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REVIEW ARTICLE

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

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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

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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.

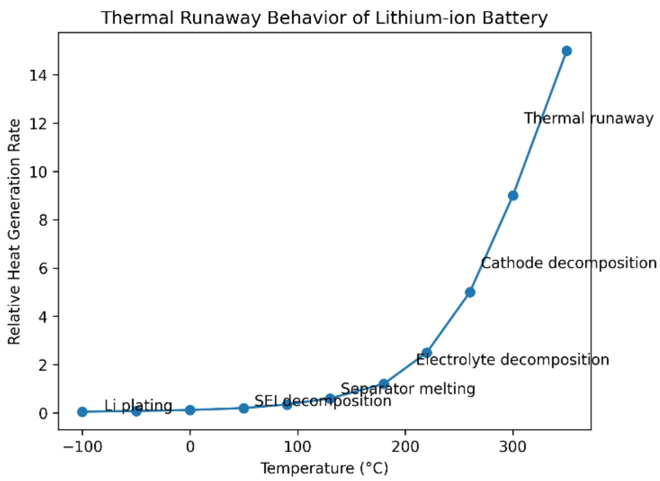

Figure 1. Effect of temperature on battery chemistry [Adopted from Panchal et al [36]

Battery Thermal Management System (BTMS) is required to limit the temperature of the battery pack within a preffered range to enhance the life. Existing methods are classfied 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,

$$CaO_2 + xLi + xe^- \rightarrow Li_xCoO_2 (Co^{4+} \text{ to } Co^{3+}) \quad (1)$$

Anode,

$$Li_xC_6 \rightarrow \text{Graphite} + xLi^+ + e^- \quad (2)$$

Charging reactions,

Cathode,

$$Li_xCoO_2 \rightarrow CaO_2 + xLi + xe^- (Co^{4+} \text{ to } Co^{3+}) \quad (3)$$

Anode,

$$\text{Graphite} + xLi^+ + e^- \rightarrow Li_xC_6 \quad (4)$$

Overall reaction,

$$yC + Li(z)O_2 \leftrightarrows Li_xC_y + Li_{(1-x)} + (Z)O_2 \quad (5)$$

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

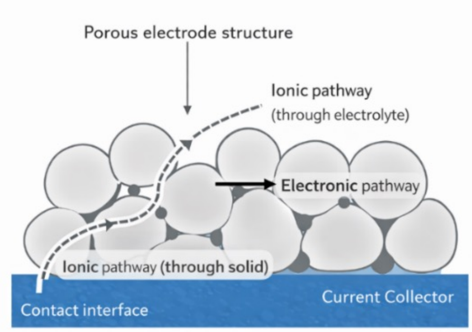

Figure 2. Microscopic view of material interface [From Kumar et al. [63], licensed under CC BY 4.0]

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 ^{0}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 ^{0}C) and Novec 649 (boiling temperature 39 ^{0}C). From the experimental results it was inferred that the boiling liquids controlled the temperature within 35 ^{0}C at 20C discharge rate. Also, cell temperature difference was maintained at 1 ^{0}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.

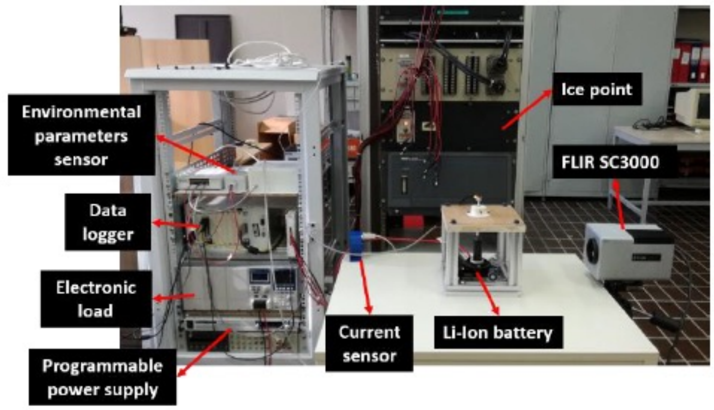

Figure 3. Experimental setup of dielectric cooling [From Giammichele et al. [88], licensed under CC BY 4.0]

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 ^{0}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 ^{0}C. At a discharge rate of 4C, the temperature was cooled down to 40.5 °C from 71.2 °C.

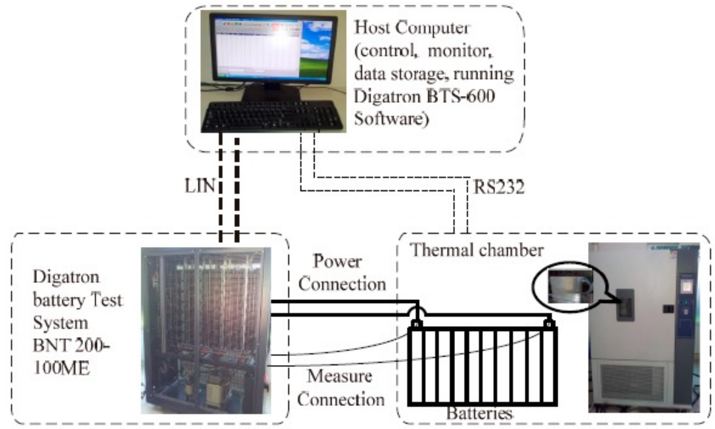

Figure 4. Liquid based heating and cooling system [From Wang and Xie J [104], licensed under CC BY 4.0]

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.

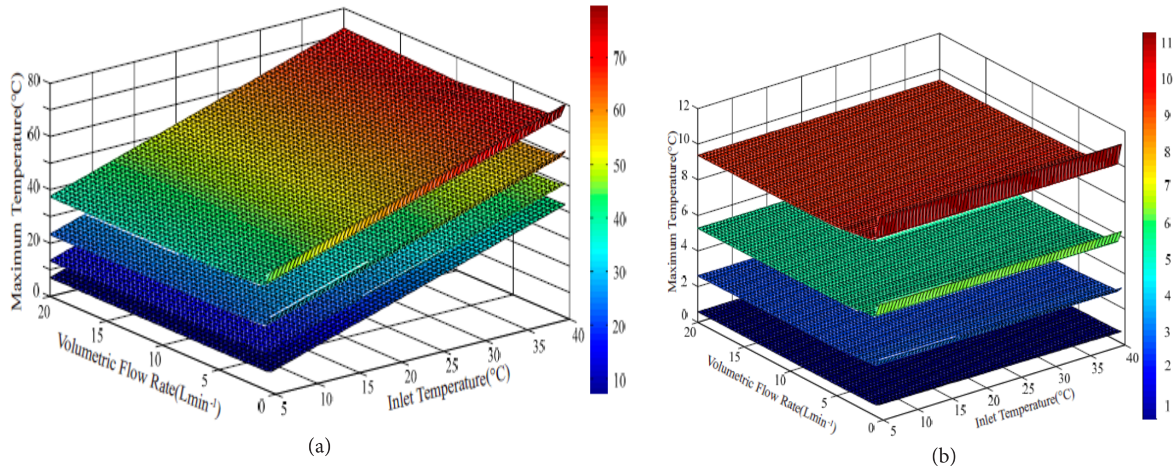

Figure 5. Effect of inlet temperature and flow rate **(a)** Battery maximum temperature **(b)** Cell temperature difference [From Wang and Xie J [104], licensed under CC BY 4.0]

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 ¾ -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).

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

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.

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

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

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, U_{ocv} – 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].

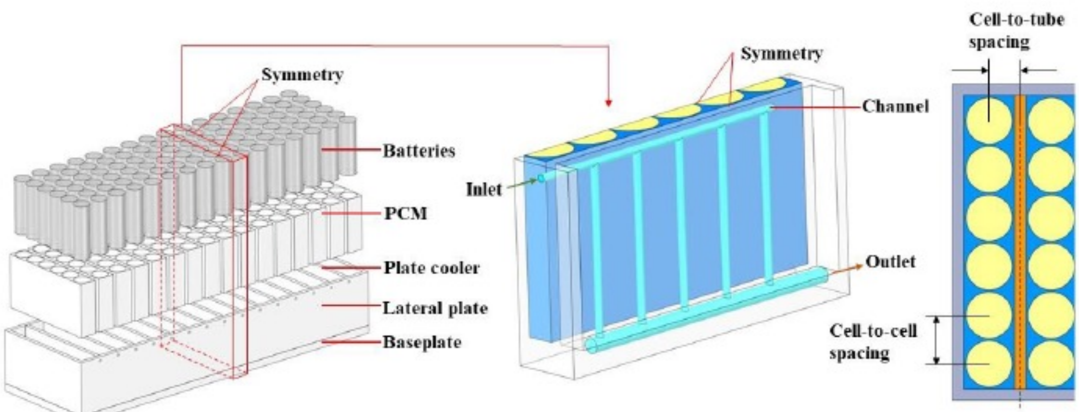

Figure 6. PCM assisted liquid cooling [From Zhang et al. [158] licensed under CC BY 4.0]

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 microencapsulated PCM. This offers enhanced thermal performance and leak free operation [177-181]. However, the preparation of PCM capsules often increases production costs.

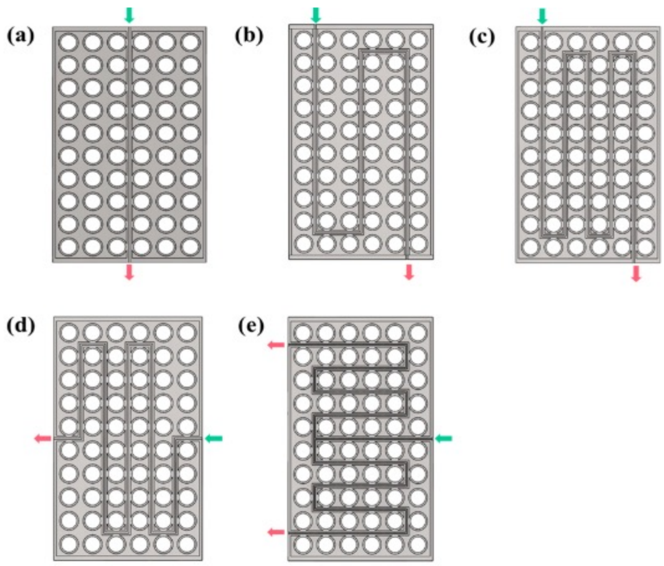

Figure 7. Flow pattern in a Novel liquid-PCM cooling [From Zhang et al. [167], licensed under CC BY 4.0]

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 $LiFePO_4$ 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-basedbattery 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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