and three outlets are positioned on the top of battery module. Each manifold channel includes thirteen nozzles with the size of 20×20 mm². For boiling-based BTMS, the battery module is fully

submerged into liquid pool, which has a height of 1.2 times that of LIB to reserve the vapor zone.

Mathematical model

Figure 2 schematically describes the models used for thermal performance evaluation of energy storage LIBs. The battery heat generation derived from intrinsic reaction can be calculated through electrochemical-thermal coupled model, and then it is utilized as heat source in heat transfer model. Consequently, the temperature distribution of energy storage battery module can be regarded as the collaborative result of external thermal boundary and internal heat generation. Meanwhile, when batteries are subjected to high temperature, variations in side reactions and temperature-dependent parameters in turn affects the electrochemical behaviors. On this basis, the proposed multi-physics model can track the evolution of battery temperature and thermal management performance of different BTMSs. Subsequently, the mathematical description for each physical field is presented below.

Battery model. From the perspective of BTMS simulation, battery module is often simplified as a heat source in heat transfer model. Nevertheless, due to complex mechanisms occurred in LIBs, empirical-based model cannot precisely describe the thermal characteristics of batteries, in particular the side reactions under long-term cycles and high-temperature decomposition. For this reason, three sub-models, i.e., electrochemical-thermal coupled model, aging model, and thermal runaway are included in battery model to predict the wide temperature behaviors of LIB at preheating, normal cooling, and thermal runaway conditions.

1. Electrochemical-thermal coupled model. During the charging/discharging process, electrons continuously pass through the external circuit, while an equal number of lithium-ions (Li^+) diffuse between electrodes. The heat emission or adsorption is inevitable occurred inside LIBs due to the conversion between electrical and chemical energy. However, it remains challenging to establish a battery model which can fully account for the multiple scale and physical mechanisms. Based on concentrated solution and porous electrode theories, Newman et al. built a pseudo-two-dimensional electrochemical model to describe the ion diffusion, charge conservation, and electrochemical kinetics inside LIBs.⁴⁵ Meanwhile, this model can also be coupled with

thermal model via several concentration- and temperature-dependent parameters, such as open circuit potential, diffusion coefficient, reaction rate, and so on. In this study, a pseudo-four-dimensional electrochemical and thermal coupled model developed from previous work is used to obtain the spatiotemporal heat generation of 280 Ah energy storage LIB.⁴⁶ Before proceeding simulations, several assumptions are invoked to simplify model complexity: 1) active particle is viewed as the spherical material with homogenous dimension; 2) phase change and gas do not occur during the operation; 3) volume of two electrodes remains invariable. The governing equations of electrochemical and thermal models are summarized in Table S2. Since the deviation of heat generation and temperature is negligible along thickness direction of battery,⁴⁷ cross-scale method is utilized to couple the source terms of electrochemical and thermal models. More specifically, non-uniform heat generation obtained from electrochemical model is averaged along thickness direction and then projected into thermal model. At the same time, volume-averaged temperature derived from thermal model is fed back to electrochemical model because temperature distribution weakly affects the reactions.²¹ This multi-physics coupling is achieved by iteratively performing the mentioned steps and is formulated by Eqs. (S14) and (S15). Since the principles of electrochemical-thermal coupled model have been extensively explained in other studies,^{48,49} more details are no longer repeated. Besides, all parameters used in this model can be found in previous work.⁴⁶

2. Aging model. When lithium-ions intercalate or de-intercalate in anode, some secondary reactions gradually occur at anode-electrolyte interface, leading to the formation of SEI film and the consumption of available lithium-ion. These phenomena account for the underlying mechanisms of capacity fading.⁵⁰ Since battery degradation is unavoidably in real-world applications, the SEI formation model is considered to determine the aging effect during the cycling process. According to the work of Ekström and Lindbergh,⁵¹ the accumulation of charge loss caused by SEI formation can be formulated by

$$\frac{dq_{SEI}}{dt} = -i_{SEI} \quad (1)$$

$$i_{SEI} = -(1 + HK) \frac{J_{iC}}{\exp\left(\frac{a\eta_{SEI}F}{RT}\right) + \frac{q_{SEI}fJ}{i_{iC}}} \quad (2)$$

where a is the transfer factor which is set to 0.69, K is the expansion factor relating to state of charge, and H , J , and f are the lumped fitting parameters relating to temperature.⁵²

$$K = \begin{cases} -2i/i_{iC} & i < 0 \text{ and } SOC < 0.3 \\ -i/i_{iC} & i < 0 \text{ and } SOC > 0.7 \\ 0 & i < 0 \text{ and } 0.3 \leq SOC \leq 0.7 \text{ or } i \geq 0 \end{cases} \quad (3)$$

$$H = 7.18e^{10040\left(\frac{1}{T} - \frac{1}{298.15}\right)} \quad (4)$$

$$J = -6.667 \times 10^{-8} T^2 + 8.009 \times 10^{-5} T - 0.01777 \quad (5)$$

$$f = 1580e^{15470\left(\frac{1}{T} - \frac{1}{298.15}\right)} \quad (6)$$

3. Thermal runaway model. Once battery temperature surpasses the critical threshold, a variety of unstoppable thermal abuse reactions take place inside LIBs, which may evolve into thermal runaway. With the increase of battery temperature, four main exothermic reactions progressively occur, including SEI film decomposition (Q_{SEI}), negative electrode-electrolyte reaction (Q_{ne}), positive electrode-electrolyte reaction (Q_{pe}), and electrolyte decomposition (Q_{ele}).⁵³ The reaction rate is often quantified via Arrhenius equation and the thermal abuse heat can be formulated as follows:⁵⁴

$$Q_{abuse} = \sum Q_i = Q_{SEI} + Q_{ne} + Q_{pe} + Q_{ele} \quad (7)$$

$$Q_i = H_i W_i R_i \quad (8)$$

$$R_i = -\frac{da_i}{dt} = -A_i \exp\left(-\frac{E_i}{RT}\right) f(a_i) \quad (9)$$

where H is the enthalpy of reactant, W is the content of active material, R is the reaction rate, a is the extent of conversion, E is the activation energy, $f(a)$ is the reaction model. Besides, the decomposition reaction for each decomposition is described as below.⁵⁵

$$R_{SEI} = -\frac{dc_{SEI}}{dt} = A_{SEI} \exp\left(\frac{E_{SEI}}{RT}\right) c_{SEI}^{m_{SEI}} \quad (10)$$

$$R_{ne} = -\frac{dc_{ne}}{dt} = A_{ne} \exp\left(\frac{E_{ne}}{RT}\right) c_{ne}^{m_{ne}} \exp\left(-\frac{t_{SEI}}{t_{SEI,ref}}\right) \quad (11)$$

$$R_{pe} = A_{pe} \exp\left(-\frac{E_{pe}}{RT}\right) a^{m_{pe,1}} (1-a)^{m_{pe,2}} \quad (12)$$

$$R_{ele} = -\frac{dc_{ele}}{dt} = A_{ele} \exp\left(-\frac{E_{ele}}{RT}\right) c_{ele}^{m_{ele}} \quad (13)$$

where m is the reaction order, t is the dimensionless thickness of SEI film. Additionally, all parameters included in thermal runaway model are summarized in Table S3.

Flow model. In this study, the velocity ranging from 1 to 7 m s⁻¹ is set to the channel inlet of air convection, liquid plate, and immersion methods. The flowing state is usually identified into laminar or turbulent based on Reynolds numbers (Re).³³

$$Re = \frac{\rho_i u_i d_h}{\mu} \quad (14)$$

where ρ , u , and μ are the density, inlet velocity, and dynamic viscosity of fluid. d_h is the hydraulic diameter of channel inlet. Given the flow condition, obtained Re are within 3884-27194 for air-based BTMS, 4464-31257 for liquid plate-based BTMS, and 1652-5785 for immersion-based BTMS, respectively. Depending on the change of Re value, the flow regime for air- and liquid plate-based BTMSs is turbulent, while it can be either laminar or turbulent for immersion-based BTMS. In this section, only the mathematical description of turbulent model is presented.

For air-, liquid plate-, and immersion-based BTMSs, single-phase convective heat transfer can be determined by solving mass conservation, momentum conservation, and energy conservation equations, which are formulated as below.³⁸

Mass conservation:

$$\nabla \cdot (\rho_i \vec{u}_i) = 0 \quad (15)$$

Momentum conservation:

$$\rho_i \left[\frac{\partial \vec{u}_i}{\partial t} + \nabla \cdot (\vec{u}_i \vec{u}_i) \right] = -\nabla p_i + [\nabla \cdot (\mu \nabla \vec{u}_i) - \varphi] \quad (16)$$

Energy conservation:

$$\frac{\partial T_i}{\partial t} + (\vec{u}_i \cdot \nabla) T_i = \nabla \cdot \left[\left(\frac{\mu}{Pr} + \frac{\mu_t}{Pr_t} \right) \nabla T_i \right] \quad (17)$$

where φ is the Reynolds stress and Pr is the Prandtl number. The subscript t is turbulent state. To simulate the hydrodynamic behaviors of fluid inside flowing channel, standard k - ε turbulence model is used due to its good robustness and accuracy for broad-ranging flow issues.³²

$$\frac{\partial \rho_i k}{\partial t} + \nabla \cdot (\rho_i \vec{u}_i k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + G_k - \rho_i \varepsilon \quad (18)$$

$$\frac{\partial \rho_i \varepsilon}{\partial t} + \nabla \cdot (\rho_i \vec{u}_i \varepsilon) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_1 \frac{\varepsilon}{k} G_k - C_2 \rho_i \frac{\varepsilon^2}{k} \quad (19)$$

$$\mu_t = \rho_i C_\mu \frac{k^2}{\varepsilon} \quad (20)$$

where k is the kinetic energy and ε is the dissipation rate. G_k is the kinetic energy caused by velocity gradient. σ_k , σ_ε , C_1 , C_2 , and C_μ are the model constants, which are identical to the setting of previous literature.⁵⁶

In this simulation, 50 % ethylene glycol/water solvent and pentaerythritol esters are selected as the working fluid for liquid plate and single-phase immersion systems, respectively, for preheating and cooling applications. The 50 % ethylene glycol/water solvent has been commonly employed because it can satisfy the broad operational temperature range of $-30\sim 60\text{ }^{\circ}\text{C}$.³⁸ Meanwhile, given the well-proven feasibility and safety of esters in electronic equipment, as well as their biodegradable properties,^{46,57} pentaerythritol esters is selected as the single-phase immersion fluid in this work. In addition, deionized water is employed as a cooling medium for immersion boiling. Besides, thermophysical properties of materials used in simulations are summarized in Table S4.

Boiling heat transfer model. The principle behind the boiling heat transfer method relies on the high latent heat of vaporization of the boiling medium, which absorbs large amounts of energy during liquid-to-vapor phase transition at battery surfaces. This results in efficient temperature clamping near the coolant's boiling point, even under extreme heat loads such as those encountered during thermal runaway. Additionally, bubble-induced agitation enhances local mixing and disrupts thermal boundary layers, further improving the heat transfer compared to single-phase convection. In practical battery system thermal management applications, deionized water can be utilized in two-phase immersion cooling systems due to its high specific heat capacity, high latent heat of vaporization, and sound environmental compatibility. Beyond this, various fluids can be employed for boiling medium in battery systems, such as fluorinated fluids, refrigerants such as R134a/R245fa, and cryogenic agents like liquid nitrogen, liquid ammonia, and liquid CO_2 .^{20,58} From thermodynamic, safety, and economic perspectives, deionized water stands as an ideal candidate working fluid for suppressing thermal runaway propagation. Particularly, deionized water possesses a latent heat of vaporization as high as 2257 kJ/kg, significantly exceeding most organic working fluids (e.g., Novec 7200 at approximately 120 kJ/kg).⁵⁹ Despite issues like electrical conductivity and freezing, deionized water retains significant advantages in sealed systems and emergency applications. While insulating fluids such as fluorinated liquids can be used for direct contact cooling, their cost and sustainability limitations currently prevent them from replacing water in large-scale energy storage systems.⁶⁰

When pool boiling is used after thermal runaway, thermal abuse heat quickly raises battery temperature close to the saturation temperature (T_s) of liquid pool. At this time, the battery surface can experience the heat transfer condition for pool boiling. Based on the relationship between temperature and heat flux, various heat transfer modes appear sequentially at the battery surface, i.e., natural convection, nucleate boiling, transition boiling, and film boiling.²⁰ As a result, boiling heat transfer boundary derived from different temperature ranges can be set at the battery surface. Referring from previous work,⁶⁰ a constant heat transfer coefficient is assigned before the battery temperature exceeds 373.15 K, and the corresponding correlations are adopted to describe the heat transfer coefficient at different boiling regimes.

$$h = \text{Constant} (T_b < 373.15\text{K}) \quad (21)$$

$$h = \frac{0.149h_{fg}\rho_v^{1/2}[\sigma g(\rho_l - \rho_v)]^{1/4}}{T_b - T_s} (373.15\text{K} \leq T_b \leq 403.15\text{K}) \quad (22)$$

$$h^{4/3} = h_c^{4/3} + h_r^{4/3} (T_b \geq 483.15\text{K}) \quad (23)$$

$$h_c = 0.62 \left[\frac{gh_{fg}\rho_v(\rho_l - \rho_v)\lambda_v^3}{\mu_v d(T_b - T_s)} \right]^{1/4} \quad (24)$$

$$h_r = \frac{\epsilon_{rad}\sigma_{rad}(T_b^4 - T_s^4)}{T_b - T_s} \quad (25)$$

where h_{fg} is the vaporization enthalpy, σ is the surface tension, g is the gravitational acceleration, λ is the thermal conductivity, ϵ_{rad} is the emissivity coefficient, and σ_{rad} is the Stefan-Boltzmann constant.

Model validation

Prior to numerical analysis, the validation of established model is

confirmed using experimentally measured results. For electrochemical-thermal coupled model, battery voltage and temperature changes during the discharge process is recorded based on the experimental platform, which has been detailed in previous study.³⁸ To exclude the uncertainty caused by surrounding environment, the energy storage LIB is wrapped with insulating cotton and then rested in the temperature-controlled chamber at different temperatures. Fig. S1A-1 shows the voltage comparison between experimental results and numerical values under discharge rate of 0.75 C and three environmental temperatures. Note that the symbol C denotes the relative ratio between discharge current and normal capacity of LIBs. The cutoff voltage of tested battery is set to 2.5 V according to battery manufacturer. It is found that the built model can accurately track the voltage value and trend in relation to experimental curves. Fig. S1A-2 shows the battery temperature rise obtained from experiments and simulations. Here, the surface-averaged temperature is recorded. Notably, average temperature rise trends of simulated and experimental data are basically consistent under three environmental temperatures. The maximum errors of temperature rise are about 1.1, 0.9, 1.0 K at environmental temperatures of 278.15, 298.15, and 318.15 K, respectively. Overall, the proposed model can provide reasonable predictions on electrochemical and thermal performance of energy storage batteries.

On the other hand, the aging model has been validated by performing the identical condition as described in the previous experiment.⁵¹ The tested battery is exposed to three environmental temperatures to conduct aging cycles. The experimental procedure includes four steps, i.e., constant current and constant voltage charging, 60 min resting, constant current discharging, and 60 min resting. Note that 0.75 C rate is used for both charging and discharging process. Fig. S1B compares the state of health (SOH) derived from experimental and simulated data during 1000 cycles. Results reveal that the aging model shows good consistency with the experimental trend in terms of battery capacity degradation. The maximum error of SOH is limited within approximately 0.97 %. The deviation may arise from two sources: 1) the aging parameters are primarily obtained from fitted data of existing literature, which possibly differ from the conditions in this testing; 2) some assumptions are invoked to simplify the complexity of battery model.

Besides, the validation of thermal runaway model of energy storage battery is also confirmed by comparing the experiment data derived from Zhang et al.⁶² The tested battery in thermal runaway experiment is a fully charged 280 Ah LIB. An electric heater with a heating power of 500 W is installed on one side surface of battery to trigger local overheating. Then, the average surface temperature of another side of LIB is recorded and compared with numerical results. Meanwhile, insulating cotton is used to avoid the thermal dissipation from side surface. Fig. S1C shows transient temperature obtained from simulation and experiment during local overheating process. The thermal runaway model approximately tracks the overheating and thermal reaction behaviors in relation to experiment. In fact, the gaps between battery and heater may raise thermal resistance. In addition, the thermal convection from bottom side of heater and battery also leads to heat loss. All these phenomena potentially cause the discrepancies between simulation and experiment. It is known that thermal runaway process in LIBs is inherently complex, involving not only exothermic decomposition reactions of internal materials but also coupled physical phenomena such as short circuits, mechanical deformation, electrolyte vaporization, and rapid gas generation. These multi-physics interactions contribute to highly nonlinear and transient thermal behaviors that are challenging to capture fully in a single predictive model. While incorporating more detailed sub-models for internal shorting, gas dynamics, or mechanical degradation can marginally improve prediction accuracy, this approach would significantly increase computational complexity, making the model less suitable for system-level design and real-time control. Therefore, we have intentionally maintained a balance between physical fidelity and practical usability. The largest relatively deviation in battery temperature is about 13.2 %, which is within the acceptable range in predicting thermal runaway.

RESULTS AND DISCUSSION

Comparative study of low-temperature preheating

The operational performance of LIBs is influenced by the collective interaction of electrochemical reaction and thermal characteristics. Figure 3A shows

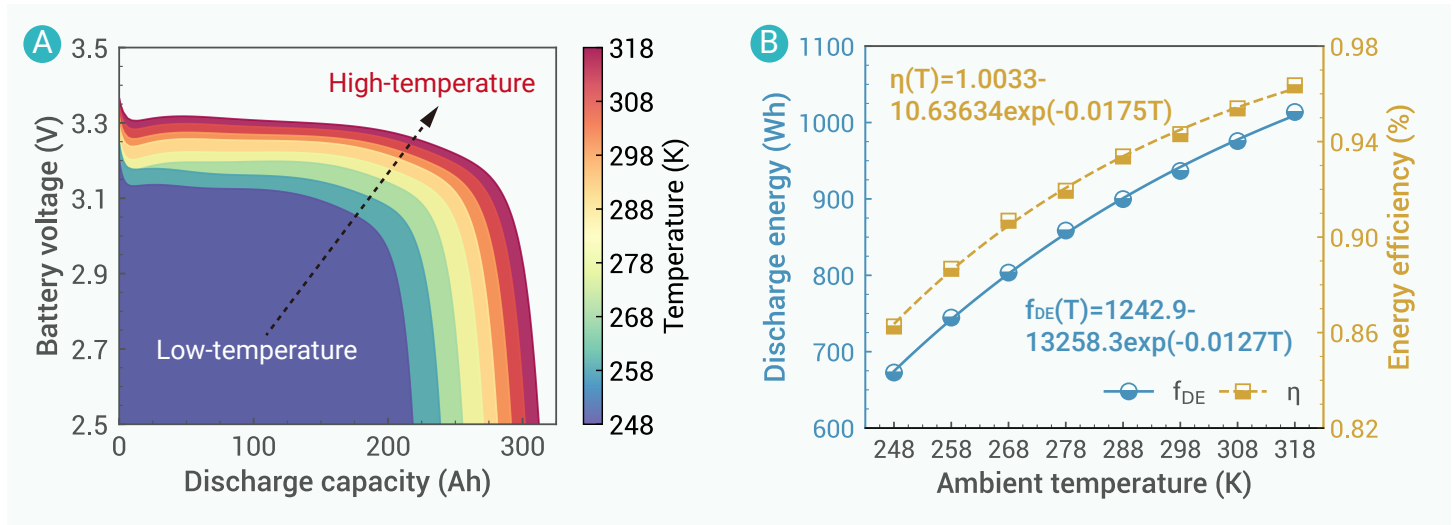


Figure 3. (A) Electrochemical characteristics of energy storage battery under different temperatures; (B) Summary of discharge energy and energy efficiency in terms of ambient temperature.

battery discharge voltage at the ambient temperature ranging from 248.15 to 318.15 K. When the ambient temperature is 288.15 K, the available discharge capacity of LIB is approximately 280 Ah. However, as the temperature decreases to 248.15 K, the battery discharge capacity is significantly reduced to about 218 Ah. Note that the area enclosed by the voltage and capacity axis refers to the total discharge energy (DE) that LIB can release at the given temperature condition. It is observed from Figure 3B that total discharge energy of LIB has more sensitive to low-temperatures, thus leading to an exponential correlation $f_{DE}(T)$ between DE and ambient temperature. More specifically, due to the increased diffusion resistance at low-temperature, a higher overpotential is required to drive ionic migration, which in turn causes a short time to obtain the cutoff voltage. As a result, the discharge duration and available amount of battery energy are greatly reduced at cold environment. Figure 3B also compares the energy efficiency η of energy storage battery under different ambient temperatures. The energy efficiency loss is derived from the generation of total irreversible heat ($Q_{tot,irr} = \int_0^{t_{cutoff}} \int_0^V Q_{irr} dV dt$) and evaluates the available energy that can be recovered after discharging process, i.e., $\eta = 1 - Q_{tot,irr}/f_{DE}$. The calculated η exhibits a sharp reduction at low-temperatures. For real-time application of BESS that is subjected to cold environment, the intrinsic transport resistance of batteries can result in a shift in resistance-based heating, thereby increasing the loss of available capacity.

This section comprehensively evaluates the effects of different strategies, like film heating (FH), liquid heating plate (LHP), and immersion heating (IH) on the preheating performance of battery module. Considering the trade-off between preheating energy consumption and battery performance recovery, the cut-off temperature (T_{cutoff}) is set to 297.35 K for fully charged LIB.⁶³ Actually, the non-uniform temperature distribution of LIBs inevitably arises from intrinsic thermal heterogeneity and external convective boundary conditions, such as single-phase flow generates axial temperature gradients due to progressive sensible heat exchange along the flow direction. As a result, T_{cutoff} is defined based on the volume-averaged temperature of the battery module, not local temperatures. Figure 4A shows the average battery temperature of three BTMSs under different preheating conditions. The heating power used for FH is varied from 500 to 2000 W m⁻² with an interval of 250 W m⁻², while the inlet velocity imposed on LHP and IH ranges from 1 to 7 m s⁻¹ with an interval of 1 m s⁻¹. As shown in Figure 4B, battery heating rate presents an almost linear rise with an increase in heating power of FH. When the heating power varies from 500 to 2000 W m⁻², the heating rate can be increased from 0.47 to 2.19 K min⁻¹. In contrast, preheating efficiency of LHP and IH exhibits an obvious improvement at the lower inlet velocity (≤ 3 m s⁻¹) and then becomes less sensitive to increased flow strengths. This suggests that a threshold exists making further increase in inlet velocity reduce the preheating efficiency. In addition, the heating rate of IH is higher than that of LHP when inlet velocity exceeds 3 m s⁻¹. Excess heat generated from LIB is

transferred to liquid heating plate through thermal contact interface with battery bottom, resulting in the increase in conduction resistance. In IH-based BTMS, battery module is directly contacted with the flowing fluid, which enables the larger heat exchange area and shorter thermal transfer route. As a result, the heating rate of IH is superior to that of LHP, especially at the high inlet velocities. When the inlet velocity ranges from 1 to 7 m s⁻¹, the obtained heating rate of IH is within 2.05–3.23 K min⁻¹.

Figure 4C also compares the time-averaged temperature uniformity of batteries under four preheating strategies. Since maximum temperature difference is greatly affected by localized hotspot and coldest point within battery module, the statistical uniformity ($T_{uni} = \int_A |T - T_{avg}| dA / \int_A dA$) is calculated.⁴⁶ While increasing inlet velocity allows LIBs to warm up quickly at cold environments, an imbalance of temperature distribution is inevitably occurred. To clearly showcase the thermal gradient along flow direction, Figure 4E shows the temperature contours of battery module at the moment of attaining T_{cutoff} with heating power of 1000 W m⁻² or inlet velocity of 3 m s⁻¹. For battery module, thermal gradient may be derived from two sources, i.e., internal inconsistency caused by the anisotropic thermal conductivity and external differences due to the thermal boundaries of BTMSs.³⁸ It is noted that the in-plane thermal conductivity of prismatic LIBs is relatively high, an order of magnitude above the through-plane thermal conductivity. In view of this, it is difficult to transfer thermal energy along the thickness-direction of LIBs, even though FH located on battery side features a large heat exchange area. In addition, the spatial temperature distribution within the battery module varies significantly due to fundamental differences in heat transfer mechanisms, thermal boundary conditions, and flow dynamics inherent to each BTMS design. IH-based BTMS applies volumetric-like internal heating with relatively uniform power distribution, resulting in more homogeneous temperature rise and hence the milder contour in Figure 4E. However, both LHP- and FH-based BTMS rely on surface-boundary heating, where heat must conduct through the casing into the core of the cells. Furthermore, LHP- and IH-based BTMSs mainly exhibit an obvious thermal gradient along the flowing direction and stagnation vortex regions. In contrast to IH system, the boundary heating of LHP- and FH-based BTMSs are affected by natural convection of surrounding environment and thermal coupling of preheating system. For this reason, LHP- and FH-based BTMS have larger temperature inconsistencies at high heating powers and inlet velocities.

To quantitatively describe the preheating efficiency of various preheating methods, Figure 4D shows the power consumption required to obtain T_{cutoff} with varying conditions. The increase in inlet velocity is expected to reduce the thickness of boundary layer, thus improving convective heat transfer. On the other hand, the increased flow circulation also leads to the undesired flow resistance and power consumption. It is found that the additional power consumption of LHP and IH has a non-linear relation to inlet velocity due to

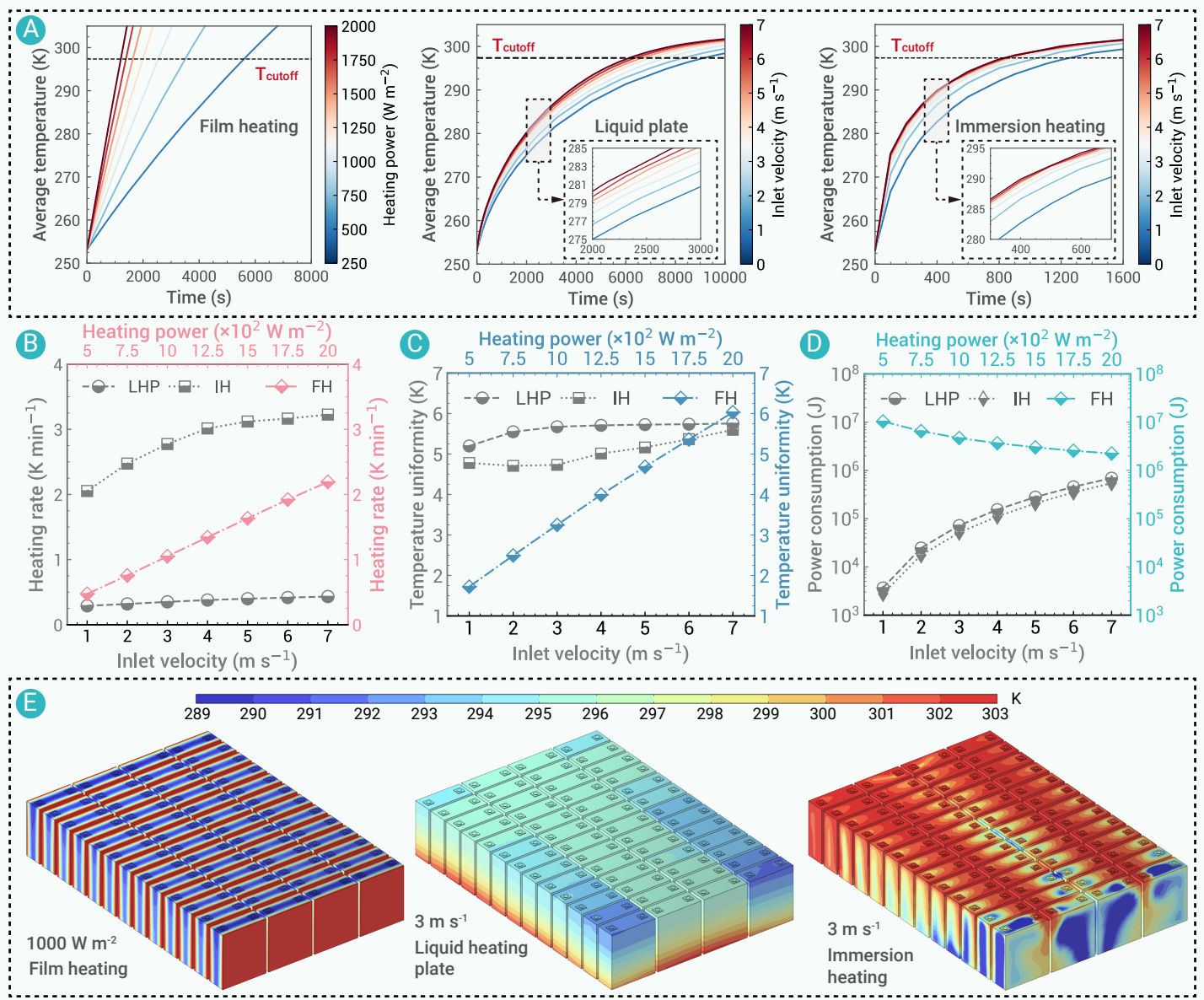


Figure 4. (A) Evolution of average temperature of battery module under different preheating methods and operating conditions; (B-D) Comparison of heating rate, temperature uniformity, and power consumption obtained from three BTMSs; (E) Temperature distribution of battery module at the end of preheating period with heating power of $1000 W m^{-2}$ or inlet velocity of $3 m s^{-1}$.

the secondary flow resistance caused by sharp corners and bends. However, the pumping power required to drive the fluid flow scales with both flow rate and pressure drop across the system, i.e., $P_{pump} \propto \Delta P \times u_{in}$. Thus, even though higher velocities reduce heating time, the non-linear rise in pressure drop ΔP leads to a sharp increase in parasitic pump power. Consequently, the total power consumption increases with inlet velocity, leading to a positive correlation trend. For film heating, the instantaneous power input is directly proportional to heating power P_{film} , but the total energy consumed depends on both heating power and time, i.e., $E_{preheating} = P_{film} \times t_{cutoff}$. When the heating power is increased, thermal response of the battery becomes significantly faster due to enhanced heat generation rates at thermal contact interface, thereby reducing the preheating time. The ultimate goal of preheating strategies is to maintain the temperature of battery system within a recommended range at cold environments, thereby reducing the battery performance degradation and improving the available charging/discharge energy. When the batteries warm up to a relatively high level, their operational performance gradually recover, but at the same time, additional energy consumption caused by preheating system also reduces the output energy of BESS. While the FH-based BTMS, increasing heating power leads to relatively lower specific energy consumption due to reduced preheating time, this does not imply

superior overall energy efficiency when compared to other two heating methods—LHP and IH. As shown in Figure 4D, energy consumption of FH remains approximately two orders of magnitude higher than that of LHP and IH under comparable operating conditions. In this model, fifty-two LIBs are series-connected to form the energy storage module with the energy power of 46.592 kWh. Compared to FH, which depletes about 1.3 % of the total energy of battery module at heating power of $500 W m^{-2}$, the rest of preheating methods have negligible power consumption (within 0.1 %) at relatively low inlet velocities ($\leq 3 m s^{-1}$).

Comparative study of normal cooling

Understanding the thermal characteristics of LIBs can provide valuable guidance for the development of BTMS. Figure S2 shows the average temperature of energy storage battery module under different discharge rates. Note that the batteries are subjected to natural convection boundaries ($h=15 W m^{-2} K^{-1}$) without the implementation of external cooling strategies. For all discharge rates, battery temperature experiences three distinct stages, namely, increasing with decreasing slope at the initial period of discharge (DOD $\leq 20\%$), followed by a continual rise during the middle period of discharge, and rapidly growing at the end period of discharge (DOD $\geq 80\%$).

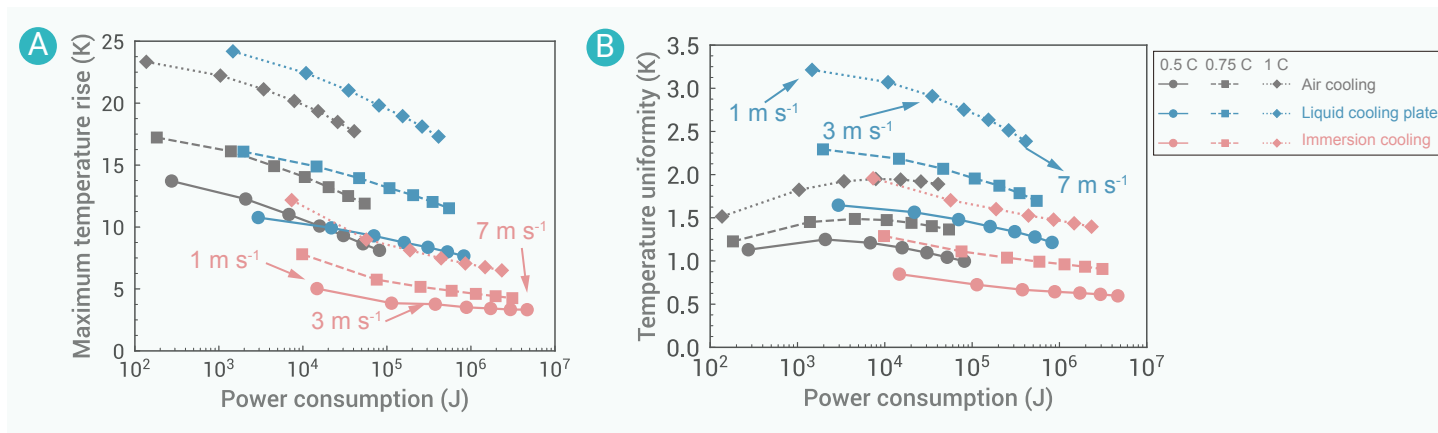


Figure 5. Comparison of maximum temperature rise, temperature uniformity, and power consumption obtained from three BTMSs

This change is attributed to the dynamic battery heat generation obtained from battery electrodes.⁴⁶ Moreover, the average temperature of batteries can reach about 320.7, 321.8, and 326.3 K at the end, respectively, for the discharge rates of 0.5, 0.75, and 1 C. It indicates that the LIBs with no external cooling may undertake an undesired rise in temperature during the working process and even surpass the recommended temperature range at high current densities.

This section comprehensively discusses the impact of cooling methods including air cooling (AC), liquid cooling plate (LCP), and immersion cooling (IC) on the thermal management performance of energy storage battery module. Figure S3 shows the average temperature evolution of three BTMSs under various discharge rates. In which, the inlet boundary of AC, LCP, and IC is constant velocity which is varied from 1 to 7 m s⁻¹ with an interval of 1 m s⁻¹. As expected, the higher velocity enables a larger convective heat transfer coefficient, thus reducing the temperature rise of batteries. Taking the discharge rate of 0.5 C as an example, when inlet velocity increases from 1 to 4 m s⁻¹, final average temperature of AC, LCP, and IC is decreased by 10.2, 2.6, and 0.6 K, respectively. With it, however, since convective heat transfer coefficient grows slowly with small thermal gradients, the reduction in battery temperature becomes less sensitive at the higher inlet velocity.³³ Meanwhile, when AC or LCP is implemented, the temperature of battery module presents an upward trend throughout the discharge process, indicating that their cooling capacity is insufficient to tackle the heat generated by LIBs. In contrast, IC-based BTMS performs the superior cooling performance regardless of discharge rate. The average temperature of IC exhibits an increasing trend first and then decreases at low discharge rate or remains almost unchanged at relatively high discharge rates. This phenomenon suggests that IC-based BTMS can effectively respond to the variations in battery heat generation and current density, and therefore shows a promising potential in terms of dynamic working conditions.

Figure 5 shows the time-averaged maximum temperature and temperature uniformity versus power consumption required for three cooling strategies. Although the cooling performance of these strategies can be improved as inlet velocity increases, the parasitic power consumption required to drive fluid increases dramatically. It is noted that when the operational condition remains constant, IC-based BTMS exhibits the lowest power consumption required to maintain maximum temperature and temperature uniformity of battery module within recommended ranges. Additionally, LCP-based BTMS shows undesired temperature rise and uniformity than those of AC at relatively high discharge rates. For one thing, since LCP has a lower flowing path, inlet fluid with higher velocity may reach outlet in a short period of time, which in turn leads to the insufficient heat exchange between LIBs and cooling fluid. For another, due to limited thermal contact area at LCP-LIBs interfaces, battery temperature can significantly increase along height direction, thus causing the sharp thermal gradient and weakened heat dissipated through LCP. As a result, considering the trade-off between energy-saving and cooling capacity, the priority of three BTMSs used for batteries can be ranked as follows: IC > LCP > AC at low discharge rate (0.5 C) and IC > AC > LCP at rela-

tively high discharge rates (0.75 and 1 C).

On the other hand, when the batteries are subjected to long-term operation, lithium plating and SEI formation inevitably appears, which in turn influence electrochemical and thermal behaviors of LIBs. Based on Arrhenius equation, electrochemical reaction rate of battery is exponentially dependent on temperature.²⁰ This indicates that high-temperature environment may promote the electrochemical reaction and thus accelerate capacity fading. The battery degradation performance under different cooling methods is also determined by coupling the aging model as detailed in Section 2.2.1. As shown in Figure 6A, thermal characteristics of LIBs perform an obvious difference before and after 0.75 C discharge-charging cycles. The average temperature of aged battery module is increased by about 6.37, 3.69, and 1.32 K, respectively, for AC-, LCP-, and IC-based BTMS. In which, the inlet velocity of three cooling approaches is set to 3 m s⁻¹. Notably, AC and LCP only regulate the temperature rise of battery module at beginning but are unable to maintain the average temperature within recommended range for aged energy storage battery module after 1000 cycles. In comparison, IC-based BTMS can suppress battery temperature rise effectively throughout the cycling process. More importantly, the increased temperature also achieves higher heat generation rate of aged LIBs, which adversely exacerbates the thermal management demands (as seen in Figure 6A). To clearly identify aging effect, Figure 6B shows the formation of SEI film during cycling process. The reduction of available lithium-ion and formation of SEI film are the primary cause for significant rise of battery temperature and heat generation. It is observed that high-temperature state contributes to thicker SEI film due to reduced diffusive resistance and intensified parasitic reaction inside batteries.⁶⁴ As a result, the BTMSs with different cooling strategies present the varied trends of SEI formation. Overall, IC-based BTMS achieves the optimum performance to control SEI thickness, which is reduced by about 39.3 and 21.2 mm compared to AC and LCP, respectively, after 1000 cycles. As for battery aging, the reduction of SOH matches well with the change of SEI thickness. The SOH of energy storage battery module becomes smaller as repeated discharging-charging operations and further decreased at high battery temperature. From this perspective, the module integrated with suitable BTMS is expected to slow down capacity fading by controlling the temperature rise. In contrast to AC and LCP, the final SOH of IC-based BTMS after 1000 cycles can be improved by about 4.85 and 2.65 %, respectively.

3.3 Comparative study of thermal runaway protection

The thermal runaway evolution of LIBs can be regarded as a transient propagation process caused by exothermic reaction and convective diffusion process due to external heat dissipation. To illustrate the thermal runaway behaviors of LIBs, Figure S4 shows the temperature evolution of failed batteries under natural convection condition. Note that an electric heater with the same size of energy storage LIB is applied instead of a battery to transfer plenty of thermal energy into the system and thus induce thermal runaway. To facilitate the analysis, four LIBs in the vicinity of heat source are monitored, which are labeled as cell-1, cell-2, cell-3 and, cell-4. From the perspective of temperature rise, the thermal runaway process of LIBs can be classi-

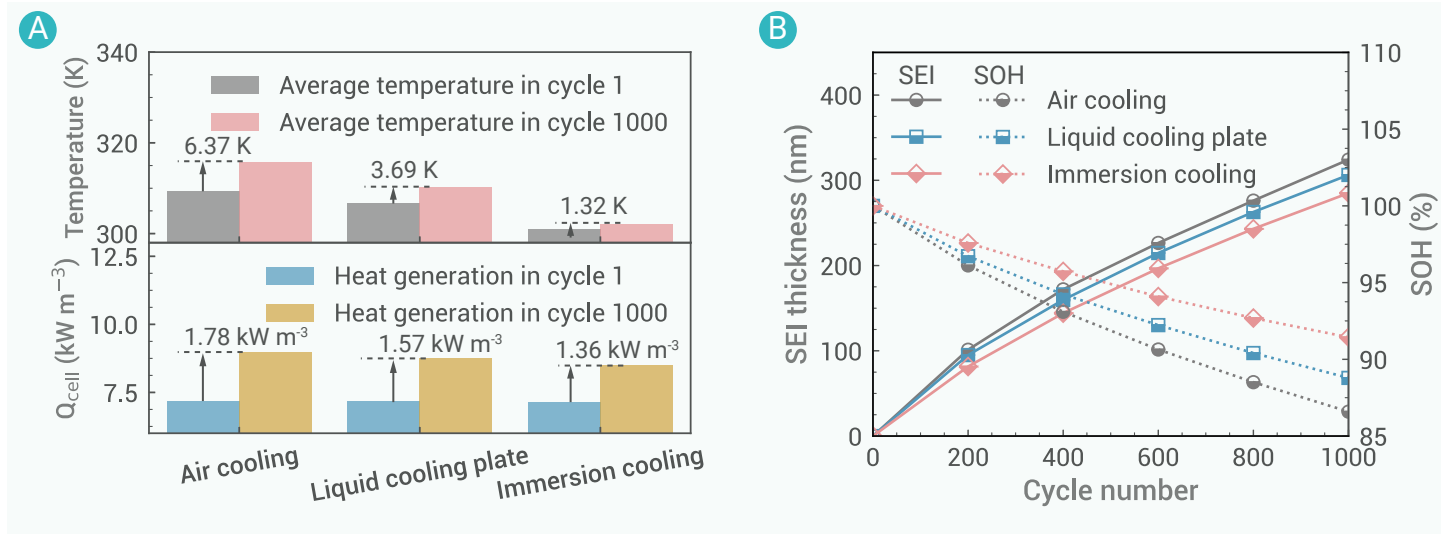


Figure 6. (A) Comparison of average temperature and heat generation obtained from cycle 1 and cycle 1000; (B) Comparison of SEI thickness and SOH of three BTMSs during cycling process.

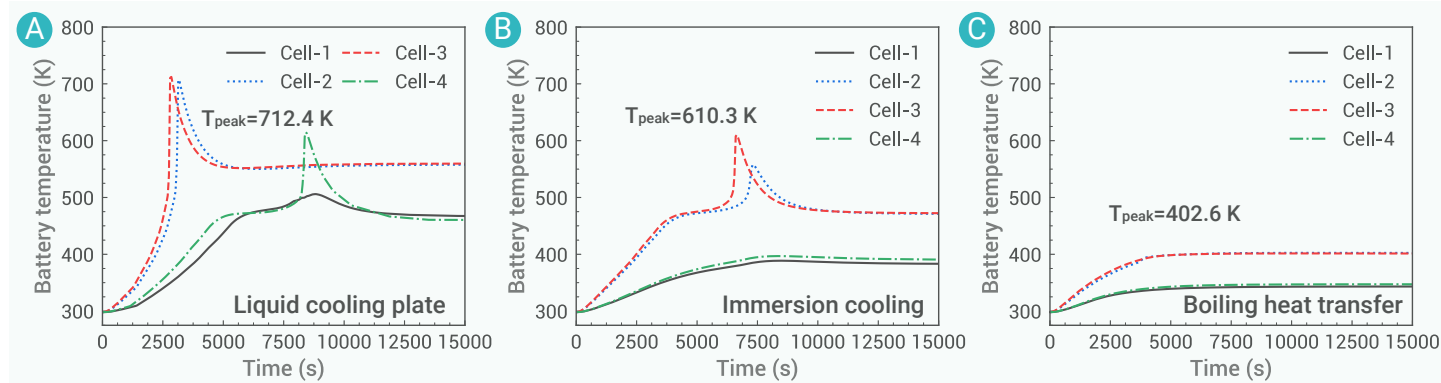


Figure 7. Comparison of battery temperature rise of three BTMSs during local overheating process.

fied into three distinctive periods: 1) heating period where the local temperature of batteries gradually increases with a slow trend; 2) thermal runaway process where the self-heating reactions of LIBs are triggered and causes extremely high temperature rise; 3) cooling period where the temperature of LIBs is gradually reduced due to the end of exothermic reactions. Taking the cell-3 as an example, Figure S4 shows the accumulation of abuse heat obtained from thermal failure process. It is noted that the energy storage LIB sharply falls into thermal runaway once the chain heat generation reaction is occurred under overheating condition. The battery temperature matches well with the generation of abuse heat, showing an almost linear growth trend up to 735.4 K at around 2250 s. Additionally, the reaction heat generated from anode-electrolyte and cathode-electrolyte decomposition contributes the primary portion of self-heating behaviors.

This section assesses the thermal runaway protection of different cooling methods, including LCP, IC, and boiling heat transfer. Figure 7 shows the temperature variations of heated batteries under three BTMSs. For LCP-based BTMS, LIBs adjacent to heating source undergoes a rapid rise in temperature because the cooling capacity is insufficient to accommodate the excessive thermal energy (as seen in Figure 7A). The side reactions of cell-3 are induced at around 2560 s, accompanied by the temperature peak (T_{peak}) of 712.4 K. Moreover, the interval between cell-3 and cell-2 is only about 440 s, indicating that LCP-based BTMS cannot provide protective measures to cease the occurrence and propagation of thermal runaway within energy storage battery module. As shown in Figure 7B, the initiation time of thermal runaway is greatly reduced in IC compared to LCP-based BTMS. This phenomenon is attributed to the enhanced heat removal effect of IC, which enables the rapid thermal dissipation between batteries rather than accumu-

lating it. While IC-based BTMS delays thermal propagation from heating source to adjacent batteries, the system cannot effectively dissipate side reaction heat, resulting in thermal runaway of cell-3 at around 5940 s. Meanwhile, due to high temperature environment, thermal runaway of cell-2 also begins to appear after 810 s. More importantly, since the thermal transport between different columns of LIBs is mainly achieved by surrounding convection and bottom heat conduction, cell-1 and cell-4 cooled by IC-based BTMS do not experience thermal runaway after a long-term heating period. As a result, when the thermal load of batteries exceeds to a certain level, the single-phase cooling approaches such as LCP and IC may fall short of satisfying thermal protection requirements. In this context, boiling heat transfer served as an advanced technique can be utilized in BTMS.²⁰ As shown in Figure 7C, the temperature variation of batteries adjacent to the heating source first rises and remains almost unchanged after nucleate boiling occurs regardless of heating time. The final T_{peak} of boiling-based BTMS is only about 402.6 K for which no thermal runaway occurs. This suggests that boiling heat transfer allows for efficient response to thermal load and performs the great thermal regulation potential in dynamic scenarios.

Selection guidance of BTMSs under different conditions

Based on the aforementioned results, Figure 8 provides the comparison of different thermal management approaches in terms of preheating, normal cooling, and thermal runaway protection. As shown in Figure 8A, FH shows better mass energy density and volumetric energy density than that of LHP and IH, but its performance on heating rate and energy-saving is relatively poor. The preheating results of FH-, LHP-, and IH-based BTMSs are obtained at the conditions of heating power of 1000 W m^{-2} or inlet velocity of 3 m s^{-1} .

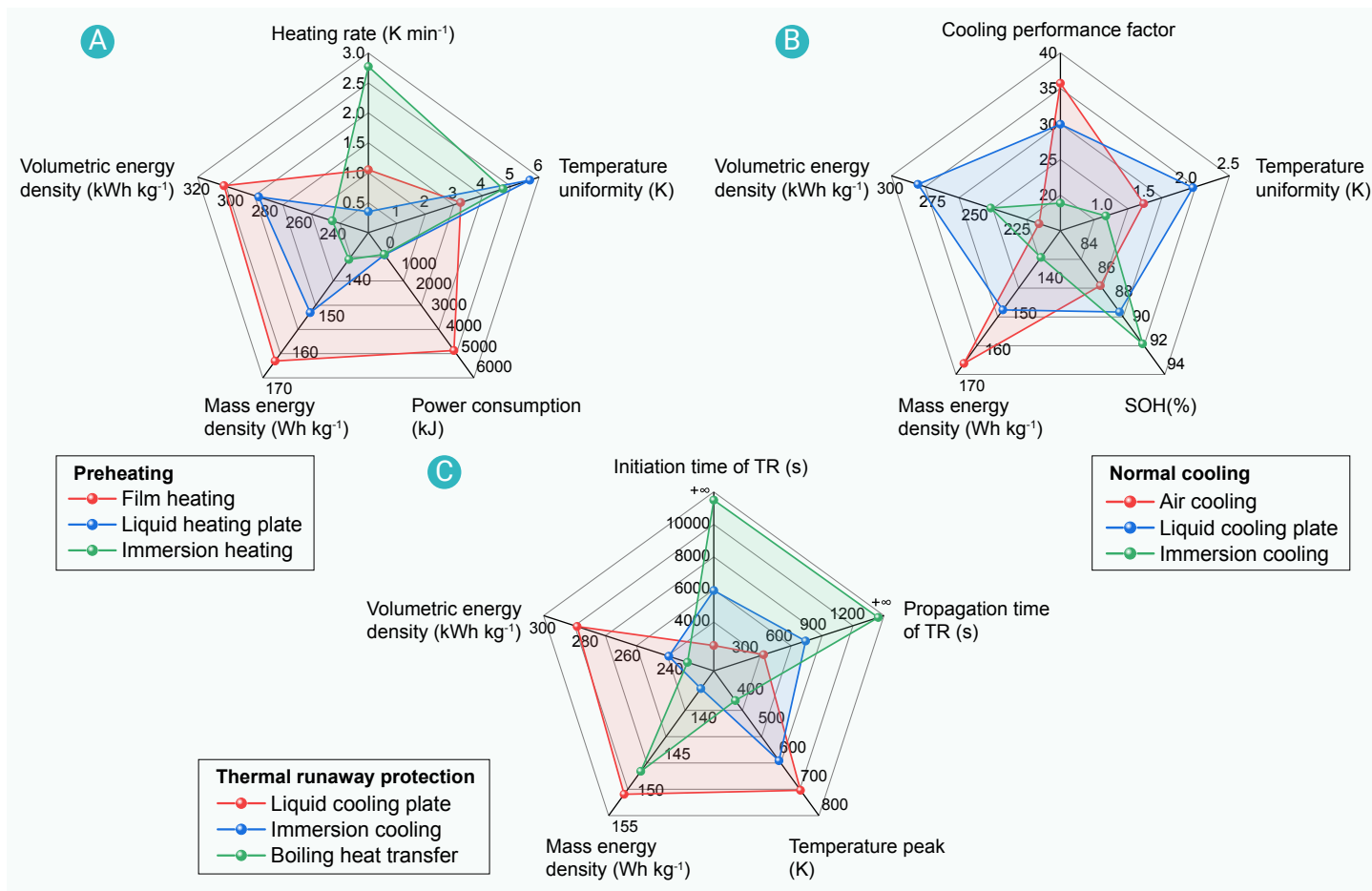


Figure 8. Comprehensive comparison of various BTMSs used for low-temperature preheating, normal cooling, and thermal runaway protection.

When inlet velocity is set to 3 m s^{-1} , IH can achieve excellent preheating efficiency and power consumption due to shortened heating time required to obtain cutoff temperature. As shown in Figure 4C, although FH exhibits a smaller T_{uni} (3.25 K at 1000 W m^{-2}) compared to LHP (5.67 K at 3 m s^{-1}) and IH (4.73 K at 3 m s^{-1}), this does not reflect better uniformity when contextualized against their respective system designs. More importantly, the trend matters—temperature difference in FH increases linearly with heating power, indicating deteriorating thermal uniformity under higher loads, whereas both LHP and IH maintain flatter T_{uni} profiles across flow rates. On the other hand, the extra weight and volume caused by immersion fluids inevitably leads to reduced energy density of energy storage battery module. For the application of normal cooling, cooling performance factor and residual SOH after 1000 cycles are also taken into account (as seen in Figure 8B). The cooling performance factor β can assess the heat transfer rate per unit power consumption, i.e., $\beta = m_{in} c_p (T_{out} - T_{in}) / P$.³⁷ In which, m_{in} , T_{out} , and T_{in} are inlet velocity, outlet temperature, and inlet temperature of cooling fluid. The normal cooling results of AC-, LCP-, and IC-based BTMSs are obtained at the conditions of inlet velocity of 3 m s^{-1} and discharge rate of 0.75 C. It is observed that the cooling performance factor and mass energy density of AC is superior to that of LCP and IC due to the extremely low viscosity and density of air. Nevertheless, the poor conductivity of air can cause an evident thermal gradient along flow direction, which in turn worsens the temperature uniformity of energy storage battery module. While LCP-based BTMS is characterized as compact design, i.e., high volumetric energy density, the limited thermal contact area between cold plate and batteries cannot satisfy the heat dissipation demands, especially at the high current densities ($\geq 0.75 \text{ C}$). Since the batteries exposed to high-temperature environment may achieve the higher loss of lithium-ion caused by the formation of SEI film, IC-based BTMS which features lower temperature rise and thermal inconsistency provides the reduction in capacity fade after long-term operations. The thermal runaway results of LCP- and IC-based BTMSs are obtained at the conditions of inlet

velocity of 4 m s^{-1} . For the protection of thermal runaway, LCP- and IC-based BTMSs have been proven to delay the initiation and subsequent propagation of decomposition reactions within energy storage battery module (as seen in Figure 8C). Despite this, it remains hard for LCP and IC to fully inhibit the occurrence of thermal runaway under continuous heating condition. From the safety concern, boiling-based BTMS exhibits a superior thermal runaway suppression due to its phase-change cooling effect.

According to the unique merits and drawbacks of different thermal management methods, the following selection guidance can be made:

- For small-scale BESSs which do not require high current density, the BTMSs with suitable heat transfer performance, like AC and LCP, can be adopted to improve energy density and reduce power consumption.
- For large-scale BESSs which have no strict requirements on volume and weight, the BTMSs with sufficient thermal exchange area between cooling medium and batteries, such as AC and IC are recommended to achieve temperature consistency and prolong service life.
- For BESSs which are subjected to dynamic and wide-temperature conditions, the BTMS with multi-functional performance, i.e., IC is expected to fulfill preheating and normal cooling demands without complex system design. Meanwhile, when the immersion fluids with proper boiling temperature are used, the heat dissipation performance caused by phase-phase effect can provide desired protection against thermal runaway.

CONCLUSION

With the ever-increasing growth in energy storage capacity of BESS, the efficient and reliable BTMS is essential to address thermal concerns of LIBs. Despite different BTMSs being established in literature, the comparative study on thermal management efficiency and system design has been rarely evaluated for energy storage LIBs. In this work, a multi-physics model that considers electrochemical reaction heat, aging effect, thermal abuse reaction, and fluidic behaviors is built and experimentally verified. Then, the influences

of different BTMSs on preheating, normal cooling, and thermal runaway protection are systematically determined based on the simulation framework.

- When energy storage LIB is exposed to low-temperature environments, increased overpotential caused by reduction of ionic diffusion and formation of irreversible heat can obviously reduce the available battery energy. Increasing inlet velocity leads to improved heating rate of LHP and IH before exceeding 3 m s^{-1} , whereas the preheating performance of FH shows an almost linear relation to heating power. From the viewpoint of energy-saving, LHP and IH need lower power consumption ($\leq 0.1 \%$) than FH, which consumes about 1.3 % of the total battery module energy.

- Compared to IH, AC- and LCP-based BTMSs is insufficiently to limit temperature rise and maintain thermal uniformity throughout the discharge process, especially at high current densities. While IC-based BTMS needs higher power consumption required to liquid circulation, its improved cooling performance reduces SEI film formation, with 4.85 % and 2.65 % reduction in SOH after 1000 cycles versus AC and LPC, respectively.

- When operating temperature exceeds a certain value, battery may sharply fall into thermal runaway after triggering chain exothermic reactions. LCP- and IC-based BTMSs allow for delaying the onset of thermal runaway among battery module, but cannot completely suppress local overheating, with propagation interval of 440 and 810 s, respectively. In contrast, boiling-based BTMS features excellent phase change cooling effect, resulting in the inhibition of thermal runaway regardless of heating time.

According to the mentioned results, the practical performance and safety of energy storage batteries is strongly dependent on operating temperatures. Even through various BTMSs are discussed at wide temperature ranges, some problems potentially be further improved. The selected BTMSs, including system configuration and operating factors, are obtained from previous studies or other literature without the optimization for a given battery system. Meanwhile, the comparative study only focuses on single battery module and constant operating factors, which may be further extended to larger systems, variable current protocol and dynamic environments. Besides, analysis of potential fire and gas generation occurring at thermal runaway should be taken into account in future works.

REFERENCES

- Zheng Y., Che Y., Hu X., et al. (2024). Thermal state monitoring of lithium-ion batteries: Progress, challenges, and opportunities. *Prog. Energy Combust. Sci.* **100**:101120. DOI:10.1016/j.pecs.2023.101120
- Liu L. and Shao S. (2023). Recent advances of low-temperature cascade phase change energy storage technology: A state-of-the-art review. *Renew. Sustain. Energy Rev.* **186**:113641. DOI:10.1016/j.rser.2023.113641
- Lin J., Zhang X., Fan E., et al. (2023). Carbon neutrality strategies for sustainable batteries: from structure, recycling, and properties to applications. *Energy Environ. Sci.* **16**:745–791. DOI:10.1039/D2EE03257K
- Yu H., Wang L., Zhang Z., et al. (2024). Insight Understanding of External Pressure on Lithium Plating in Commercial Lithium-Ion Batteries. *Adv. Funct. Mater.* **34**:2406966. DOI:10.1002/adfm.202406966
- Lin X., Zhang X., Ji J., et al. (2021). Development of flexible form-stable phase change material with enhanced electrical resistance for thermal management. *J. Clean. Product.* **311**:127517. DOI:10.1016/j.jclepro.2021.127517
- Li Y., Kong B., Qiu C., et al. (2025). Numerical study on air-cooled battery thermal management system considering the shear altitude effect. *Appl. Therm. Eng.* **258**:124707. DOI:10.1016/j.applthermaleng.2024.124707
- Hu X., Zheng Y., Howey D. A., et al. (2020). Battery warm-up methodologies at subzero temperatures for automotive applications: Recent advances and perspectives. *Prog. Energy Combust. Sci.* **77**:100806. DOI:10.1016/j.pecs.2019.100806
- Wang Y., Zhang X. and Chen Z. (2022). Low temperature preheating techniques for Lithium-ion batteries: Recent advances and future challenges. *Appl. Energy* **313**:118832. DOI:10.1016/j.apenergy.2022.118832
- Huang X., Meng J., Jiang W., et al. (2024). Alternating current heating techniques for lithium-ion batteries in electric vehicles: Recent advances and perspectives. *J. Energy Chem.* **96**:679–697. DOI:10.1016/j.jchem.2024.05.027
- Liu L., Zhang X. and Lin X. (2022). Recent Developments of Thermal Management Strategies for Lithium-Ion Batteries: A State-of-The-Art Review. *Energy Tech.* **10**:2101135. DOI:10.1002/ente.202101135
- Yang X.G., Liu T. and Wang C.Y. (2021). Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles. *Nat. Energy* **6**:176–185. DOI:10.1038/s41560-020-00757-7
- Wang C.Y., Zhang G., Ge S., et al. (2016). Lithium-ion battery structure that self-heats

at low temperatures. *Nature* **529**:515–518. DOI:10.1038/nature16502

- Qin Y., Du J., Lu L., et al. (2020). A rapid lithium-ion battery heating method based on bidirectional pulsed current: Heating effect and impact on battery life. *Appl. Energy* **280**:115957. DOI:10.1016/j.apenergy.2020.115957
- Zhang Z., Chen Z., Zhu W., et al. (2024). Study of the effects of preheating on discharge characteristics and capacity benefit of Li-ion batteries in the cold. *J. Energy Storage* **86**:111228. DOI:10.1016/j.est.2024.111228
- Song Z., Hofmann H., Li J., et al. (2015). The optimization of a hybrid energy storage system at subzero temperatures: Energy management strategy design and battery heating requirement analysis. *Appl. Energy* **159**:576–588. DOI:10.1016/j.apenergy.2015.08.120
- An Z., Zhang C., Luo Y., et al. (2023). Cooling and preheating behavior of compact power Lithium-ion battery thermal management system. *Appl. Therm. Eng.* **226**:120238. DOI:10.1016/j.applthermaleng.2023.120238
- Lin X.-W., Zhou Z.-F., Liu T.-F., et al. (2023). Rate capability and Ragone plots for designing battery thermal management system based on phase change material. *J. Energy Storage* **74**:109539. DOI:10.1016/j.est.2023.109539
- Ramadas P., Haran B., White R., et al. (2002). Capacity fade of Sony 18650 cells cycled at elevated temperatures: Part I. Cycling performance. *J. Power Sources* **112**:606–613. DOI:10.1016/S0378-7753(02)00474-3
- Seong W. M., Park K.-Y., Lee M. H., et al. (2018). Abnormal self-discharge in lithium-ion batteries. *Energy Environ. Sci.* **11**:970–978. DOI:10.1039/C8EE00186C
- Lin X.-W., Li Y.-B., Wu W.-T., et al. (2024). Advances on two-phase heat transfer for lithium-ion battery thermal management. *Renew. Sustain. Energy Rev.* **189**:114052. DOI:10.1016/j.rser.2023.114052
- Lin X.-W., Zhou Z.-F., Zhu X.-G., et al. (2023). Non-uniform thermal characteristics investigation of three-dimensional electrochemical-thermal coupled model for pouch lithium-ion battery. *J. Clean. Product.* **417**:137912. DOI:10.1016/j.jclepro.2023.137912
- Liu F., Yang Q., Zheng D., et al. (2025). A novel battery thermal management system with air-liquid coupled cooling based on particle swarm optimization. *Appl. Therm. Eng.* **271**:126391. DOI:10.1016/j.applthermaleng.2025.126391
- Wu C., Sun Y., Tang H., et al. (2024). A review on the liquid cooling thermal management system of lithium-ion batteries. *Appl. Energy* **375**:124173. DOI:10.1016/j.apenergy.2024.124173
- Han H., Xiong F., Qin M., et al. (2025). Intrinsic flame-retardant phase change materials for battery thermal management during rapid cycling and thermal runaway. *Energy Storage Mater.* **77**:104175. DOI:10.1016/j.jensm.2025.104175
- Chen K., Tang A., Pan J., et al. (2024). Experimental study on heat transfer characteristics and Capillary-Assisted enhancement of Dual-Phase immersion battery thermal management system. *Energy Convers. Manag.* **322**:119149. DOI:10.1016/j.enconman.2024.119149
- He Z., Li R., Yang L., et al. (2024). Performance analysis of a battery thermal management system based on phase change materials with micro heat pipe arrays. *Energy Convers. Manag.* **311**:118506. DOI:10.1016/j.enconman.2024.118506
- Lander L., Kallitsis E., Hales A., et al. (2021). Cost and carbon footprint reduction of electric vehicle lithium-ion batteries through efficient thermal management. *Appl. Energy* **289**:116737. DOI:10.1016/j.apenergy.2021.116737
- Zhang X., Gao Q., Yang S., et al. (2023). Co-regulation of integrated thermal management based on refrigerant cooling for electric vehicles. *Appl. Therm. Eng.* **226**:120306. DOI:10.1016/j.applthermaleng.2023.120306
- Haddad R. A., Mansour C., Kim N., et al. (2025). Comparative analysis of thermal management systems in electric vehicles at extreme weather conditions: Case study on Nissan Leaf 2019 Plus, Chevrolet Bolt 2020 and Tesla Model 3 2020. *Energy Convers. Manag.* **332**:119706. DOI:10.1016/j.enconman.2025.119706
- Wang C.-Y., Liu T., Yang X.-G., et al. (2022). Fast charging of energy-dense lithium-ion batteries. *Nature* **611**:485–490. DOI:10.1038/s41586-022-05281-0
- Chen D., Jiang J., Kim G.-H., et al. (2016). Comparison of different cooling methods for lithium ion battery cells. *Appl. Therm. Eng.* **94**:846–854. DOI:10.1016/j.applthermaleng.2015.10.015
- Akbarzadeh M., Kalogiannis T., Jaguemont J., et al. (2021). A comparative study between air cooling and liquid cooling thermal management systems for a high-energy lithium-ion battery module. *Appl. Therm. Eng.* **198**:117503. DOI:10.1016/j.applthermaleng.2021.117503
- Lin X.-W., Zhou Z.-F., Yin J., et al. (2024). A comparative investigation of two-phase immersion thermal management system for lithium-ion battery pack. *J. Clean. Product.* **434**:140472. DOI:10.1016/j.jclepro.2023.140472
- Wang Y., Wang Y., He T., et al. (2024). A numerical study on a hybrid battery thermal management system based on PCM and wavy microchannel liquid cooling. *Renew. Energy* **235**:121273. DOI:10.1016/j.renene.2024.121273
- Dong H., Chen X., Yan S., et al. (2025). Multi-objective optimization of lithium-ion battery pack thermal management systems with novel bionic lotus leaf channels using NSGA-II and RSM. *Energy* **314**:134226. DOI:10.1016/j.energy.2024.134226
- Khoshvaght-Aliabadi M., Ghodrati P. and Kang Y. T. (2025). Developing a novel battery thermal management system utilizing supercritical CO₂ as the cooling medium. *Appl. Energy* **381**:125207. DOI:10.1016/j.apenergy.2024.125207
- Amer M. M., Salem M. S., Kannan A. M., et al. (2025). Exploratory study on electric batteries thermal performance metrics and thermal management systems evaluation. *J. Energy Storage* **110**:115282. DOI:10.1016/j.est.2024.115282

38. Lin X.-W., Zhou Z.-F., Li M.-X., et al. (2024). Exploration on the liquid-based energy storage battery system from system design, parametric optimization, and control strategy. *Renew. Energy* **237**:121904. DOI:10.1016/j.renene.2024.121904
39. Zhang Y., Zhang W. and Kong W. (2024). Numerical and experimental study on thermal behavior of prismatic lithium-ion battery for large-capacity energy storage. *J. Energy Storage* **83**:110620. DOI:10.1016/j.est.2024.110620
40. Lin X.-W., Shi M.-Y., Zhou Z.-F., et al. (2025). Multi-objective topology optimization design of liquid-based cooling plate for 280 Ah prismatic energy storage battery thermal management. *Energy Convers. Manag.* **325**:119440. DOI:10.1016/j.enconman.2024.119440
41. Zhang F., Liu P., He Y., et al. (2022). Cooling performance optimization of air cooling lithium-ion battery thermal management system based on multiple secondary outlets and baffle. *J. Energy Storage* **52**:104678. DOI:10.1016/j.est.2022.104678
42. Xu Y., Zhao J., Chen J., et al. (2024). Performance analyses on the air cooling battery thermal management based on artificial neural networks. *Appl. Therm. Eng.* **252**:123567. DOI:10.1016/j.applthermaleng.2024.123567
43. Shi Q., Liu Q., He K., et al. (2025). Optimization study on the immersion flow structure design for high-capacity battery module using 4-heat-source electro-thermal model. *Appl. Therm. Eng.* **262**:125226. DOI:10.1016/j.applthermaleng.2024.125226
44. Shi Q., Liu Q., Zhang B., et al. (2025). Multi-objective optimization of an immersion cooling battery module with manifold jet impingement: Based on precision model for high-capacity batteries. *Int. Commun. Heat Mass Tran.* **161**:108448. DOI:10.1016/j.icheatmasstransfer.2024.108448
45. Doyle M., Newman J., Gozdz A. S., et al. (1996). Comparison of Modeling Predictions with Experimental Data from Plastic Lithium Ion Cells. *J. Electrochem. Soc.* **143**:1890. DOI:10.1149/1.1836921
46. Lin X.-W., Jiang Y., Yu H.-T., et al. (2024). A comprehensive investigation on the electrochemical and thermal inconsistencies for 280 Ah energy storage lithium-ion battery. *Energy Convers. Manag.* **315**:118750. DOI:10.1016/j.enconman.2024.118750
47. Mastali M., Foreman E., Modjtahedi A., et al. (2018). Electrochemical-thermal modeling and experimental validation of commercial graphite/LiFePO₄ pouch lithium-ion batteries. *International J. Therm. Sci.* **129**:218–230. DOI:10.1016/j.ijthermalsci.2018.03.004
48. He T., Zhang T., Wang Z., et al. (2022). A comprehensive numerical study on electrochemical-thermal models of a cylindrical lithium-ion battery during discharge process. *Appl. Energy* **313**:118797. DOI:10.1016/j.apenergy.2022.118797
49. He C. X., Yue Q. L., Wu M. C., et al. (2021). A 3D electrochemical-thermal coupled model for electrochemical and thermal analysis of pouch-type lithium-ion batteries. *Int. J. Heat Mass Trans.* **181**:121855. DOI:10.1016/j.ijheatmasstransfer.2021.121855
50. Guo Z., Xu Q., Wang Y., et al. (2023). Battery thermal management system with heat pipe considering battery aging effect. *Energy* **263**:126116. DOI:10.1016/j.energy.2022.126116
51. Ekström H. and Lindbergh G. (2015). A Model for Predicting Capacity Fade due to SEI Formation in a Commercial Graphite/LiFePO₄ Cell. *J. Electrochem. Soc.* **162**:A1003. DOI:10.1149/2.0641506jes
52. Guo Z., Xu Q. and Ni M. (2023). A numerical study on the battery thermal management system with mini-channel cold plate considering battery aging effect. *Appl. Therm. Eng.* **219**:119564. DOI:10.1016/j.applthermaleng.2022.119564
53. Ouyang T., Liu B., Xu P., et al. (2022). Electrochemical-thermal coupled modelling and multi-measure prevention strategy for Li-ion battery thermal runaway. *Int. J. Heat Mass Trans.* **194**:123082. DOI:10.1016/j.ijheatmasstransfer.2022.123082
54. Yang S., Luo X., Li X., et al. (2024). Comparing different battery thermal management systems for suppressing thermal runaway propagation. *J. Energy Storage* **101**:114005. DOI:10.1016/j.est.2024.114005
55. Zhang W., Huang L., Zhang Z., et al. (2022). Non-uniform phase change material strategy for directional mitigation of battery thermal runaway propagation. *Renew. Energy* **200**:1338–1351. DOI:10.1016/j.renene.2022.10.070
56. Hussain M., Khan M. K. and Pathak M. (2024). Thermal management of high-energy lithium titanate oxide batteries using an effective channeled dielectric fluid immersion cooling system. *Energy Convers. Manag.* **313**:118644. DOI:10.1016/j.enconman.2024.118644
57. Huang C., Zhu H., Ma Y., et al. (2023). Evaluation of lithium battery immersion thermal management using a novel pentaerythritol ester coolant. *Energy* **284**:129250. DOI:10.1016/j.energy.2023.129250
58. Zhang C., Wang H., Huang Y., et al. (2025). Immersion liquid cooling for electronics: Materials, systems, applications and prospects. *Renew. Sustain. Energy Rev.* **208**:114989. DOI:10.1016/j.rser.2024.114989
59. Volodin O. A., Shvetsov D. A., Serdyukov V. S., et al. (2025). Enhanced boiling and evaporation of dielectric fluids on modified surfaces for immersion cooling of electronic components – a review. *Appl. Therm. Eng.* **277**:127088. DOI:10.1016/j.applthermaleng.2025.127088
60. Hong Y., Wu H., Wong S. K., et al. (2024). Dynamic thermophysical modeling and parametric sensitivity analysis of flood cooling suppressing the thermal runaway propagation for electric bicycle battery. *J. Energy Storage* **98**:113084. DOI:10.1016/j.est.2024.113084
61. Zhao W., Meng C., Zhao Y., et al. (2025). Research on aging-thermal characteristics coupling and aging thermal management analysis of large-capacity LiFePO₄ battery. *J. Energy Storage* **114**:115675. DOI:10.1016/j.est.2025.115675
62. Zhang Y., Song L., Tian J., et al. (2024). Modeling the propagation of internal thermal runaway in lithium-ion battery. *Appl. Energy* **362**:123004. DOI:10.1016/j.apenergy.2024.123004
63. Tao Z., Lin C., Tian Y., et al. (2025). A systematic approach for determining the optimal battery preheating cut-off temperature for electric vehicles operating in cold climates. *Appl. Energy* **383**:125308. DOI:10.1016/j.apenergy.2025.125308
64. Guo Z., Wang Y., Zhao S., et al. (2023). Investigation of battery thermal management system with considering effect of battery aging and nanofluids. *Int. J. Heat Mass Trans.* **202**:123685. DOI:10.1016/j.ijheatmasstransfer.2022.123685

FUNDING AND ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Grant No. 524B2089 and 52176163), the Ministry of Science and Technology of Shaanxi Province of China (Grant Nos. 2024JC-JCQN-58 and 2023GXLH-003), the Fundamental Research Funds for the Central Universities, and the Cyrus Tang Foundation.

AUTHOR CONTRIBUTIONS

Xiang-Wei Lin: Conceptualization, Data curation, Investigation, Methodology, Software, Writing - original draft. **Bai-Jian Rong**: Investigation, Writing - review & editing. **Xin-Yi Lin**: Validation, Writing - review & editing. **Zhi-Jun Li**: Data curation, Formal analysis, Validation. **Xin-Yu Ding**: Investigation, Writing - review & editing. **Deng-Wei Jing**: Formal analysis, Writing - review & editing. **Youjun Lu**: Resources, Writing - review & editing. **Zhi-Fu Zhou**: Funding acquisition, Resources, Supervision, Writing - review & editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

It can be found online at: <https://doi.org/10.59717/j.xinn-energy.2026.100133>