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Review

A Review of Advanced Cooling Strategies for Battery Thermal Management Systems in Electric Vehicles

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Abstract: Electric vehicles (EVs) offer a potential solution to face the global energy crisis and climate change issues in the transportation sector. Currently, lithium-ion (Li-ion) batteries have gained popularity as a source of energy in EVs, owing to several benefits including higher power density. To compete with internal combustion (IC) engine vehicles, the capacity of Li-ion batteries is continuously increasing to improve the efficiency and reliability of EVs. The performance characteristics and safe operations of Li-ion batteries depend on their operating temperature which demands the effective thermal management of Li-ion batteries. The commercially employed cooling strategies have several obstructions to enable the desired thermal management of high-power density batteries with allowable maximum temperature and symmetrical temperature distribution. The efforts are striving in the direction of searching for advanced cooling strategies which could eliminate the limitations of current cooling strategies and be employed in next-generation battery thermal management systems. The present review summarizes numerous research studies that explore advanced cooling strategies for battery thermal management in EVs. Research studies on phase change material cooling and direct liquid cooling for battery thermal management are comprehensively reviewed over the time period of 2018–2023. This review discusses the various experimental and numerical works executed to date on battery thermal management based on the aforementioned cooling strategies. Considering the practical feasibility and drawbacks of phase change material cooling, the focus of the present review is tilted toward the explanation of current research works on direct liquid cooling as an emerging battery thermal management technique. Direct liquid cooling has the potential to achieve the desired battery performance under normal as well as extreme operating conditions. However, extensive research still needs to be executed to commercialize direct liquid cooling as an advanced battery thermal management technique in EVs. The present review would be referred to as one that gives concrete direction in the search for a suitable advanced cooling strategy for battery thermal management in the next generation of EVs.

Keywords: battery; direct liquid cooling; electric vehicle; lithium-ion; phase change material cooling; thermal management

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1. Introduction

In addition to rapidly increasing environmental pollution and global warming being major concerns worldwide, increasing energy demands have raised the issue of the depletion of fossil fuels. From 2013 to 2019, the predicted increase in worldwide CO_2 emissions is 43.2 gigatons (Gt) per year, of which 14% is contributed by the transportation sector [1]. The transportation sector is dominated by IC engine vehicles which are the main reason for the excessive consumption of fuel resources and environmental degradation. EVs with outstanding advantages of zero emissions and energy saving have the most potential as a solution to the problems of environmental protection and replacement of IC engine vehicles in the future [2]. Therefore, in recent years the global transportation market is growing with the increasing demand for EVs.

Currently, Li-ion batteries are the best and most widely used source of power in EVs with their outstanding advantages of high energy density, high power factor, low self-discharge rate, good stability, and long lifecycles [3–7]. In order to achieve comparable performance with IC engine vehicles, EVs are incorporated with high energy density batteries. The issues of high heat generation occur in such high power-density batteries under fast and higher charging/discharging conditions [8,9]. The heat generation changes the battery operating temperature which affects the charging/discharging performance, internal electrochemical reactions, reliability, service life, and safety of the battery [10,11]. The maximum temperature and temperature uniformity of the battery should be restricted to 20–45 °C and 5 °C, respectively, to achieve the efficient and safe operations of the battery in EVs [12]. When operating outside the above range, the performance of the Li-ion battery rapidly degrades [13], the battery life shortens [14], and, in particular, it faces a thermal runaway [15], which leads to a fire and an explosion when operating at too high temperature. Battery operations at different charging/discharging rates lead to local degradation [16]. Furthermore, the battery degradation rate and aging phenomenon are accelerated when the maximum temperature of the battery module exceeds 50 °C [17]. Therefore, the research and development of a battery thermal management system is essential to bring safety, reliability, and high performance to Li-ion battery applications in EVs [18,19].

Extensive research has been conducted to develop an efficient thermal management system using conventional and advanced cooling strategies to achieve the optimal operating temperature, symmetrical temperature distribution, and prevention of a thermal runaway. The recent reviews reported on battery thermal management are listed in Table 1 to highlight the key issues covered for battery cooling using various thermal management strategies.

Currently, direct liquid cooling is a competitive advanced cooling strategy to phase change material cooling and is emerging as a new-generation cooling strategy for battery thermal management. One of the reasons for its gaining popularity as an emerging technology for direct liquid cooling is its minimal thermal resistance between coolant and battery as well as its compact and low-weight structure due to the absence of cooling plate/mini channels, unlike widely-used indirect liquid cooling for battery thermal management. Furthermore, the heat dissipation performance of direct liquid cooling is superior compared to phase change material cooling as a competitive emerging cooling strategy. Even in extreme operating conditions such as a thermal runaway, direct liquid cooling has the capability to enable safe battery operation due to the high fire point and phase transition characteristics of coolants.

Numerous reviews have been reported in recent years on battery thermal management based on various cooling strategies, primarily focusing on air cooling and indirect liquid cooling. Owing to the limitations of these conventional cooling strategies the research has been diverted to advanced cooling strategies for battery thermal management. Considerable research has been reported on phase change material cooling and direct liquid cooling as a replacement for conventional air and indirect liquid cooling for battery thermal management. There are review articles reported recently that solely focus on phase change material cooling as an advanced battery thermal management technique. However, the open literature is lacking to present a comprehensive review that solely focuses on direct liquid cooling for next-generation battery thermal management. It should be noted that there are reviews that explain the research studies on direct liquid cooling for battery thermal management but only as a subpart of the entire review. The focus of these review articles is not direct liquid cooling. Based on the conducted literature review and the authors' knowledge, there has been no concrete review that explains the recent advancements in direct liquid cooling for battery thermal management. The present review summarizes the key research works reported in the past five years on advanced cooling strategies namely, phase change material cooling and direct liquid cooling for battery thermal management in EVs. The focus of the current review is diverted to direct liquid cooling research work, after discussing the key advancements and limitations of phase change material cooling. The outline has been drawn through the present review to further carry forward the research tasks with an aim to adopt direct liquid cooling as a commercialized advanced cooling strategy for high power density battery thermal management in next-generation EVs. The review is organized as follows: Section 2 offers an explanation of the thermal characteristics of the Li-ion battery. This is followed by a summary of various research studies on battery thermal management with conventional cooling strategies and advanced cooling strategies in Sections 3 and 4, respectively. Finally, Section 5 highlights the key points of the review with recommendations.

Table 1. Recent reviews on battery thermal management systems with key highlights.

Review	Focus of Review	Highlights
Deng et al. (2018) [20]	Battery thermal management based on liquid cooling	Summary of types of liquid cooling structures, the performance of various coolants, and battery pack design
Chen et al. (2019) [21]	Battery thermal management based on phase change material cooling	Summary of battery cooling research works on pure, composite, and hybrid phase change materials
Wu et al. (2019) [22]	Battery thermal management based on liquid and heat pipe cooling	Summary of research works on direct liquid cooling, indirect liquid cooling, and heat pipe cooling
Akinlabi and Solyali (2020) [23]	Battery thermal management based on air cooling	Summary of research works on active and passive air cooling of the battery
Karthik et al. (2020) [24]	Battery thermal management based on air cooling, liquid cooling, and phase change material cooling	Summary of articles on various cooling strategies to mitigate the thermal runaway propagation in battery
Thakur et al. (2020) [25]	Battery thermal management based on air, liquid, and heat pipe cooling	Summary of research works on natural and forced air cooling, direct and indirect liquid cooling, and heat pipe cooling for battery
Tete et al. (2021) [26]	Battery thermal management based on air, liquid, heat pipe, phase change material, and refrigeration cooling	Summary of experimental and numerical research works on battery thermal management systems for hybrid EVs and full EVs
Murali et al. (2021) [27]	Battery thermal management based on passive phase change material cooling	Summary of research on various battery cooling strategies combined with phase change material. In addition, the research on composite phase material cooling for the battery is also summarized
Jiang et al. (2022) [28]	Battery thermal management based on air, liquid, heat pipe, phase change material, and combined cooling	Summary of research on battery thermal management with various cooling strategies under normal and abusive conditions
Hamed et al. (2022) [29]	Battery thermal management based on air, liquid, and phase change material cooling	Summary of research studies on external cooling strategies for the battery
Roe et al. (2022) [30]	Battery thermal management system based on immersion cooling	Summary of various dielectric fluids for immersion cooling of battery and related research works
Zhao et al. (2023) [31]	Battery thermal management based on liquid cooling	Research studies focus on optimization and design improvement of liquid cooling systems for batteries are summarized

2. Thermal Characteristics of Li-Ion Battery

The thermal characteristics of the Li-ion battery affect its performance and thus the autonomy of EVs. Increasing energy density causes high heat generation in Li-ion batteries under extreme operating conditions [32]. The heat generation of Li-ion batteries is directly related to their thermal behavior. The heat generation in Li-ion batteries and the thermal issues of Li-ion batteries are elaborated in Sections 2.1 and 2.2, respectively.

2.1. Heat Generation in Li-Ion Battery

The total heat generation of a Li-ion battery is dominated by two components: namely, reversible heat and irreversible heat. The change in entropy results in reversible heat generation whereas polarization results in irreversible heat. The heat generation could be estimated using Bernardi's equation as presented [33],

$$Q_{total} = Q_{irreversible} + Q_{reversible} \tag{1}$$

$$Q_{total} = I(U - V) - I \times \left(T\frac{dU}{dt}\right) \tag{2}$$

In Equation (2), the irreversible heat comprises ohmic heat within battery cells and an over-potential charge transfer at the interface. In this term, the open circuit voltage and operating voltage of battery cells are presented by U and V, respectively. The reversible heat comprises entropy generation in which $\frac{dU}{dt}$ indicates the entropy coefficient as a function of battery cell temperature and density. The value of $\frac{dU}{dt}$ is either negative or positive depending on the charging/discharging modes of the battery cell and its value approaches zero when the current flow in the battery cell is terminated [25]. The battery cell is exposed to irreversible heat at high C-rates and reversible heat at low C-rates [34,35]. The accelerated rate or isothermal heat conduction calorimeter model is used to determine the irreversible heat through experiments. From the several implementation methods, the potentiometric method is commonly adopted to determine the entropy coefficient [36,37]. However, this method is complex and time-consuming hence, recently, numerous studies have been performed to accurately evaluate the entropy change. Murashko et al. proposed the heat flux measurement model to evaluate the profiles of thermal diffusivity and entropy change simultaneously [38]. Damay et al. estimated entropy variation curves using the thermal inversion model based on the calorimeter method [39]. Panchal et al. developed Bayesian Regularization based on the neural network model to predict the thermal characteristics of the battery under various discharge conditions [40]. Furthermore, Panchal et al. predicted and verified battery temperature distribution through thermos-graphic measurements based on infrared radiation [41,42]. Xie et al. proposed the electro-thermal model which predicts the thermal dynamics of the battery with an error of 0.72 °C [43].

2.2. Thermal Issues in Li-Ion Battery

A higher amount of heat is generated in the battery during fast charging and discharging operations; the heat generation at the positive tab is particularly high. The higher temperature owing to the higher heat generation affects the specific power, efficiency, and life cycle of the battery. In addition, the higher battery temperature can cause a reaction within the cathode and electrolyte, decomposition of the electrolyte and anode, and film formation at the interface of the electrolyte [44].

One of the major consequences of high battery temperature is capacity/power loss. The capacity or power loss of the battery causes a self-discharge, short life cycle, and autonomy losses. It is very complex to evaluate the capacity or power loss in batteries because of the various electrode materials and chemistries associated with them. Ineffective thermal management in the case of battery discharge operation at high temperatures is not able to dissipate the heat from the battery which results in the overheating of the battery. The carbon-based anode dissolution, cathode material with the formation of solid electrolyte formation, and crystal structure volatility pump up the internal resistance and thus it causes the capacity to fade, power reduction, and at last the energy loss of battery [45,46].

The high temperature of the battery creates the issue of an electrical imbalance which is defined as a cell-capacity difference in the battery pack because the battery capacity depends on the battery's temperature. Under an electrical imbalance state, the energy produced by the battery pack reduces. The cell charging under an electrical imbalance condition causes the overcharging of a weak cell and thus issues of power loss and temperature rise are observed in the battery pack.

The increase in battery temperature under extreme conditions can cause thermal runaway propagation within battery cells. The thermal runaway propagation in Li-ion batteries is presented in Figure 1 [47]. The main source of thermal runaway is a larger amount of heat generation with gases as a result of exothermic reactions which starts the chain of chemical reactions during improper charging/discharging modes. The battery temperature can reach up to 500 °C when additional heat is released during thermal runaway as a result of the thermal shrink [48]. When the temperature approaches 90 °C, the metastable part within solid electrolytes decomposes exothermally. The graphite electrode, approaching 200 °C, can exothermally react with solvent at 100 °C under the condition that it is partially exposed to a solid electrolyte interface. However, this reaction could be slowed down due to the presence of $LiPF_6$ salt. The interface of solid electrolyte decomposes on the graphite electrode during the exothermal reaction when the battery's temperature approaches 85 °C. With a further increase in the battery's temperature to up to 110 °C, the decomposition of the secondary layer occurs which causes electrolyte evaporation and the temperature reaches 140 °C. At this temperature, the separator can melt which creates a short circuit in the battery pack. Furthermore, the state of charge of the battery varies with the temperature of the thermal runaway [45].

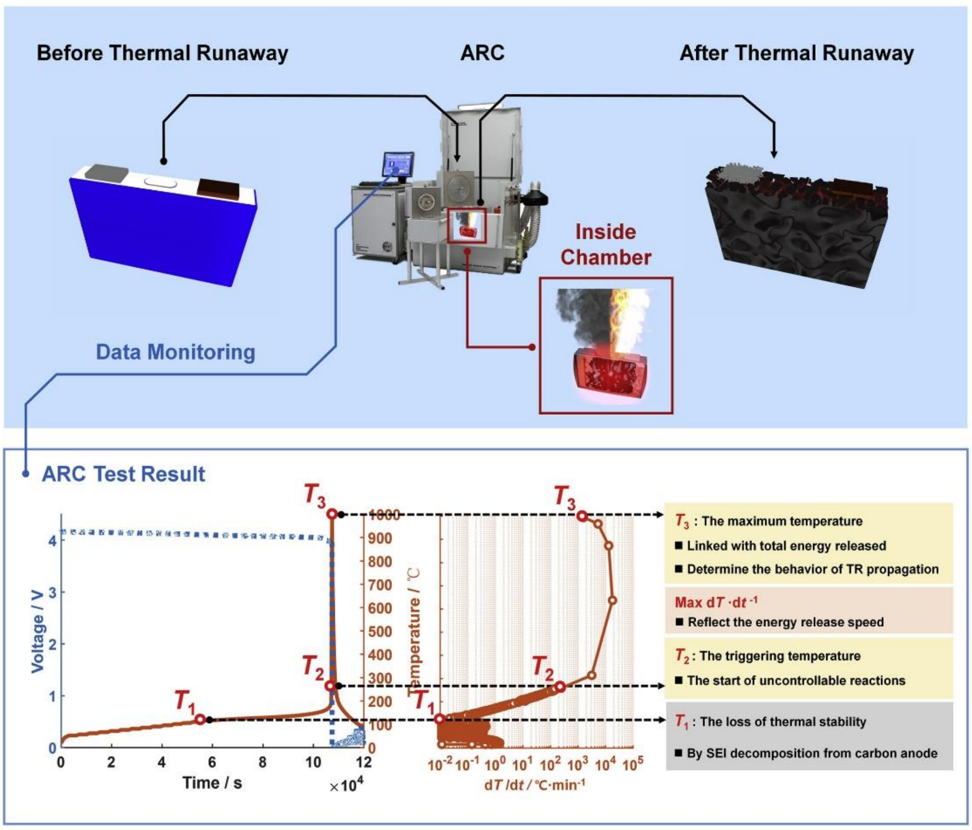

Figure 1. Thermal runaway propagation in lithium-ion battery [47].

The thermal issues, which occurred as consequences of the failure to maintain the operating temperature of the battery within the desired permissible limit, have been discussed. The temperature of the Li-ion battery should be maintained within the stated permissible limit to achieve the desired performance and avoid a thermal runaway. The thermal management of the battery could be addressed by implementing a suitable cooling strategy with excellent heat dissipation characteristics.

3. Battery Thermal Management with Conventional Cooling Strategies

A battery thermal management system enables control of the temperature characteristics of a battery in normal and extreme operating conditions and thus assures its safety and performance [49]. An efficient battery thermal management system can prevent electrolyte freezing, lithium plating, and thermal runaways, helping to provide favorable operating conditions for Li-ion batteries [50]. The commercially employed battery thermal management system includes air cooling and indirect liquid cooling as conventional cooling strategies. This section summarizes recent improvements implemented on air and indirect liquid cooling systems for efficient battery thermal management.

3.1. Air Cooling

Numerous research studies have been conducted with several design improvements to enhance the efficiency of air-cooling-based battery thermal management systems as listed in Table 2.

Table 2. Recent research studies on the air-cooling-based battery thermal management system.

Reference	Design Improvements	Key Findings
Shahid et al. (2018) [51]	Wedge-shaped inlet plenum with an optimized separating plate for air cooling system	Maximum temperature was reduced by 18.3% and the temperature uniformity was maintained at less than 5 °C
Na et al. (2018) [52]	Unidirectional airflow and reverse layered airflow configurations for a cylindrical battery module.	Reverse layered airflow configuration significantly reduces the maximum temperature and increases the temperature uniformity of the battery pack compared to unidirectional airflow configuration
Fan et al. (2019) [53]	Air-cooling of the battery pack with cells arranged in aligned, cross, and staggered arrangements	Battery pack with aligned cells provides the best temperature uniformity and the lowest energy consumption compared to other arrangements
Yuanzhi Liu et al. (2019) [54]	Air cooling system with J-type, U-type, and Z-type structures	Air cooling system with a J-type structure shows the best thermal management performance compared to the other two structures, with a temperature rise of the battery reduced to 31.18%
Kai et al. (2020) [55]	A symmetrical air-cooling system with asymmetrical distribution of cell spacing	The maximum cell temperature difference was reduced by 43% and the energy consumption was reduced by 33% compared with the asymmetrical air-cooling system
Hou et al. (2022) [56]	Optimize the parallel channel width distribution and plenum angle for the air-cooled battery thermal management system	The temperature difference of the battery pack reduces by 49% after optimizing the parallel channel width and 56% after optimizing the plenum angle
Zhang et al. (2021) [57]	Forced-air cooling system with multiple vents, different position and size of vents and various cell spacings	The maximum temperature and temperature difference of battery were reduced by 16.4% and 48.7%, respectively, for optimized model compared to original model
Saechan et al. (2022) [58]	Optimize the cell arrangement structure for air cooling	Superior cooling performance for an optimal arrangement distance between cells as 1.5 mm

The battery thermal management system with air cooling is widely used in EVs owing to its advantages such as low cost, simple structure, easy installation, and maintenance, as well as the lower weight of the overall system and lack of leakage when compared with other cooling techniques [55]. However, the air has poor thermophysical properties, so the air-cooled battery thermal management system is only suitable for applications with low heat dissipation requirements. When operating in extreme conditions, it cannot control the temperature rise and maintain a uniform temperature of the battery pack [59].

As an alternative to air cooling, indirect liquid cooling has gained popularity as a widely adopted commercial battery thermal management technique owing to the superior thermophysical properties of liquid compared to air [30]. Indirect liquid cooling enables better control over temperature rise and assures great improvement in temperature uniformity for the battery when compared to air cooling [20].

3.2. Indirect Liquid Cooling

In the indirect liquid cooling-based battery thermal management system, the cooling liquid has no direct contact with the battery cell surface, but heat exchange between the battery and the cooling liquid occurs through a cold plate, tube, or jacket [25]. Some of the liquids used in indirect cooling systems are water, nanofluids, liquid metals, or glycol/water mixtures [31]. The summary of recent advancements in indirect liquid cooling-based battery thermal management systems is explained in Table 3.

Table 3. Recent advancements in indirect liquid cooling-based battery thermal management systems.

Reference	System Specifications	Key Findings
Du et al. (2018) [60]	Water cooling tubes for cylindrical battery	Achieves maximum temperature of 31.8 °C and temperature uniformity of 4.2 °C under 1C discharge rate
Lv et al. (2019) [61]	Water cooling tubes for cylindrical battery	Maximum temperature and temperature uniformity of battery as 42 °C and 4–5 °C, respectively at 3C discharge rate
Zhou et al. (2019) [62]	Water cooling with a half helical duct for cylindrical battery	Proposed cooling shows battery maximum temperature and temperature uniformity as 30.9 °C and 4.3 °C, respectively under a 5C discharge rate
Shang et al. (2019) [63]	Water and glycol mixture-based cooling plate for prismatic battery	Cooling configuration attends the maximum temperature and temperature uniformity of battery as 38.89 °C and 5.31 °C, respectively at a 1.2C discharge rate
Deng et al. (2019) [64]	Cold plate cooling with water for rectangular battery	Maintains the maximum temperature and temperature difference at 31.18 °C and 1.15 °C under 5C discharge rate
Xu et al. (2019) [65]	Water jacket cooling for prismatic battery	The achievable maximum temperature and temperature uniformity are 32.5 °C and 1.5 °C under a 1C discharge rate
Li et al. (2019) [66]	Cold plate cooling using water for prismatic battery	The battery maximum temperature and temperature uniformity are maintained within 41.92 °C and 1.78 °C for a 5C discharge rate

Table 3. *Cont.*

Reference	System Specifications	Key Findings
Chen et al. (2019) [67]	Mini channels-based jacket cooling using water for soft-pack battery	The proposed cooling restricts the maximum temperature and temperature uniformity of the battery within 32.8 °C and 2 °C under 1C discharge rate
Wiriyasart et al. (2020) [68]	Nanofluid flow in corrugated mini channels for battery module cooling	The proposed cooling module shows a maximum temperature lower by 28.65% compared to the conventional cooling module
Du et al. (2020) [69]	Water cooling plate for pouch battery	Under 2C discharge rate, maintains maximum temperature and temperature difference at 32 °C and 6.2 °C
Patil et al. (2020) [70]	U-shaped mini channels cooling for pouch cell battery	The maximum temperature and temperature uniformity is maintained below 40 °C and 4 °C for a 50 V battery pack
Liu et al. (2020) [71]	Water and liquid metal-based cooling tubes for pouch cell battery	Proposed cooling achieves maximum temperature and temperature difference of battery below 40 °C and 5 °C, respectively at a 5C discharge rate
Monika et al. (2021) [72]	Rectangular mini-channel cold plate sandwiched between the battery cells and providing a constant flow of coolant in the mini-channels across the cold plate.	A cold plate consisting of 4 mm width, parallel flow design with water inlet near the charging port, and coolant flow rate and temperature of 0.003 kg·s $^{-1}$ and 25 °C, respectively show superior battery cooling performance
Yates et al. (2021) [73]	Water cooling channels for cylindrical battery	Maximum temperature and temperature difference of battery are restricted within 39.85 °C and 3.15 °C, respectively under a 5C discharge rate
Huang et al. (2022) [74]	Optimize the cooling plate structure	The optimized structure improves the cooling efficiency by 10.82% compared with the original design

However, indirect liquid cooling systems have the limitation of high thermal resistance due to the use of a cold plate, tube, or jacket cooling for heat exchange, resulting in reduced heat transfer efficiency [30]. In addition, the structure of the cooling system is more complicated, the cost is higher, and the weight is heavier. In particular, coolant leakage is also a concern [75]. Therefore, optimizing the design and structure of indirect liquid cooling is very important to improve the overall cooling performance. Despite the superior heat transfer coefficient in comparison to air cooling and several structure modifications, the key limitations associated with indirect liquid cooling unfavored its effectiveness for the next generation of EV battery packs with higher power densities. This issue demands the search for advanced cooling strategies which can serve as next-generation battery thermal management techniques. In this search, two advanced cooling strategies, namely phase change material cooling and direct liquid cooling, have been widely researched during the last five years.

4. Battery Thermal Management System with Advanced Cooling Strategies

Phase change material cooling and direct liquid cooling are elaborated as advanced cooling strategies for battery thermal management systems in the present review. In phase change material cooling, the battery is surrounded by materials that absorb the heat generated by the battery during charging/discharging operations. This material changes its phase owing to the heat absorbed from the battery and thus maintains the optimum temperature of the battery. Phase change material cooling is considered a passive battery thermal management technique. In direct liquid cooling, the coolant with high electrical resistance makes direct contact with the battery surface and absorbs the heat during battery operations. Thus, the battery's optimal temperature is maintained due to direct heat dissipation from the battery to the coolant. Direct liquid cooling could be considered an active as well as passive battery thermal management technique. The recent advancements in battery thermal management considering phase change material cooling and direct liquid cooling between the years 2018–2023 are summarized in Sections 4.1 and 4.2, respectively.

4.1. Phase Change Material Cooling

Huang et al. conducted an experimental study to evaluate the cooling efficiency of thermal management systems for cylindrical Li-ion batteries by comparing pure phase change material, combined heat pipe with air-assisted phase change material (PCM/HP-Air), heat pipe combined with liquid-assisted phase change material (PCM/HP-Liquid) cooling. The battery thermal management system with three cooling configurations is shown in Figure 2. Compared to pure phase change material cooling and PCM/HP-Air cooling, PCM/HP-Liquid cooling shows a longer working time to achieve a temperature of 44 °C and exhibits better temperature control with the highest possible temperature being maintained at 50 °C at a discharge rate of 3C. The battery temperature comparison for the three cooling configurations under various discharge conditions is depicted in Figure 3. Furthermore, the temperature non-uniformity of the battery module for PCM/HP-Liquid cooling is about 3 °C lower than the other two cooling methods. During the cycle test at a 3C discharge rate, PCM/HP-Liquid cooling achieves the same temperature profile stability as the first cycle, with the average temperature being maintained at about 45 °C. In contrast, the other two cooling methods show a continuously rising temperature profile, especially for pure phase change material cooling [76].

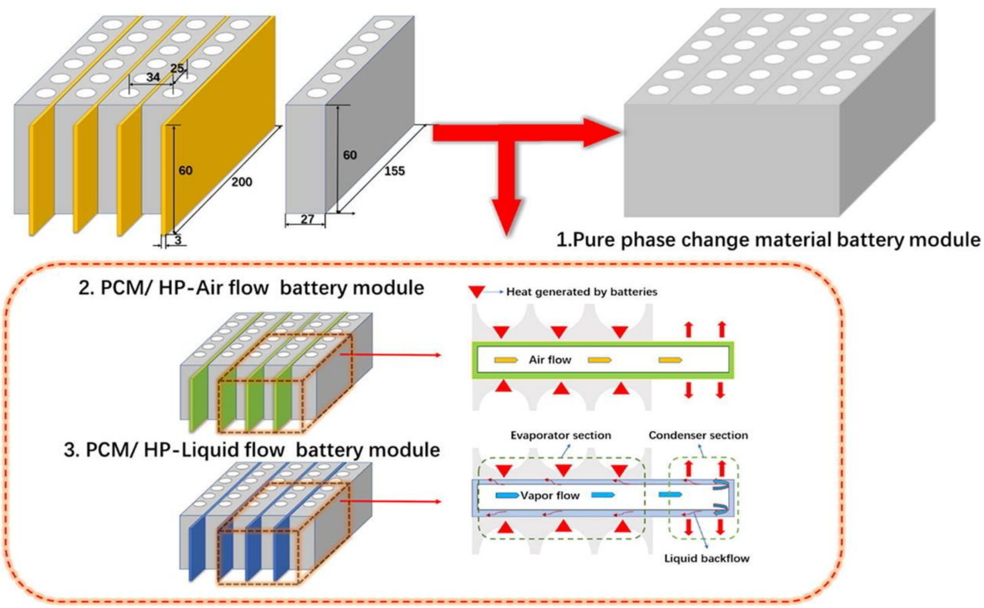

Figure 2. Battery thermal management system with three cooling configurations [76].

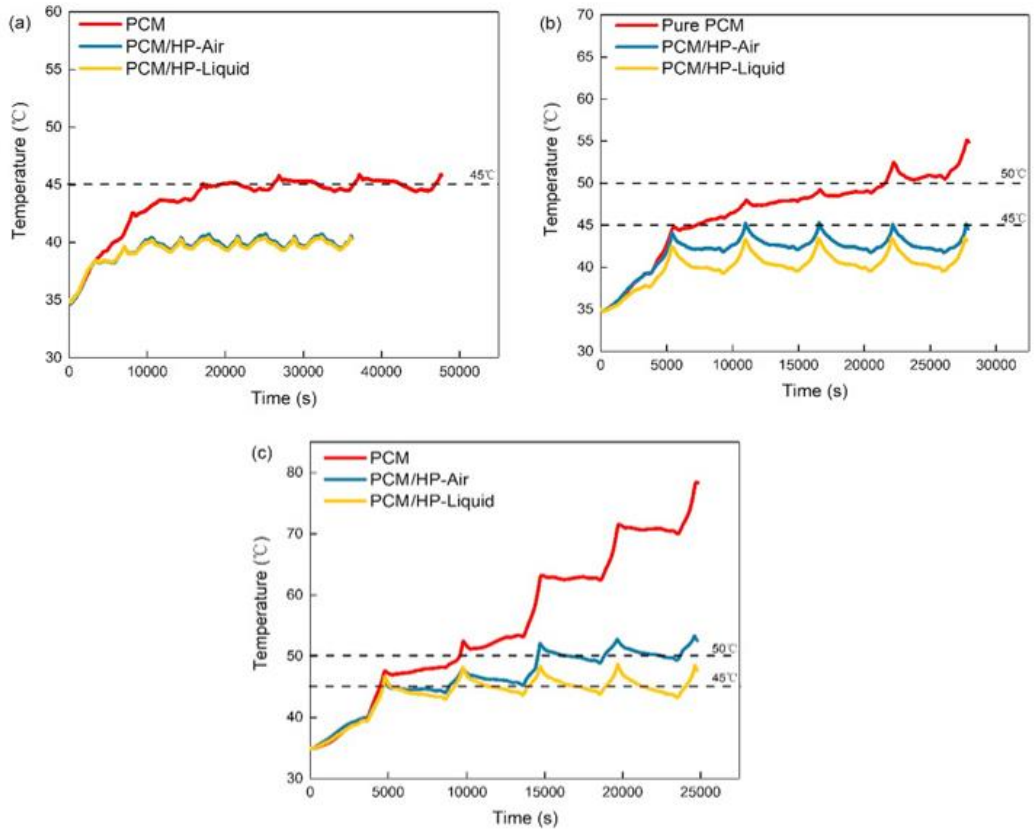

Figure 3. Battery temperature comparison for three cooling configurations under (**a**) 1C (**b**) 2C and (**c**) 3C discharge conditions [76].

Koyama et al. employed trimethylolethane (TME) hydrate-based phase change material cooling for the thermal management of Li-ion batteries in EVs. The maximum battery temperature was maintained at 29.6 °C with the largest heat dissipation of 190.1 kJ kg^{-1} for the proposed phase change material cooling at the mass fraction of 0.60 [77]. Gou et al. investigated the maximum temperature and the temperature uniformity of batteries in EVs by comparing phase change material cooling, and heat-pipe-assisted phase change material cooling. The maximum battery temperature is maintained within 35.5 °C and 31.5 °C for phase change material cooling and heat-pipe-assisted phase change material cooling, respectively. The heat-pipe-assisted phase change material cooling demonstrates the best thermal performance for the battery with a maximum temperature and temperature uniformity of 33.8 °C and 0.9 °C, respectively, at a 3C discharge rate [78]. Zhao et al. showed improved maximum temperature and temperature uniformity for copper/paraffin foam composite phase change material cooling. The maximum temperature of the battery is 39 °C in the case of pure phase change material cooling whereas, the copper/paraffin foam composite phase change material cooling depicts a 14 °C lower maximum temperature of battery compared to pure phase change material cooling. The battery temperature distribution contours for pure phase change material and composite phase change material cooling are shown in Figure 4 [79]. Kshetrimayum et al. researched a cooling method that integrates the phase change material and microchannel cooling plate to manage the temperature of the battery module, prevent heat propagation, and thermal runaways due to nail penetration. The pure phase change material cooling could not prevent the thermal abuse of battery cells under nail penetration however, the phase change material integrated with microchannel cooling maintains the operating temperature of battery module within 317 K. This indicates that the phase change material design approach with an integrated microchannel cooling plate has a higher thermal efficiency than the design without a microchannel cooling plate [80]. Jiang et al. investigated a method for battery thermal management in EVs using phase change material incorporating a heat pipe. The melting point temperature of phase change material should be at least 3 °C higher than the ambient temperature to maintain the latent heat stability of phase transition materials. Hence, considering the melting point temperature of phase change material, the heat transfer coefficient at the condenser side of the heat pipe is effective for the proposed combined cooling to achieve battery safety when operating for longer amounts of time, and for the energy saving and energy density of the battery module [81]. Zhang et al. conducted an experimental study to evaluate the cooling efficiency of a large-sized power battery module for phase change material based on liquid cooling. Combining phase change material with liquid cooling provides excellent efficiency in controlling the maximum temperature and temperature uniformity of the battery module. Compared to liquid cooling, the phase change material with liquid cooling reduces the maximum temperature and temperature uniformity of battery module by 10.6 °C and 1.7 °C, respectively. In addition, the phase change material with liquid cooling restricts the maximum temperature and temperature uniformity of battery module at 50 °C and 3.4 °C, respectively, under continuous test cycles [82].

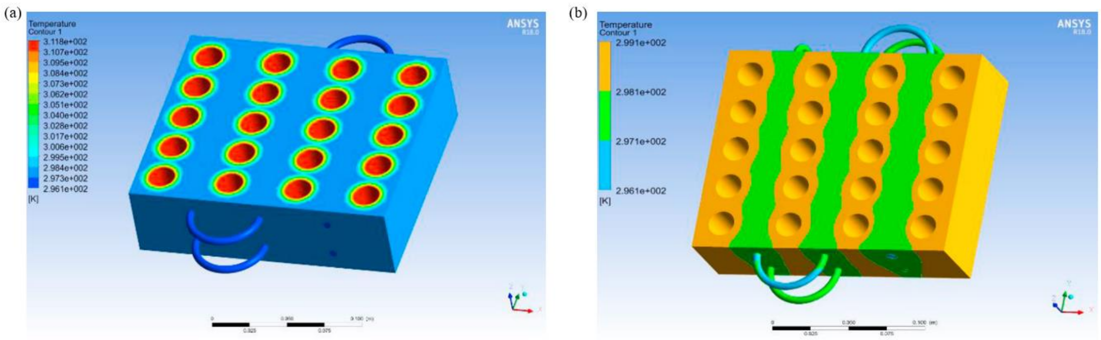

Figure 4. Battery temperature distribution contours for (**a**) pure phase change material cooling and (**b**) composite phase change material cooling [79].

Putra et al. compared the performance of battery thermal management for EVs considering that heat pipe cooling was integrated with the two types of phase change materials. The heat pipe cooling with beeswax and Rubitherm RT 44 HC type phase change materials show a reduction of the battery's surface temperature by 31.9 °C and 33.2 °C, respectively, compared with passive cooling. The RT 44 HC has been suggested as an optimal phase change material for battery thermal management, since its melting point is within the battery temperature range and uses latent heat to store thermal energy. In contrast, beeswax phase change material can only use its sensible heat within the battery′s operating temperature range [83]. Nofal et al. developed phase change material composites consisting of expanded graphite and paraffin wax (PW/EG) using a 3D printing technique to improve the temperature uniformity, operating safety, and service life of Li-ion battery. The developed 3D-printing-based phase change materials achieve comparable efficiency of battery thermal management as a phase change material developed by conventional techniques with issues of complex and lenghty manufacturing processes and wastage of material [84].

Sun et al. proposed a new method to improve the low thermal conductivity of phase change material as well as improve the efficiency of battery thermal management for EVs by combining phase change material and fin in straight and arc shapes. The heat exchange area has been significantly improved with the additional design of the fin structure, which contributes to improving the efficiency of the heat dissipation process generated in the battery during operation. The combined method of phase change material and fin structure has greatly improved the safe operation time of battery from 54% to 90% compared to the standalone phase change material cooling system. The results also demonstrated that the battery thermal management system with the combination of phase change material and fin achieves increment in working time by 157%, 189%, and 238% at ambient temperatures of 20 °C, 30 °C, and 40 °C, respectively, compared with standalone phase change material cooling systems [85]. Chen et al. studied the method of phase change material cooling combined with a heat pipe to evaluate the performance of battery thermal management system for EVs. The combined heat pipe with phase change material cooling significantly reduces the temperature of the battery when compared to standalone heat pipe cooling. The maximum temperature of the battery reduces as the equivalent thermal conductivity of the phase change material improves for the proposed combined cooling. However, to enhance the temperature uniformity of the battery, the melting point temperature of the phase change material should be lower than the heat pipe's initial temperature for the combined cooling. An improvement of 30% is observed in the temperature uniformity of the battery pack after the optimization of the phase change material's thickness distribution [86]. Yang et al. proposed a new honeycomb-like thermal management system that integrates a hexagonal cooling plate with a bionic liquid mini-channel and a phase change material to improve the cooling performance of cylindrical Li-ion batteries. The proposed hexagonal cooling-plate-based thermal management system reduces the maximum temperature, temperature difference, and pressure drop for the battery module by 0.36 K, 2.3 K, and 4.37 Pa, respectively, compared to the rectangular cooling-plate-based thermal management system. The suggested hybrid cooling maintains the maximum temperature, temperature difference, and pressure drop for the battery module at 309.15 K, 3.8 K, and 11.95 Pa, respectively, under a discharge current of 32.2 A. The back propagation neural network is developed to predict the inlet flow rate in the case of proposed hybrid cooling according to the driving cycle and ambient conditions for which the maximum temperature and temperature difference of the battery module is maintained at 312.0 K and 3.5 K, respectively [87].

Youssef et al. proposed a phase change material with jute fiber cooling to improve thermal performance, energy saving, weight reduction, and environmental sustainability of battery thermal management systems in EVs. The maximum temperatures of the battery for no-cooling, phase change material cooling, and phase change material with jute fiber cooling are 47.27 °C, 41.06 °C, and 36.29 °C, respectively [88].

Fan et al. proposed a new method of battery thermal management by combining phase change material and multistage Tesla valve liquid cooling. The proposed combined cooling system can maintain the peak temperature, temperature uniformity, and pressure drop for the battery at 33.12 °C, 1.5 °C, and 647.8 Pa, respectively. Furthermore, the peak temperature and temperature uniformity are constrained within 39.53 °C and 2.6 °C, respectively, under high discharge conditions using phase change material with multistage Tesla valve liquid cooling. The energy consumption reduces by 79.9% for the proposed combined cooling compared to the phase change material-based linear channel cooling plate [13]. Wang et al. presented a new design for the thermal management system of a cylindrical battery using a combination of phase change material and a wavy microchannel cold plate as shown in Figure 5. The heat storage capacity of the proposed combined cooling system could be improved by increasing the thickness and height of the phase change material. The temperature distributions for combined phase change material with wavy microchannel cold plate cooling and wavy microchannel cold plate cooling are shown in Figure 6. The combined phase change material with wavy microchannel cold plate cooling shows that the maximum temperature and temperature uniformity of the battery is lower by 2.3 K and 0.5 K, respectively when compared to wavy microchannel cold plate cooling. In addition, the weight of phase change material with the wavy microchannel cold plate cooling system is 45% lower than the wavy microchannel cold plate cooling system [14]. Yang et al. proposed combined cooling strategy comprising phase change material/aluminum foam composite with parallel Z-style liquid cooling channels for battery thermal management system in EVs. Compared with the baseline cold plate design, the hybrid cold plate design can reduce the total weight of the system by up to 53% because the phase change material density is much lighter than that of the aluminum metal. Compared to the baseline design, the phase change material with D1 cold plate design can reduce the total power consumption by more than 90% and 50% at battery discharge rates of 1C and 2C, respectively. However, at a discharge rate of 3C, the cooling performance of phase change material with D1 cold plate design degrades. Hybrid phase change material with D1 cold plate design is beneficial only in case the heat generation rate of the battery pack is low. In contrast, hybrid phase change material with a D8 cooling plate design provides an excellent cooling performance improvement even when operating at high discharge rates. Compared to the baseline design, the hybrid phase change material with D8 cold plate design can reduce the total energy consumption by more than 50% and 85% at battery discharge rates of 2C and 3C, respectively. It is concluded that hybrid phase change material with a D8 cold plate design improves the cooling efficiency of Li-ion batteries when operating at high discharge rates [89].

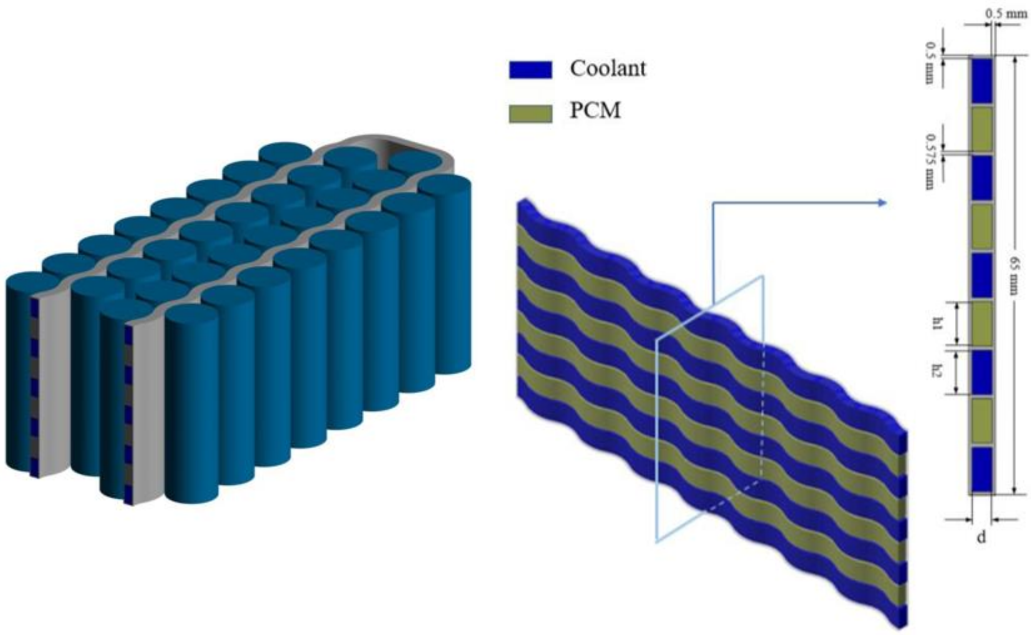

Figure 5. Configuration of battery thermal management with combination of phase change material and wavy microchannel cold plate cooling [14].

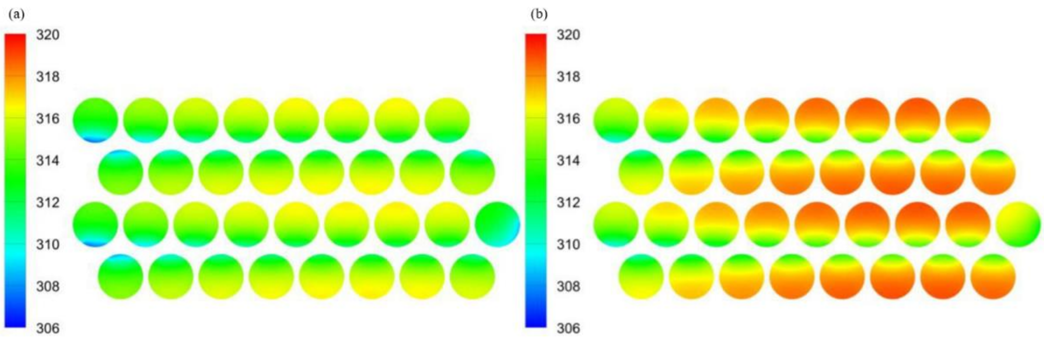

Figure 6. Temperature distributions for (**a**) combined phase change material with wavy microchannel cold plate cooling and (**b**) wavy microchannel cold plate cooling [14].

The performance of phase change material cooling is superior until the point at which the battery temperature reaches the melting temperature, beyond this point the performance of phase change material cooling degrades. The thermal conductivity of phase change materials is very low, hence the heat transfer characteristics of corresponding cooling is poor. To improve the heat transfer efficiency of phase change material cooling, it needs to be added with additives or combined with other cooling techniques which make it complex and expensive. Therefore, despite significant research being conducted on phase change material cooling, the question arises as to its practical feasibility for commercial battery thermal management systems. To find a solution to this question, increasing research has been reported on direct liquid cooling for battery thermal management.

4.2. Direct Liquid Cooling

Zhoujian et al. studied a battery thermal management system with direct liquid cooling using NOVEC 7000 coolant. The proposed cooling system provides outstanding thermal management efficiency for battery, with further maximum temperature of the battery's surface, reducing as the flow rate of coolant increases. During cyclic charging/discharging, the maximum battery surface temperature is controlled between 34 °C and 36 °C due to boiling of the NOVEC 7000 coolant [90].

Jilte et al. compared a liquid-filled battery cooling system and a liquid-circulated battery cooling system to propose an effective battery management system. The liquid-filled battery cooling system is suitable for low ambient temperature conditions and when the battery operates at a moderate discharge rate (2C). Whereas, the battery can operate at higher discharge rates with the maximum temperature maintained within safe limits using a liquid-circulated battery cooling system. The liquid-filled battery cooling system is more cost-effective than the liquid-circulated battery cooling system because it does not have components such as heat exchangers and liquid circulation pumps. However, battery temperature uniformity is better in the liquid-circulated battery cooling system [91].

Zhou et al. proposed heat-pipe-based phase change liquid cooling to improve performance of the battery's thermal management system and control its thermal runaway. The maximum temperature and temperature difference of battery are maintained at 47 ± 1 °C and 2.1 °C, respectively, for the proposed hybrid cooling under high discharge rates and high-power cycles. Under thermal runaway conditions, the hybrid cooling effectively prevents heat propagation with a maximum cell temperature below 185 °C and stable above 14 °C for 14 s. The effectiveness of phase change liquid cooling for battery cells with overcharging conditions is shown in Figure 7 [92]. Sundin et al. evaluated the thermal management performance of batteries with single-phase liquid immersion cooling as shown in Figure 8. Immersion cooling with AmpCool AC-100 dielectric coolant maintains the average temperature of the cell at 22.5 °C, 6.2 °C lower than the temperature of the cell cooled by forced air convection [93]. Bhattacharjee et al. optimized immersion cooling-based thermal management system for Li-ion battery stack. The maximum temperature of the battery stack is 49.76 °C in case of air cooling which drops to 27.43 °C with a reduction of 44.87% in case of immersion cooling under a 2C discharge rate [94]. Hong et al. conducted a study to compare the cooling efficiency of direct two-phase refrigerant cooling with conventional liquid cooling for batteries in EVs. Direct two-phase refrigerant cooling controlled the maximum cell temperature below 45 °C even under extreme environmental conditions, whereas liquid cooling exceeded the limit under normal environmental conditions. During battery aging, compared with liquid cooling, direct two-phase refrigerant cooling provided 16.1% higher battery capacity and 15.0% lower internal resistance under harsh environmental conditions. Compared with liquid cooling, direct two-phase refrigerant cooling reduced the weight of the cooling module by up to 56% due to its compact structure with mini channels [95]. Pulugundla et al. enabled the submerged cooling of 21,700 cylindrical cell which allows direct heat transfer to a flowing dielectric coolant. The submerged-cell cooling method has a lower overall thermal resistance, resulting in a high heat transfer efficiency and a positive impact on the temperature profile of the battery cell. Furthermore, the direct contact of the flowing dielectric coolant with 90% of the outer cell surface leads to a decrease in the thermal gradient in vertical direction of the cell [96]. Wang et al. employed HFE 7000 dielectric fluid for direct liquid cooling of battery in EVs. The maximum temperature of battery module is maintained at 35.10 °C under 5C discharge rate by a forced convection heat transfer of dielectric fluid through a single phase mode. The temperature uniformity of the battery module with direct liquid cooling is improved by a heat transfer of dielectric fluid through nucleate boiling [97].

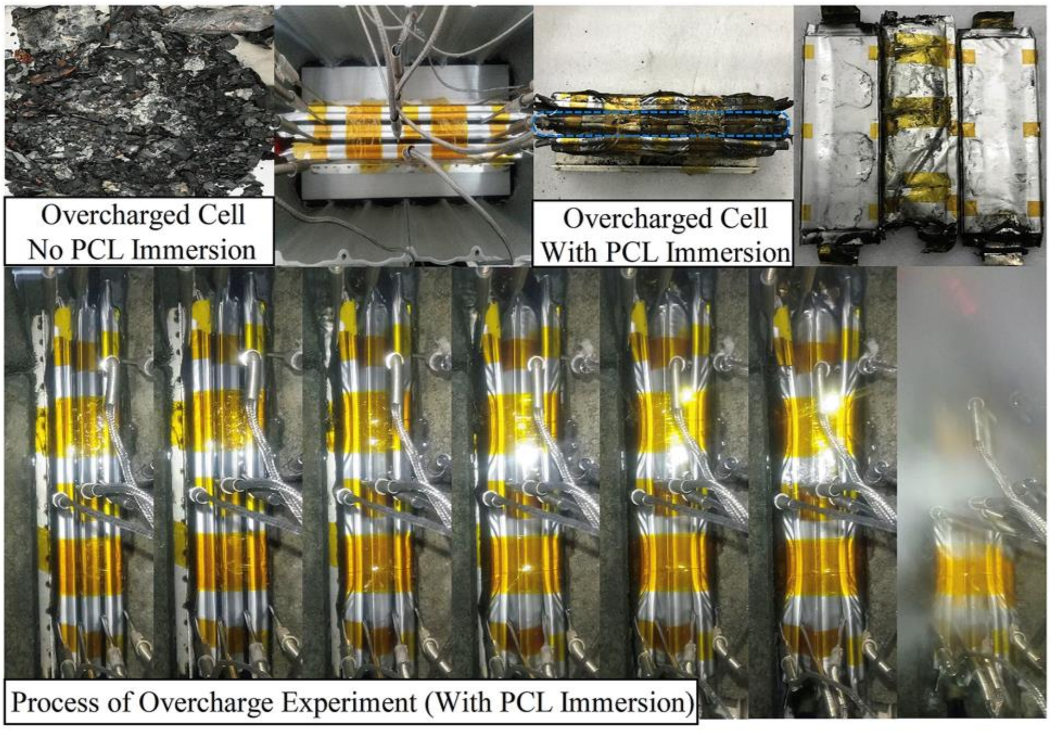

Figure 7. Effectiveness of phase change liquid cooling for battery cells with overcharging condition [92].

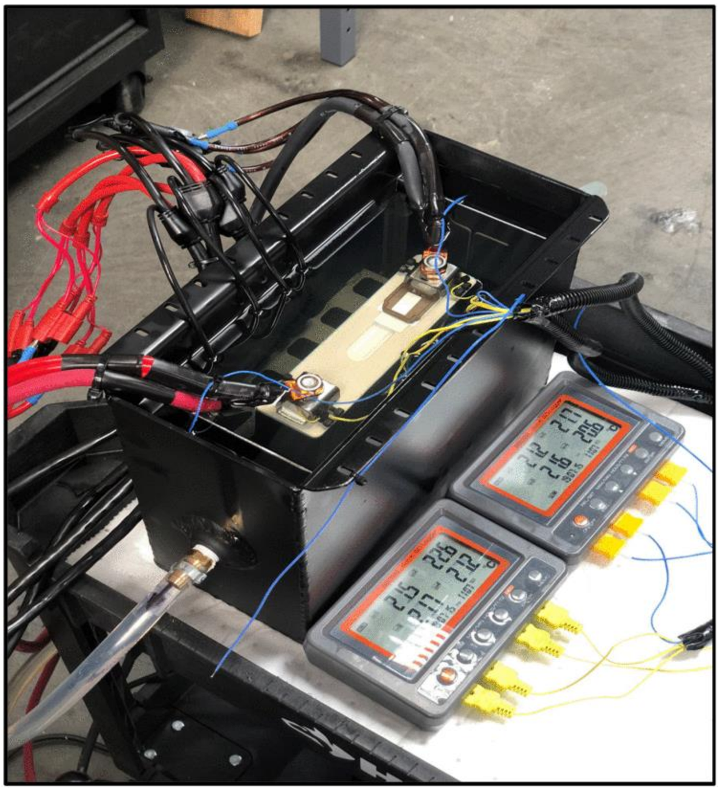

Figure 8. Test set-up for battery immersion cooling [93].

Patil et al. developed dielectric fluid immersion with tab air cooling as shown in Figure 9 for thermal management of Li-ion battery which reduces the maximum temperature of positive tab by 46.8% compared to natural convection cooling at 3C discharge rate.

The proposed cooling maintains the maximum temperature of the battery pack within 40 °C at 3C and 5C discharge rates with corresponding pumping powers of 6.52 W and 81.5 W. Dielectric fluid immersion with tab air cooling improves the battery thermal performance by 9.3% superior to water/ethylene glycol cooling. Under thermal abuse conditions, the dielectric fluid immersion with tab air cooling restricts the peak cell temperature to 341.7 °C, as shown in Figure 10 [98]. Tan et al. investigated direct liquid cooling based on a hydrofluoroether (HFE-6120) coolant for the thermal management of fast-charging battery packs. The maximum temperature rise, maximum temperature difference, and temperature standard deviation of direct liquid cooling are lower than air-cooling by 96.5%, 98.7%, and 97.0%, respectively. The cooling parameters improve with a rise in energy consumption as the flow rate and height of the flow channel increase [99]. Dubey et al. compared the thermal management performance of a cylindrical Li-ion battery module with immersion cooling and cold plate cooling. Immersion cooling has 2.5–3 times higher thermal conductance than cold-plate cooling. In addition, with different coolant flow rates, immersion cooling displays a 15–25 times lower pressure drop than cold plate cooling. At a lower discharge rate of 0.5C, the difference in the peak temperature of the battery for both cooling strategies was only 2 °C. However, immersion cooling showed a greater improvement in the thermal performance of the battery than the cold plate cooling at higher discharge rates [100].

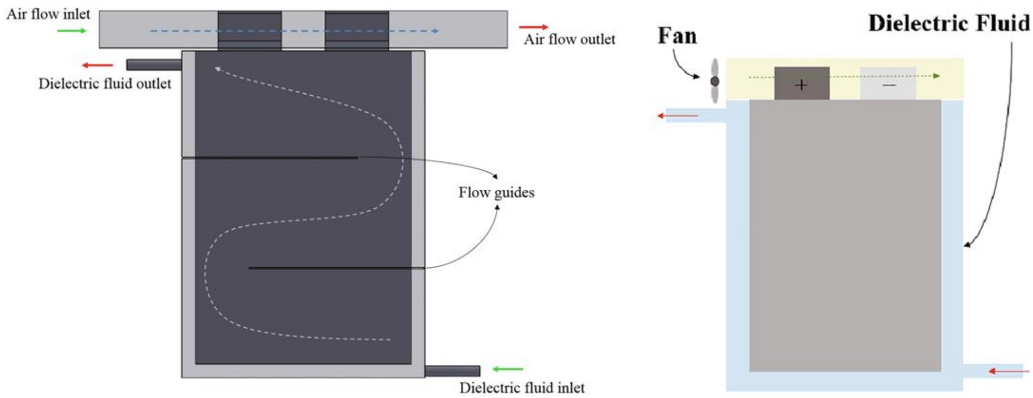

Figure 9. Proposed dielectric fluid immersion with tab cooling for battery cell and module [98].

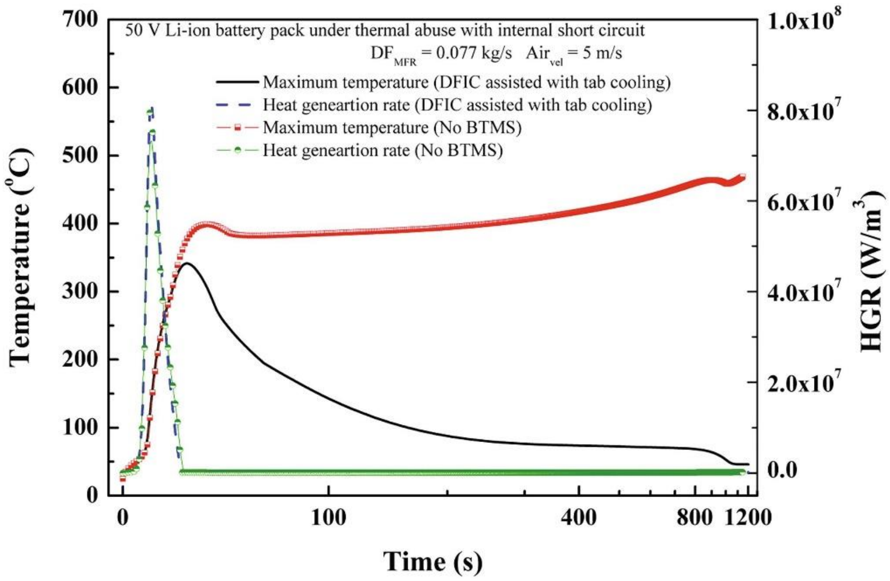

Figure 10. Elimination of thermal runaway propagation using proposed cooling [98].

Solai et al. proposed a numerical model to simulate heat transfer and electric performances of Li-ion battery packs with immersion cooling. The temperature, voltage, current, and state of health are evaluated as performance parameters for battery packs with immersion cooling. The sensitivity analysis shows that the SOH is the most influential parameter for the voltage of the battery pack and internal resistance has a considerable impact on the maximum temperature of a battery pack [101]. Li et al. conducted an experimental study to cool 18,650 Li-ion batteries by immersion with SF33 liquid under high discharge rate conditions. Under the 4C discharge rate, the temperature rises of 4.97 °C and 14.06 °C are observed for immersion cooling with SF33 liquid and forced air cooling, respectively. The maximum temperature of the battery is maintained at 34.5 °C at a 7C discharge rate for immersion cooling due to a significant increase in heat transfer coefficient as the SF33 liquid transits from single phase to two phase [102]. Wu et al. immersed Li-ion batteries in silicone oil, which is flowing, to improve safety and performance. Direct liquid cooling has the mass and volume integration ratio of the battery pack as high as 91% and 72%, respectively; 1.1 and 1.5 times that of indirect liquid cooling with the same envelope space. The maximum temperature rise and maximum temperature difference of the battery with direct liquid cooling are only 20–30% compared to that with indirect liquid cooling. The operating temperature range of the cells in the battery pack is maintained between 17.5–32.8 °C, and the temperature difference is less than 8.8 °C at 1C discharge for direct liquid cooling [103]. Liu et al. conducted a study on the battery thermal management system using static and circulating immersion cooling with transformer oil as coolant. The maximum temperature of battery is maintained within 37.35 °C for static immersion cooling which is 33% lower than air cooling. In addition, the circulating immersion cooling maintains the maximum temperature of battery within 35 °C. The temperature differences in case of static and circulating immersion cooling are observed as 3 °C and 1.5 °C, respectively. The cooling performance of the battery with circulating immersion cooling improves with the increase in flow rate of coolant. However, the flow rate of 15 mL/min is the optimum point [104]. Ezeiza et al. demonstrated a direct contact liquid cooling strategy to evaluate the maximum temperature and temperature difference of large-scale Li-ion pouch cells. The developed direct contact liquid cooling configuration with flow pattern for battery cell and module is shown in Figure 11. The maximum temperature of the battery cell is maintained at a stable 30 °C for direct liquid cooling despite the decrease in power consumption from 58.9 mW to 2.4 mW. The direct liquid cooling reduces the maximum temperature from 41.68 °C to 32.58 °C and the temperature difference from 5.71 °C to 0.36 °C, in comparison to indirect liquid cooling. The maximum temperature and temperature difference of the cell were stabilized below 38 °C and 1.3 °C, respectively, under 2C and 3C discharge rates using direct liquid cooling [105]. Wang et al. concluded that the maximum temperature of the battery module reduced from 59 °C to 40 °C (32.2%) and the highest temperature uniformity of the battery module decreased from 5 °C to 2 °C (75.3%) using liquid immersion cooling [106]. Li et al. conducted three-dimensional thermal simulations to investigate the cooling performance of a 54 V Li-ion battery pack with indirect liquid cooling and direct liquid cooling under rapid discharge conditions. The indirect liquid cooling results in a maximum temperature over 100 °C and a temperature difference of 28 °C under a 10C discharge rate. However, direct liquid cooling using HFE-7000 coolant can maintain the maximum temperature of the battery pack at 65 °C and below 35 °C in the case of single-phase and two-phase modes, respectively, under a 10C discharge rate [107]. Jithin et al. compared the cooling efficiency of single-phase liquid immersion cooling for Li-ion batteries considering different dielectric fluids. Mineral oil and engineered fluid exhibit a temperature rise of 6.1 °C and 5.2 °C, respectively, at a discharge rate of 2C, however, engineered fluid consumes 76.43% less power. Therefore, engineered fluid may be preferred over mineral oils due to their lower viscosity values. In addition, deionized water is more effective at maintaining a temperature rise below 2.2 °C at a discharge rate of 3C with a low energy consumption of 0.52 mW [108].

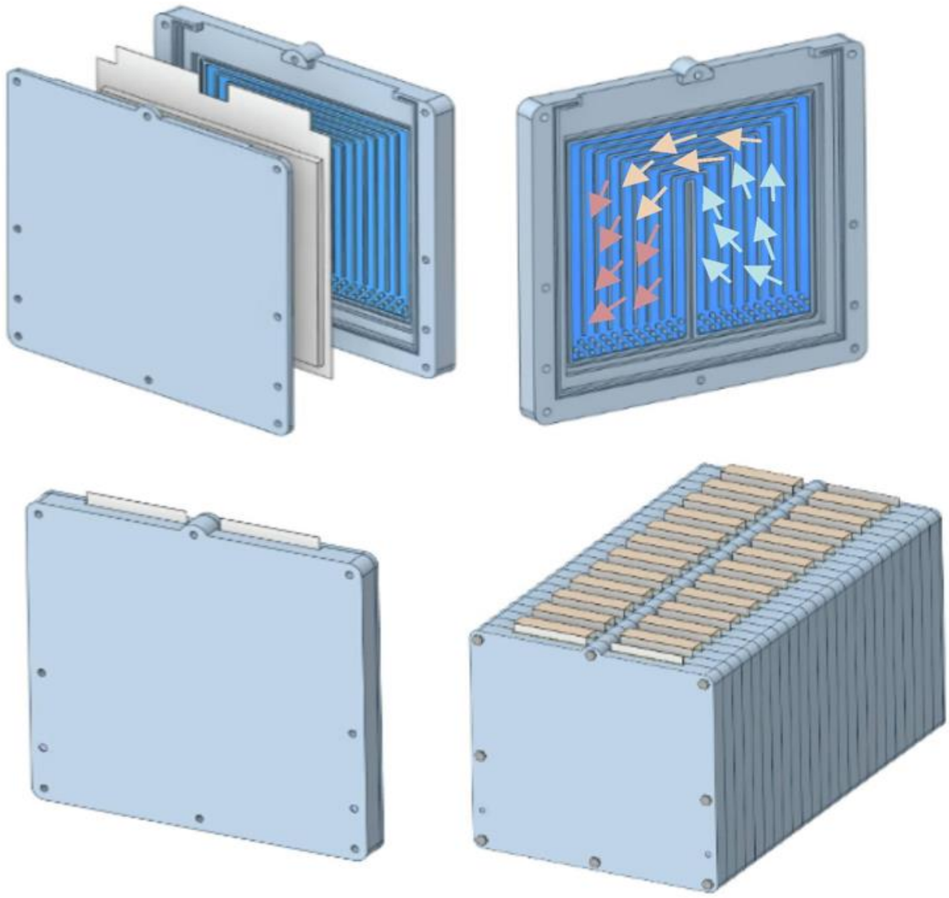

Figure 11. Developed direct contact liquid cooling configuration with flow pattern for battery cell and module [105].

Le et al. proposed the manifold immersion cooling structure for the thermal management of the battery. The maximum temperature, bulk temperature non-uniformity and surface temperature non-uniformity of battery pack are achieved as 35.06 °C, 6.66 °C, and 3.52 °C, respectively for the optimized manifold immersion cooling structure at a 5C discharge rate [109]. Liu et al. researched an immersion cooling system subjected to static and flowing mineral oil to investigate the thermal behavior of a battery. The battery maximum temperature is controlled within 35 °C and 30 °C for the immersion cooling system with an oil flow rate of 5 mL/min and 15 mL/min, respectively, under a 4C discharge rate [110]. Ezeiza et al. conducted a numerical study to optimize the parameters of direct liquid cooling for a large-scale Li-ion pouch cell. The input parameters of the fluid height, number of cooling channels, number of distributors, and flow rate are optimized to determine the optimal thermal performance of the battery. The battery cell temperature comparison for direct liquid cooling with various structures of distributors is shown in Figure 12. The optimal values of maximum temperature, temperature uniformity, volumetric energy density, and power consumption are evaluated as 27.72 °C, 0.65 °C, 279.7 Wh/L, and 0.11 W, respectively, based on the conducted optimization [111]. Giammichele et al. conducted an experimental study to evaluate the cooling efficiency of a 18,650 battery with low-boiling dielectric immersion. When coolant is at boiling point, it experiences a change of phase near the battery surface and, thus, this results in a higher convective heat transfer coefficient. The greater amounts of heat absorbed during the change of phase of the coolant in the case of immersion cooling shows an almost constant battery surface temperature [112]. Williams et al. conducted an experimental study to evaluate the thermal management performance of cylindrical Li-ion battery cells with single-phase and two-phase dielectric fluid immersion cooling. The battery temperature rise is 1.64 °C in the case of two-phase immersion cooling, which increased to 6.84 °C in the case of single-phase immersion cooling under a 4C discharge rate. With different discharge rates, the two-phase immersion cooling demonstrates an outstanding cooling performance for the battery [113]. Han et al. conducted an experimental study to investigate the discharge and heat-transfer characteristics of a Li-ion battery that is directly cooled by dielectric fluid. At the discharge rate of 4C, the heat transfer coefficient is significantly improved from 1109.02 W/m^{2}K to 2884.25 W/m^{2}K as the coolant volume flow rate increases from 400 mL/min to 1000 mL/min. Under the same discharge rate, the battery average temperature rises from 38.94 °C to 58.06 °C owing to a decrease in the heat-transfer coefficient from 2290.19 W/m^{2}K to 1639.79 W/m^{2}K with an increase in coolant inlet temperature from 15 °C to 35 °C [114]. Zhou et al. proposed a battery thermal management system by immersing Li-ion cells in non-conductive dimethyl silicone oil. At a 3C discharge, flowing immersion cooling can significantly reduce the maximum temperature of the cell and the temperature of the tabs even at a flow rate of 1 mm/s when compared to natural cooling and stationary immersion cooling. However, both stationary immersion cooling and flowing immersion cooling at 1 mm/s show an increased maximum temperature difference of the cell. The maximum temperature and temperature difference of the cell can be significantly improved by increasing the flow rate and specific heat capacity of the coolant within a certain range. Increased coolant thermal conductivity can reduce the maximum temperature of the cell but has a negligible effect on the maximum temperature difference. The viscosity of the coolant has no influence on the temperature of the cell. The pressure drop of the coolant varies with the flow rate and viscosity of the coolant. The pressure drop is unaffected by the specific heat capacity and thermal conductivity of the coolant [115]. Xin et al. conducted a numerical analysis to compare the cooling performance of the battery with single-phase immersion cooling considering different flow types and directions. Compared with static-flow immersion cooling, forced-flow immersion cooling significantly reduces the maximum temperature on the battery surface and improves temperature uniformity. The inlet and outlet fluid flow in the YZ plane for immersion cooling has a low-temperature rise and the best temperature uniformity of the battery compared to other designs. The best fluid flow structure in the YZ plane with baffles for immersion reduces the maximum temperature and temperature difference of the battery by 8 °C and 15 °C, respectively, compared to other designs under a 5C discharge rate [116]. Luo et al. conducted an experimental study to evaluate the cooling performance of immersion cooling using water for the battery. A special sealing structure is designed to prevent contact between water and the battery's electrodes. The proposed water-based immersion cooling maintains the battery's temperature at below 50 °C with a small flow rate of 200 mL/min at a discharge rate of 3C. At a discharge rate of 2C, the maximum temperature difference of the battery pack drops below 5 °C when the cooling water flow rate increases to 500 mL/min. It is also suggested that adding a buffer structure at the inlet/outlet could reduce the negative effect of turbulent flow and improve the temperature uniformity of the battery pack. In addition, the temperature difference of the battery pack can be improved by designing multiple inlets and outlets and crossflow [117]. Guo et al. proposed a direct contact liquid-cooling system with multichannel for the thermal management of Li-ion battery modules. At a discharge rate of 3C, the maximum temperature of the battery can be maintained below 36 °C and the temperature difference of the battery is controlled at 0.65 °C through the proposed cooling system. In addition, the accessory weight ratio of the battery module is also reduced to 10.25% [118]. Ho et al. conducted an experimental study on batteries with immersion cooling using a mixture of mineral oil and graphene. At discharge rates of 1C, 2C, 3C, and 4C, the 0.025 wt% graphene-based mineral oil immersion cooling shows the battery's temperature is 0.2–0.6 °C lower than mineral oil immersion cooling [119].

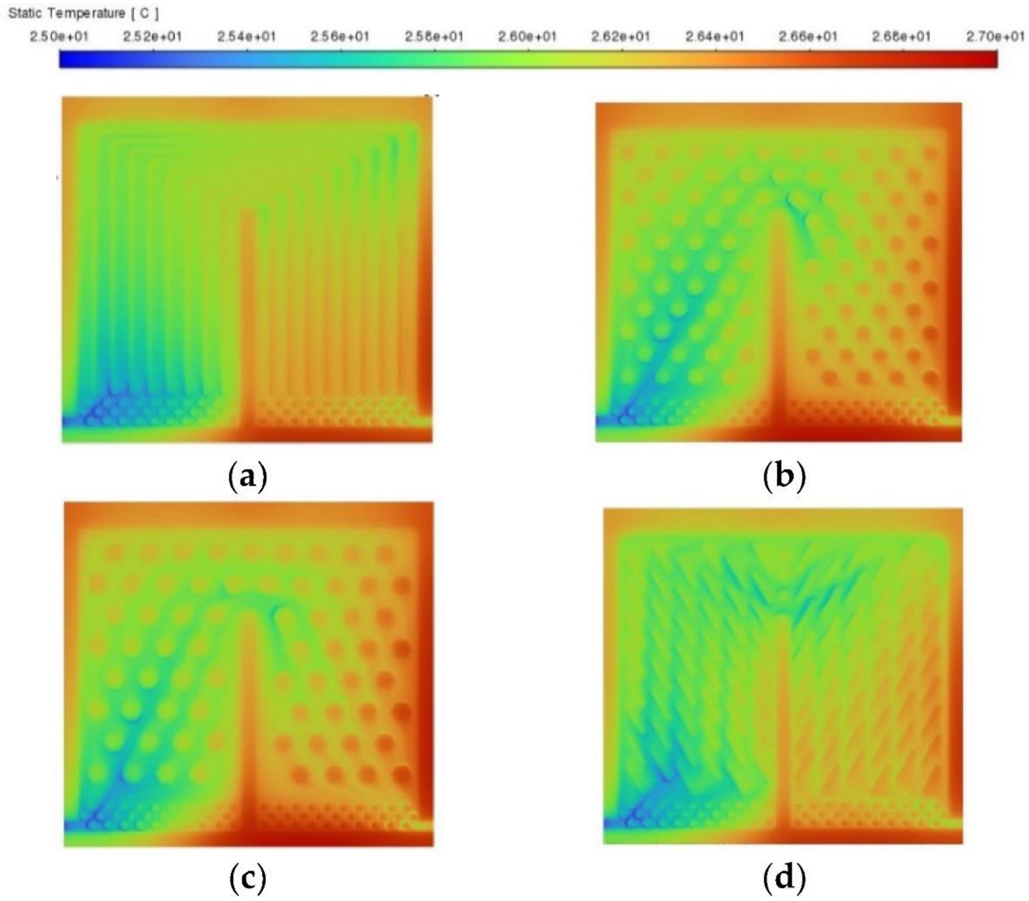

Figure 12. Battery cell temperature comparison for direct liquid cooling with (**a**) U-shape distributors (**b**) convex distributors (**c**) honeycomb distributors and (**d**) airfoil distributors [111].

Sun et al. developed an optimized simulation model to improve the thermal performance of a cylindrical Li-ion 21,700 battery with mineral oil immersion cooling. The flow rate of mineral oil should be increased as the resistance of the battery cell increases in order to maintain the base temperature. The flow velocity of mineral oil was adjusted to 0.05 m/s and 0.12 m/s for battery cell internal resistances of 50 mΩ and 75 mΩ, respectively, at a discharge rate of 2C [120]. Wang et al. experimentally studied the Li-ion batteries with immersion phase change cooling using mixed refrigerant R1233ZD(E)/Ethanol to improve the temperature uniformity of the battery module and the cooling performance of battery thermal management systems in EVs. The proposed cooling improves the temperature uniformity of the battery up to 57% and reduces the temperature rise of the battery to 14.8% with a rise in coolant flow rate from 652 mL/min to 1086 mL/min [121]. Satyanarayana et al. experimentally investigated the battery cooling performance for direct liquid cooling with mineral oil and therminol oil as coolants under different discharge rates. The maximum temperature of the battery for forced air cooling, immersion cooling with thermal oil, and immersion cooling with mineral oil are lower by 43.83%, 49.17%, and 51.54%, respectively, compared to natural convection cooling at a 3C discharge rate. The comparison of the maximum temperature and temperature difference of the battery for immersion cooling with different cooling oils is depicted in Figure 13 [122]. Li et al. proposed FS49 liquid immersion cooling to improve the thermal performance of a cylindrical Li-ion battery module under fast charging conditions. The liquid immersion cooling shows the maximum temperature of the battery lower by 7.7 °C and 19.6 °C, and energy consumption lower by 85.6% and 59.6% when compared to forced-air cooling at discharge rates of 2C and 3C, respectively [123]. Wang et al. investigated the thermal management of a battery immersed in stationary fluid in combination with direct cooling tubes. The proposed cooling enables an extended operation time with a temperature limit of 35 °C which is 150.3% and 45.7% higher compared to the natural convection and immersion cooling, respectively. The thermal resistance between immersion fluid and ambient is 6.7 K/W, which is reduced to 0.3 K/W for heat transfer between immersion fluid and direct cooling tubes [124]. Li et al. experimentally evaluated the cooling performance of a cylindrical Li-ion battery with reciprocating liquid immersion cooling. The reciprocating immersion cooling restricts the battery maximum temperature at 50 °C during fast-charging [125]. Koster et al. compared cooling performance of a 18,650 battery pack with air cooling and immersion cooling. The immersion cooling shows temperature uniformity of the battery pack as 1.5 °C, which is 10 times higher in case of air cooling. In addition, the capacity of the battery pack is enhanced by 3.3% with immersion cooling after 600 cycles [126]. Goodarzi et al. conducted an experimental study to evaluate battery-cooling performance using a liquid-vapor phase change based on direct cooling. Under a 4C discharge rate, the maximum temperature and temperature uniformity of the battery pack are reduced from 71.2 °C to 40.5 °C and 11.6 °C to 2 °C, respectively, with immersion cooling compared to the no-cooling case [127]. Han et al. investigated the effect of various fin structures on the heat-transfer characteristics of a Li-ion battery module with dielectric fluid immersion cooling. Figure 14 shows various fin structures considered for dielectric fluid immersion cooling. The dielectric fluid immersion cooling system with triangular fin structure shows the lowest maximum temperature of the battery and superior value of performance evaluation criteria (combination of Nusselt number and pressure drop) compared to that with other fin structures. The battery module temperatures for dielectric fluid immersion cooling with various fin structures are shown in Figure 15. Furthermore, the triangular fin structure with the base length to height ratio (A/B) of 4.304 is suggested as the best configuration for dielectric fluid immersion cooling system which achieves the lowest maximum temperature and temperature difference of the battery as 35.07 °C and 7.95 °C, respectively [128]. Anisha et al. analyzed liquid cooling methods, namely direct/immersive liquid cooling and indirect liquid cooling, to improve the efficiency of battery thermal management systems in EVs. The liquid cooling method can improve the cooling efficiency up to 3500 times and save energy for the system up to 40% compared to the air-cooling method. Direct liquid cooling gives better cooling effect for battery and effectively prevents the risk of thermal runaway than indirect liquid cooling [129]. Celen conducted an experimental study to evaluate the thermal management efficiency of 20 Ah LiFePO4 pouch battery with single-phase immersion cooling using distilled water. At a discharge rate of 4C, the maximum temperature of the battery with 100% distilled water based immersion cooling is 33 °C, much lower than the air cooling method which shows the maximum temperature of the battery as 45 °C. The temperature non-uniformity of the battery for 100% immersion cooling is reduced by 4 °C, whereas the temperature non-uniformity of the battery is recorded as 11 °C and 12 °C for 50% immersion cooling and air cooling, respectively [130]. Choi et al. proposed a hybrid immersion-cooling structure with a pass partition and graphite fin to improve the thermal management performance of a battery module under fast charging and extreme conditions. Hydrofluoroether fluid exhibits the best battery cooling performance among dielectric fluids owing to its lowest viscosity. The bottom-to-top dielectric-fluid configuration provides better cooling for battery cells than the top-to-bottom fluid configuration. At a 3C charging rate, the proposed hybrid cooling structure reduces the pressure drop and energy consumption by 45.4% and 61.0%, respectively, and enables a better battery temperature profile than the baseline structure. In addition, the hybrid cooling structure maintains the maximum temperature and temperature difference of the battery lower by 6.7 °C and 3 °C than that of a conventional structure of the same weight [131]. Gu et al. conducted an experimental study to evaluate the battery cooling performance for immersion cooling with a mixture of nanocapsules and insulation oil. The battery temperature was reduced by up to 3.95 °C for immersion cooling with a mixture of nanocapsules and insulation oil compared to that with only insulation oil [132].

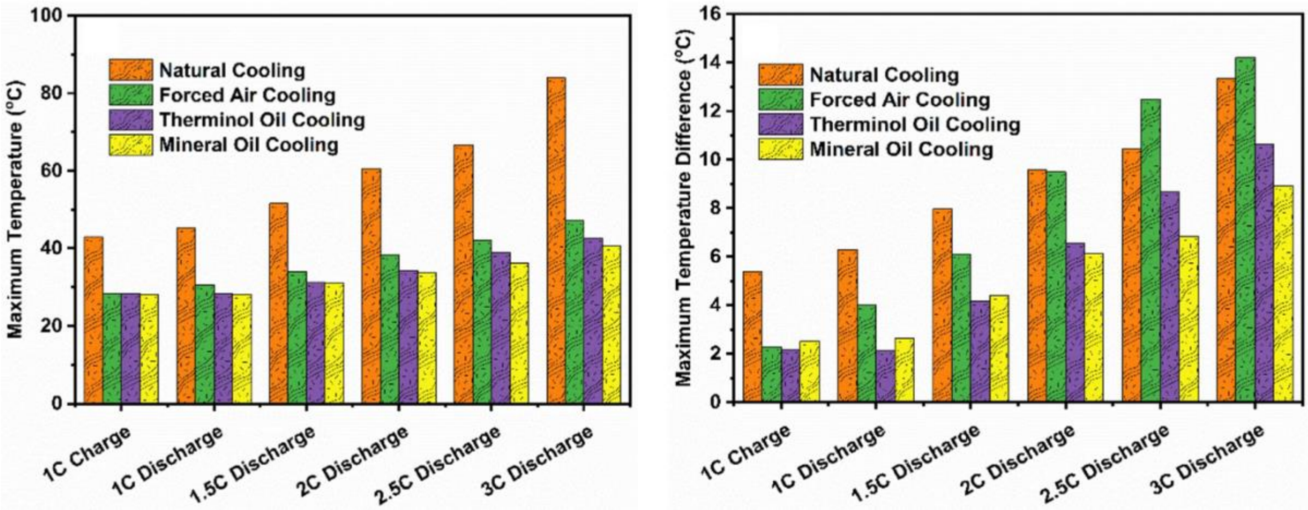

Figure 13. Comparison of maximum temperature and temperature difference of battery for immersion cooling with different cooling oils [122].

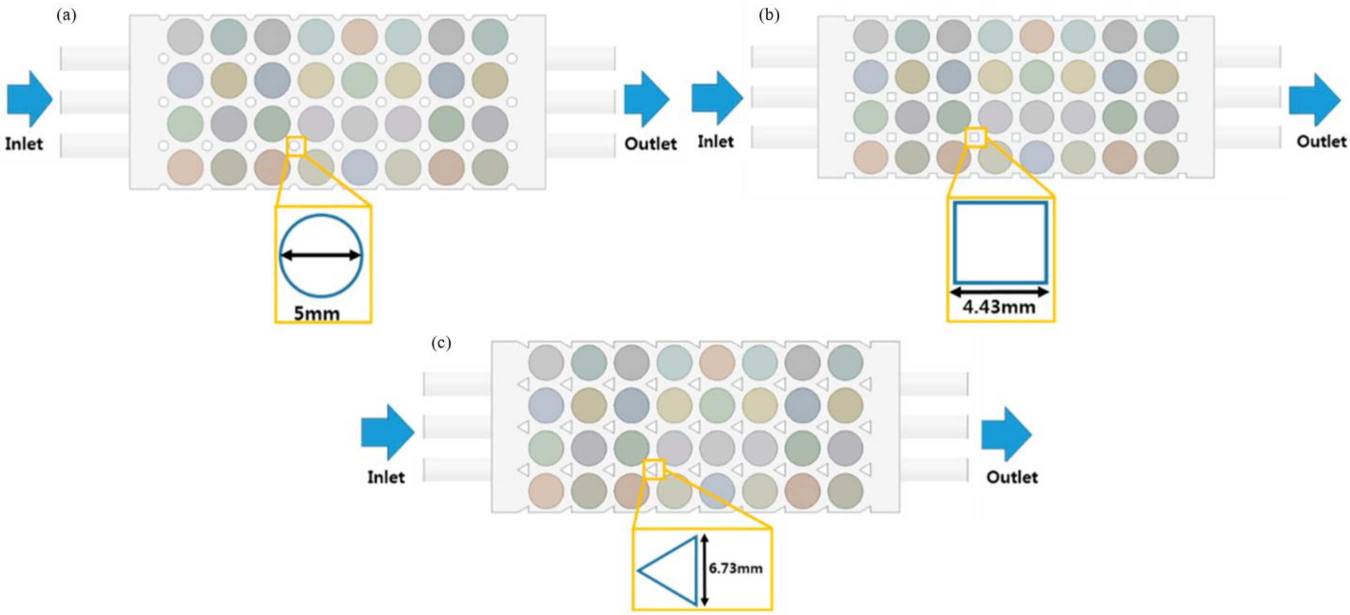

Figure 14. (**a**) Circular (**b**) rectangular and (**c**) triangular fin structures considered for dielectric fluid immersion cooling [128].

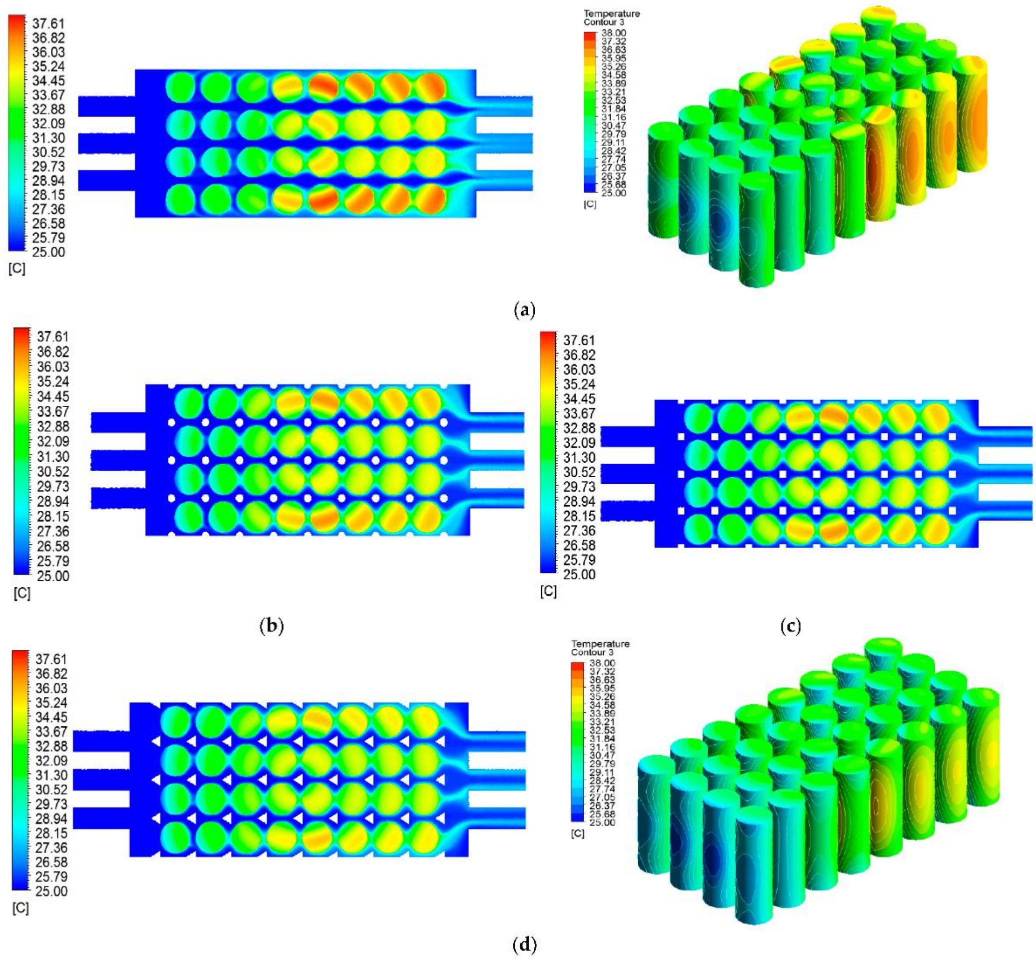

Figure 15. Battery module temperatures for dielectric fluid immersion cooling with (**a**) base (**b**) circular (**c**) rectangular and (**d**) triangular fin structures [128].

5. Summary and Recommendations

The current review summarizes recent research works over the span of 2018–2023 on advanced cooling strategies for battery thermal management systems in EVs. Research studies on air cooling and indirect liquid cooling, used as conventional techniques for battery thermal management, are briefly elaborated. After discussing the limitations of conventional cooling techniques, the advancements in phase change material cooling and direct liquid cooling used as advanced techniques for battery thermal management are comprehensively explained. Research studies about experiment and simulation works that evaluate the battery cooling performance based on phase change material cooling and direct liquid cooling are presented. The main findings and recommendations from the present review are highlighted as follows.

(a) In the early stages, air cooling with the advantages of simple structure, low cost, easy installation and maintenance, and no leakage issue was widely used for battery thermal management. However, the low thermal conductivity of the air makes it suitable only for battery thermal management with low heat dissipation requirements.

(b) Compared to air, liquids have a better thermal conductivity and higher specific heat capacity. Therefore, indirect liquid cooling demonstrated superior ability to control the maximum temperature and temperature distribution of the battery compared to air cooling. For large-scale battery thermal management, indirect liquid cooling is a more effective cooling strategy than air cooling. However, some concerns in particular for indirect liquid cooling such as complex structure, larger energy consumption, heavier overall weight, liquid leakage, and an increased thermal resistance between the battery cell and the coolant are obstacles to consider for future higher-capacity electric vehicle applications.

(c) From the extensive research conducted on air cooling and indirect liquid cooling for battery thermal management in EVs, it is observed that these commercial cooling techniques could not promise improved thermal management for future, high-capacity battery systems despite several modifications in design/structure and coolant type. There is a need to propose a suitable cooling strategy considering the target energy density of the EV battery which is expected to be attained in the future. Therefore, phase change material cooling and direct liquid cooling were recently investigated as an alternative to conventional, commercial cooling strategies with a vision to employ them in future generations of battery cooling systems.

(d) The heat dissipation efficiency of phase change material cooling is excellent as it uses a larger latent heat when the phase change occurs. The phase change material cooling provides an enhanced temperature uniformity for the battery when the battery's temperature approaches the melting point temperature of the phase change material. The addition of carbon materials or metal foam can greatly improve the thermal conductivity of phase change materials, which has a positive effect on the temperature uniformity of the battery pack. However, it is necessary to consider the balance between latent heat and conduction heat, filling density, pore size, and mass fraction to avoid affecting the natural convection of liquid phase change material.

(e) The performance of phase change material cooling decreases when the temperature of the battery is higher than its melting point temperature. The thermal conductivity of phase change material is low, which forces additives to improve heat dissipation performance. The control of temperature rise and temperature difference of the battery could be excellent for phase change material cooling when it is combined with a heat pipe, cold plate, microchannel cooling plate, fin structure, and liquid cooling. This hybrid battery thermal management system is bulky and impractical for long-term commercial applications.

(f) Direct liquid cooling eliminates the thermal resistance between the battery and the coolant and thus significantly enhances the heat dissipation efficiency. Furthermore, direct liquid cooling when employed with low boiling temperature coolant enables the benefit of two-phase cooling which has a superior heat transfer coefficient compared to single-phase direct liquid cooling and indirect liquid cooling. Therefore, irect liquid cooling can maintain the battery's maximum temperature and temperature uniformity under a permissible operating range under fast and high charging/discharging conditions and even in extreme conditions, it could prevent thermal runaway propagation effectively.

(g) There are several factors such as coolant type, coolant flow direction, flow rate, coolant immersion height, ambient temperature, and packing compartment pressure which have a strong impact on battery thermal characteristics with direct liquid cooling. The recommended coolants for immersion cooling are dielectric fluid, hydrofluoroethers, hydrocarbons, esters, mineral oils, silicone oils, and water-glycol mixtures, based on relevant properties such as viscosity, density, thermal conductivity, electrical conductivity, specific heat, boiling point/flash point and GWP.

(h) Based on this review of recent research studies and the points discussed above, it is expected that direct liquid cooling has the potential to be considered as an advanced cooling strategy for battery thermal management in next-generation EVs. However, to commercialize direct liquid cooling at a larger scale, some key issues such as complexity in evaporation and condensation modes of coolant, coolant flow distribution, higher pump loss with high viscosity coolants, high cost of coolants, increased fluid weight, and material compatibility need to be addressed. Therefore, comprehensive research is still needed to propose optimal solutions for Li-ion batteries with direct liquid cooling systems in future EVs.

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Nomenclature & Abbreviation

I	operating current (A)
$Q_{irreversible}$	reversible heat generation (W)
$Q_{reversible}$	reversible heat generation (W)
Q_{total}	total heat generation (W)
T	battery temperature (°C)
U	open circuit voltage (V)
V	operating voltage (V)
CO_2	carbon dioxide
C-rate	charging/discharging rate
EV	electric vehicle
HP	heat pipe
IC	internal combustion
Li-ion	lithium-ion
SOH	state of health

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