

REVIEW ARTICLE

Evaluation of liquid based battery thermal management system in electric vehicles; a review

Prem Kumar S.^{1,*} , Krishnappa G.B.² , Sanjay S.S.³ ¹Department of Mechanical Engineering, Seshadripuram Institute of Technology, Mysuru, Karnataka, 570001, India²Department of Mechanical Engineering, Vidyavardhaka College of Engineering, Mysuru, Karnataka, 570001, India³Department of Chemistry, RNS Institute of Technology, Bengaluru, Karnataka, 560098, India

Abstract

In an electric vehicle, a battery serves as the power source for its various operations. Lithium-ion batteries are preferred because of their excellent performance. A battery pack comprises multiple cells that undergo repeated charge-discharge cycles, resulting in temperature changes due to heat generation. The performance and longevity of the battery are sensitive to temperature variations. It is critical to maintain the pack temperature between 15°C and 45°C. In addition, the cell temperature gradient shall be limited to 5°C. In recent years, significant research in this field has led to the development of several innovative solutions. Among them, liquid-based thermal management systems have received considerable interest owing to their superior thermal control and their ability to meet the needs of today's electric vehicles. This article presents the latest developments in liquid-based thermal management techniques. A brief discussion of battery preheating strategies for cold climates is also presented.

Keywords: Battery cooling, thermal management, liquid-based battery cooling, battery preheating, li-ion battery

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1. Introduction

The majority of modern automobiles are still powered by petroleum-based fuels. However, the demand for vehicles requires additional use of these fuels, contributing significantly to air pollution [1]. As a result, urban areas often experience poor Air Quality Index (AQI), mainly due to vehicular emissions [2]. Vehicle exhaust pollutants also contribute to global warming, prompting regulatory agencies worldwide to adopt strict regulations. These include reducing the use of aged vehicles, increasing emission standards, and incorporating mass transportation system in a wider scale. Automobile sector is focusing on battery operated vehicles to cope with the challenges associated with conventional automobiles.

The core of an EV is its battery, which powers the vehicle's propulsion. Popular battery types include Lithium-ion (Li-ion), Nickel-metal hydride, Lead-acid, and Ultra-capacitor batteries [3-5]. However, Li-ion batteries offer better prospects in terms of high energy density, long lifespan, low self-discharge rates,

minimal memory effect, and higher circuit voltage [6-12]. These batteries are extensively employed in consumer electronics because of compact size [13], and they are increasingly adopted in EVs due to these benefits. EV battery pack comprises of various interconnected cells to produce necessary power for vehicle traction. The battery pack often undergoes repeated charging and discharging cycles. These cycle produces significant heat and induces temperature rise in the battery. Studies recommend maintaining the battery pack temperature between 15°C to 45°C [14-16], while some suggest a slightly higher range of 20°C to 55°C [17]. Additionally, cell temperature variations should ideally remain within 5°C [18-24].

The lower temperature decreases the rate of lithium-ion diffusion, results in poor discharge of ions and causes increase of internal independence [25]. The studies made in this regard depict that the battery capacity reduces with decreases in temperature [26, 27]. Further, a drop in performance is also observed at lower temperatures [28, 29]. Cellular chemical properties are affected by elevated temperatures. This results

*Corresponding Author

E-mail Address: kumar.prem000@gmail.com

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in thermal runaway— caused by mechanical, thermal, or electrical abuse— and is a significant safety concern in Li-ion battery packs [30-33]. Thermal runaway is the state of a battery in which the temperature rises continuously due to heat generated by chemical reactions [34]. At this stage, heat generation is significantly higher and also harmful gases may release [35]. Figure 1 depicts the chemical reactions that occur as a function of temperature. It is evident from Figure 1 that an increase in battery temperature triggers different chemical reactions that may result in melting of the separator, decomposition of the electrolyte and the cathode, and intercalation into the anode.

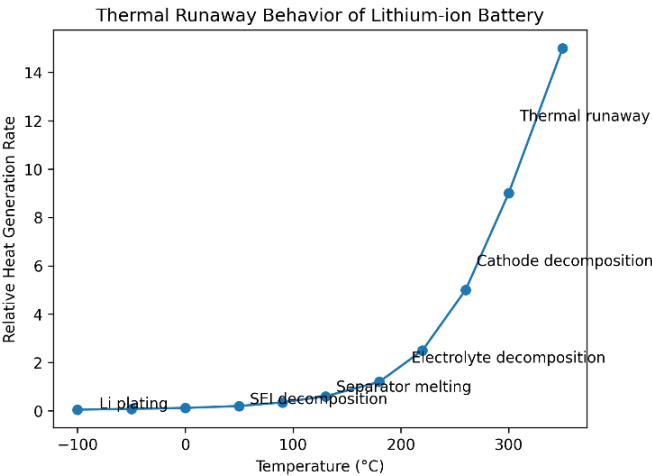


Figure 1. Effect of temperature on battery chemistry [Adopted from Panchal et al [36]

Battery Thermal Management System (BTMS) is required to limit the temperature of the battery pack within a preferred range to enhance the life. Existing methods are classified as air-based systems, liquid-assisted systems, phase-change material (PCM) methods, heat-pipe arrangements, and combined techniques.

An air-based system relies on ambient air circulation and is generally regarded as the most economical option among available cooling strategies [37, 38]. In fluid-assisted systems, water-based coolants are commonly employed for heat removal. Such systems can be operated via direct contact with cells or in an indirect configuration that uses intermediate channels. PCM-based techniques incorporate substances that absorb and release heat during phase transitions. These systems can provide better temperature uniformity than air- and fluid-based approaches. However, it is associated with challenges like leakage problems and poor thermal conductivity of PCM [39]. To enhance the heat transfer, carbon fiber is commonly incorporated into PCMs [40]. A heat-pipe approach removes heat from the battery pack through evaporation and condensation. The combined strategies integrate two or more of the above techniques to achieve improved performance. A detailed comparison of different approaches is provided in Table 1.

Table 1. Different cooling methods [41]

Method	Advantages	Challenges
Air cooling	• Easy to design • Low cost • Lower payload	• Low thermal conductivity of air • Poor temperature uniformity • Difficult to meet high heating loads
Liquid cooling (direct)	• Better thermal contact • Improved cooling performance • More temperature uniformity	• Prone to leakages and short-circuit
Liquid cooling (indirect)	• Liquids possess better thermal conductivity • Rate of heat transfer can be controlled by altering the flow and structural features	• System becomes more complex. Pumping power is necessary • Increase the significant load on the system
PCM Cooling	• No need of an auxiliary heat dissipation system • Better temperature uniformity • PCM acts as the insulator also	• The volume occupied by the PCM increases after the heat absorption • Low thermal conductivity • Cooling effect reduces during continuous cooling cycles
Hybrid	• Overall performance increases due to combined features • Easy to achieve system optimization	• Structure becomes complex. • Increases additional load on the vehicle • Combined system maintenance is difficult

Many current EV models have adopted liquid-based BTMS configurations. According to Sander Clerick et al. [42], the automotive sector is rapidly transferring from air-based cooling approaches to liquid based systems to meet the higher performance requirements in modern EVs. This paper discusses the latest developments in liquid-based battery thermal management in EVs and emphasizes important technological advances and prospective research opportunities.

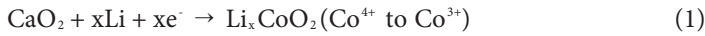
2. Heat generation mechanism

A Li-ion battery comprises a cathode and an anode, both submerged in an electrolytic solution. A separator is incorporated to prevent direct electrical contact between the electrodes. The electrons flow between the electrodes through an external circuit during the operation. Whereas, ions flow through the electrolyte [43]

Various chemical reactions occur during electron flow, generating substantial heat. Heat generation tends to be highly non-uniform, with higher concentrations near the electrodes, leading to greater temperature variations during discharge [44, 45]. The main electrochemical reactions taking place within the cell are as follows:

Discharging reactions,

Cathode,

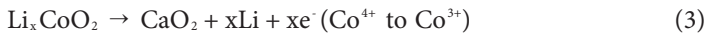


Anode,



Charging reactions,

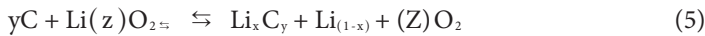
Cathode,



Anode,



Overall reaction,



The approximate values are $x = 0.5$ and $y = 6$. Z may be cobalt, nickel, or manganese.

In a battery, the primary sources of heat are irreversible Joule heating and reversible heat from electrochemical processes. Researchers have attempted to elucidate the mechanisms of heat generation in a battery pack. The heat generation in a battery pack was calculated using Equation (6) [46].

$$Q = Q_{ir} + Q_r = I^2 R_{in} - I T \frac{dE_o}{dT} \quad (6)$$

Where, I is the current, R_{in} is the internal resistance, T is the temperature and $\frac{dE_o}{dT}$ is the entropy coefficient.

Reversible heat is generated at both electrodes from entropy changes associated with chemical reactions. From 1C to 2C, its value initially increases but decreases at 2C [47]. This heat may be endothermic or exothermic, based on the depth of charge (DOC) [48]. It can be positive or negative, and over a complete cycle its value reaches a minimum. Therefore, reversible heat is often neglected in EVs [49]. Irreversible heat accounts for approximately 70% of total heat. The heat produced at various parts of the battery is highly non-uniform [50]. The pattern of heat generation is influenced by various factors such as charging and discharging conditions, and properties of electrode materials [51]. Shen et al. [52] studied a pouch type Li-ion battery pack with a capacity of 4.2 Ah. Their analysis indicates that the State of Health (SOH) decreases as the number of cycles increases. This reduces in capacity over time led to increased heat generation, which may lead to various side reactions. These reactions significantly influence battery aging. However, changes in OCV affect the

state of charge (SOC) and material properties. Frank Richter et al. [53] analyzed the aging influences the thermal conductivity of battery materials. It was inferred that electrolyte decomposition rates increase as the battery ages. This degradation reduces thermal conductivity, indicating the importance of maintaining adequate electrolyte levels for optimal thermal performance. The fluctuation of OCV can also be mitigate adequate electrolyte level [54].

As a Li-ion battery ages, the internal resistance of its components increases, causing a higher rate of heat generation [55–56]. A battery was fabricated from various materials. The interfaces between these materials exhibit contact resistance to electron flow. This interface resistance contributes significantly to heat generation, especially at junctions of the materials [57]. Figure 2 illustrates the microscopic view of the interface between the cathode and the current collector. To reduce this contact resistance and its thermal effects, improvements in fabrication techniques and selection of materials with lower thermal resistance are essential. Advanced models were developed to predict heat generation in Li-ion batteries. Liu et al. [58] employed a surface response method to correlate the effects of charge discharge cycles with temperature distribution. Similarly, Pan et al. [59] proposed a dynamic heat generation model derived from the experimental data. These studies depict that a battery is a complex assembly of materials whose thermal and electrochemical properties changes dynamically due to the chemical reactions caused by heat generation [60]. However, heat generation is highly nonuniform across the cell. Elevated temperatures near the electrodes during discharge further contribute to uneven distribution. Among the available models, electrochemical and thermal models have shown the highest accuracy in predicting battery behavior [61, 62]. Current models are still unable to precisely estimate heat generation and internal temperature profiles. Therefore, further research is needed to enhance model reliability.

3. Liquid cooling

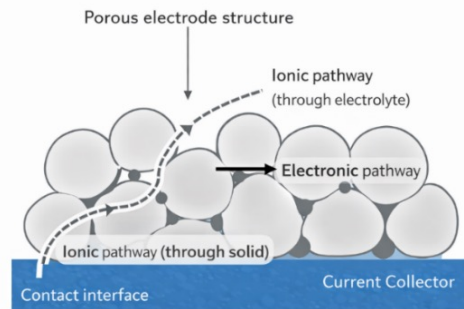


Figure 2. Microscopic view of material interface [From Kumar et al. [63], licensed under CC BY 4.0]

Liquid cooling provides higher performance and compactness than the air-based systems [64]. Both direct and indirect techniques can be used in this approach. Direct liquid cooling, which involves submerging the battery cells in a non-conductive fluid, improves heat dissipation from the battery. Indirect cooling is achieved by circulating a liquid over a cooling plate or structure that houses the cells, removing heat without direct immersion [65]. To combine the features of both approaches, hybrid systems have been developed in recent years. Additionally, passive cooling methods, such as PCMs, can be integrated into these systems. The direct approach is also called as immersion cooling [66, 67] is known for its simple design and higher rate of cooling. This technique uses a heat transfer fluid (HTF) to rapidly dissipate heat. For optimal performance, the HTF must possess favorable thermo-physical characteristics, while remaining non-reactive with the battery material [68]. Common coolants include water, oil, nano- fluid, boiling liquid, liquid metals and refrigerants [69,70]. Water is the most widely used cooling medium throughout the sections. The popular EV manufacturers Tesla and BYD incorporate water cooling in various models. Direct contact between water and a battery can cause a short circuit. Thus, indirect contact is achieved by incorporating cold plate, tubes and water jackets [71-73]. The studies made in this regard shown the satisfactory cooling performance [74, 75]. However, freezing of water under extremely low operating conditions poses a problem in water-cooling systems. The freezing of water can be prevented by adding antifreeze compounds such as ethylene glycol. The mixture of water and glycol (6:4) retains liquid state at extreme low temperature of about -45°C [76]. The oil coolant has superior thermophysical properties compared to water. Oil coolants can carry a large heat load. Mineral and synthetic oils are preferred for BTMS. However, oil cooling requires more pumping power than water cooling. Nanofluids provide higher thermal conductivity, enabling more rapid heat dissipation from the battery pack. Nano-fluids are prepared by adding nanoparticles into the coolants such as water and water-glycol mixture. Commonly used nanoparticles include silver, aluminum, nickel, and copper. These metals can also be used in the form of oxides, such as silver oxide, cupric oxide, aluminum oxide, and nickel oxide. However, Nano-fluids are costly and require complex system, make it difficult to maintain [77]. The study made by Jilte et al. [78] on Nano-fluid based BTMS depict that cooling performance was not significantly higher than the water cooling. Further studies are needed in this area. Liquid metals offer excellent cooling performance as they offer higher thermal conductivity [79, 80]. The liquid metal exhibits a heat transfer coefficient approximately three times that of water under similar conditions. In addition, liquid metals have lower viscosity than water [81]. A study conducted by Yang et al. [82] shown the liquid metal cooling had superior performance than water cooling in terms of cooling, temperature uniformity, and energy consumption. Liquids with low boiling temperatures also exhibit favorable properties for BTMS. Hirano et al. [83] made significant work in this regard. They employed Novec 7000 (boiling temperature 34°C) and Novec 649 (boiling temperature 39°C). From the experimental results it was inferred that the boiling liquids controlled the temperature within 35°C at 20C discharge rate. Also, cell temperature

difference was maintained at 1°C . A study made by An et al. [84] infer the similar results. Li et al. [85] tried to find the suitability of fluor-carbon based coolants for BTMS. The experimental results demonstrate that fluorocarbon-based coolants provide effective cooling for batteries. However, further research is required to establish the suitability of the liquid boiling technique for BTMS.

4. Direct cooling

In this technique, the working fluid establishes physical contact with the battery pack, which enhances the rate of heat transfer. However, safety and leakage are major concerns associated with this method. The preferred cooling medium is a dielectric fluid with superior chemical and thermo-physical properties [86, 87]. Luca Giammichele et al. [88] conducted a study by considering 18650 LiFePO₄ commercial scale battery under dielectric cooling. Figure 3 depicts the experimental setup employed for the study. The battery was submerged in a dielectric fluid, and T-type thermocouples were placed on the surface for continuous temperature measurement. The experimental observations were made at different discharge currents. The results demonstrate that direct immersion in the liquid—particularly when the liquid is near its boiling point—efficiently cools the battery. Nelson et al. [89] by using a battery pack made of 12 series connected cells. A 1-mm-wide cooling channel was provided at the centre. Experiments were conducted by flowing silicone oil through the cooling passage. The results suggest that silicone cooling is more efficient than air cooling. Sathyanarayana et al. [90] studied the performance of BTMS by employing terminal oil and mineral oil. The results showed that the mineral oil exhibited higher cooling rates than the terminal oil. This study found that mineral oil effectively controlled the battery's maximum temperature owing to its low viscosity. G. Karimi and A. R. Dehghan [91] developed lumped and flow network models to study the behavior of cooling fluids air, water and silicone oil. A pouch-type battery pack was considered for the analysis. The Simulation was done by varying the flow patterns such single- inlet multi- outlet and vice-versa. Results indicate that the three-inlet, single-outlet pattern exhibits improved performance. In addition, it reduces the required pumping power. Air-cooling performance was poor at the high discharge rate of 5C. The cooling performance of the silicone oil was satisfactory. However, it requires significant pumping power. Among the three cooling fluids, water demonstrated the best overall performance, even under high-discharge conditions, and exhibited lower pumping power consumption than the other fluids. Low-boiling liquids have been employed in recent years. These liquids can provide improved cooling performance.

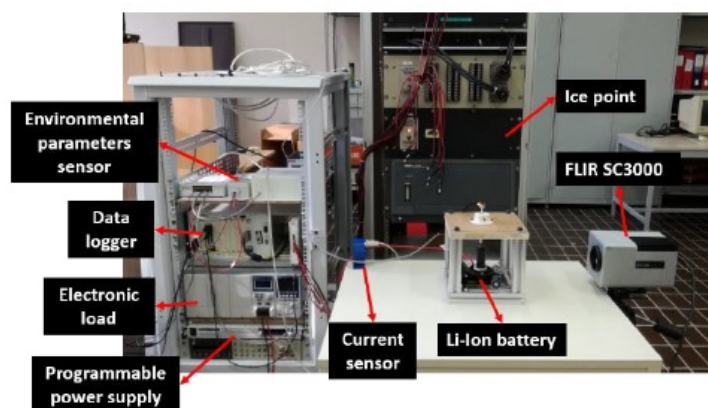


Figure 3. Experimental setup of dielectric cooling [From Giammichele et al. [88], licensed under CC BY 4.0]

Nan Wu [92] used NOVEC 7000 for cooling of large format Li-ion battery (20-Ah LiFePO₄). Experiments were conducted under both constant-voltage and constant-current conditions. Cooling performance was tested under static and flow conditions. The results depict that the temperature of the battery was maintained below 36 °C. In addition, satisfactory temperature uniformity of cell temperature was attained under static mode. However, prolonged coolant stagnation was a major drawback. Under flow conditions, rapid heat dissipation occurred. Heat dissipation was insufficient at higher flow rates. Finally, optimal performance was achieved by combining stagnant and intermittent flow modes.

M S Patel et al. [93] carried out the performance study on 50 V Li-ion battery packs by incorporating tab cooling. The dielectric liquid was passed upward through the battery pack. Two flow guides were used to ensure uniform liquid flow through the battery pack. Additional cooling was achieved by passing air through the channels provided at the top of the tabs. Studies have also suggested that the modeling of Li-ion battery has multi-domain features and it is difficult to consider all the parameters for the simulation analysis [94, 95]. Therefore, the modeling analysis was carried out using a multidimensional approach. The Newman, Tiedemann, Gu, and Kim (NTGK) model was used. Previous studies suggested that NTGK model fits better for the 3D-modeling of Li-ion battery [96-100]. A small-scale prototype was developed to validate the results of the modeling analysis.

Different methodologies were employed to enhance cooling performance. Methods such as drop injection and multi-channel direct approaches have shown improved heat dissipation rates [101, 102]. Majid Goodarzi [103] et al. conducted experiments by employing liquid refrigerant (R141b). The cubic battery pack was fully immersed in the refrigerant bath. An aluminum plate was provided on top to facilitate heat exchange with the surroundings. Results depict

that the battery pack temperature was minimized to 30.8 °C. At a discharge rate of 4C, the temperature was cooled down to 40.5 °C from 71.2 °C.

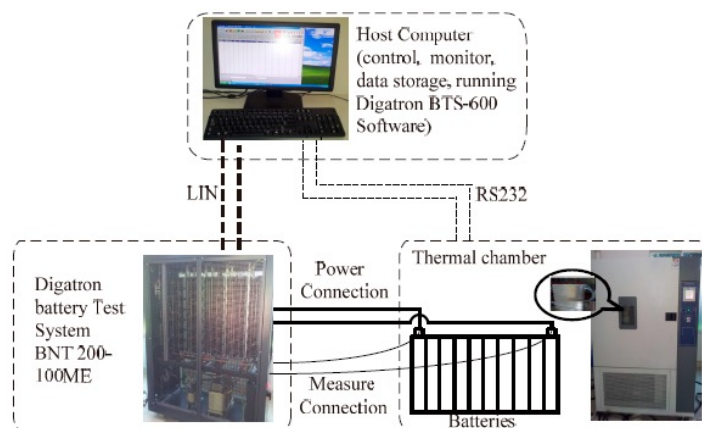


Figure 4. Liquid based heating and cooling system [From Wang and Xie J [104], licensed under CC BY 4.0]

Wang and Xie J [104] proposed a liquid-based system for both cooling and heating as shown in Figure 4. The system utilizes a water-ethylene glycol mixture to remove heat from or to supply heat to, the battery pack, depending on the operating requirement. Experimental and numerical investigations, including heat-removal and preheating tests, were conducted to evaluate the system. A 3D numerical model was used to study the thermal behavior of the battery. This study shown that the increasing coolant circulation rate and reducing the inlet temperature decreased the surface temperature of the battery pack within a desirable range. Further, the improvement in temperature uniformity was also observed. Figure 5 shows the temperature profiles at various flow rates. The system controls the battery temperatures below 50 °C during high-discharge. Higher flow rates combined with elevated inlet temperatures reduced the preheat time.

The direct cooling techniques focused on properties of coolant and its dynamic behavior. This method provides effective thermal management as establishes direct contact between the coolant and battery pack. However, this approach has several practical challenges. Prolonged coolant stagnation may reduce the rate of heat dissipation. Many cooling liquids have high viscosity and low thermal conductivity, which reduces the cooling effectiveness. The considerable amount of liquid required may increase the total mass of the system. If a cell fails, chemical reactions may contaminate the circulating fluid. Structural damage can also cause leakage of the working fluid and damage to vehicle components. These issues limit the large-scale implementation of direct cooling strategies.

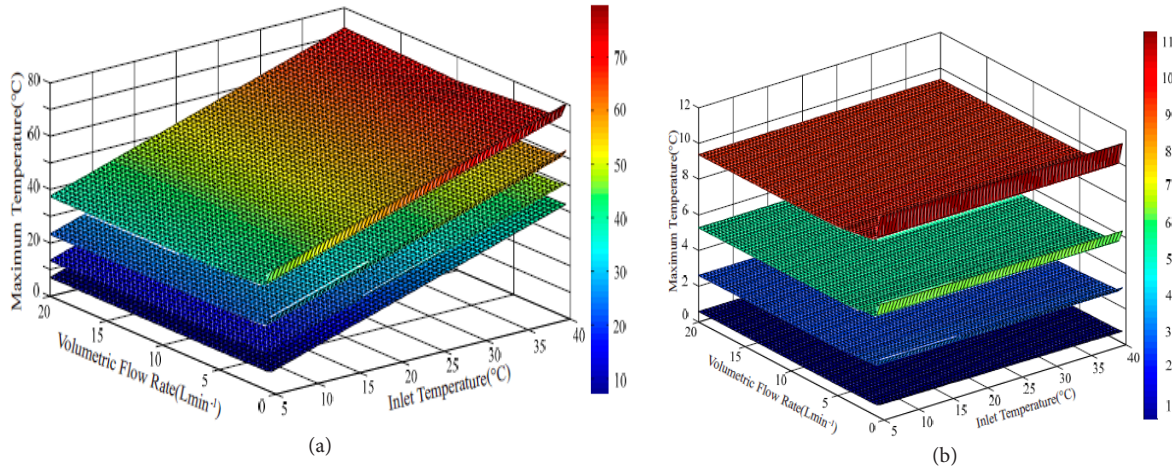


Figure 5. Effect of inlet temperature and flow rate (a) Battery maximum temperature (b) Cell temperature difference [From Wang and Xie J [104], licensed under CC BY 4.0]

5. Indirect cooling

In this approach, a metal plate or tube acts as a heat exchanger between the battery pack and the coolant [105]. Currently, indirect methods are widely employed due to their advantages, such as compact design and improved thermal performance [106, 107]. Indirect thermal management approaches are generally classified into two categories: single-phase and two-phase systems. Various configurations have been investigated to optimize both flow behavior and structural design. Zhao et al. [108] introduced a mini-channel configuration in cylindrical battery pack and employed water as the working fluid. The system consists of three aluminum plates: an inlet plate, a flow-distribution plate, and a collection plate. Water enters through the inlet plate, is uniformly distributed to the cooling channels, and is subsequently collected at the outlet plate. Numerical analysis was performed using FLUENT. Good agreement was noticed between numerical and experimental results. It was observed that the mini-channel configuration maintains the battery pack temperatures below 40°C and cell temperature graduation within 5°C. However, higher mass flow rates were necessary to meet the increased thermal loads. Attempts were also made to develop compact battery configurations without reducing safety and performance. Basu et al. [109] proposed an electrochemical model for a Li-ion battery to enhance structural compactness. A commercial-scale Li-NCA/C 18650 cell was used, with two aluminum flow channels along its sides and additional conductive elements to transfer heat from the cell to the cooling passages. A pseudo-two-dimensional framework was adopted for electrochemical modeling and validated by CFD simulations. The pack temperature was maintained within acceptable limits even under low coolant flow rates and high discharge conditions.

Deng et al. [110] employed a leaf-like channel configuration integrated with cold plates for a rectangular battery pack. These channels function as diffusion pathways, enhancing the cell's cooling

performance. The results of structural optimization indicated that a $\frac{3}{4}$ -width ratio, a 0.5-length ratio, and a bifurcation angle of 30°–50° were optimal. Liu et al. [111] carried out an experimental investigation of the thermal characteristics of an MnNiCo-type cell. The experimental setup consisted of a battery module enclosed by a cold plate assembly. A radiator was connected to the cold plate via a hose equipped with a regulating valve. Separate fans, humidifier, and cooling coils were used to provide airflow across the battery module and the radiator. A half cold-plate design with a U-flow configuration were incorporated to minimise uneven coolant distribution within the channel. The results indicated that active cooling offers better performance than passive cooling. The results indicate that at identical rates, charging generates more heat than discharging, and that the overall pack temperature increases under elevated ambient conditions.

N Wang et al. [112] employed surrogate approach to optimize the heat dissipation in Li-ion battery (LIB TLP80A5E6-50AH). The battery pack was placed between the cooling plates, ensuring surface contact between the battery cells and the plates. Water was used as the coolant. The 3D-thermal model was developed by using equation (7) considering Cartesian coordinate system [113-115]. The influence of thermophysical parameters was investigated using equations (8) and (9).

$$\rho C_p = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} + q_{v \ i(x,y)} S_{soc} - q_{diss} \quad (7)$$

where, ρ – density of battery, C_p – specific heat, T – operating temperature of the battery, t – time interval, c_x , λ_y , λ_z – thermal conductivity along x, y and z directions, $q_{v \ i(x,y)} S_{soc}$ – volumetric heat, and q_{diss} – heat dissipation.

$$\rho C_p = \frac{1}{m} \sum \rho_n V_n \sum c_n m_n \quad (8)$$

$$q_{v \ i(x,y)} S_{soc} = [(U_{ocv} - U) + T_a \frac{\rho U_{ocv}}{\rho T}] \quad (9)$$

Where, m – mass of the battery, ρ_n – density of constituent material, V_n – volume of the constituent material, c_n – specific heat of the constituent material, $\frac{\rho U_{ocv}}{\rho T}$ – open circuit voltage, U – cell potential and $\frac{\rho U_{ocv}}{\rho T}$ – temperature influence coefficient, and T_a – ambient temperature.

Reversing the direction of water flow resulted in enhanced thermal performance. However, the heat-transfer capability of the cooling plate and the associated pressure drop remain challenges requiring further attention. Mo X et al. [116] used topology optimizing technique for cooling plate design to resolve these issues. It was observed that the optimized plate exhibits superior thermal performance while also reducing the pressure drop.

As discussed above, single-phase cooling employs a working fluid. Attempts were made to improve performance by optimizing the flow pattern and the physical design. However, issues such as contact resistance, pressure, and the uniform distribution of the working medium need to be addressed. Further research is required in this regard. On other hand, the concept of phase change cooling is more effective to the single-phase cooling due higher latent heat vaporization [117, 118]. The nucleate flow boiling condition which has the capability to take significant amount heat is helpful in this regard [119]. Research on BTMS using phase-change boiling has attracted attention in recent years. In this approach, low-boiling-point fluids are used as cooling media. S D Ammar et al. [120] performed an experimental investigation on flat tubes by using tetrafluoroethant (R134a) as a working fluid. Smooth and grooved tubes were included in the experiments. Heat exchange rates were higher in the grooved tube. The results indicate that heat flux increases with mass flux. Heat flux often decreased as the saturation temperature increased. Al-Zareer et al. [121] employed a pool-based approach using R134a. The experiments were conducted using prismatic and cylindrical battery packs. It was shown that pool-based cooling is more effective for cylindrical batteries than for prismatic batteries. S Park et al [122] performed a simulation study of BTMS using PCM cooling techniques. A paraffin-graphite combination was used as the PCM and as the passive cooling method. R134a was used as the refrigerant for phase-change cooling. The cooling performance was evaluated under different discharge and cycling conditions. The results were validated by referring the model developed by C Lin et al. [123]. Results indicate that phase-change cooling provides better overall cooling performance than PCM-based cooling. PCM cooling is influenced by ambient temperature. However, this influence is less pronounced in phase-change cooling.

S H Hong et al. [124] tested the performance of BTMS by incorporating two phase refrigerant cooling under actual conditions of EV. The results were compared with conventional single-phase cooling. Results indicate that two-phase cooling outperformed single-phase cooling. Even under harsh working conditions, the battery temperature was effectively controlled within acceptable limits. Similar studies conducted on cooling of fuel cell and electronic devices also infer the better performance in two phase cooling [125, 126]. Wang et al. [127] proposed the thermal management system by direct heating and cooling approach by utilizing R134a as the heat carrier. An expansion valve equipped with electronic circuitry was incorporated to achieve uniform heat distribution. Wu et al. [128] conducted experimental study on liquid cooling and phase change cooling. Novec 7000 and deionized water were used as test liquids. The battery pack was placed between the cold plates. Two structural configurations, straight fin and copper foam, were incorporated. Both methods improve cooling performance and limit temperature rise within the desired levels. However, deionized water shown better heat-carrying capacity to Novec 7000. In addition, the copper-foam structure produced higher heat-transfer rates than the straight-fin arrangement. Bonab et al. [129] claims that combination air cooling and boiling in helical tubes wrapped over the battery pack exhibit effective cooling. The boiling of the working fluid in the wrapped helical tubes helps maintain a constant battery temperature. The study also indicates that increases in mass flux and air velocity decrease the battery temperature.

J Wang et al. [130] studied liquid cooling and direct refrigerant cooling. The experiments were conducted under real-time conditions. In liquid cooling, the single-phase working fluid passes through the cold plate of the battery pack and dissipates heat to the refrigerant cooling circuit. The refrigerant was circulated through the battery pack during phase-change cooling. The results indicate that direct phase-change cooling exhibits a higher heat dissipation rate than single-phase cooling. An approximately 28.3% reduction in maximum battery temperature was observed with direct refrigerant cooling. A significant decrease in heat transfer coefficient (about 73.6% under 2C discharge) was observed when the cooling circuit was shifted from direct single-phase cooling to liquid cooling.

Various optimization approaches for liquid-cooling systems have been developed to improve BTMS performance in modern EVs. Most optimization techniques focus on the structural design, spatial location, working fluid, and materials of a battery. The important optimization techniques developed in liquid cooling approach are summarized in Table 2.

Table 2. Liquid cooling optimization techniques

Researcher	Parameter	Observations
	Jarrett et al. [131] Geometry of the cooling channel	Lower battery temperature Minimum pressure drops
Qian et al. [132]	Geometry of the cooling channel Fluid flow	Higher flow rate results in effective control of maximum battery temperature Pumping power varies with width of flow channel Increase in fluid friction in small channel
Zhao et al. [133]	Operating conditions Flow conditions Structural design	Higher mass flow rate enables the effective control of the temperature rise and uniform temperature distribution across the battery pack
Chung et al. [134]	Structural design	Improved cooling performance Improved temperature uniformity
Guo et al. [135]	Structure (control circuit)	Suitable for different climatic conditions Independent control of cabin and battery pack temperature
Akbarzadeh et al. [136]	Flow conditions Structure	Better temperature uniformity Improved cooling performance
Li et al. [137]	Flow conditions Structure (side cooling and terminal cooling)	Side cooling approach outperforms the terminal cooling More number of flow channels result in improved cooling rate.
Zeng et al. [138]	Discharge rate Flow conditions	Battery pack temperature was highly influenced by initial cooling temperature and of the fluid Decrease in battery temperature observed with increase in discharge rate up to 8C. there afterwards, no significant decrease in temperature was resulted
Monika et al. [139]	Flow channel; straight, U-type, serpentine, hexagonal, and pumpkin)	Serpentine flow had better cooling performance.
Tang et al. [140]	Flow channel Cold plate	Improved cooling performance Suitable of large capacity square batteries
Xu et al. [141]	Flow channel (serpentine and U-channel)	Satisfactory cooling performance was obtained in both channels. However, Serpentine channel outperforms the U-channel.
Xie et al. [142]	Flow channel (adding baffles)	Improved heat dissipation rate. Rate of heat dissipation increases with number of baffles and baffle height.
Sheng et al. [143]	Flow direction Structural (channel width)	Cooling performance significantly influenced by flow rate and direction of flow Flow channel width influences the pressure drop and temperature uniformity
Duan et al. [144]	Flow channel size Inlet boundary conditions	Channel size influences the temperature distribution Higher flow rate results in higher rate of heat dissipation
Yates et al. [145]	Flow channel Fluid flow	Battery temperature was controlled below 313 K by maintaining flow rate above 0.00005 kg/s
Gao et al. [146]	Flow gradient channel	Improved temperature uniformity
Ke et al. [147]	Flow channel (serpentine)	Higher flow rate (96 L/h) helps to control thermal runaway
Sarchami et al. [148]	Flow channel (wave/staircase type)	Improved cooling performance Improved temperature uniformity

One of the major issues associated with liquid cooling systems is the thermal resistance introduced at material interfaces. Heat produced within the battery pack must be transferred through the battery casing and cooling-plate walls; thermal contact resistance can significantly impede heat flow and reduce overall thermal performance. This limitation can be eliminated by improving the interfacial area of the battery module and the cooling plate. In addition, air gaps at the interface may be minimized by incorporating fillers, such as

graphene [149]. According to Zhou et al. [150], increasing the number of channels and increasing the contact surface area are effective measures for reducing thermal resistance.

6. Combined liquid and pcm cooling

This hybrid approach combines liquid-cooling and PCM-based techniques. This method offers improved thermal management. However, further studies are required to find its practical feasibility in EV applications. Javani et al. [151] performed an energy analysis

of a PCM assisted approach. The Coefficient of Performance (COP) of the hybrid arrangement increased with rising PCM mass fraction. The overall energy efficiency improved from 19.9% to 21%. However, the use of two separate heat sinks in the system increases design complexity and overall cost. Sudhakaran et al. [152] performed simulation work by adopting different PCMs (decanoic acid, RT-35 PA, RT-42 PA, and RT-55 PA). Copper foam was used as an additive in PCMs. The results indicate that heat transfer increases with increasing mass fraction of PCM. Increasing PCM thickness reduced the cell temperature. The optimum PCM fraction of 0.2–0.4 was recommended for the better performance. Zhao et al. [153] evaluated BTMS performance using copper foam and EG-enhanced PCMs. The results show that both materials perform satisfactorily, with the EG-based composites performing marginally better. The conductivity of PCM plays a crucial role in determining pack and cell temperatures. Zhang et al. [154] conducted a study in this regard and reported that increasing PCM conductivity resulted in reduced pack and cell temperatures. However, the performance declined beyond a critical threshold. Similar observations were reported by Wang et al.

[155] and Ling et al. [156]. Ouyang et al. [157] conducted a similar work by integrating liquid coolant, composite PCM, and an insulating layer. The coolant circulated through designated channels; the PCM surrounded the cells; the insulation separated adjacent cells. The combined configuration was effective in mitigating thermal runaway propagation. Zhang et al. [158] employed flow and spatial optimization approaches to enhance the performance of PCM assisted liquid cooling systems. Figure 6 shows a schematic diagram of the battery module used in the analysis. Increasing the spacing between cells enables the use of significant volume of PCM. This leads to improved thermal performance. Higher heat dissipation was achieved by placing liquid flow channels near the cells. However, optimizing cell spacing relative to channel placement is an issue needs to be addressed. Lebrouhi et al. [159] studied the influence of coolant inlet temperature and reported that lower inlet temperatures corresponded to reduced cell temperatures. In addition, several studies have proposed to develop advanced BTMS by incorporating innovative cooling plate designs, delayed cooling strategies, and nano-enhanced PCMs [160–166].

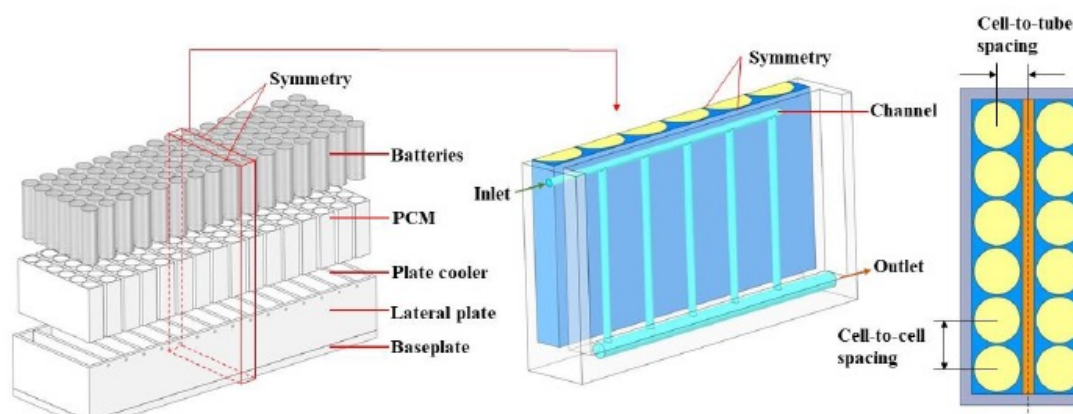


Figure 6. PCM assisted liquid cooling [From Zhang et al. [158] licensed under CC BY 4.0]

W Zhang et al. [167] proposed a BTMS by using liquid-based PCM cooling. An aluminum cold plate was designed to conform to the shape of the battery cell. PCM was provided between the cells. This novel cold-plate design provides a leak-proof seal. The cooling performance was tested by varying the flow pattern, as shown in Figure 7. The simulation analysis was performed using ANSYS FLUENT. The results were compared with those obtained from a conventional liquid-based PCM system under the same test conditions. This unique design offers better cooling performance. Fan et al. [168] proposed a multistage tesla-valve liquid cooling system in combination with PCM. The analysis was performed using a hybrid numerical model. The results shown that the thermal performance was significantly improved. It is also possible to enhance heat transfer in a PCM-based system by using finned surfaces [169, 170].

The combined technique offers improved performance. However, the structural complexity increases. Further, the cost of the combined system is higher. In addition, placing PCM around the battery

pack is difficult. Attempts have been made to incorporate porous medium such as metal foams to hold the PCM around the battery pack [171–174]. Often, this approach poses challenges during volumetric changes in PCM. In addition, inserting PCM into the slots is difficult. In another approach, the battery pack is fully submerged in a bath of PCM containing textile fibers. These fibers act as heat carriers between the battery pack and the PCM. This approach results in better temperature control, but care should be taken to ensure electrical safety. Further, heat dissipation takes significant time [175, 176]. Studies have also examined the incorporation of micro-encapsulated PCM. This offers enhanced thermal performance and leak free operation [177–181]. However, the preparation of PCM capsules often increases production costs.

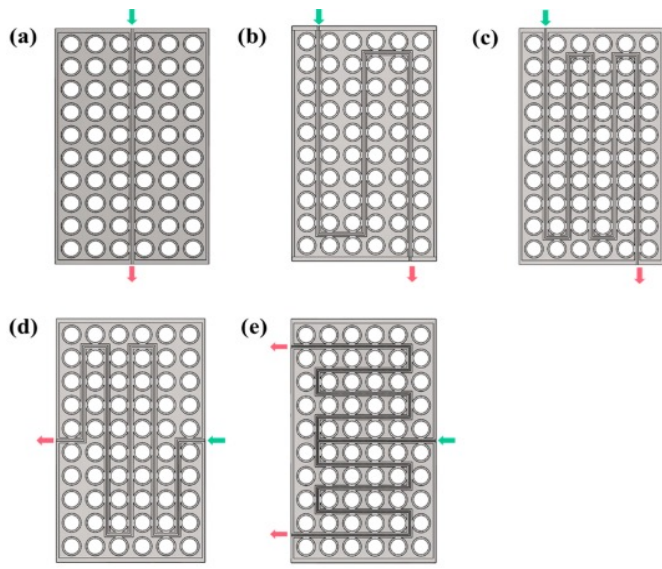


Figure 7. Flow pattern in a Novel liquid-PCM cooling [From Zhang et al. [167], licensed under CC BY 4.0]

7. Battery pre-heating

Thermal management in cold conditions has received less attention. Cold conditions can lower battery temperatures. To address this issue, battery preheating techniques are commonly employed. Preheating can be achieved by internal or external methods. The internal heating approach incorporates techniques such as current excitation. However, safety factors are the major issues associated with internal heating [182]. External heating involves using external heat sources such as hot air, hot liquids, or thermoelectric heaters [183]. External heating is generally considered a safe and more economical option for battery preheating. External heating can be classified as direct heating, in which the battery pack is immersed in a heated liquid, or indirect heating, in which a tube or plate heat exchanger transfers heat to the battery pack.

Commonly used external heating techniques involve the use of hot air, liquids, and PCMs [184]. Yi et al. [185] attempted to increase the battery temperature by passing hot air through heating passages at high pressure. However, the low thermal conductivity of air and the requirement for a high flow rate are major challenges for air-based heating. However, heat transfer fluids (HTFs) offer higher thermal conductivity. This enables faster battery preheating. The flow pattern of the heating fluid plays a crucial role in the preheating rate. Significant improvements have been accomplished using microchannel flow. Jin et al. [186] investigated a small battery pack using microchannel flow and obtained improved heat transfer. Zhu et al. [187] utilized a heating plate placed under the battery pack. The heat was conducted to the battery through the solid interface. This method achieved a battery temperature rise of 0.55°C per minute. However, the small contact area in this approach limits the temperature rise by reducing heat transfer. The contact area can be improved by incorporating side plates. Further, higher flow rates can help to achieve a

fast temperature rise [188]. Immersion heating techniques provide better thermal contact by submerging the battery pack in a bath of heating fluid. Experiments using this method shown a temperature increase of 4.18 °C within 60 seconds [189]. However, the possibility of short-circuiting is a major concern.

It has been observed that many external preheating techniques are not suitable for achieving rapid temperature elevation and results in temperature non-uniformity [190]. These limitations can be addressed by incorporating electrical heating approaches, such as resistance-wire and pipe-based heating systems [191]. Zhang et al. [192] incorporated a method to enhance the effectiveness of liquid based preheating under extremely cold conditions (−40°C) by integrating hollow aluminum tubes. Hot water was circulated from a thermal reservoir through the tubes. Experimental measurements and CFD simulations were carried out to evaluate the influence of fluid temperature, tube diameter, and flow rate. A 72-Ah, 3.2-V cell was employed for the analysis. The results show that enlarging the tube diameter enhances the rate of heat transfer, thereby decreasing the preheating duration. Increased flow rates, corresponding to higher Reynolds numbers, further enhance the heat transfer rate. The inlet coolant temperature varied from 25 °C to 50 °C. Preheating was faster in the 30 °C–50 °C range. However, the variation in cell temperature exceeded 5°C under these conditions. In contrast, improved temperature uniformity (variation confined within 5 °C) was achieved at an inlet temperature of 25 °C.

Thermoelectric BTMS can limit temperature in both hot and cold conditions. Luo et al. [193] proposed a thermoelectric-based BTMS. The system comprises of an aluminum heat sink with fins for heat dissipation. A thermoelectric controller made of copper sheets and ceramic plates was used. An aluminum honeycomb structure housing was used to house LiFePO₄ battery. The system operates on the Peltier principle. Thermoelectric heating attains fast rise because of direct heating cells. For the safe operation, DC power is preferred over AC power [194]. However, thermoelectric systems often require integration of liquid cooling to manage the heat generated, which increases structural complexity and system costs. These challenges can be minimized by employing variable frequency pulse techniques [195].

8. Summary and recommendations for future work

The preceding sections of this article discuss various aspects of BTMS in electric vehicles. Special emphasis is placed on liquid-based systems, and recent developments are reviewed. Thermal management using liquid media may be achieved through either direct immersion or indirect contact arrangements with the battery. In direct systems, the battery is immersed in a coolant bath. This method provides effective heat removal via direct interaction between the battery pack and the cooling medium. However, this method is prone to short circuits and leakage. To prevent electrical short circuits, dielectric fluids are employed. Several efforts have been undertaken to improve the efficiency of direct cooling by adopting different strategies

such as enhancing the thermophysical properties of the working fluid, modifying battery structure, immersion-based configurations, and tab-cooling techniques. However, in many cases, the coolant remains stagnant, which impedes rapid heat dissipation from the battery pack. Strong sealing mechanisms are necessary to prevent leakage; however, they increase system costs.

Indirect cooling is implemented using plates and tubes. In this approach, heat is dissipated through a solid surface into the coolant, thereby eliminating the risk of short circuits. The cooling rate can be adjusted, as required, by regulating the coolant flow. Numerous studies have focused on enhancing the efficiency of the indirect method. These optimization approaches primarily focus on fluid properties, flow distribution, and battery structural configuration. These methods aim to dissipate heat more effectively and more rapidly.

In recent years, phase-change-based thermal management has been introduced into BTMS. In this approach, the working medium undergoes a phase transition during heat absorption and release. Refrigerants are commonly used as the working fluids in such systems. The efficiency of phase-change cooling is generally superior to single-phase cooling because of its ability to absorb large amounts of latent heat. Attempts have also been made to combine single-phase and phase-change cooling features to further improve thermal performance. PCM-assisted liquid cooling has been incorporated in recent years; however, further research is required. The literature indicates that PCM-based liquid cooling has the potential to handle high thermal loads. However, the system becomes more complex, increasing its overall weight and cost. Irrespective of the cooling technique adopted, emphasis should be placed on reducing energy consumption, structural complexity, and overall system cost [196–201].

The BTMS works in a cold-climate conditions requires an effective battery preheating system. It has been observed from the literature that research has focused on developing battery-heating methods. Preheating can be achieved by external or internal heating. External heating can be achieved by incorporating heat exchangers (e.g., tubes or plates). The internal heating uses heating elements within the battery pack. External heating is generally preferred because its advantages such as higher safety and reduced system complexity.

The future adoption of EVs depends on long driving ranges, fast charging capabilities, and safety. Therefore, the future research should focus on these issues. The dynamic variation of battery temperature is major issue. Most of the existing BTMS failed to achieve better temperature uniformity. Hybrid approaches have shown improved performance. They were often associated with structural complexity. Further, insufficient research has been conducted under cold-climate conditions. The slow preheating rates observed in existing techniques is a major issue. Attention must also be given to minimizing the temperature nonuniformity caused by preheating.

Thermal contact resistance is another significant challenge in all BTMS designs. Reducing contact resistance at various interfaces within the system could significantly enhance thermal performance. However, limited efforts have been made in this area. Attention should be paid to advances in battery fabrication techniques. The development of new materials with higher thermal conductivity specifically for battery applications is also important. Currently, battery manufacturers are focusing on safety, quality, sustainability, and cost-effectiveness. Achieving fire safety and ensuring leakage-proof operation have become major objectives. Quality can be improved by increasing the precision of manufacturing processes such as drilling, riveting, welding, and coating. Additionally, selecting energy-efficient fabrication techniques, such as replacing traditional spot welding with self-piercing rivets, can reduce overall energy consumption during production.

The overall performance of conventional BTMS can be significantly improved by incorporating emerging techniques, such as Artificial Intelligence (AI) and Machine Learning (ML). Incorporating AI and ML enables the system to become intelligent and adaptive. The development of AI-enabled BTMS has the potential to improve the reliability of an EV. An AI-based system can analyze real-time data from various BTMS components, providing accurate information about battery conditions such as temperature, SOC, SOH, and aging factors [202–205]. ML algorithms can predict potential battery failures, enabling proactive measures. AI and ML also impart adaptability to the BTMS, enabling it to respond dynamically to factors such as climate conditions and driving patterns. Further, the reliability of the system can be enhanced by incorporating Internet of Things (IoT) devices and data analytics techniques [206–208].

9. Conclusion

Lithium-ion batteries are widely used in EVs because of their advantageous properties. The performance and life of Li-ion batteries are highly sensitive to temperature variations. Hence, an effective BTMS is required to maintain temperature within the permissible range. This article discusses various aspects of liquid-based battery thermal management. Liquid-based systems have received considerable attention because of their ability to manage the high thermal loads required in modern electric vehicles (EVs). In the direct-liquid approach, the battery pack contacts the cooling medium. However, this method is limited in managing very high thermal loads and is prone to leakage. The indirect liquid approach facilitates heat transfer between the battery and the coolant through a heat exchanger, such as a cooling plate or a tubular channel. This approach can handle high thermal loads for shorter durations. The thermophysical properties of the working fluid, the channel configuration, and the battery's structural design influence the overall performance. PCM-assisted liquid cooling systems have demonstrated promising results due to their combined cooling mechanism. However, structural complexities associated with PCM-integrated systems pose major challenges. Battery preheating is essential in cold climates. Slow heating rates and non-uniform cell temperature distribution remain challenges

in existing preheating methods. Additional research is required to overcome these issues. Thermal contact resistance at material interfaces also influenced on the performance of BTMS. Comparatively little work has been carried out to reduce the influence of thermal contact resistance.

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References

- [1] Osorio C. Nanduri K. Urban transportation emissions mitigation: Coupling high-resolution vehicular emissions and traffic models for traffic signal optimization. *Transp. Res. Part B: Methodol.* 2015;81:520–538. doi:10.1016/j.trb.2014.12.007.
- [2] Gireesh Kumar P. Lekhana P. Tejaswi M. Chandrakala S. Effects of vehicular emissions on the urban environment – A state of the art. *Mater. Today: Proc.* 2021;45:6314–6320. doi:10.1016/j.matpr.2020.10.739.
- [3] Fernández M. Valenciano J. Trinidad T. Muñoz N. The use of activated carbon and graphite for the development of lead-acid batteries for hybrid vehicle applications. *J. Power Sources* 2010;195:4458–4469. doi:10.1016/j.jpowsour.2009.12.131.
- [4] Jie Deng C. Chulheung Bae. Adam Denlinger. Theodore Miller. Electric vehicles batteries: Requirements and challenges. *Joule* 2020;4:511–515. doi:10.1016/j.joule.2020.01.013.
- [5] U.S. Department of Energy. Alternative Fuels Data Center, Electric Batteries.
- [6] Aneke M. Wang M. Energy storage technologies and real-life applications – A state of the art review. *Applied Energy* 2016;179:350–377. doi:10.1016/j.apenergy.2016.06.097.
- [7] Bukhari S. Maqsood J. Baig J. Ashraf M. Khan S. Comparison of characteristics of lead acid, nickel-based, lead crystal, and lithium-based batteries. In: *Proceedings of the 17th UK-Sim-AMSS International Conference on Modelling and Simulation(UKSim)*; Cambridge, UK; 2015:444–450. doi:10.1109/UKSim.2015.69.
- [8] Olabi AG. The 3rd international conference on sustainable energy and environmental protection SEEP 2009 – Guest Editor's Introduction. *Energy* 2010;35:4508–4509. doi:10.1016/j.energy.2010.09.053.
- [9] Olabi AG. Developments in sustainable energy and environmental protection. *Energy* 2012;39:2–5. doi:10.1016/j.energy.2011.12.037.
- [10] Kim T. Wentao S. Dae-Yong Son. Luis K. Ono. Yabing Qi. Lithium-ion batteries: Outlook on present, future, and hybridized technologies. *J. Mater. Chem.* 2019;7:2942–2964. doi:10.1039/c8ta10513h.
- [11] Song Li. Shi-Qi Zhang. Lu Shen. Qi Liu. Jia-Bin Ma. Wei Lv. Yan-Bing He. Quan-Hong Yang. Progress and perspective of ceramic/polymer composite solid electrolytes for lithium batteries. *Adv. Sci.* 2020;7:1903088. doi:10.1002/advs.201903088.
- [12] Lu Y. Jun Chen. Prospects of organic electrode materials for practical lithium batteries. *Nat. Rev. Chem.* 2020;4:127–142. doi:10.1038/s41570-020-0160-9.
- [13] Dunn B. Tarascon JM. Electrical energy storage for the grid: A battery of choices. *Science* 2011;334:928–935. doi:10.1126/science.1212741.
- [14] Naik I. Nandgaonkar M. Review of the approaches and modeling methodology for lithium-ion battery thermal management systems for electric vehicles. In: *Advances in Material and Mechanical Engineering, Select Proceedings of ICFT-MME*. 2020:75–109. doi:10.1007/978-981-16-0673-1_8.
- [15] Pandey C. Goyat V. Goel S, Eds. *Advances in Material and Mechanical Engineering*. Springer Nature Singapore Pte Ltd., Singapore, 2021:75–112.
- [16] Kitoh K. Nemoto H. 100 Wh large size Li-ion batteries and safety tests. *J. Power Sources* 1999;81–82:887–890. doi:10.1016/S0378-7753(99)00125-1.
- [17] Abhijeet Mitra. Rajan Kumar. Dwesh Kumar Singh. Zafar Said. Advances in the improvement of thermal conductivity of phase change material-based lithium-ion battery thermal management systems: An updated review. *J. Energy* 2022;53:105195. doi:10.1016/j.est.2022.105195.
- [18] Rugh JP. Pesaran A. Smith K. Electric vehicle battery thermal issues and thermal management techniques(Presentation). NREL(National Renewable Energy Laboratory):Golden, CO, USA, 2011.
- [19] Pesaran A. Tools for designing thermal management of batteries in electric drive vehicles(Presentation);technical report. National Renewable Energy Lab.(NREL).USA, 2013.
- [20] Zhao C. Zhang B. Zheng Y. Huang S. Yan T. Liu X. Hybrid battery thermal management system in electric vehicles: A review. *Energies* 2020;13(23). doi:10.3390/en13236257.
- [21] Raza W. Ko GS. Ko GS. Induction heater based battery thermal management system for electric vehicles. *Energies* 2020;13(21):5711. doi:10.3390/en13215711.
- [22] Jeffs J. Dinh TQ. Widanage DW. Picarelli A. Optimisation of direct battery thermal management for EVs operating in low-temperature climates. *Energies* 2020;13(22):6004. doi:10.3390/en13226004.
- [23] Ahoutou Y. Ilinca A. Mohamad I. Electrochemical Cells and Storage Technologies to Increase Renewable Energy Share in Cold Climate Conditions—A Critical Assessment. *Energies* 2022;15(4). doi:10.3390/en15041579.

- [24] Wang Q. Jiang B. Li B. Yan Y. A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles. *Renew. Sustain. Energy Rev.* 2016;64:106–128. doi:10.1016/j.rser.2016.05.033.
- [25] An Z. Jia L. Ding Y. Dang C. Li X. A review on lithium-ion power battery thermal management technologies and thermal safety. *J. Therm. Sci.* 2017;26:391–412. doi:10.1007/s11630-017-0955-2.
- [26] Jaguemont J. Boulon L. Dubé Y. A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures. *Appl. Energy* 2016;164:99–114. doi:10.1016/j.apenergy.2015.11.034.
- [27] Zhang Y. Ge H. Huang J. Li Z. Zhang J. A comparative degradation study of commercial lithium-ion cells under low temperature cycling. *RSC Adv.* 2017;7:23157–23163. doi:10.1039/C7RA02581E.
- [28] Petzl M. Kasper M. Danzer MA. Lithium plating in a commercial lithium-ion battery—A low-temperature aging study. *J. Power Sources* 2015;275:799–807. doi:10.1016/j.jpowsour.2014.11.065.
- [29] Broussely M. Biensan P. Bonhomme F. Blanchard P. Herreyre S. Nechev K. Staniewicz RJ. Main aging mechanisms in Li-ion batteries. *J. Power Sources* 2005;146:90–96. doi:10.1016/j.jpowsour.2005.03.172.
- [30] Xuning Feng. Minggao Ouyang. Xiang Liu. Languang Lu. Yong Xia. Xiangming He. Thermal runaway mechanism of lithium-ion battery for electric vehicles: A review. *Energy Storage Mater.* 2018;10:246–267. doi:10.1016/j.ensm.2017.05.013.
- [31] Tran M-K. Fowler M. A review of lithium-ion battery fault diagnostic algorithms: Current progress and future challenges. *Algorithms* 2020;13(3):62. doi:10.3390/a13030062.
- [32] Binghe Liu. Yikai Jia. Chunhao Yuan. Lubing Wang. Xiang Gao. Sha Yin. Jun Xu. Safety issues and mechanisms of lithium-ion battery cell upon mechanical abusive loading: A review. *Energy Storage Mater.* 2020;24:85–112. doi:10.1016/j.ensm.2019.06.036.
- [33] Liao Z. Zhang S. Li K. Zhang G. Abetler T. A survey of methods for monitoring and detecting thermal runaway of lithium-ion batteries. *J. Power Sources* 2019;436:226879. doi:10.1016/j.jpowsour.2019.226879.
- [34] Jaguemont J. Van Mierlo J. A comprehensive review of future thermal management systems for battery-electrified vehicles. *J. Energy Storage* 2020;31:101551. doi:10.1016/j.est.2020.101551.
- [35] Wang H. Tao T. Xu J. Mei X. Liu X. Gou P. Cooling capacity of a novel modular liquid-cooled battery thermal management system for cylindrical lithium-ion batteries. *Appl. Therm. Eng.* 2020;178:115591. doi:10.1016/j.applthermaleng.2020.115591.
- [36] Panchal S. Mathew M. Fraser R. Fowler M. Electrochemical thermal modeling and experimental measurements of 18650 cylindrical lithium-ion battery during discharge cycle for an EV. *Appl. Therm. Eng.* 2018;135:123–132. doi:10.1016/j.applthermaleng.2018.02.046.
- [37] Qin P. Liao M. Zhang D. Liu Y. Sun J. Wang Q. Experimental and numerical study on a novel hybrid battery thermal management system integrated forced-air convection and phase change material. *Energy Convers. Manag.* 2019;195:1371–1381. doi:10.1016/j.enconman.2019.05.084.
- [38] Xia G. Cao L. Bi G. A review on battery thermal management in electric vehicle application. *J. Power Sources* 2017;367:90–105. doi:10.1016/j.jpowsour.2017.09.046.
- [39] Zhou R. Chen Y. Zhang J. Guo P. Research progress in liquid cooling technologies to enhance the thermal management of LIBs. *Mater. Adv.* 2023;4:4011–4040. doi:10.1039/d3ma00299c.
- [40] Eddahech A. Briat O. Vinassa JM. Performance comparison of four lithium-ion battery technologies under calendar aging. *Energy* 2015;84:542–550. doi:10.1016/j.energy.2015.03.019.
- [41] Ma S. Jiang M. Tao P. Song C. Wu J. Wang J. Deng T. Shang W. Temperature effect and thermal impact in lithium-ion batteries: A review. *Prog. Nat. Sci. Mater. Int.* 2018;28:653–666. doi:10.1016/j.pnsc.2018.11.002.
- [42] Clerick S. Leivens S. Buytaert G. Chore A. Water-based cooling fluids to mitigate the thermal management challenges in new energy vehicles. *ARAI J. Mobil. Technol.* 2022;2(3):256–264. doi:10.37285/ajmt.2.3.2.
- [43] Balasundaram M. Ramar V. Yap C. Lu L. Tay AAO. Palani B. Heat loss distribution: Impedance and thermal loss analyses in LiFePO₄/graphite 18650 electrochemical cell. *J. Power Sources* 2016;328:413–421. doi:10.1016/j.jpowsour.2016.08.045.
- [44] Mevawalla A. Panchal S. Tran MK. Fowler M. Fraser R. Mathematical heat transfer modeling and experimental validation of lithium-ion battery considering: tab and surface temperature, separator, electrolyte resistance, anode-cathode irreversible and reversible heat. *Batteries* 2020;6:61. doi:10.3390/batteries6040061.
- [45] Vignesh BR. Grandjean TRB. McGordon A. Greenwood D. Thermal modelling of lithium ion batteries for temperature rise predictions in hybrid vehicle application. In: *Proc. 13th Int. Conf. Ecological Vehicles and Renewable Energies(EVER)*; 2018; Monte Carlo, Monaco. doi:10.1109/ever.2018.8362331.
- [46] Lai Y. Du S. Ai L. Cheng Y. Tang Y. Jia M. Insight into heat generation of lithium ion batteries based on the electrochemical-thermal model at high discharge rates. *Int. J. Hydrogen Energy* 2015;40:13039–13049. doi:10.1016/j.ijhydene.2015.07.079.
- [47] Smith K. Wang CY. Power and thermal characterization of a lithium-ion battery pack for hybrid-electric vehicles. *J. Power Sources* 2006;160:662–673. doi:10.1016/j.jpowsour.2006.01.038.
- [48] Park C. Jaura AK. Dynamic thermal model of Li-Ion battery for predictive behaviour in hybrid and fuel cell vehicles. In: *SAE Tech. Pap.; SAE International*; 2003. doi:10.4271/2003-01-2286.

- [49] Pesaran AA. Burch S. Keyser M. An approach for designing thermal management systems for electric and hybrid vehicle battery packs. In: *Vehicle Thermal Management Systems Conference(VTMS 4)*; London, England; 1999.
- [50] Kalaf O. Ahmed S. Zhang Y. Li J. Experimental and simulation study of liquid coolant battery thermal management system for electric vehicles: A review. *Int. J. Energy Res.* 2020;45(5):6495–6517. doi:10.1002/er.6268.
- [51] Maleki H. Hallaj S. Selman JR. Dinwiddie R. Wang C. Thermal properties of lithium-ion battery and components. *J. Electrochem. Soc.* 1999;146:947–954. doi:10.1149/1.1391704.
- [52] Shen W. Wang N. Zhang J. Wang F. Zhang G. Heat generation and degradation mechanism of lithium-ion batteries during high-temperature aging. *ACS Omega* 2022;7(49):44733–44742. doi:10.1021/acsomega.2c04093.
- [53] Richter F. Vie PJS. Kjelstrup S. Burheim OS. Thermal conductivity and internal temperature profiles of Li-ion secondary batteries. *J. Power Sources* 2017;359:592–600. doi:10.1016/j.jpowsour.2017.05.045.
- [54] Maleki H. Al Hallaj S. Selman JR. Dinwiddie RB. Wang H. Thermal properties of lithium-ion battery and components. *J. Electrochem. Soc.* 1999;146:947–954. doi:10.1149/1.1391704.
- [55] Nyman A. Zavalis TG. Elger R. Behm M. Lindbergh G. Analysis of the polarization in a Li-ion battery cell by numerical simulations. *J. Electrochem. Soc.* 2010;157:A1236. doi:10.1149/1.3486161.
- [56] Tanim TR. Rahn CD. Aging formula for lithium-ion batteries with solid electrolyte interphase layer growth. *J. Power Sources* 2015;294:239–247. doi:10.1016/j.jpowsour.2015.06.014.
- [57] Jiang Y. Zhang C. Zhang W. Shi W. Liu Q. Modeling charge polarization voltage for large lithium-ion batteries in electric vehicles. *J. Ind. Eng. Manag.* 2013;6:2. doi:10.3926/jiem.895.
- [58] Liu S. Zhang H. Xu X. A study on the transient heat generation rate of lithium-ion battery based on full matrix orthogonal experimental design with mixed levels. *J. Energy Storage* 2021;36:102446. doi:10.1016/j.est.2021.102446.
- [59] Haihong Pan. Yijing Li. Mo Zhang. Gang Liang. Lin Chen. Multiple factors dynamic heat generation rate model of lithium-ion battery. *Automot. Eng.* 2021;43:204–209. doi:10.19562/j.chinasae.qcgc.2021.02.007.
- [60] Xie Y. Zheng J. Hu X. Liu J. Wang H. An improved resistance-based thermal model for prismatic lithium-ion battery charging. *Appl. Therm. Eng.* 2020;180:115794. doi:10.1016/j.applthermaleng.2020.115794.
- [61] Patil M S. Sharma A. Kumar R. Singh V. A novel dielectric fluid immersion cooling technology for Li-ion battery thermal management. *Energy Convers. Manag.* 2021;229:113715. doi:10.1016/j.enconman.2020.113715.
- [62] Roe C. Zhang Y. Brown T. Wilson J. Immersion cooling for lithium-ion batteries – A review. *J. Power Sources.* 2022;525:231094. doi:10.1016/j.jpowsour.2022.231094.
- [63] Kumar P S. Krishnappa G B. Devegowda M. A comprehensive review on air-cooled battery thermal management system of electric vehicles. *J. Therm. Eng.* 2026;12(2):830–841
- [64] Thakur AP. Rajendran Elkadeem. Mohamed R. Sharshir. Swellam W. Arıcı M. Wang C. Zhao W. Hwang JY. Saidur R. A state of art review and future viewpoint on advanced cooling techniques for lithium-ion battery systems of electric vehicles. *J. Energy Storage* 2020;32:101771. doi:10.1016/j.est.2020.101771.
- [65] Li H. Ashwani S. Liu C. Wang Y. Zhang H. Electrochemical and thermal characteristics of prismatic lithium-ion battery based on a three-dimensional electrochemical-thermal coupled model. *J. Energy Storage.* 2021;42:102976. doi:10.1016/j.est.2021.102976.
- [66] Liu S. Zhang T. Zhang C. Yuan L. Xu Z. Jin L. Non-uniform heat generation model of pouch lithium-ion battery based on regional heat generation rate. *J. Energy Storage* 2023;63:107074. doi:10.1016/j.est.2023.107074.
- [67] Patel JR. Rathod MK. Recent developments in the passive and hybrid thermal management techniques of lithium-ion batteries. *J. Power Sources* 2020;480. doi:10.1016/j.jpowsour.2020.228820.
- [68] Kim GH. Pesaran A. Battery thermal management design modelling. *World Electr. Vehicle Assoc. J.* 2007;1(1):126–133. doi:10.3390/wevj1010126.
- [69] Wang YF. Wu JT. Thermal performance predictions for an HFE-7000 direct flow boiling cooled battery thermal management system for electric vehicles. *Energy Convers. Manag.* 2020;207:112569. doi:10.1016/j.enconman.2020.112569.
- [70] Zhao Y. Zhang X. Yang B. Cai S. A review of battery thermal management systems using liquid cooling and PCM. *J. Energy Storage* 2024;76:109836. doi:10.1016/j.est.2024.109836.
- [71] Xu J. Chen Z. Qin J. Minqiang P. A lightweight and low-cost liquid-cooled thermal management solution for high energy density prismatic lithium-ion battery packs. *Appl. Therm. Eng.* 2021;203:117868. doi:10.1016/j.applthermaleng.2021.117871.
- [72] Sheng L. Zhang H. Su L. Zhang Z. Li H. Fang K. Ye W. Effect analysis on thermal profile management of a cylindrical lithium-ion battery utilizing a cellular liquid cooling jacket. *Energy* 2020;220:119775. doi:10.1016/j.energy.2020.119725.
- [73] Ren R. Zhao Y. Diao Y. Liang L. Experimental study on the bottom liquid cooling thermal management system for lithium-ion battery based on multichannel flat tube. *Appl. Therm. Eng.* 2022;219:119636. doi:10.1016/j.applthermaleng.2022.119636.
- [74] Akbarzadeh M. Kalogiannis T. Jaguemont J. Jin L. Behi H. Karimi D. A comparative study between air cooling and liquid cooling thermal management systems for a high-energy lithium-ion battery module. *Appl. Therm. Eng.* 2021;198:117503. doi:10.1016/j.applthermaleng.2021.117503.
- [75] Malik M. Dincer I. Rosen MA. Mathew M. Fowler M. Thermal and electrical performance evaluations of series connected Li-ion batteries in a pack with liquid cooling. *Appl. Therm. Eng.* 2018;129:472–481. doi:10.1016/j.applthermaleng.2017.10.029.

- [76] Azmi WH, Hamid KA, Usri NA, Mamat R, Sharma KV. Heat transfer augmentation of ethylene glycol: water nanofluids and applications—a review. *Int. Commun. Heat Mass Transfer* 2016;75:13–23. doi:10.1016/j.icheatmasstransfer.2016.03.018.
- [77] Ma K, Liu J. Liquid metal cooling in thermal management of computer chips. *Front. Energy Power Eng. China* 2007;1(4):384–402. doi:10.1007/s11708-007-0057-3.
- [78] Jilte RD, Kumar R, Ahmadi MH. Cooling performance of nanofluid submerged vs. nanofluid circulated battery thermal management systems. *J. Clean. Prod.* 2019;240:118131. doi:10.1016/j.jclepro.2019.118131.
- [79] Ma KQ, Liu J. Heat-driven liquid metal cooling device for the thermal management of a computer chip. *J. Phys. D Appl. Phys.* 2007;40(15):4722–4729. doi:10.1088/0022-3727/40/15/055.
- [80] Deng Y, Jiang Y, Liu J. Low-melting-point liquid metal convective heat transfer: a review. *Appl. Therm. Eng.* 2021;193:117021. doi:10.1016/j.applthermaleng.2021.117021.
- [81] Dobosz A, Plevachuk Y, Sklyarchuk V, Sokoliuk B, Tkach O, Gancarz T. Liquid metals in high-temperature cooling systems: the effect of Bi additions for the physicochemical properties of eutectic Ga–Sn–Zn. *J. Chem. Eng. Data* 2018;64(2):404–411. doi:10.1021/acs.jced.8b00519.
- [82] Yang XH, Tan SC, Liu J. Thermal management of Li-ion battery with liquid metal. *Energy Convers. Manag.* 2016;117:577–585. doi:10.1016/j.enconman.2016.03.054.
- [83] Hirano H, Tajima T, Hasegawa T, Sekiguchi T, Uchino M. Boiling liquid battery cooling for electric vehicle. In: 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific); IEEE; 2014:1–4. doi:10.1109/ITEC-AP.2014.6940931.
- [84] An Z, Jia L, Li X, Ding Y. Experimental investigation on lithium-ion battery thermal management based on flow boiling in mini-channel. *Appl. Therm. Eng.* 2017;117:534–543. doi:10.1016/j.applthermaleng.2017.02.053.
- [85] Li X, Zhou Z, Zhang M, Zhang F, Zhou X. A liquid cooling technology based on fluorocarbons for lithium-ion battery thermal safety. *J. Loss Prev. Process Ind.* 2022;78:104818. doi:10.1016/j.jlp.2022.104818.
- [86] Patel JR, Rathod MK. Recent developments in the passive and hybrid thermal management techniques of lithium-ion batteries. *J. Power Sources* 2020;480:2298820. doi:10.1016/j.jpowsour.2020.228820.
- [87] Li X, Zhou Z, Zhang M, Zhang F, Zhou X. A liquid cooling technology based on fluorocarbons for lithium-ion battery thermal safety. *J. Loss Prev. Process Ind.* 2022;78:104818. doi:10.1016/j.jlp.2022.104818.
- [88] Giammichele L, D'Alessandro V, Falone M, Ricci R. Experimental Study of a Direct Immersion Liquid Cooling of a Li-Ion Battery for Electric Vehicles Applications. *Int. J. Heat Technol.* 2022;40(1):1–8. doi:10.18280/ijht.400101.
- [89] Nelson P, Dees D, Amine K, Henriksen G. Modeling thermal management of lithium-ion PNGV batteries. *J. Power Sources* 2002;110(2):349–356. doi:10.1016/S0378-7753(02)00197-0.
- [90] Satyanarayana G, Sudhakar DR, Muthya Goud V, Ramesh J, Pathanjali GA. Experimental investigation and comparative analysis of immersion cooling of lithium-ion batteries using mineral and therminol oil. *Appl. Therm. Eng.* 2023;225:120187. doi:10.1016/j.applthermaleng.2023.120187.
- [91] Karimi G, Dehghan AR. Thermal analysis of high-power lithium-ion battery packs using flow network approach. *Int. J. Energy Res.* 2014;38(14):1793–1811. doi:10.1002/er.3173.
- [92] Wu N, Ye X, Yao J, Zhang X, Zhou X, Yu B. Efficient thermal management of the large-format pouch lithium-ion cell via the boiling-cooling system operated with intermittent flow. *Int. J. Heat Mass Transfer* 2021;170:121018. doi:10.1016/j.ijheatmasstransfer.2021.121018.
- [93] Patil MS, Seo JH, Lee MY. A novel dielectric fluid immersion cooling technology for Li-ion battery thermal management. *Energy Convers. Manag.* 2021;229:113715. doi:10.1016/j.enconman.2020.113715.
- [94] Wang YF, Wu JT. Thermal performance predictions for an HFE-7000 direct flow boiling cooled battery thermal management system for electric vehicles. *Energy Convers. Manag.* 2020;207:112569. doi:10.1016/j.enconman.2020.112569.
- [95] ANSYS Inc. ANSYS Fluent: Release 19.1, Help System. Theory Guide; 2018.
- [96] Kim GH, Smith K, Lee KJ, Santhanagopalan S, Pesaran A. Multi-domain modeling of lithium-ion batteries encompassing multi-physics in varied length scales. *J. Electrochem. Soc.* 2011;158(8):A955–A965. doi:10.1149/1.3597614.
- [97] Kim US, Shin CB, Kim CS. Modeling for the scale-up of a lithium-ion polymer battery. *J. Power Sources* 2009;189(1):841–846. doi:10.1016/j.jpowsour.2008.10.019.
- [98] Yi J, Kim US, Shin CB, Han T, Park S. Three-dimensional thermal modeling of a lithium-ion battery considering the combined effects of the electrical and thermal contact resistances between current collecting tab and lead wire. *J. Electrochem. Soc.* 2013;160(3):A437–A443. doi:10.1149/2.027303jes.
- [99] Kwon KH, Shin CB, Kang TH, Kim CS. A two-dimensional modeling of a lithium-polymer battery. *J. Power Sources* 2006;163(1):151–157. doi:10.1016/j.jpowsour.2006.03.012.
- [100] Kim US, Shin CB, Kim CS. Effect of electrode configuration on the thermal behavior of a lithium-polymer battery. *J. Power Sources* 2008;180(2):909–916. doi:10.1016/j.jpowsour.2007.09.054.
- [101] Yi J, Kim US, Shin CB, Han T, Park S. Modeling the temperature dependence of the discharge behavior of a lithium-ion battery. *Energy* 2023;271:127049. doi:10.1016/j.energy.2023.127049.
- [102] Goodarzi M, Jannesari H, Ameri M. Experimental study of Li-ion battery thermal management based on the liquid-vapor phase change in direct contact with the cells. *J. Energy Storage* 2023;62:106834. doi:10.1016/j.est.2023.106834.

- [103] Zha YF. Meng XF. Qin SS. Hou NR. He SQ. Huang CY. Performance evaluation with orthogonal experiment method of drop contact heat dissipation effects on electric vehicle lithium-ion battery. *Energy* 2023;271:127049. doi:10.1016/j.energy.2023.127049.
- [104] Wang D. Xie J. Investigation of the liquid cooling and heating of a lithium-ion battery package for an electric vehicle. *World Electr. Veh. J.* 2023;14:16 Kim GH. Pesaran A. Battery thermal management design modeling. *World Electr. Veh. J.* 2007;1(1):126–133. doi:10.3390/wevj10101269. doi:10.3390/wevj14070169.
- [105] Guo Z. Xu J. Xu Z. Mubashir M. Wang H. Mei X. A light-weight multichannel direct contact liquid-cooling system and its optimization for lithium-ion batteries. *IEEE Trans. Transp. Electrification* 2022;8:2334–2345. doi:10.1109/TTE.2021.3131718.
- [106] Xu J. Guo ZC. Xu ZM. Zhou X. Mei XS. A systematic review and comparison of liquid-based cooling systems for lithium-ion batteries. *eTransportation* 2023;17:100242. doi:10.1016/j.etrans.2023.100242.
- [107] Jiang W. Zhao J. Rao Z. Thermal performance enhancement and prediction of narrow liquid cooling channel for battery thermal management. *Int. J. Therm. Sci.* 2022;171:107250. doi:10.1016/j.ijthermalsci.2021.107250.
- [108] Zhao J. Rao Z. Li Y. Thermal performance of mini-channel liquid cooled cylinder based battery thermal management for cylindrical lithium-ion power battery. *Energy Convers. Manag.* 2015;103:157–165. doi:10.1016/j.enconman.2015.06.056.
- [109] Basu S. Hariharan KS. Kolake SM. Song T. Sohn DK. Yeo T. Coupled thermal modeling of a novel Li-ion battery pack thermal management system. *Appl. Energy* 2016;181:1–13. doi:10.1016/j.apenergy.2016.08.049.
- [110] Deng T. Ran Y. Zhang G. Yin Y. Novel leaf-like channels for cooling rectangular lithium-ion batteries. *Appl. Therm. Eng.* 2019;150:1186–1196. doi:10.1016/j.applthermaleng.2019.01.065.
- [111] Liu JW. Li H. Li WY. Shi JY. Wang HH. Chen JP. Thermal characteristics of power battery pack with liquid-based thermal management. *Appl. Therm. Eng.* 2020;164:114421. doi:10.1016/j.applthermaleng.2019.114421.
- [112] Wang N. Li C. Li W. Chen X. Li Y. Qi D. Heat dissipation optimization for a serpentine liquid cooling battery thermal management system: An application of surrogate-assisted approach. *J. Energy Storage* 2021;40:102771. doi:10.1016/j.est.2021.102771.
- [113] Li X. He F. Zhang G. Huang Q. Zhou D. Experiment and simulation for pouch battery with silica cooling plates and copper mesh based air cooling thermal management system. *Appl. Therm. Eng.* 2019;146:866–880. doi:10.1016/j.applthermaleng.2018.10.061.
- [114] Bai F. Chen M. Song W. Yu Q. Li Y. Feng Z. Wang H. Investigation of thermal management for lithium-ion pouch battery module based on phase change slurry and mini channel cooling plate. *Energy*. 2019;167:561–574. doi:10.1016/j.energy.2018.10.137.
- [115] Pan C. Tang Q. He Z. Wang L. Chen L. Structure optimization of battery module with a parallel multi-channel liquid cooling plate. *J. Electrochem. Energy Convers. Storage* 2020;17:021104. doi:10.1115/1.4045197.
- [116] Mo X. Zhi H. Xiao Y. Hua H. He L. Topology optimization of cooling plates for battery thermal management. *Int. J. Heat Mass Transfer* 2021;178:121612. doi:10.1016/j.ijheatmasstransfer.2021.121612.
- [117] Al-Zareer M. Dincer I. Rosen MA. Novel thermal management system using boiling cooling for high-powered lithium-ion battery packs for hybrid electric vehicles. *J. Power Sources* 2017;363:291–303. doi:10.1016/j.jpowsour.2017.07.067.
- [118] Zhao Z. Yin C. Cheng J. Orthogonal optimization of a liquid cooling structure with straight microtubes and variable heat conduction blocks for battery module. *J. Energy Eng.* 2022;148(3). doi:10.1061/(ASCE)EY.1943-7897.0000840.
- [119] Sun YL. Liang FY. Tang H. Tang Y. Zhang SW. Chua KJ. Ultrathin flexible heat pipes with Microsorium fortunei structural-like wick for cooling flexible electronic devices. *Int. J. Heat Mass Transfer* 2023;202:123743. doi:10.1016/j.ijheatmasstransfer.2023.123743.
- [120] Ammar SM. Abbas N. Abbas S. Ali HM. Hussain I. Janjua M. Shiwei. Condensing heat transfer coefficients of R134a in smooth and grooved multiport flat tubes of automotive heat exchanger: An experimental investigation. *Int. J. Heat Mass Transfer* 2019;134:366–376. doi:10.1016/j.ijheatmasstransfer.2019.01.054.
- [121] Al-Zareer M. Dincer I. Rosen MA. Comparative assessment of new liquid-to-vapor type battery cooling systems. *Energy* 2019;188:116010. doi:10.1016/j.energy.2019.116010.
- [122] Park S. Jang DS. Lee D. Hong SH. Kim Y. Simulation on cooling performance characteristics of a refrigerant-cooled active thermal management system for lithium-ion batteries. *Int. J. Heat Mass Transfer* 2019;135:131–141. doi:10.1016/j.ijheatmasstransfer.2019.01.109.
- [123] Lin C. Xu S. Chang G. Liu J. Experiment and simulation of a LiFePO₄ battery pack with a passive thermal management system using composite phase change material and graphite sheets. *J. Power Sources* 2015;275:742–749. doi:10.1016/j.jpowsour.2014.11.068.
- [124] Hong SH. Jang DS. Park S. Yun S. Kim Y. Thermal performance of direct two-phase refrigerant cooling for lithium-ion batteries in electric vehicles. *Appl. Therm. Eng.* 2020;173:115213. doi:10.1016/j.applthermaleng.2020.115213.
- [125] ang H. Xia L F. Tang Y. Weng C X. Hu Z. Wu X Y. Fabrication and pool boiling performance assessment of micro-groove array surfaces with secondary micro-structures for high power applications. *Renew. Energy*. 2022;187:790–800. doi:10.1016/j.renene.2022.01.115.

- [126] Sun YL. Tang Y. Zhang SW. Yuan W. Tang H. A review on fabrication and pool boiling enhancement of three-dimensional complex structures. *Renew. Sustain. Energy Rev.* 2022;162:112437. doi:10.1016/j.rser.2022.112437.
- [127] Wang ZR. Huang LP. He F. Design and analysis of electric vehicle thermal management system based on refrigerant-direct cooling and heating batteries. *J. Energy Storage* 2022;51:104318. doi:10.1016/j.est.2022.104318.
- [128] Wu N. Chen YS. Lin BS. Li JJ. Zhou XL. Experimental assessment and comparison of single-phase versus two-phase liquid cooling battery thermal management systems. *J. Energy Storage* 2023;72:108727. doi:10.1016/j.est.2023.108727.
- [129] Bonab SA. Zonouzi SA. Aminfar H. Combination of flow boiling cooling by taking advantage of helical pipes and air cooling for thermal management of lithium-ion batteries. *J. Energy Storage* 2023;72:108322. doi:10.1016/j.est.2023.108322.
- [130] Wang JB. Gao S. Zhu JH. Mao JN. Thermal performance analysis and burning questions of refrigerant direct cooling for electric vehicle battery. *Appl. Therm. Eng.* 2023;232:121055. doi:10.1016/j.applthermaleng.2023.121055.
- [131] Jarrett A. Kim IY. Design optimization of electric vehicle battery cooling plates for thermal performance. *J. Power Sources* 2011;196(23):10359–10368. doi:10.1016/j.jpowsour.2011.06.090.
- [132] Qian Z. Li Y. Rao Z. Thermal performance of lithium-ion battery thermal management system by using mini-channel cooling. *Energy Convers. Manag.* 2016;126:622–631. doi:10.1016/j.enconman.2016.08.063.
- [133] Zhao C. Cao W. Dong T. Jiang F. Thermal behavior study of discharging/charging cylindrical lithium-ion battery module cooled by channeled liquid flow. *Int. J. Heat Mass Transfer* 2018;120:751–762. doi:10.1016/j.ijheatmasstransfer.2017.12.083.
- [134] Chung Y. Kim MS. Thermal analysis and pack level design of battery thermal management system with liquid cooling for electric vehicles. *Energy Convers. Manag.* 2019;196:105–116. doi:10.1016/j.enconman.2019.05.083.
- [135] Guo J. Jiang F. A novel electric vehicle thermal management system based on cooling and heating of batteries by refrigerant. *Energy Convers. Manag.* 2021;237:114145. doi:10.1016/j.enconman.2021.114145.
- [136] Akbarzadeh M. Kalogiannis T. Jagueмонт J. Jin L. Behi H. Karimi D. Behi H. Karimi D. A comparative study between air cooling and liquid cooling thermal management systems for a high-energy lithium-ion battery module. *Appl. Therm. Eng.* 2021;198:117503. doi:10.1016/j.applthermaleng.2021.117503.
- [137] Li L. Ling L. Xie Y J. Zhou W C. Wang T B. Zhang L C. Comparative study of thermal management systems with different cooling structures for cylindrical battery modules: side-cooling vs. terminal-cooling. *Energy.* 2023;274:127414. doi:10.1016/j.energy.2023.127414.
- [138] Zeng J X. Feng S. Lai C G. Song J. Fu L J. Chen H. Prediction on thermal performance of refrigerant-based battery thermal management system for a HEV battery pack. *Int. J. Heat Mass Transfer.* 2023;201:123657. doi:10.1016/j.ijheatmasstransfer.2023.123657.
- [139] Monika K. Datta SP. Comparative assessment among several channel designs with constant volume for cooling of pouch-type battery module. *Energy Convers. Manag.* 2022;251:114936. doi:10.1016/j.enconman.2022.114936.
- [140] Tang A. Zhang H. Liu Y. Wang X. Chen J. Optimization design and numerical study on water cooling structure for power lithium battery pack. *Appl. Therm. Eng.* 2019;159:113760. doi:10.1016/j.applthermaleng.2019.113760.
- [141] Xu H. Li Y. Zhao J. Wang P. Optimization of liquid cooling and heat dissipation system of lithium-ion battery packs of automobile. *Case Stud. Therm. Eng.* 2021;26:101012. doi:10.1016/j.csite.2021.101012.
- [142] Xie L. Zhang Y. Chen H. Liu J. Coupled prediction model of liquid-cooling based thermal management system for cylindrical lithium-ion module. *Appl. Therm. Eng.* 2020;178:1155599. doi:10.1016/j.applthermaleng.2020.1155599.
- [143] Sheng L. Wang Z. Li M. Numerical investigation on a lithium-ion battery thermal management utilizing a serpentine channel liquid cooling plate exchanger. *Int. J. Heat Mass Transfer.* 2019;141:658–668. doi:10.1016/j.ijheatmasstransfer.2019.07.033.
- [144] Duan J. Liu Q. Zhang H. Modeling and analysis of heat dissipation for liquid cooling lithium-ion batteries. *Energies.* 2021;14(14):4187. doi:10.3390/en14144187.
- [145] Yates M. Brown R. Smith T. Analysing the performance of liquid cooling designs in cylindrical lithium-ion batteries. *J. Energy Storage.* 2021;33:100913. doi:10.1016/j.est.2019.100913.
- [146] Gao R. Chen Y. Li J. A gradient channel-based novel design of liquid-cooled battery thermal management system for thermal uniformity improvement. *J. Energy Storage.* 2022;48:104014. doi:10.1016/j.est.2022.104014.
- [147] Ke Q. Wang L. Zhao Y. The retarding effect of liquid-cooling thermal management on thermal runaway propagation in lithium-ion batteries. *J. Energy Storage.* 2022;48:104063. doi:10.1016/j.est.2022.104063.
- [148] Sarchami A. Hosseini S. Rezaei M. Experimental study of thermal management system for cylindrical Li-ion battery pack based on nanofluid cooling and copper sheath. *Int. J. Therm. Sci.* 2022;171:107244. doi:10.1016/j.ijthermalsci.2021.107244.
- [149] Leng Z. Yuan Y. Cao X. Zeng C. Zhong W. Gao B. Heat pipe/phase change material thermal management of Li-ion power battery packs: A numerical study on coupled heat transfer performance. *Energy* 2022;240:122754. doi:10.1016/j.energy.2021.122754.
- [150] Zhou R. Chen Y. Zhang J. Guo P. Research progress in liquid cooling technologies to enhance the thermal management of LIBs. *Mater. Adv.* 2023;4:4011–4040. doi:10.1039/d3ma00299c.

- [151] Javani N. Dincer I. Naterer GF. Yilbas BS. Exergy analysis and optimization of a thermal management system with phase change material for hybrid electric vehicles. *Appl. Therm. Eng.* 2014;64(1–2):471–482. doi:10.1016/j.applthermaleng.2013.11.053
- [152] Sudhakaran S. Terese M. Mohan Y. Thampi AD. Rani S. Influence of various parameters on the cooling performance of battery thermal management systems based on phase change materials. *Appl. Therm. Eng.* 2023;222:116586. doi:10.1016/j.applthermaleng.2023.116586.
- [153] Zhao Y. Zou B. Li C. Ding Y. Active cooling based battery thermal management using composite phase change materials. *Energy Procedia.* 2019;158:4933–4940. doi:10.1016/j.egypro.2019.01.697.
- [154] Zhang W. Ling G. Zhuang L. Liang Z. The effect of reducing the thermal contact resistance on the performance of battery thermal management system. *Int. J. Energy Res.* 2021;45(7). doi:10.1002/er.6491.
- [155] Weng J. Zhang H. Liu Y. Chen X. Li M. An energy-saving battery thermal management strategy coupling tubular phase-change-material with dynamic liquid cooling under different ambient temperatures. *Renew. Energy.* 2022;195:918–930. doi:10.1016/j.renene.2022.06.025.
- [156] Ling Z. Cao J. Zhang W. Zhang Z. Fang X. Gao X. Compact liquid cooling strategy with phase change materials for Li-ion batteries optimized using response surface methodology. *Appl. Energy* 2018;228:777–788. doi:10.1016/j.apenergy.2018.06.143.
- [157] Ouyang T. Liu B. Xu P. Wang C. Ye J. Electrochemical-thermal coupled modelling and multi-measure prevention strategy for Li-ion battery thermal runaway. *Int. J. Heat Mass Transf.* 2022;194:123130. doi:10.1016/j.ijheatmasstransfer.2022.123130.
- [158] Zhuang Y. Chen T. Chen J. Li J. Guan M. Chen Y. Thermal uniformity performance of a hybrid battery thermal management system using phase change material and cooling plates arrayed in the manner of honeycomb. *Therm. Sci. Eng. Prog.* 2021;26:100836. doi:10.1016/j.tsep.2021.100836.
- [159] Lebrouhi BE. Lamrani B. Ouassaid M. Abd-Lefdil M. Maaroufi M. Kousksou T. Low-cost numerical lumped modelling of lithium-ion battery pack with phase change material and liquid cooling thermal management system. *J. Energy Storage* 2022;54. doi:10.1016/j.est.2022.105293
- [160] Bai J J. Sun Y L. Huang H Z. Chen G. Tang Y. Yuan W. Zhang L. An open super hydrophilic microchannel heat sink for thin film boiling with a high coefficient of performance. *Renew. Sustain. Energy Rev.* 2023;186:113684. doi:10.1016/j.rser.2023.113684.
- [161] Ren R. Zhao Y. Wang J. Liu Q. Zhang H. Experimental study on the bottom liquid cooling thermal management system for lithium-ion battery based on multichannel flat tube. *Appl. Therm. Eng.* 2023;219:119636. doi:10.1016/j.applthermaleng.2022.119636.
- [162] Drummond KP. Back D. Sinanis MD. Janes DB. Peroulis D. Weibel JA. Garimella SV. A hierarchical manifold micro-channel heat sink array for high-heat-flux two-phase cooling of electronics. *Int. J. Heat Mass Transfer* 2018;117:319–330. doi:10.1016/j.ijheatmasstransfer.2017.10.015.
- [163] Drummond K. Weibel J. Garimella S. Two-phase flow morphology and local wall temperatures in high-aspect-ratio manifold microchannels. *Int. J. Heat Mass Transfer* 2020;153:119551. doi:10.1016/j.ijheatmasstransfer.2020.119551.
- [164] Wang J. Mei W. Mao B. Wang Q. Investigation on the temperature control performance and optimization strategy of a battery thermal management system combining phase change and liquid cooling. *Appl. Therm. Eng.* 2023;232:121053. doi:10.1016/j.applthermaleng.2023.121053.
- [165] Zhang Y. Fu Q. Liu Y. Lai B. Ke Z. Wu W. Investigations of lithium-ion battery thermal management system with hybrid PCM/liquid cooling plate. *Processes* 2022;11(1). doi:10.3390/pr11010057.
- [166] Chen X. Zhou F. Yang W. Gui Y. Zhang Y. A hybrid thermal management system with liquid cooling and composite phase change materials containing various expanded graphite contents for cylindrical lithium-ion batteries. *Appl. Therm. Eng.* 2022;200(3):117702. doi:10.1016/j.applthermaleng.2021.117702.
- [167] Zhang W. Zhang W. Zhang G. Hu Y. Shao D. Jiang L. Wen Y. A novel leak-proof thermal conduction slot battery thermal management system coupled with phase change materials and liquid-cooling strategies. *Energies* 2024;17(4):939. doi:10.3390/en17040939.
- [168] Fan Y. Zhang X. Liu J. Wang H. Li M. Novel concept design of low energy hybrid battery thermal management system using PCM and multistage Tesla valve liquid cooling. *Appl. Therm. Eng.* 2023;220:119680. doi:10.1016/j.applthermaleng.2022.119680.
- [169] Akbarzadeh M. Kalogiannis T. Jin L. Karimi D. Van Mierlo J. Berecibar M. Experimental and numerical thermal analysis of a lithium-ion battery module based on a novel liquid cooling plate embedded with phase change material. *J. Energy Storage* 2022;50:104673. doi:10.1016/j.est.2022.104673.
- [170] Cao J. Ling Z. Fang X. Zhang Z. Delayed liquid cooling strategy with phase change material to achieve high temperature uniformity of Li-ion battery under high-rate discharge. *J. Power Sources* 2020;450:227673. doi:10.1016/j.jpowsour.2019.227673.
- [171] Zhang Y. Fu Q. Liu Y. Lai B. Ke Z. Wu W. Investigations of lithium-ion battery thermal management system with hybrid PCM/liquid cooling plate. *Processes* 2022;11(1). doi:10.3390/pr11010057.
- [172] An Z. Luo Y. Zhang C. Li D. Performance of chocolate bar-shaped modular thermal management system combined metal lattice liquid-cooling plate with paraffin in high-rate discharge. *J. Energy Storage* 2022;56. doi:10.1016/j.est.2022.106017.

- [173] Hu S. Wang S. Ma C. Li S. Liu X. Zhang Y. A hybrid cooling method with low energy consumption for lithium-ion battery under extreme conditions. *Energy Convers. Manag.* 2022;266(7):115831. doi:10.1016/j.enconman.2022.115831.
- [174] Hou G. Wang L. Zhang Y. Liu H. Chen J. An equivalent circuit model for battery thermal management system using phase change material and liquid cooling coupling. *J. Energy Storage.* 2022;55:105834. doi:10.1016/j.est.2022.105834
- [175] Liu L. Niu J. Wu J. Preparation of stable phase change material emulsions for thermal energy storage and thermal management applications: A review. *Materials* 2021;15:121. doi:10.3390/ma15010121.
- [176] Priyadarsini P. Sahoo S. Parida PK. Sathapathy PK. Effect of trapezoidal fin on heat transfer enhancement in PCM thermal energy storage system: a computational approach. *Int. J. Energy Environ. Eng.* 2022;23(7):13–28. doi:10.1615/InterJEnerCleanEnv.2021038462.
- [177] Priyadarsini P. Beuria A. Satapathy PP. Sahoo SS. Computational study of melting and solidification behavior of PCM thermal energy storage system using extended surface. *Adv. Mater. Process. Technol.* 2022:123–133. doi:10.1007/978-981-16-3297-6_8.
- [178] Chen J. Yang D. Jiang J. Ma A. Song D. Research progress of phase change materials (PCMs) embedded with metal foam (a review). *Procedia Mater. Sci.* 2014;4:389–394. doi:10.1016/j.mspro.2014.07.579.
- [179] Lazzarin R. Noro M. Righetti G. Mancin S. Application of hybrid PCM thermal energy storages with and without Al foams in solar heating/cooling and ground source absorption heat pump plant: An energy and economic analysis. *Appl. Sci.* 2019;9:1007. doi:10.3390/app9091007.
- [180] Babu Sanker S. Baby R. Phase change material based thermal management of lithium-ion batteries: A review on thermal performance of various thermal conductivity enhancers. *J. Energy Storage* 2022;50:104606. doi:10.1016/j.est.2022.104606.
- [181] Mehrabi-Kermani M. Houshfar E. Ashjaee M. A novel hybrid thermal management for Li-ion batteries using phase change materials embedded in copper foams combined with forced-air convection. *Int. J. Therm. Sci.* 2019;141:47–61. doi:10.1016/j.ijthermalsci.2019.03.026.
- [182] Guimarães TC. Gomes OdFM. Oliveira de Araujo OM. Lopes RT. da Gloria MYR. Toledo Filho RD. Koenders E. Caggiano A. Mankel C. Nazari Sam M. PCM-impregnated textile-reinforced cementitious composite for thermal energy storage. *Textiles* 2023;3:98–114. doi:10.3390/textiles3010008.
- [183] Kadam G. Kongi P. Battery thermal management system based on PCM with addition of nanoparticles. *Mater. Today Proc.* 2023;72:1543–1549. doi:10.1016/j.matpr.2022.09.384.
- [184] Rathore PKS. Shukla SK. Potential of macroencapsulated PCM for thermal energy storage in buildings: A comprehensive review. *Constr. Build. Mater.* 2019;225:723–744. doi:10.1016/j.conbuildmat.2019.07.221.
- [185] J E. Yi F. Li W. Effect analysis on heat dissipation performance enhancement of a lithium-ion-battery pack with heat pipe for central and southern regions in China. *Energy* 2021;226:120336. doi:10.1016/j.energy.2021.120336.
- [186] Jin LW. Lee PS. Kong XX. Fan Y. Chou SK. Ultra-thin minichannel LCP for EV battery thermal management. *Appl. Energy* 2014;113:1786–1794. doi:10.1016/j.apenergy.2013.07.013.
- [187] Zhu L. Xiong F. Chen H. Wei D. Li G. Ouyang C. Thermal analysis and optimization of an EV battery pack for real applications. *Int. J. Heat Mass Transf.* 2020;163:120384. doi:10.1016/j.ijheatmasstransfer.2020.120384.
- [188] Kheradmand M. Castro-Gomes J. Azenha M. Silva PD. Aguiar JLB. Zoorob SE. Assessing the feasibility of impregnating phase change materials in lightweight aggregate for development of thermal energy storage systems. *Constr. Build. Mater.* 2015;89:48–59. doi:10.1016/j.conbuildmat.2015.04.031.
- [189] Adesina A. Use of phase change materials in concrete: Current challenges. *Renew. Energy Environ. Sustain.* 2019;4:9. doi:10.1051/rees/2019006.
- [190] Wang F. Nasajpour-Esfahani N. Alizadeh A. Fadhil Smaism G. Abed AM. Hadrawi SK. Aminian S. Sabetvand R. Toghraye D. Thermal performance of a phase change material (PCM) microcapsules containing Au nanoparticles in a nanochannel: A molecular dynamics approach. *J. Mol. Liq.* 2023;373:121128. doi:10.1016/j.molliq.2023.121128.
- [191] Memon SA. Cui H. Lo TY. Li Q. Development of structural-functional integrated concrete with macro-encapsulated PCM for thermal energy storage. *Appl. Energy* 2015;150:245–257. doi:10.1016/j.apenergy.2015.03.137.
- [192] Zhang C. Huang J. Sun W. Xu X. Li C. Li Y. Research on liquid preheating performance for battery thermal management of electric vehicles at low temperature. *J. Energy Storage* 2022;55:105497. doi:10.1016/j.est.2022.105497.
- [193] Luo D. Zhao Y. Cao J. Wu Z. Yang X. Chen H. Effective temperature control of a thermoelectric-based battery thermal management system under extreme temperature conditions. *J. Energy Storage* 2024;103:114344. doi:10.1016/j.est.2024.114344.
- [194] Wu S. Xiong R. Li H. Nian V. Ma S. The state of the art on preheating lithium-ion batteries in cold weather. *J. Energy Storage* 2020;27:101059. doi:10.1016/j.est.2019.101059.
- [195] Wang Y. Zhang X. Chen Z. Low temperature preheating techniques for lithium-ion batteries: Recent advances and future challenges. *Appl. Energy* 2022;313:118832. doi:10.1016/j.apenergy.2022.118832.
- [196] Wu S. Xiong R. Li H. The state of the art on preheating lithium-ion batteries in cold weather. *J. Energy Storage* 2020;27:101059. doi:10.1016/j.est.2019.101059.
- [197] Gharehghani A. Effect analysis on performance improvement of battery thermal management in cold weather. *J. Energy Storage* 2022;45:103728. doi:10.1016/j.est.2022.103728.

- [198] Zhu T. Min H. Yu Y. Wang X. Li J. Chen L. Zhang H. An optimized energy management strategy for preheating vehicle-mounted Li-ion batteries at subzero temperatures. *Energies*. 2017;10(2):243. doi:10.3390/en10020243.
- [199] Wang Y. Rao Z. Liu S. Evaluating the performance of liquid immersing preheating system for lithium-ion battery pack. *Appl. Therm. Eng.* 2021;190:116758. doi:10.1016/j.applthermaleng.2021.116758.
- [200] Zhong G. Zhang G. Yang X. Researches of composite phase change material cooling/resistance wire preheating coupling system of a designed 18650-type battery module. *Appl. Therm. Eng.* 2017;127:176–183. doi:10.1016/j.applthermaleng.2017.08.022.
- [201] Lei Z. Zhang C. Li J. Fan G. Lin Z. Preheating method of lithium-ion batteries in an electric vehicle. *J. Mod. Power Syst. Clean Energy* 2015;3(2):289–296. doi:10.1007/s40565-015-0115-1.
- [202] Jin X. Li J. Zhang C. Wu P. Researches on modeling and experiment of Li-ion battery PTC self-heating in electric vehicles. *Energy Procedia* 2016;104:62–67. doi:10.1016/j.egypro.2016.12.012.
- [203] Wu X. Li L. Du J. Preheating strategy of variable-frequency pulse for lithium battery in cold weather. *Int. J. Energy Res.* 2020. doi:10.1002/er.5715.
- [204] Tan X. Lyu P. Fan Y. Rao J. Ouyang K. Numerical investigation of the direct liquid cooling of a fast-charging lithium-ion battery pack in hydrofluoroether. *Appl. Therm. Eng.* 2021;196:117279. doi:10.1016/j.applthermaleng.2021.117279.
- [205] Jithin KV. Rajesh PK. Numerical analysis of single-phase liquid immersion cooling for lithium-ion battery thermal management using different dielectric fluids. *Int. J. Heat Mass Transf.* 2022;188:122608. doi:10.1016/j.ijheatmasstransfer.2022.122608.
- [206] Li Q. Cho JR. Zhai J. Optimization of thermal management system with water and phase change material cooling for Li-ion battery pack. *Energies* 2021;14:5312. doi:10.3390/en14175312.
- [207] Farman PMK. Nikhila J. Sreeja AB. Roopa BS. Sahithi K. Kumar DG. AI-enhanced battery management systems for electric vehicles: Advancing safety, performance, and longevity. *E3S Web Conf.* 2024;591:04001. doi:10.1051/e3s-conf/202459104001.
- [208] Cavus QM. Dissanayake D. Bell M. Next generation of electric vehicles: AI-driven approaches for predictive maintenance and battery management. *Energies* 2025;18(5):1041. doi:10.3390/en18051041.