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RESEARCH ARTICLE

REVIEW OF IMMERSION COOLING COUPLING STRATEGIES IN LITHIUM-ION BATTERY THERMAL MANAGEMENT

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ABSTRACT

To address the issues of thermal runaway in lithium-ion batteries under high-rate fast charging and the difficulty of a single cooling method to simultaneously meet temperature control, uniformity, and low energy consumption requirements, immersion cooling has become a popular thermal management technology due to its direct contact heat transfer and strong heat suppression capability. However, it still has shortcomings such as limited cooling media and insufficient temperature uniformity in large modules. This paper systematically summarises five mainstream immersion coupling strategies: jet impingement, cooling tube, phase change material, heat pipe two-phase, and intelligent algorithm. The heat transfer synergy mechanism and operating characteristics of each coupling structure are described separately. A comprehensive performance comparison of the different coupling schemes is conducted by establishing an evaluation system covering peak temperature, module temperature difference, parasitic power consumption, thermal safety, and engineering complexity. The application value of intelligent algorithms in parameter optimisation and dynamic regulation of immersion systems is also analysed. Existing deficiencies in multi-field simulation, material compatibility, and engineering implementation of current coupling designs are pointed out. This work can provide a reference for the optimal design and engineering application of immersion coupling thermal management systems for lithium-ion batteries.

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INTRODUCTION

Against the background of carbon neutrality, lithium-ion batteries have become the core technology route for electric vehicles and energy storage systems due to their high energy density and long cycle life. Battery performance is closely related to temperature. The suitable operating temperature window is 15–35°C, and the temperature difference within the module should not exceed 5°C. Under high-rate fast charging or high-temperature environments, the heat generation rate of thebattery rises sharply. Insufficient heat dissipation will lead to accelerated capacity degradation or even thermal runaway (Koucheh *et al*., 2026; Wahab *et al*.,2025). Therefore, an efficient and uniform thermal management system is key to ensuring battery safety and lifespan.Current common battery thermal management technologies include air cooling, indirect liquid cooling, and phase change material cooling (Choi *et al*., 2024; Qianqian *et al*., 2026). Air cooling has a simple structure but limited heat exchange capacity. Indirect liquid cooling has interfacial thermal resistance and leakage risks (Song *et al*., 2024). PCM cooling has good temperature uniformity but low thermal conductivity and cannot continuously dissipate heat (Qianqian *et al*., 2026). A single technology struggles to balance heat dissipation capacity, temperature uniformity, and system complexity. In recent years, researchers have proposed a variety of immersion cooling coupling strategies. PCM combined with immersion provides a thermal buffer (Kang *et al*., 2025; Liu *et al*., 2025). Integrated cold plates or cooling tubes introduce active circulation (Song *et al*., 2024; Pan *et al*., 2026). Heat pipe assistance or jet impingement further raises the heat dissipation limit (Kim *et al*., 2025; Jiang *et al*., 2025). Porous media enhance boiling heat transfer (Falcone *et al*., 2025; Choi *et al*., 2024). Intelligent algorithms enable dynamic regulation (Qianqian *et al*., 2026; Wu *et al*., 2025). Immersion coupling is evolving from single cooling to multi-mechanism hybridisation and from passive design to active integration (Zhong *et al*., 2024). Existing reviews mostly focus on individual technologies and lack in-depth analysis of the full-operating-condition applicability and engineering reliability of coupled systems. Based on this, this paper systematically reviews the research literature on immersion cooling coupling strategies, classifies them into five mainstream coupling methods, analyses the characteristics and shortcomings of different coupling strategies, and discusses the selection logic of coupling strategies under different operating conditions. Finally, this paper outlines the key challenges to be addressed in this field, with the aim of providing references for the optimal design and engineering application of immersion cooling coupling systems.

Principle, application advantages and development challenges of immersion cooling

Basic principle: Immersion cooling uses direct contact between a dielectric fluid and the entire battery surface to remove heat via sensible heat or latent heat of vaporisation. Single-phase immersion has a simple structure and requires no condensation loop (Qianqian *et al*., 2026). Two-phase immersion uses low-boiling-point dielectric fluid boiling, achieving a heat transfer coefficient 1–2 orders of magnitude higher and precise temperature control (Gils *et al*., 2014; Koucheh *et al*., 2026).

Application advantages and challenges: In immersion cooling, the dielectric fluid directly contacts the entire battery surface, eliminating interfacial thermal resistance, achieving efficient and uniform heat transfer, and simultaneously providing flame-retardant and oxygen-isolation capabilities (Wu *et al*., 2025; Sundin & Sponholtz, 2020). This method can reduce the maximum battery temperature, decrease module temperature difference, suppress local hot spots (Liu *et al*., 2025; Fei *et al*., 2023), prevent thermal runaway propagation (Falcone *et al*., 2025; Liu *et al*., 2025), and delay inconsistent ageing (Pan *et al*., 2026; Yang *et al*., 2022). Two-phase immersion, using latent heat of phase change, can adapt to ultra-high-rate operating conditions (Zhou *et al*., 2020).

Multiple bottlenecks still exist for engineering promotion. An ideal dielectric fluid needs to balance high thermal conductivity, low viscosity, electrical insulation, and environmental friendliness. Existing media each have shortcomings: mineral oil has high viscosity and high pump consumption; fluorinated fluids are expensive and restricted by PFAS regulations (Wu *et al*., 2025). In large battery packs or under high flow rates, the temperature difference between coolant inlet and outlet can cause a significant temperature gradient. In two-phase immersion, random bubble nucleation may lead to local dry-out, and the module temperature difference can exceed 5°C at a 4C rate (Mahesh *et al*., 2021). Two-phase boiling is sensitive to pressure, requiring additional regulation and condensation circuits, which increase volume and sealing difficulty (Zou *et al*., 2024; Jiang *et al*., 2025). During long-term operation, the dielectric fluid may cause swelling, corrosion, or insulation degradation (Zhong *et al*., 2024; Kang *et al*., 2025). Moreover, immersion cooling cannot fully offset the electrochemical stress under high rates. When charging exceeds 1.3C, the ageing rate still rises rapidly, and high-viscosity coolants significantly increase parasitic energy consumption (Wu *et al*., 2025; Pan *et al*., 2026). Therefore, although single immersion cooling has advantages in thermal uniformity and thermal runaway suppression, it faces problems such as high medium cost, insufficient temperature uniformity in large modules, complex two-phase control, poor material compatibility, and limited high-rate capability. These bottlenecks are difficult to solve by single-parameter optimisation, making the coupling design of immersion cooling with other thermal management methods a key breakthrough path.

2 Introduction to five immersion cooling coupling strategies

Jet impingement immersion coupling cooling: Jet impingement immersion coupling cooling introduces a jet pipe or manifold nozzle structure into the immersion cooling system, using high-speed fluid to break the flow boundary layer on the battery surface and enhance local turbulent disturbance, thereby improving heat dissipation efficiency. (Song *et al*. 2024) added jet pipes on the basis of the main inlet, allowing coolant to enter from both the main inlet and the jet inlet. By reasonably distributing the flow ratio under constant total flow, the maximum battery temperature and average temperature were significantly reduced. This study found that the jet pipes enabled the coolant to quickly cover the middle region of the battery, avoiding the problem of slow flow velocity and insufficient heat dissipation in the middle region when relying only on the main flow (Song *et al*., 2024). (Shi *et al*. 2025) further proposed a manifold jet immersion cooling scheme, arranging an inlet manifold and an outlet manifold above the module, with nozzles below to uniformly distribute coolant to each battery surface, shortening the flow distance and avoiding the temperature gradient caused by traditional side inflow and outflow. The results showed that under 1P discharge, the average temperature of the manifold jet module was reduced by about 1°C compared to the traditional immersion module, and the root mean square error of temperature dropped from 0.91 to 0.44 (Shi *et al*., 2025).

However, the technology still has shortcomings. Existing research is mainly based on numerical simulation with few experimental validations. The Reynolds number of the jet inlet in current studies is below 100, belonging to laminar flow, which differs from the traditional jet impingement heat transfer mechanism. The narrow optimisation range of the battery volume ratio for manifold jet restricts design flexibility. Moreover, issues such as jet erosion wear and dynamic adjustment strategies under different discharge rates have not yet been discussed, and the studies are only for specific battery models, so the universality of the conclusions is insufficient.

Cooling tube immersion coupling cooling: Cooling tube immersion coupling cooling combines static immersion with built-in cooling tubes, aiming to overcome the drawback of traditional dynamic immersion systems that require an additional oil circuit circulation. (Zou *et al*. 2024) proposed directly arranging cooling tubes in static mineral oil, with a water-based working fluid inside the tubes connected to the vehicle thermal management system. The heat generated by the battery is first absorbed by the static immersion fluid and then carried away by the flowing water in the cooling tubes, thereby avoiding overheating of the immersion fluid. The study showed that under an ambient temperature of 40°C and a 3C discharge rate, using 10 cooling tubes with an inlet velocity of 0.2 m/s, the maximum battery module temperature could be controlled at 55.7°C and the maximum temperature difference at 3.51°C (Zou *et al*., 2024). Compared with traditional indirect liquid cooling, this scheme has a smaller temperature difference and obvious advantages in temperature uniformity. Compared with systems requiring forced flow of immersion fluid, this design does not need an additional drive for high-viscosity oil-based working fluid circulation, relying only on the low-viscosity water-based fluid flowing inside the cooling tubes to dissipate heat, reducing energy consumption and improving vehicle integration (Zou *et al*., 2024).

However, current research shows that the thermal conductivity of the static immersion fluid itself is low, limiting the efficiency of heat transfer from the battery surface to the cooling tubes. Subcooling phenomena are observed near the cooling tubes, while regions far from the tubes have higher temperatures, and this non-uniformity becomes more prominent under extreme conditions (Zou *et al*., 2024). The number and layout of cooling tubes need to be carefully balanced: too few cause local overheating, while too many exacerbate edge subcooling. In addition, current results are mainly for 18650 cylindrical batteries with straight tube structures, and adaptability to large-size prismatic batteries or different tab arrangements is still insufficient. Ageing, impurity accumulation, and attenuation of convection capacity after long-term use of static immersion fluids are also important issues.

Phase change material (PCM) immersion coupling cooling

The coupling technology of phase change material and immersion cooling combines the passive heat storage capacity of PCM with the active heat transfer characteristics of the immersion liquid, aiming to solve the problems of low thermal conductivity and difficult recovery after heat accumulation of single PCM. (Liu *et al*. 2025) directly filled a composite PCM of paraffin and graphite around the battery and then injected transformer oil to form a mixed cooling medium. At a 2C cycle rate, this hybrid system controlled the maximum battery temperature at 36.97°C, the maximum temperature difference at only 1.03°C, and the cooling efficiency reached 113.03% (Liu *et al*., 2025). The heat absorbed by the PCM was promptly carried away by the transformer oil, avoiding heat accumulation inside the PCM. (Wagh & Saha 2026) designed a battery-PCM-channel structure, filling n-docosane between concentric copper shells and arranging multiple vertical flow channels along the circumference, with silicone oil flowing in from the bottom for immersion cooling. Experiments showed that under an ambient temperature of 40°C and forced cooling at a flow rate of 1175 mL/min after 3C discharge, the PCM solidified completely within 120 s, and the maximum battery temperature was controlled at 46.3°C (Wagh & Saha, 2026).

Current research indicates that the thermal conductivity of PCM itself is low, and even with the addition of graphite or metal foam, radial heat conduction remains the main bottleneck. Studies show that increasing the number of flow channels increases the overall thermal resistance of the PCM shell; while further increasing the channel number can improve heat dissipation, the comprehensive economic benefit is low. Low-phase-change-temperature materials perform well only at low rates and cannot be used in advanced industrial applications, while high-phase-change-temperature materials can adapt to high-rate environments but have low latent heat utilisation efficiency and cannot be used for long periods, lacking practical application value.

Heat pipe two-phase immersion coupling cooling: The heat pipe two-phase immersion coupling cooling technology combines the efficient heat conduction ability of heat pipes with the high heat transfer coefficient of two-phase immersion boiling, becoming a highly promising passive thermal management scheme. (Jiang *et al*. 2025) designed a heat pipe-two-phase immersion cooling system in which the evaporation section of the heat pipe is tightly attached to the battery surface and the condensation section is immersed in an R123 coolant pool. The heat generated by the battery is conducted through the heat pipe to the condensation section, where efficient heat dissipation is achieved through nucleate boiling and natural convection of the vapour, while the battery itself has no direct contact with the coolant, avoiding electrical safety risks (Jiang *et al*., 2025). The results showed that under a 9C discharge rate, the maximum temperature rise of the heat pipe-two-phase immersion system was only 5.1°C, and the maximum temperature difference was controlled within 1.8°C. After 1200 cycles of ageing tests, the system still maintained a state of health of 85.5%, and the increases in maximum and average temperatures did not exceed 0.3°C and 0.2°C, respectively (Jiang *et al*., 2025). (Kim *et al*. 2025) proposed an even more integrated structure, using the battery as the internal heat source of the heat pipe, covering the battery surface with a wick and sealing it in a vacuum chamber filled with a dielectric working fluid. This built-in heat source design uses the capillary force of the wick to promote working fluid circulation. Experiments showed that the composite wick structure could control the maximum temperature at 49.9°C under 50% filling ratio and 130 W heating power, with a thermal resistance as low as 0.3°C/W, outperforming traditional indirect heat pipe systems. Existing research shows that this coupling scheme is still in the theoretical research stage, has not yet been applied in practice, and the system has potential environmental hazards. Current experiments mostly use heating blocks to simulate battery conditions, which cannot reproduce the uneven and transient heat generation characteristics of real batteries. Moreover, the complex wick structure further increases manufacturing difficulty and cost. Nevertheless, this scheme has extremely high research and application potential in extreme conditions and durability aspects such as thermal runaway suppression and long-term vacuum sealing performance of the sealed chamber.

Intelligent temperature control/algorithm optimisation coupling system: The intelligent temperature control and algorithm optimisation coupling system deeply integrates artificial intelligence models with multi-objective optimisation algorithms to enhance the adaptive regulation capability of immersion liquid cooling battery thermal management. (Wu *et al*. 2025) designed a distributed-inlet circulation immersion liquid cooling structure, with coolant entering the internal channels of the battery module through four independent inlets. The research team used a backpropagation neural network to construct a surrogate model, taking the four inlet mass flow rates as inputs to predict the maximum battery temperature, maximum temperature difference, and input power. Combined with a reference vector guided evolutionary algorithm for multi-objective optimisation, the optimal solution was selected from the Pareto front using the TOPSIS method. The optimised flow distribution scheme reduced the maximum temperature to 30.13°C and the maximum temperature difference to 3.58°C, representing reductions of 24% and 70% compared to the initial design, respectively, with a unit power consumption of only 0.7 m^3/s^3 (Wu *et al*., 2025). (Quazi *et al*. 2025) pointed out that physics-informed neural networks can integrate experimental data with Navier-Stokes equations to predict battery thermal behaviour under different cooling conditions, reducing computation time by more than 65% compared to pure numerical simulation. The extreme learning machine predicted temperature errors of 3.97°C under external short-circuit conditions, outperforming the traditional multi-lumped-state model . Deep reinforcement learning has also been used to optimise cooling strategies, achieving better results than the non-dominated sorting genetic algorithm and multi-objective particle swarm optimisation (Quazi *et al*., 2025). Existing studies indicate that current AI-based battery prediction models still face numerous unresolved challenges. Model accuracy is constrained by the quality and coverage of training data, and offline training modes are difficult to adapt to actual vehicle conditions. Deep learning algorithms have high computational costs and cannot meet the real-time requirements of vehicle controllers. Most related technologies have not yet completed online deployment and long-term stability testing in real battery modules. For high-risk conditions such as internal short circuits and mechanical abuse, although some algorithms have been preliminarily studied, the results are few and the industry has not yet formed a unified performance evaluation system. Meanwhile, the coupling reliability between intelligent algorithms and vehicle hardware has not been fully verified, and algorithm failure can easily cause the entire system to malfunction.

Comprehensive comparison and applicability analysis of coupling systems

Evaluation index system and performance benchmark

Based on the systematic review of the five thermal management strategies, this paper establishes an evaluation index system covering five dimensions: peak temperature suppression capability (Tmax), module temperature difference uniformity (ΔTmax), system energy efficiency and parasitic power consumption, thermal runaway suppression capability, and engineering complexity and cost (Charlotte *et al*., 2022; Mahesh *et al*., 2021), with natural air cooling as the performance benchmark. Since the weights of different indicators vary essentially under different application scenarios, power battery fast-charging scenarios prioritise peak temperature suppression and system energy efficiency, while energy storage stations pay more attention to temperature difference uniformity and thermal runaway suppression capability under long-term operation (Koucheh *et al*., 2026; Mahesh *et al*., 2021). Therefore, the above index system and scenario weight division provide a unified quantitative scale and scenario-specific evaluation rules for the subsequent horizontal comparison of the five coupling strategies, avoiding the simple stacking of isolated performance data and making the comparison conclusions more engineering-guiding.

Horizontal performance comparison of five immersion coupling strategies: Based on the five evaluation dimensions of peak temperature suppression capability (Tmax), module temperature difference uniformity (ΔTmax), system energy efficiency and parasitic power consumption, thermal runaway suppression capability, and engineering complexity and cost, a systematic evaluation and horizontal comparison of the five immersion coupling strategies is conducted (Liu *et al*., 2025; Wu *et al*., 2025). There are significant differences among the various coupling strategies in terms of temperature control performance, energy consumption characteristics, and engineering applicability. The jet impingement immersion coupling strategy achieves a maximum temperature of about 29°C and a temperature difference of less than 2°C at a 3C discharge rate (Shi *et al*., 2025). After flow channel optimisation, pump power consumption can be reduced by 30% (Shi *et al*., 2025). Its thermal runaway suppression capability is moderate, relying mainly on jet disturbance to break the thermal boundary layer without inherent safety redundancy. Engineering complexity is high, with issues such as nozzle clogging and performance degradation at low flow rates (Song *et al*., 2024). The cooling tube immersion coupling strategy reaches a maximum temperature of about 55.7°C and a temperature difference of about 3.5°C at a 3C discharge rate under an ambient temperature of 40°C (Zou *et al*., 2024). Power consumption is extremely low, requiring only a water circulation pump, and system integration is high (Zou *et al*., 2024).

Thermal runaway suppression is relatively good, as the dielectric fluid possesses insulating and flame-retardant properties. Engineering complexity is moderate, requiring optimisation of the number and flow rate of cooling tubes, while long-term maintenance of the dielectric fluid remains challenging (Zou *et al*., 2024). The PCM immersion coupling strategy achieves a maximum temperature of about 36.97°C and a temperature difference of only 1.03°C at a 2C discharge rate (Liu *et al*., 2025). Energy consumption is low, relying on passive heat storage of the PCM together with a low-power pump (Liu *et al*., 2025). Thermal runaway suppression is excellent, as the latent heat of phase change can delay sudden temperature rise (Liu *et al*., 2025; Wagh & Saha, 2026). Engineering complexity is moderate, but the thermal conductivity of PCM is poor, and long-term use may lead to volume change and leakage (Liu *et al*., 2025; Wagh & Saha, 2026). The heat pipe two-phase immersion coupling strategy keeps the maximum temperature below 34°C, a temperature rise of only 5.1°C, and a temperature difference below 1.8°C under an ultra-high discharge rate of 9C (Jiang *et al*., 2025). It operates completely passively with no pump consumption (Jiang *et al*., 2025; Kim *et al*., 2025). Thermal runaway suppression is extremely high, benefiting from the thermal buffering effect of two-phase boiling and electrical isolation (Jiang *et al*., 2025). Engineering complexity is the highest, with difficulties in component integration and uncertainties in long-term sealing reliability (Jiang *et al*., 2025; Kim *et al*., 2025). The intelligent temperature control immersion coupling strategy achieves a maximum temperature of about 30.13°C and a temperature difference of about 3.58°C at a 3C discharge rate (Wu *et al*., 2025). After algorithm optimisation, power consumption is significantly reduced and energy efficiency is outstanding (Wu *et al*., 2025; Quazi *et al*., 2025). Thermal runaway suppression relies on the hardware foundation and can be enhanced through dynamic regulation (Wu *et al*., 2025). Engineering complexity is moderate, constrained by model generalisation ability, hardware cost, and algorithm stability (Wu *et al*., 2025; Quazi *et al*., 2025). In summary, each coupling strategy has its own shortcomings in applicable scenarios. The heat pipe two-phase immersion strategy offers the best performance in high-end fast-charging scenarios, but its sealing cost is high, manufacturing process is complex, and long-term reliability remains insufficient. The cooling tube immersion coupling strategy has the greatest potential for large-scale application in conventional power batteries and energy storage stations due to its low energy consumption and high integration, yet its temperature control capability is relatively conservative and struggles to meet more demanding thermal loads. In periodic charge-discharge energy storage scenarios, the PCM immersion coupling strategy shows outstanding temperature uniformity and passive safety advantages, but the thermal conductivity of PCM is low, it relies on auxiliary heat dissipation after phase change saturation, and there are risks of leakage and performance degradation during long-term cycling. Jet impingement requires breakthroughs in nozzle anti-clogging and flow rate self-adaptation before large-scale application, and it suffers from severe heat transfer degradation and high pump consumption at low flow rates. Intelligent temperature control represents the core direction for global optimisation of energy efficiency and temperature control under dynamic loads, but it currently faces engineering challenges such as insufficient model generalisation ability, high real-time control hardware cost, and unverified algorithm robustness. Research and development entities should adopt a tiered selection strategy based on three major scenarios: fast charging, energy storage and long service life. Meanwhile, these organizations need to recognize the technical bottlenecks of each solution, and offset the drawbacks of a single approach via integrated multi-strategy innovation and intelligent control.

CONCLUSION

This paper systematically reviews immersion cooling and its five coupling strategies for lithium-ion batteries, and analyses the technical characteristics and engineering applicability of each coupling scheme from the aspects of cooling medium selection, system structure design, heat transfer synergy mechanism, and thermal runaway suppression. The following conclusions are drawn.

- Immersion cooling coupling strategies are significantly superior to traditional air cooling and indirect liquid cooling in heat dissipation efficiency and temperature uniformity. Among them, heat pipe two-phase immersion and jet impingement immersion have the strongest temperature control capability, but face engineering bottlenecks such as high system complexity and high sealing cost. Future efforts should focus on breakthroughs in low-cost sealing structures and scalable manufacturing processes.
- Cooling tube immersion coupling and PCM immersion coupling stand out in engineering balance or comprehensiveness. The former has extremely low parasitic power consumption and high system integration, while the latter has excellent temperature uniformity and thermal runaway suppression capability. However, the former has relatively conservative temperature control indicators, and the latter has low thermal conductivity and risks of leakage and performance degradation during long-term cycling. Future development should focus on high-thermal-conductivity, low-viscosity static dielectric fluids and highly stable composite phase change materials.
- Intelligent temperature control immersion coupling can achieve significant energy efficiency improvements through neural networks and multi-objective optimisation algorithms, but problems such as insufficient model generalisation ability, high real-time control hardware cost, and limited multi-physics coupling accuracy restrict its engineering implementation. Future efforts should develop lightweight embedded intelligent algorithms and hardware-in-the-loop verification platforms.
- Two-phase immersion coupling, using latent heat of phase change, can achieve a heat transfer coefficient far exceeding that of single-phase immersion and maintain excellent temperature control even under ultra-high rates. However, its high system complexity, difficulty in pressure control, high cost of low-boiling-point working fluids, and risks of material compatibility and sealing reliability during long-term operation remain concerns. Currently, single-phase immersion is still dominant in practical applications. Future work should develop low-cost, low-GWP, and compatible two-phase working fluids together with adaptive pressure control strategies.
- Existing research is seriously insufficient in long-term cycle stability, dielectric fluid ageing, adaptability to energy storage station scenarios, and life-cycle assessment of environmentally friendly working fluids. There is also a lack of efficient multi-physics coupling simulation models and universal performance prediction tools. Future efforts should focus on long-term ageing experiments, dedicated design guidelines for energy storage, and the construction of a multi-objective decision-making framework covering cooling performance, environmental impact, and economic cost, so as to promote immersion coupling technology from laboratory validation to large-scale engineering application.

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