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Review

A Review on Advanced Battery Thermal Management Systems for Fast Charging in Electric Vehicles

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Abstract: To protect the environment and reduce dependence on fossil fuels, the world is shifting towards electric vehicles (EVs) as a sustainable solution. The development of fast charging technologies for EVs to reduce charging time and increase operating range is essential to replace traditional internal combustion engine (ICE) vehicles. Lithium-ion batteries (LIBs) are efficient energy storage systems in EVs. However, the efficiency of LIBs depends significantly on their working temperature range. However, the huge amount of heat generated during fast charging increases battery temperature uncontrollably and may lead to thermal runaway, which poses serious hazards during the operation of EVs. In addition, fast charging with high current accelerates battery aging and seriously reduces battery capacity. Therefore, an effective and advanced battery thermal management system (BTMS) is essential to ensure the performance, lifetime, and safety of LIBs, particularly under extreme charging conditions. In this perspective, the current review presents the state-of-the-art thermal management strategies for LIBs during fast charging. The serious thermal problems owing to heat generated during fast charging and its impacts on LIBs are discussed. The core part of this review presents advanced cooling strategies such as indirect liquid cooling, immersion cooling, and hybrid cooling for the thermal management of batteries during fast charging based on recently published research studies in the period of 2019–2024 (5 years). Finally, the key findings and potential directions for next-generation BTMSs toward fast charging are proposed. This review offers an in-depth analysis by providing recommendations and potential solutions to develop reliable and efficient BTMSs for LIBs during fast charging.

Keywords: battery; electric vehicle; fast charging; thermal management

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1. Introduction

The use of ICE vehicles creates the issues of greenhouse gas emissions, air pollution, and climate change. According to research, transportation contributes about 17% of total global greenhouse gas emissions [1]. In addition, the depletion and scarcity of fossil fuel resources have forced countries to limit the use of traditional ICE vehicles and invest in alternative forms of energy [2]. Owing to zero emissions, high efficiency, and good stability, EVs are emerging as a sustainable and environmentally friendly solution to replace ICE vehicles [3].

Nowadays, LIBs are a widely employed energy supply in EVs owing to high power density, good stability, low self-discharge rate, long cycle life, and no memory effect [4–6]. However, to achieve optimal performance, LIBs should be kept in the 25–40 °C temperature range and the non-uniformity of the temperature within the battery module should be controlled to under 5 °C [7,8]. The performance of the lithium-ion battery rapidly degrades and the battery life shortens if the aforementioned permissible working range is not maintained. Especially, the lithium-ion battery faces thermal runaway at very high temperatures, which causes high heat generation and leads to fire and explosion [9,10].

In addition, another challenge for EVs is the shorter operating range compared to ICE vehicles. The limitation of EVs' operating range is mainly due to battery weight and long charging time. With the rapid increase in the number of EVs on the road, users increasingly want to be able to charge their vehicle batteries in the shortest time to ensure flexibility and convenience in travel. Fast charging and ultra-fast charging technologies not only significantly reduce waiting time, but also allow users to easily make long trips without worrying about running out of energy in the middle. Research shows that the battery pack in EVs charges for 200 miles through ultra-fast charging in the same time required to refuel a conventional vehicle [11]. The need for fast charging for EVs is becoming an important factor in promoting the transition from traditional vehicles to EVs, contributing to environmental protection and reducing dependence on fossil fuels. However, fast charging and ultra-fast charging also pose challenges for battery thermal management. LIBs may experience high heat generation during fast charging. The uneven heat generation owing to resistive heating causes degradation and safety concerns for the lithium-ion battery during fast charging [12]. Therefore, a reliable battery thermal management system (BTMS) is required to maintain the optimal operating temperature of LIBs during fast charging and ultra-fast charging [13,14].

While battery thermal management systems (BTMSs) are essential for optimizing battery performance, safety, and longevity under fast charging conditions, they also pose potential hazards that must be considered and addressed. A serious risk is that the loss of thermal control due to improper battery thermal management can cause the battery to overheat uncontrollably, leading to a fire or explosion. Additionally, many BTMSs use liquid coolants that are prone to leakage. These liquids can damage battery components or create short circuits, further increasing the risk of thermal failure. Furthermore, some coolant fluids or materials used in BTMSs can be chemically hazardous, toxic, or corrosive if accidentally leaked. Therefore, it is important to ensure that BTMSs are designed and operated with high reliability and efficiency to minimize these risks.

In recent years, direct liquid cooling (immersion cooling) and phase change material (PCM) have received attention as advanced BTMSs for EVs [15]. Direct liquid cooling has superior heat transfer coefficients than PCM cooling [16]. The battery cell makes direct contact with the non-conductive dielectric fluid in the case of immersion cooling, thus greatly improving the heat transfer efficiency over indirect cooling [17]. In addition, immersion cooling can effectively prevent thermal runaway propagation between battery cells and significantly reduce the maximum temperature due to thermal runaway [4]. Furthermore, immersion cooling simplifies the design and reduces system complexity, lowers the production and maintenance costs, lightens the system weight, and ensures advanced safety [18].

Most of the reviews summarize research studies on BTMSs under discharge conditions. Recently, a couple of reviews have been published for the thermal management of a battery during fast charging. Table 1 presents recent reviews on battery thermal management during fast charging. These existing reviews focus more on traditional cooling, namely indirect cooling, without specifically analyzing and evaluating advanced cooling strategies, namely phase change material cooling and direct cooling. The limitations of traditional cooling forces the research direction to divert towards advanced cooling strategies for the thermal management of a battery during fast charging. As result of this, many studies are reporting on battery cooling during fast charging using advanced thermal management techniques. However, the open literature lacks an updated review that focuses solely on the thermal management of a battery considering advanced cooling strategies during fast charging. There is no specific review that analyzes and evaluates current advances in PCM and direct liquid cooling for a battery under fast charging conditions. Therefore, the current review gathers the major research studies that report battery behavior during fast charging while using advanced cooling strategies (PCM and direct liquid cooling). This review serves as a useful reference for evaluating and applying advanced thermal management methods for battery cooling during ultra-fast charging. The structure of this review is as follows: Section 2 explains the thermal characteristics of Li-ion batteries during fast charging, followed by various studies on advanced cooling strategies for the thermal management of batteries in Section 3, and Section 4 lists the notable points and recommendations from the review.

Table 1. Recent reviews on thermal management of batteries during fast charging.

Review	Focus of Review	Highlights
Keyser et al. (2017) [11]	Air cooling, liquid cooling, and refrigerant cooling for thermal management of batteries	Analysis of different cooling methods during extremely fast charging of batteries
Tomaszewska et al. (2019) [12]	Air, liquid, and phase change material cooling for thermal management of batteries	Summary of research on various cooling methods for battery fast charging
Thakur et al. (2023) [19]	Cold plate, phase change material, heat pipe, refrigerant, thermo-electric, and immersion cooling for thermal management of batteries	Summary of research works on hybrid cooling for fast charge/discharge cycles of batteries
Polat et al. (2023) [2]	Air cooling, phase change material cooling, and liquid cooling for thermal management of batteries	Compared and evaluated various cooling methods for DC fast charger systems of batteries
Khan et al. (2024) [20]	Liquid cooling, phase change material cooling, refrigerant cooling, and cooling-based machine learning for thermal management of batteries	Summary of different structures of cooling, and cooling-based machine learning for fast charge/discharge applications. The research on different cases of passive and hybrid PCM cooling for batteries

2. Battery Thermal Issues during Fast Charging

Sections 2.1 and 2.2 discuss battery thermal issues, namely generated heat losses in Li-ion batteries and the thermal behavior of Li-ion batteries.

2.1. Generated Heat Loss in Li-Ion Battery

Due to internal electrochemical reactions, a huge amount of heat is generated in LIBs during the charging/discharging process [21,22]. The high heat generation leads to a rapid increase in temperature within the battery. The C-rate determines the rate at which current is charged or withdrawn from the battery during charging/discharging. The larger current value (high C-rate) leads to rapid heat generation. Research shows that at 3C, 5C, and 8C charging rates, the amount of heat generated is about 10.5 W, 25 W, and 54 W for a 10 Ah Lithium-ion battery [23]. During the charging/discharging process, the total heat generation in the battery is denoted as Q_{gen}. It is determined by the sum of the heat between reversible heating Q_{rev} and irreversible heating Q_{irr}, in which entropy generation leads to reversible heating and Joule heating leads to irreversible heating and is represented as below [24],

$$Q_{gen} = Q_{irr} + Q_{rev} = I(U_{oc} - V_{bat}) - IT\frac{dU_{oc}}{dT} \quad (1)$$

where I represents the battery current during charging or discharging. U_{oc} and V_{bat} stand for open-circuit and battery voltages. T represents battery temperature. $\frac{dU_{oc}}{dT}$ represents the entropic coefficient.

Heat generation leads to rapid temperature increases within batteries during charging/discharging. The performance and life of LIBs are determined by temperature. Maintaining an operating temperature range of 25–40 °C and controlling temperature uniformity below 5 °C is necessary to ensure the optimal performance of LIBs. Therefore, the heat generated in a battery during charging/discharging must be dissipated from its surface quickly and safely. In some cases, the generated heat is not handled promptly, leading to heat accumulation and thermal runaway. Thermal runaway causes the battery temperature to increase rapidly and suddenly, causing the battery's electrolyte material to melt, leading to an internal short circuit that can cause serious fire/explosion [25]. The batteries in today's electric vehicles should be incorporated with faster charging rates to enable competitiveness with ICE vehicles. The batteries operated at high C rates could generate significant heat and require efficient cooling, which is a major issue that needs to be addressed [19]. Therefore, developing an effective thermal management for batteries is very important in maintaining the battery temperature in the optimal range, improving performance, extending the life, and ensuring the safety of lithium-ion battery applications.

2.2. Thermal Characteristics of Li-Ion Battery

Nowadays, most electric vehicles are equipped with large-capacity batteries, which take longer to charge. In order to compete with vehicles using traditional internal combustion engines, the development of fast charging technologies is necessary to reduce charging time and increase the driving range of electric vehicles. However, during fast charging, a lot of heat is generated by LIBs, which leads to a sudden increase in temperature. The temperature of LIBs can spike up to 150 °C and can reach 500 °C within a few seconds during fast charging [12,22]. High temperatures during fast charging cause the degradation of battery capacity, performance, and lifetime. In particular, battery performance degrades, which causes a loss of power and capacity, leading to self-discharge and a short cycle life. With the multitude of electrode and electrolyte materials, not every mechanism of performance degradation could be analyzed. However, Li loss and active material degradation are considered to be the main causes of capacity degradation [26]. The battery internal resistance degrading when operating at high temperatures is considered to be the cause of power loss [27].

In addition, uncontrolled temperature increases during the fast charging of batteries can lead to thermal runaway. Batteries with thermal runaway are exposed to exothermic chain reactions, which cause internal structure deformation, degradation, and eventually complete destruction [28]. During fast charging, thermal runaway is caused by thermal abuse, causing the electrolyte to decompose when operating at extreme temperatures, causing a short circuit between the battery electrodes. The heat generated from these processes rapidly increases the battery temperature, possibly leading to the release of a lot of flammable gases and causing fires and explosions in LIBs. Research shows that battery temperatures reach 500 °C when thermal runaway releases the extra heat due to thermal shrink [29]. Furthermore, the heat generated during thermal runaway also spreads to adjacent battery cells, causing fires and completely destroying the battery pack.

Thermal issues and the consequences of high operating temperature for batteries during fast charging have been discussed. Maintaining the working temperature of batteries within the optimal range is a key factor to obtaining high efficiency, stability, and safety of lithium-ion battery applications in electric vehicles. Under fast charging conditions, the thermal management of LIBs could be solved by applying efficient advanced cooling strategies.

3. Advanced Cooling Strategies for Thermal Management of Batteries in Fast Charging

Indirect liquid cooling, immersion cooling or direct liquid cooling, and hybrid cooling are discussed as advanced cooling strategies for the thermal management of battery fast charging within the current review and summarized in Section 3.1, Section 3.2, and Section 3.3, respectively.

3.1. Indirect Liquid Cooling

Chen et al. suggested a seven-channel cooling plate with a parallel liquid cooling system to improve temperature safety during fast charging and achieve the shortest charging time for the prismatic battery module shown in Figure 1. Research results have shown that the design factor of mini-channel depth has the greatest impact on the cooling efficiency, temperature homogeneity, and power consumption of a parallel liquid cooling structure, being 70.8%, 75.7%, and 86.1%, respectively. Through depth and width channel optimization, the volumetric energy density, maximum temperature (T_{max}), temperature difference (ΔT), and power consumption improved by 9.0%, 2.1%, 23.7%, and 26.9%, respectively, with the parallel liquid cooling system. The experimentally validated optimization model also demonstrates that the T_{max}, ΔT, and energy consumption can be controlled at 33.1 °C, 0.9 °C, and 17.29 J, respectively, with 2.5C fast charging for the battery module [30].

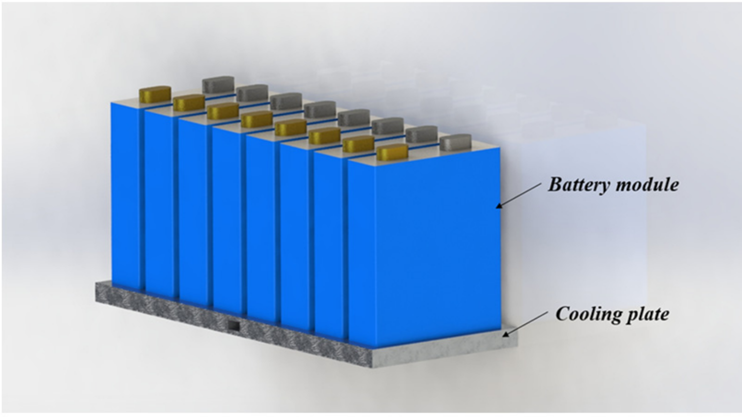

Figure 1. Diagram of the parallel liquid-cooled battery module [30].

Chen et al. developed a cooling strategy for the fast charging of LIB modules based on indirect liquid cooling with a mini-channel structure. A regression model based on neural networks was proposed to reduce the duration and expense of the design procedure for a fast charging and cooling system. Experimentally validated optimal scheduling results indicated that the SOC (state of charge) value of the battery module increased by 50% following 15 min of fast charging. This result showed that the battery charge level increased significantly in a short time, which is very important for battery fast charging applications in electric vehicles. In addition, the use of energy for fast charging was maintained at 0.02 J, and the battery modules' T_{max} and ΔT were maintained at 33.35 °C and 0.8 °C at a fast charging rate up to 2.5C [31].

Lempert et al. researched a three-compartment indirect liquid cooling structure to support the fast charging of battery modules with three Kokam NMC cells, as presented in Figure 2. The experimental results showed that the T_{max} was maintained at 22.3 °C and 28.5 °C for the battery module with typical discharge rates of 1C and 3C, respectively. Specifically, the T_{max} of the battery module was limited to 34.6 °C at the fast charging rate of 5C [32].

A double-layer cooling structure was presented by Wen et al. for the thermal management of batteries under fast charging conditions at a 3C rate. The findings of the research indicated that the T_{max} of the battery never exceeded 45 °C during high-power and high-temperature charging. Twenty minutes was the SOC charging time from 30% to 80%, and twenty-eight minutes was the SOC charging time from 0% to 80% [33].

Qin et al. suggested an external liquid cooling structure with a three-sided cold plate structure to regulate the temperature during ultra-fast charging in order to prevent thermal runaway from damaging the battery module. The proposed cooling system presented a reduction in the T_{max} of the battery module from 58 °C to 49 °C at 4C fast charging. In addition, this cooling strategy significantly improved the range to 117 km in mileage when charging at the ultra-fast charging rate of 5C [34].

The rising and homogeneous temperature of a cell-to-pack (CTP) battery module during fast charging was controlled by Sun et al. through experiments and simulations with a bottom liquid cooling plate structure. The research results indicated that the battery temperature was significantly affected by the temperature and flow rate of the cooling fluid, with the T_{max} being lowered by 10.93% and 15.12%, respectively, under identical operating conditions. Additionally, the battery module temperature was consistently managed between 30 °C to 35 °C and temperature uniformity was ensured by the proposed cooling strategy under NEDC (New European Driving Cycle) cycling conditions [35].

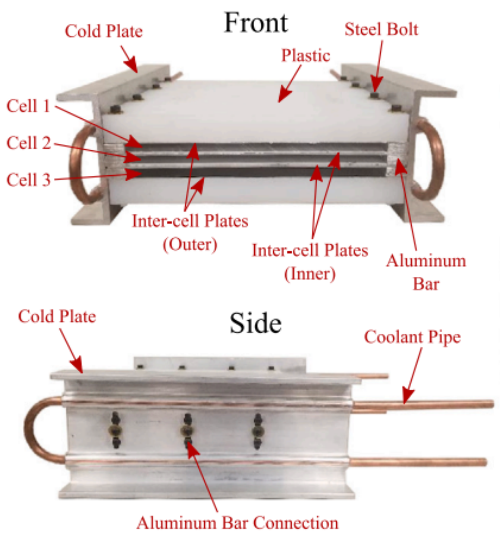

Figure 2. Model of 3P1S battery module featuring cooling plates [32].

Zhao et al. experimentally investigated the inter-cell cooling method, which involves coolant flowing between the cells of battery modules, and the edge cooling method, which involves coolant flowing along the battery module's edges under ultra-fast charging conditions. According to the study findings, with a temperature rise of only 4.1 °C, the inter-cell cooling approach offered higher cooling performance compared to the edge cooling module, which experienced a temperature rise of 14.2 °C at a 5C ultra-fast charging rate. Additionally, during repeated driving cycles and fast charging at a 4C rate, the inter-cell cooling module only raised the temperature by 3.4 °C, whereas the edge cooling module increased the temperature by 12.2 °C [36].

For a battery module under fast charging/discharging circumstances, Sarchami et al. evaluated an indirect cooling strategy with AgO nanofluid and a copper mold structure, as depicted in Figure 3. Compared to the water cooling system, the T_{max} of the battery module during fast charging/discharging was significantly reduced by 7.3%, 11.1%, and 12%, respectively, when 1%, 2%, and 4% volume fractions of silver oxide nanoparticles were added to deionized water. In addition, under optimal operating conditions with 4% AgO nanofluid and an inlet velocity of 0.28 m/s, the T_{max} and ΔT of the battery module were controlled at 31.55 °C and 2.95 °C, respectively, at a 5C fast charge/discharge rate [37].

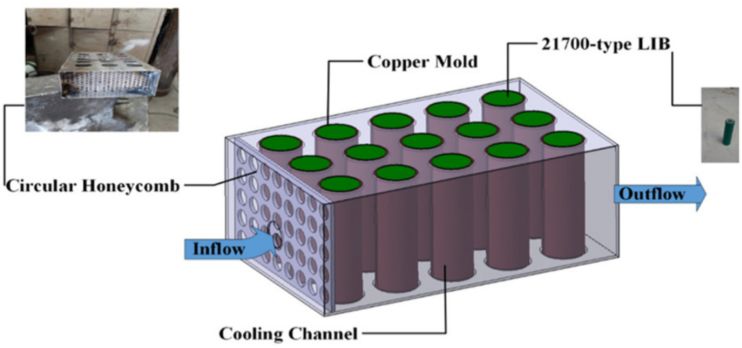

Figure 3. Indirect cooling-based battery module modeling with AgO nanofluid [37].

Han et al. tested and analyzed the cooling efficiency of a novel cooling strategy for the battery module under fast charging conditions using a hybrid fin structure combined with a heat pipe. The research results showed that the proposed cooling structure controlled the T_{max} and ΔT under 45 °C and 4.8 °C, respectively, with the battery module at 3C fast charging. In addition, the proposed cooling strategy also significantly improved the heat transfer process by lowering the overall thermal resistance by 13.7% to 28.0% [38].

Adeniran et al. evaluated the efficiency of both cooling techniques, bottom and two-side liquid cooling for pouch battery modules under fast charging conditions, according to Figure 4. The findings of the research demonstrated that with ΔT reduced by 50% from 10 °C to 5 °C and T_{max} decreased to 7 °C at a 1.98C charging rate, the two-side liquid cooling configuration with opposite flow directions significantly improved the cooling efficiency when compared to bottom liquid cooling [39].

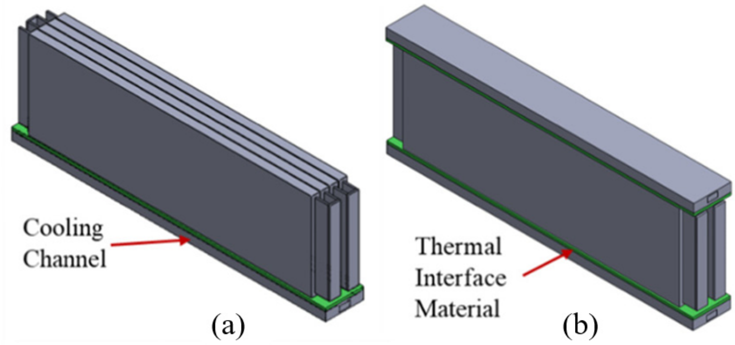

Figure 4. Modeling of (**a**) bottom cooling and (**b**) two-side cooling in thermal management for pouch battery modules under fast charging conditions [39].

Li et al. evaluated the effectiveness of a liquid cooling system with various cooling plate structures for the thermal management of battery modules under fast charging conditions. The cooling plate with three coolant inlets and opposite coolant flow directions, the adjacent cold plates controlled T_{max} and ΔT at 313 K and 5 K for the battery module at a charging rate below 3C and coolant mass flow rate of 1.2 g/s [40].

3.2. Direct Liquid Cooling

Amalesh et al. evaluated the cooling efficiency of dielectric fluid immersion cooling (STO-50) with hybrid cooling that combined immersion cooling and PCM cooling (RT35) for a prismatic battery module during 8C fast charging, as demonstrated in Figure 5. The research results showed that dielectric fluid immersion cooling (STO-50) was capable of maintaining the battery temperature below 40 °C during 8C fast charging with a 2 LPM (liters per minute) flow rate of dielectric fluid, and the coolant flow direction was along the length of the battery instead of across/transverse. To cool the battery efficiently using the hybrid cooling method under fast charging conditions, the PCM's thermal conductivity must be designed to be 1 W/mK or above. In addition, the study also demonstrated that increasing the PCM's latent heat between 160 and 200 kJ/kg had no appreciable impact on battery cooling efficiency [41].

Tan et al. applied hydrofluoroether coolant (HFE-6120) to the immersion cooling structure for thermal management of the battery pack under fast charging conditions. The research results showed that, compared with the base channel, the maximum power consumption decreased to 95.3% and the energy density was increased to 20.3%. In addition, adopting a cross-flow configuration and multi-layer structure improved the T_{max} and ΔT up to 18.1% and 25.0% [42].

A hybrid immersion cooling strategy featuring graphite fins and a pass partition was suggested by Choi et al. to enhance the cooling efficiency of lithium-ion battery modules in harsh environments and during rapid charging, as shown in Figure 6. According to the research results on dielectric fluid flow direction, because of the uniform distribution of the fluid and enhanced heat dissipation efficiency, flowing from bottom to top cooled the battery more efficiently than flowing from top to bottom. Additionally, the proposed cooling strategy significantly improved the thermal performance of the battery pack, with

T_{max} and ΔT being controlled at 35 °C and 6 °C, respectively, which were 6.7 °C and 3.0 °C lower than the conventional cooling structure at the 3C rate of charging. Furthermore, the hybrid immersion cooling approach outperformed the conventional cooling method in terms of hydraulic performance, lowering power consumption and pressure by 61.0% and 45.4%, respectively [43].

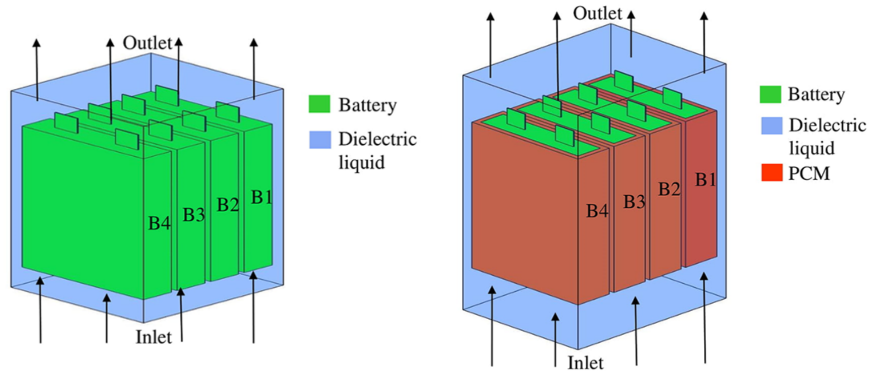

Figure 5. Schematic of dielectric fluid immersion cooling and hybrid cooling [41].

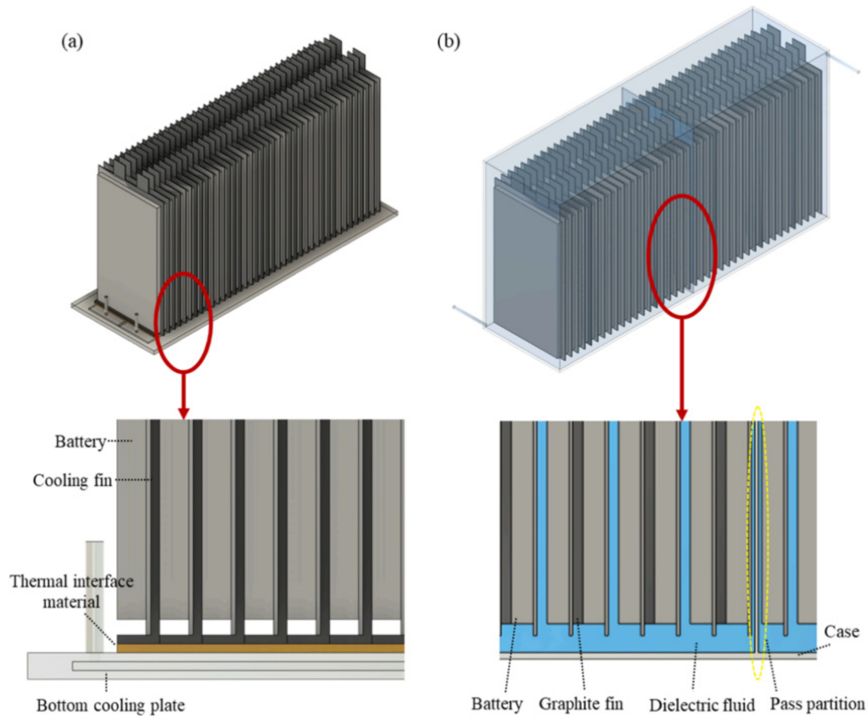

Figure 6. The modeling of (**a**) conventional bottom cooling plate and (**b**) hybrid immersion cooling structure [43].

Li et al. conducted experiments on the immersion cooling system using FS49 fluid during fast charging of the battery module, as depicted in Figure 7. According to the study findings, immersion cooling reduced the T_{max} by 7.7 °C and 19.6 °C of the battery module at 2C and 3C rates of fast charging. In addition, the proposed cooling strategy exhibited a decrement in energy consumption by 14.41% and 40.37% compared to forced-air cooling at the considered charging rates. Furthermore, the immersion cooling structure demonstrated the superior benefit of controlling the homogeneous temperature in the battery module at 1.2 °C [44].

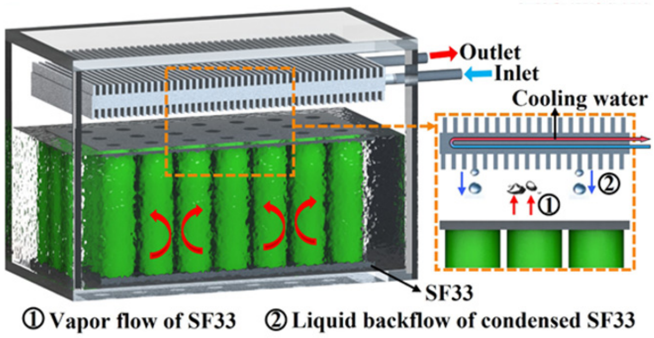

Figure 7. The modeling of the liquid-immersion-cooled battery module [44].

Ezeiza et al. presented a novel direct cooling approach for battery modules during fast charging. The novelty of this proposed cooling strategy was to directly cool the external surface of the battery as opposed to submerging the battery in a cooling liquid system. The study's findings indicated that the T_{max} and ΔT of the cell were maintained inside the ideal range for operation at 38 °C and 1.3 °C during semi-fast charging and discharging experiments at 2C and 3C, respectively [16].

Li et al. proposed a new cooling strategy with immersion cooling by applying SF33 fluid. The research results showed that immersion cooling reduced T_{max} and ΔT by 19.1 °C and 9.8 °C compared to forced-air cooling (FAC) of the battery module during 3C fast charging. Furthermore, the immersion cooling achieved superior energy efficiency by 43.76% compared to the FAC module [45].

Li et al. evaluated the reciprocating immersion cooling strategy using FS49 fluorinated fluid for cylindrical batteries during fast charging, as demonstrated in Figure 8. The findings of the research indicated that, compared to natural convection cooling, the proposed cooling strategy significantly enhanced the T_{max} and ΔT of the battery cell. During the rest period after fast charging, the considered cooling method enabled the battery temperature to decrease by up to 19.01 °C, thereby significantly improving the thermal performance and lifespan of the battery cell [46].

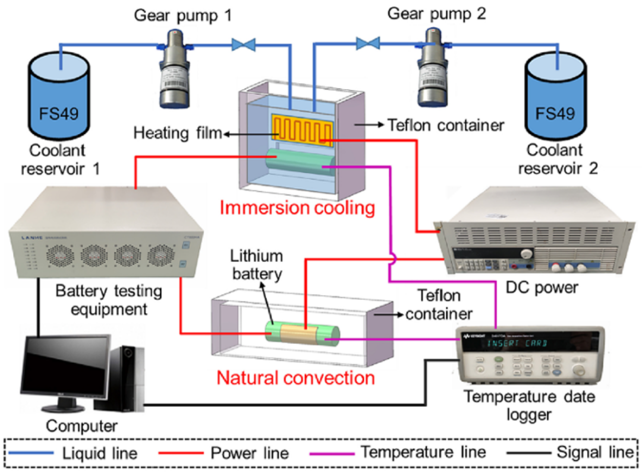

Figure 8. Schematic illustration of the reciprocating liquid immersion cooling experimental system [46].

Yao et al. showed that the immersion cooling approach offered an excellent cooling effect during fast charging conditions of the battery pack. A 5 mm distance between the battery cells and a 20 mm/s flow rate showed a superior heat transfer coefficient of 1572.3 W/m^{2}K compared to that with 10 mm and 20 mm distances. The addition of a disturbing structure with a 48 mm height optimized the heat dissipation efficiency, improved the flow uniformity, and reduced the ΔT of the cell surface by 44.3% [47].

Hong et al. suggested a two-phase refrigerant cooling strategy by R134a to improve heat dissipation during fast charging of battery modules, as illustrated in Figure 9. The findings of the research demonstrated that the proposed cooling system maintained the T_{max} under 45 °C for the battery cell during 2C fast charging. Additionally, compared to conventional cooling structures, two-phase refrigerant cooling offered 15.0% reduced internal resistance and 16.1% greater battery capacity during aging [48].

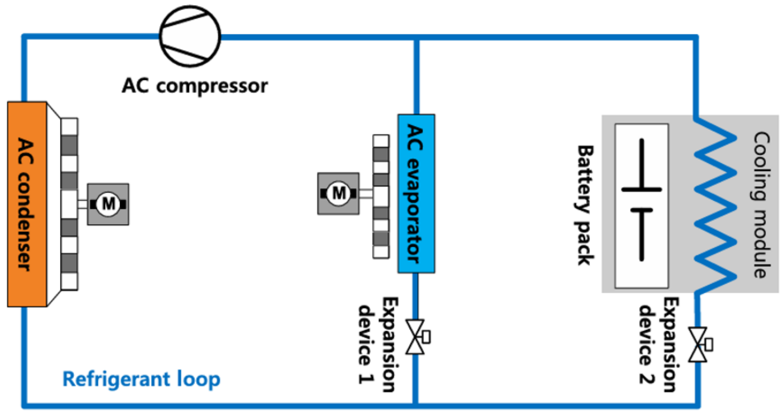

Figure 9. Diagram of battery cooling system based on direct two-phase refrigerant cooling [48].

Williams et al. experimentally investigated liquid immersion cooling using Novec 7000 dielectric fluid to evaluate the cooling efficiency during fast charging of the battery module as shown in Figure 10. The research showed that immersion cooling with two-phase cooling conditions provided superior thermal management, with the T_{max} and ΔT maintained at 35 °C and 1 °C at 4C fast charging of the battery module. In addition, research results on the impact of cell spacing showed that the heat dissipation efficiency was improved when the cells were spaced closer together, leading to limited temperature rise and enhanced temperature homogeneity for the battery module [49].

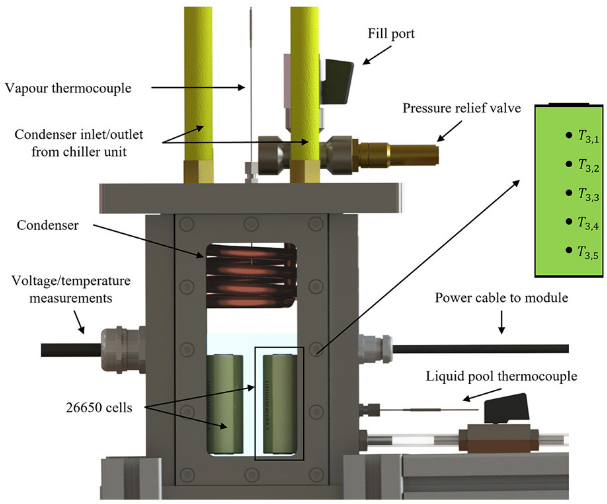

Figure 10. Two-phase cooling strategy for cylinder battery module [49].

3.3. Hybrid Cooling

Lee et al. suggested hybrid cooling that combined a cooling plate, aluminum fins, and phase change material (PCM) (Sasol, PARAFOL 18–97) to improve cooling efficiency during fast charging for the pouch battery module, as presented in Figure 11. The research results indicated that the proposed design provided the best cooling performance, with the T_{max} and ΔT controlled at 38.4 °C and 3.9 °C during 3C fast charging of the battery module, as shown in Figure 12. Additionally, the 2 mm thickness and 36.1 °C melting temperature of the PCM were selected as suitable design parameters to provide optimal cooling performance during 3C fast charging [50].

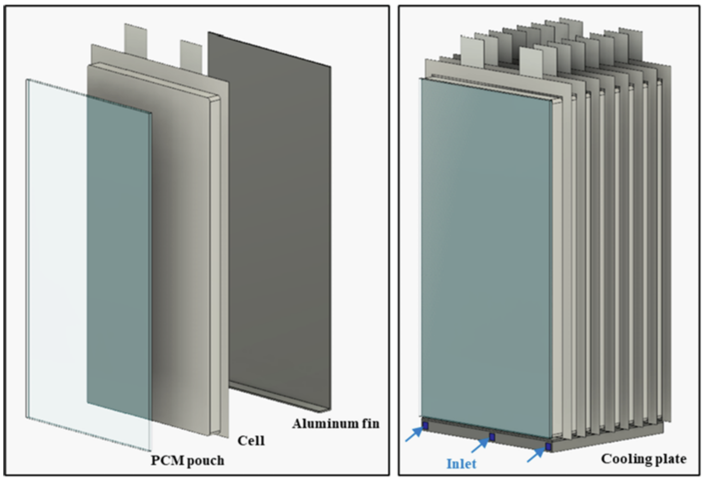

Figure 11. Schematic of hybrid cooling based on bottom cooling plate and PCM [50].

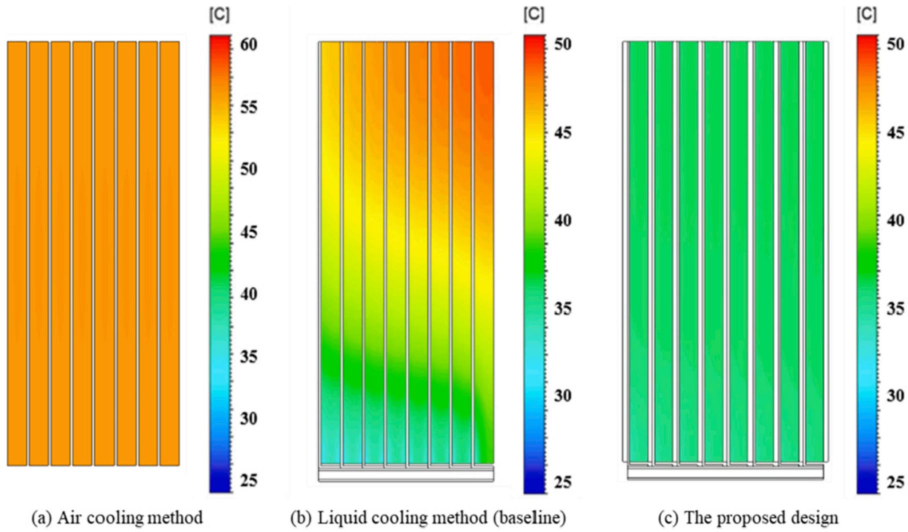

Figure 12. Temperature distribution of hybrid cooling compared with air cooling and liquid cooling for 3C fast charging battery module [50].

Behi et al. presented a hybrid cooling method using PCM combined with cooling plates to control the thermal characteristics of LTO battery modules during 4C fast charging/discharging, as demonstrated in Figure 13. The research results showed that the PCM cooling controlled the temperature of the battery module to 35.8 °C and 36.2 °C, with a temperature reduction of 13.3% and 15.8% compared to natural convection cooling. Additionally, the temperature of the charging and discharging processes was well controlled at 31.2 °C and 31.8 °C when applying the hybrid cooling system, with a temperature reduction of 24.6% and 26% compared to natural convection. Furthermore, temperature homogeneity was enhanced by 56% for charging and 34.8% for discharging when using the hybrid cooling system [51].

Zheng et al. suggested combining indirect cooling with PCM cooling for the battery pack during 8C fast charging, as depicted in Figure 14. Additionally, the cooling structure was supplemented with adiabatic polyurethane interlayers to limit heat transfer between tube cooling and ensure battery pack temperature uniformity distribution. The findings of the research indicated that the hybrid cooling method maintained the T_{max} and ΔT

of the battery pack at 44.52 °C and 10.81 °C, respectively. Furthermore, the optimized configuration with an additional design of adiabatic polyurethane interlayers provided outstanding cooling performance, with T_{max} and ΔT of the battery pack stable at 38.69 °C and 2.22 °C, respectively, after 450 s at an 8C fast charging rate [52].

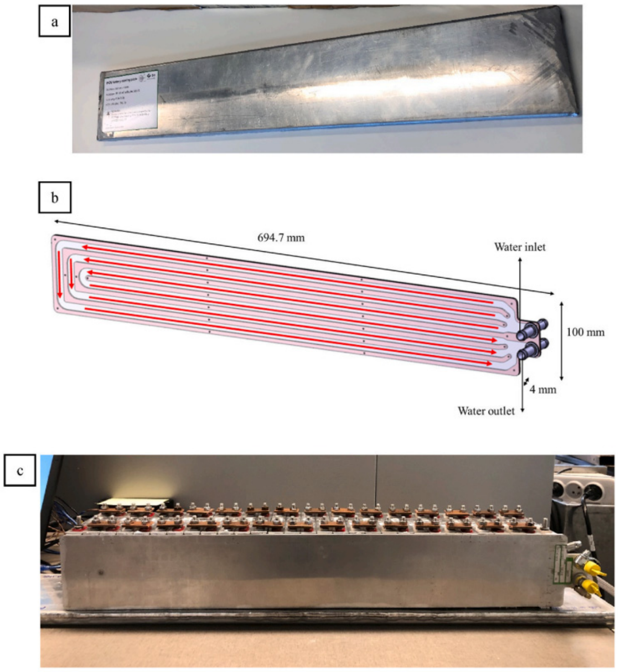

Figure 13. (**a**) PCM plate; (**b**) structure of cooling plate; (**c**) battery module with hybrid cooling between PCM cooling and liquid cooling by cooling plate [51].

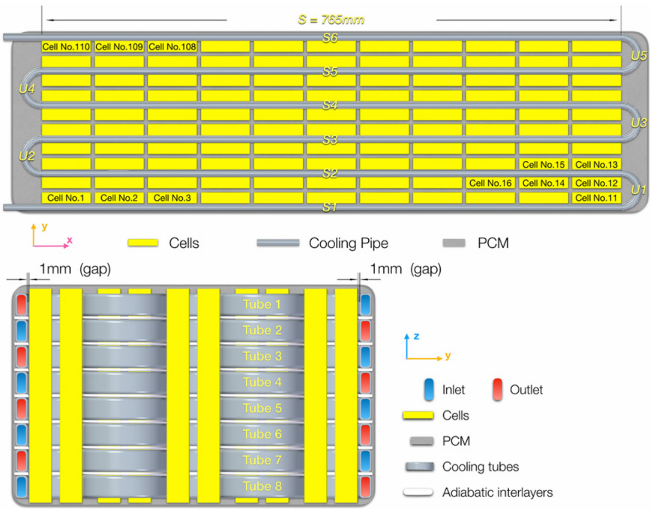

Figure 14. The modeling of hybrid cooling method with adiabatic interlayers [52].

Patil et al. presented a cooling strategy by indirect cooling incorporating PCM cooling for battery modules during fast and ultra-fast charging. The research results showed that hybrid cooling maintained the T_{max} at 31.8 °C; meanwhile, only using PCM cooling alone, T_{max} was maintained at 38.4 °C for the battery module at 4C fast charging. In addition, the ΔT was also greatly enhanced by 6.8 °C when applying the hybrid cooling method [53].

Chen et al. experimentally studied hybrid cooling comprising PCM and liquid cooling for the prismatic battery module during fast charging. The research results showed that the battery module did not have the best cooling efficiency or thermal performance at the greatest PCM thickness and the largest coolant flow rate. To ensure heat dissipation efficiency and reduce the energy usage and overall mass of the battery module, the recommended coolant flow rate and PCM thickness were 54 mL/min and 0.65 mm, respectively. The proposed cooling strategy maintained the T_{max} and ΔT of the battery module at 34.8 °C and 0.96 °C during 3C fast charging, and the low-energy consumption was limited to 459 J [54].

Choi et al. developed a novel hybrid cooling structure including PCM cooling, indirect cooling, and a polymer material heat exchanger for battery modules during fast charging. The research results showed that the hybrid cooling structure offered superior cooling performance, with the T_{max} and ΔT maintained at 30.82 °C and 2.80 °C for the battery module during 3C fast charging. Furthermore, the cooling system used low-density polymer materials and PCM, leading to the weight reduction of the BTMS and the enhanced overall performance of the electric vehicle [55].

Liu et al. proposed a cooling plate structure combined with PCM cooling in which a metallic phase change material gallium replaced a part of the RT31 organic material to enhance the heat dissipation efficiency of battery modules during fast charging/discharging requirements, as illustrated in Figure 15. The research results showed that 25% gallium filling increased the PCM's thermal conductivity and significantly improved the cooling efficiency, with T_{max} and ΔT maintained at 35.45 °C and 6.2 °C for the battery module at a fast charging/discharging rate of 9C [56].

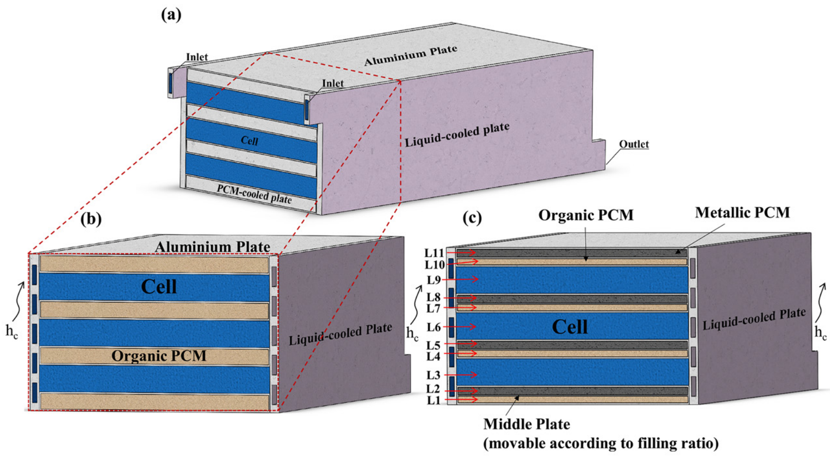

Figure 15. Schematic of hybrid cooling between cooling plates with PCM cooling [56].

Liu et al. evaluated the cooling efficiency of hybrid cooling between liquid and PCM cooling for battery modules during cyclic fast charging/discharging at high ambient temperatures of 40 °C as depicted in Figure 16. The cold plate with two layers of configuration and fins installed in the cooling system minimized the temperature unevenness of the battery along the axis and reduced T_{max} and ΔT to 4.44 °C and 4.17 °C, respectively [57].

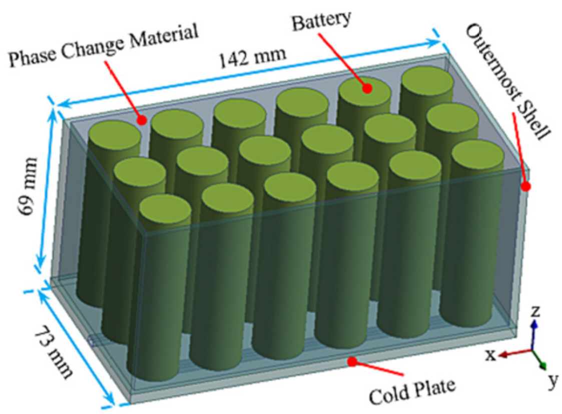

Figure 16. The modeling of hybrid cooling between cold plate and PCM [57].

Youfu et al. improved the cooling efficiency of liquid cooling by adding graphene-oxide-modified silica gel (GO-SG) for the battery module during fast charging requirements, as demonstrated in Figure 17. The findings of the research indicated that the proposed cooling strategy controlled the T_{max} at 37.7 °C and 42.0 °C and the ΔT at 4 °C and 5 °C during 2C and 3C fast charging. Additionally, the T_{max} and ΔT could be maintained within 40 °C and 4 °C during the cycling tests for the suggested cooling method [58].

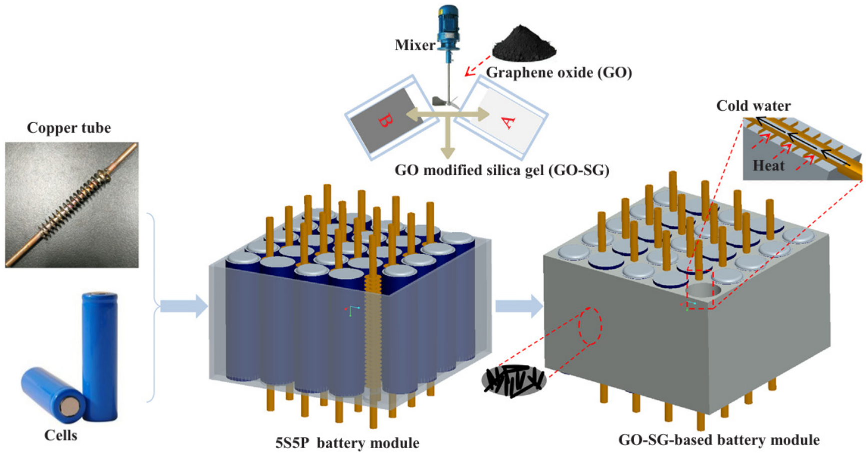

Figure 17. Diagram of the liquid cooling combined with graphene-oxide-modified silica gel (GO-SG) [58].

4. Summary and Recommendations

Electric vehicles (EVs) have been evaluated as a potential and promising solution in coping with climate change and the global energy crisis. Nowadays, LIBs are a reliable storage of energy for EVs. With the expectation of reducing charging time and increasing driving range, the heat generated in battery packs during fast charging is a serious problem, directly affecting the safety and efficiency of EV battery packs. Consequently, an advanced BTMS is really essential for fast charging applications of LIBs in EVs. The current review summarizes recent research works conducted in the last 5 years on advanced BTMSs during fast charging in EVs. Advanced battery cooling strategies during fast charging have been summarized, comprising indirect liquid cooling with cooling plates, direct liquid cooling, and hybrid cooling based on liquid cooling combined with PCM. The following summarizes the main conclusions and suggestions of the current review:

(a) Indirect cooling systems impose several concerns in the advanced battery thermal management technique such as their complex design, liquid leakage, corrosion risk, high energy consumption, increased system weight, and high maintenance cost. In addition, the large thermal resistance between the cooling structures in the indirect cooling system and the battery surface also significantly reduces the heat transfer coefficient and cooling performance. Therefore, the application of indirect cooling systems in the field of fast charging for high-capacity battery packs in the future needs to be carefully studied and evaluated.

(b) Direct liquid cooling or immersion cooling is gaining much attention as an advanced battery thermal management method. This cooling method works by allowing liquid to directly contact the battery cell surface, thereby reducing thermal resistance and significantly increasing the heat transfer coefficient, which improves heat dissipation efficiency and provides superior cooling performance. In addition, direct liquid cooling with a two-phase cooling mechanism using low-boiling point fluids has provided superior heat dissipation efficiency compared to single-phase cooling and indirect liquid cooling. Therefore, direct liquid cooling is considered a potential candidate for advanced battery thermal management. However, to guarantee the practical applicability of direct liquid cooling for battery thermal management on a larger scale, in-depth research studies need to be executed reflecting the relation between influential and performance parameters. Thus, databases generated based on these research studies will act as guidelines to design and develop the next-generation battery immersion cooling system.

(c) With the great advantage of high latent heat when the solid–liquid phase change occurs, PCM cooling has brought about superior heat dissipation performance and provided temperature uniformity by absorbing large amounts of heat released from battery packs during fast charging. In addition, PCM cooling is a passive cooling method. The application of this cooling method allows for reduced energy consumption in the system and is more compact in space requirements. However, the low thermal conductivity of PCM is a challenge that makes it difficult to meet the heat dissipation requirements of battery packs during fast charging. Therefore, the concept of hybrid cooling is considered an advanced battery thermal management strategy by combining the advantages of liquid cooling and PCM cooling.

(d) The selection of a suitable advanced cooling strategy should also be evaluated based on larger-scale production and harsh environmental operations. In the case of direct liquid cooling, the leakage of coolant is the primary concern, which could deplete the battery thermal management performance. Also, the coolant weight could make the cooling system bulky and affect the range enabled by the battery system. In addition, the highly viscous and denser coolant can cause an increase in pumping power. Therefore, while considering the commercial-scale production of a battery with an advanced cooling strategy, the overall cost of the cooling system based on the aforementioned indicators needs to be examined. In harsh environments with high temperatures, high humidity, and high corrosion, cooling systems can wear out more quickly. Therefore, the choice of materials, insulation, and sealing techniques inevitably becomes important and costly.

(e) To effectively implement advanced battery thermal management strategies for fast charging in electric vehicles, a few recommendations have been made for stakeholders, including manufacturers, policymakers, and researchers: The immersion cooling technique could be optimized at the commercial scale considering environmental friendly coolants with enhanced heat transfer performance, coolant flow distribution based on inlet/outlet configurations, cell arrangements, and spacing, as well as relevant influential operating parameters such as flow rate, temperature, and ambient condition. Thermal runaway models should be developed, and real driving tests should be conducted to ensure the safe operation of the battery system with an advanced cooling strategy under extreme operating conditions. Governments and organizations can introduce financial incentives, such as tax breaks or subsidies, to encourage the adoption of advanced cooling technologies that are highly efficient in cooling and energy saving.

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