Beyzanur Yavuz[1,2], Müslüm Arıcı[1], Sandro Nižetić[3]

A systematic review on battery thermal management systems for electric vehicles

[1]Mechanical Engineering Department, Engineering Faculty, Kocaeli University, 41001, Kocaeli, Turkey
[2]Mechanical Engineering Department, Engineering Faculty, Düzce University, 81620 Düzce, Turkey
[3]University of Split, FESB, Rudjera Boskovica 32, 21000, Split, Croatia

Abstract

The new technology of electric vehicles (EVs) is a promising alternative to deal with energy crisis, environmental pollution, global warming and climate change problems, as they are more environmentally friendly and efficient than internal combustion engine vehicles. Lithium-ion batteries, considered to be the heart of EVs, require specific operating conditions in terms of temperature. The most efficient operating temperature range for lithium-ion battery technology is between 25°C and 40°C, and the peak temperature difference between cells should be less than 5°C. The performance of battery decreases at values outside of the efficient operating temperature range. Therefore, an effective battery thermal management system (BTMS) is essential to improve the performance of the vehicle in safe and economic conditions. In this review, the methods of effectively dissipating the heat produced in the battery due to fast charging/discharging processes, controlling the undesired temperature rise in the battery, the BTMS and working principles necessary for ensuring EV safety and performance are addressed. In this regard, air-based cooling, phase change material based cooling, heat pipe based cooling, liquid-based cooling, and hybrid cooling methods have been thoroughly investigated. The advantages, drawbacks, application strategies and superior features of each method compared to the other are discussed and recommendations are given for future works.

***Keywords**: Battery thermal management system, Cooling, Electric vehicle, Charging/Discharging.*

1. Introduction

Diesel and gasoline vehicles release large amounts of CO, CO_2, SO_2, NO_x, HC, and particulate matter into the atmosphere [1,2]. Exhaust gases and particulate matter emitted from internal combustion engine vehicles bring with them problems that threaten the whole world, such as environmental pollution, global warming and climate change. 191 countries signed the Paris Climate Agreement to alleviate these problems, which are getting worse on a global scale [3]. With the depletion of fossil resources and the increasing importance of renewable energy sources, scientists have developed electric vehicles (EVs) and hybrid electric vehicles (HEVs) that are more efficient and less harmful to the environment than internal combustion engine vehicles. In addition to promising zero emissions, to create a cleaner environment and a greener future, EVs have also become an attractive vehicle that requires less energy cost per km than gasoline and diesel vehicles [4]. The energy for EVs is supplied by batteries which are one of the most vital components of the electric vehicle. The chemical properties of the battery and the type of battery determine the life of the battery, operating temperature, self-discharge rate, energy density, power capacity, and charge/discharge rate [5]. Although many types of batteries such as nickel-cadmium, lead-acid, solid-state, hybrid-nickel metal and lithium-ion have been used in electric vehicles from past to present, lithium-ion batteries stand out with their high energy density, high output voltage, being more environmentally friendly, no memory effect, less affected by temperature compared to other batteries, and low self-discharge rate [6,7]. However, lithium-ion batteries are very demanding on operating temperatures. The most suitable operating temperature for lithium-ion batteries is between 25°C and 40°C, and the temperature inequality between the battery cells should not exceed 5°C [8]. As the temperature inhomogeneity increases, the battery life decreases [9]. At higher temperatures above these conditions, battery capacity, performance characteristics, life, and chemical structure are adversely affected [10]. At extreme temperatures of 80°C and above, safety dangers such as thermal runaway, electrolytic explosion, and the release of hazardous gases may occur in the battery [11]. Thermal runaway is an undesirable situation that leads to the battery cells to heat up too much, thus shortening the service life of the battery [12]. Since the lithium-ion battery cell is limited to 2.4 - 4.2 V values, battery packs are created by connecting the cells in series and parallel to provide the desired voltage values and required performance [13]. Due to space and weight constraints, battery cells in contact positioned so closely affect each other thermally and may trigger an explosion [14]. In addition, the efforts to charge the EV in a shorter time and the applications to increase the power density to get a more effective performance from the battery also increase the heat generated in the battery, consequently, leading to a rise in the temperature of the battery pack. Considering all these, the battery thermal management system (BTMS) is necessary to ensure the safety of the vehicle, improve driving conditions and increase its performance. BTMSs perform heating and cooling as needed to keep the battery cells operating within the optimum operating temperature [15]. Considering the fact that the vehicle is constantly in motion and the ambient temperature changes depending on the climatic conditions, determining the appropriate BTMS strategy and developing and optimizing the BTMS design is an important research topic. At this point, the cooling load required by the battery, the battery type (cylindrical, prismatic and pouch type), the vehicle type and the ambient temperature are critical in managing the thermal problems of the battery [16].

2. Review Methodology

Currently, there are numerous studies on BTMS. This review paper was compiled based on the studies between 2018 and 2023, especially including recent articles. During these years, the demand for EVs has boosted due to the support of the country's administrations and various environmental concerns. In view of this situation, efforts in this field have accelerated in order to cope with the challenges. Numerous reports and research articles on BTMS in the past and present have attempted to find solutions to the challenges of heat management in electric vehicles. This article primarily focuses on the classification of BTMS, the advantages and disadvantages of each method, and the developments in battery cooling strategies in recent years. Therefore, articles published in distinguished journals by leading scientists working on BTMS were specifically investigated and included in the current study. Research and review articles fallen within the scope of this study were analyzed in detail. In addition, internationally recognized journals and studies written only in English were included in the review and discussion process. In order to determine the most relevant paper for the study, some keywords such as BTMS, BTMS types, air-cooled BTMS, PCM-based BTMS, liquid-cooled BTMS, HP-based BTMS, and Hybrid BTMS were searched. The research, which specifically focused on issues related to thermal management strategies, constraints and applicability of EV batteries, resulted in 94 articles deemed suitable for inclusion in the study. BTMS types are addressed respectively, and their advantages, disadvantages, cooling efficiency, and cost analysis are discussed. Finally, research gaps of BTMSs, possible scenarios, and future studies are presented.

3. Types of BTMS

The BTMS of an electric vehicle must ensure that the battery remains within the effective temperature range by performing heating and cooling in the battery when necessary, so that the vehicle performs within safe limits [17]. Ambient temperature is one of the important parameters affecting the performance of electric vehicles. When the ambient temperature drops below 0°C, the performance of the battery declines significantly, due to fact that, at these low temperatures, a lithium coating can suddenly form in the battery pack [18]. Therefore, BTMS performs heating to maintain the performance and chemistry of the battery. It also performs cooling at temperatures exceeding the limits of battery health and vehicle safety. In addition to the battery pack, software and hardware equipment are used in BTMS to provide thermal safety [15]. Electric vehicle developers are optimizing the use of high energy density battery packs to increase vehicle range. However, this requires BTMS to work more effectively. Techniques used for BTMS can be divided into 5 groups; liquid-based cooling, air-based cooling, heat pipe (HP) based cooling, phase change material (PCM) based cooling, and combination of at least two aforementioned methods, i.e. hybrid cooling [19]. The advantages, disadvantages, and system component of these systems are presented in Table 1. Literature survey regarding each BTMS technique mentioned above is discussed in separate subsections. The key findings in literature for each technique are summarized in the form of table.

Although the equipment, materials and design parameters used in each of these systems are different, their intended use and cooling performance also differ. Apart from this, BTMSs are also classified according to the amount of en-

Table 1. Features of BTMS used in EVs to date.

BTMS	Advantages	Disadvantages	System Components
Air based BTMS	Uncomplicated structure, long life, low cost, electrical safety, no risk of leakage as in liquid-based and PCM-based BTMS	Low cooling performance, high energy consumption	Fans, ventilation channel
Liquid based BTMS	High cooling efficiency, more uniform cell temperature distribution	High energy consumption, risk of leakage and complex structure	Cold plate, heat pipe, jacket, pump
Heat pipe based BTMS	Flexible geometry, less noise compared to air cooling and high cooling	Not sufficient when reaching high discharge rates, risk of leakage and high cost	Heat pipe
PCM based BTMS	More uniform temperature distribution, fast thermal response, no need for extra energy, effective cooling performance when integrated with other systems	Risk of leakage, lower thermal conductivity compared to liquid-based BTMS	Phase Change Material

ergy consumption, active and passive method [20]. The classification of these methods into subtitles is summarized in Figure 1. Passive methods do not require external cooling or heating equipment. The use of fins, HP, and PCM is among the most common passive methods. In the active method, unlike the passive method, an extra energy source such as a pump or fan is needed. Although this improves cooling performance, it is also considered a costly approach [21].

3.1. Air based BTMS

Air-based BTMS is one of the considerable methods that can be used to keep the battery at effective operating temperature [22]. Air-based BTMS continues to be preferred in light-duty EVs thanks to its uncomplicated structure, no risk of leakage, lightness, long life, and low cost [25-25]. However, as liquid-based BTMSs are developed and provide higher cooling performance, air-based BTMSs are falling into the background. Air-based BTMS has disadvantages compared to liquid-based BTMS, such as lower cooling performance, noise problems caused by the fan, and higher energy consumption [26]. The specific heat capacity of air is considerably lower compared to liquids, requiring higher airflow rate to reach the desired results [27]. Additionally, compared to other cooling methods, air cooling can cause high temperature differences between cells. Thus, the battery may not achieve the expected performance, which adversely affects the chemistry and service life of the battery. To prevent these problems, more air flow can be directed to the battery pack within acceptable pressure loss and cost limits or different channel geometries can be considered. However, in conditions where cooling is insufficient, it should be combined with liquid cooling or hybrid cooling methods [28].

In air-based BTMSs, the air flow rate entering the system, the ventilation channel and its structure, the battery pack, and the geometry of the battery used are of great importance [29]. In air-based BTMSs, it is possible to change the battery cell arrangement, adjust the air flow, use different geometry batteries, and change the inlet and outlet geometry to enhance the cooling performance [30].

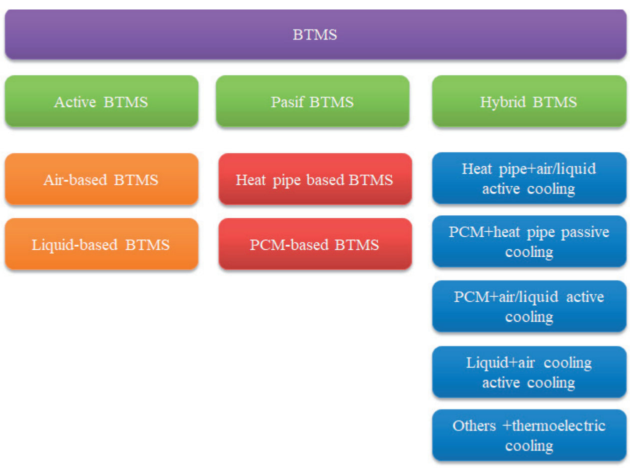

Fig. 1. BTMS classification [21].

Singh et al. [31] suggested air-based BTMS to protect the battery from temperature exposure, ensuring its durability and sustained performance. They utilized 15 cylindrical battery cells, included a straight wall and a wall with different undulation numbers, and compared the results quite comprehensively. It is clear that increasing the air inlet velocity considerably enhances the cooling performance, and the use of undulating walls compared to straight walls leads to a non-negligible temperature drop in the battery temperature. They also discussed the cooling efficiency by altering the number of battery cells. Yang et al. [32] developed a new study to improve temperature uniformity using air-based BTMS. The effect of valve opening and air flow parameters in the valve on temperature changes in the battery was investigated. It was concluded that the valve opening parameter improved the temperature uniformity in the battery and that the valve opening and pressure difference were inversely proportional.

Air-based BTMSs are basically divided into active and passive systems according to the way they use the air. While air intake to passive systems is provided from the atmosphere, auxiliary equipment such as fans are used in active systems [33]. Akbarzadeh et al. [34] compared a 48V battery pack built with 12 prismatic battery cells, air-based and liquid-based BTMS using computational fluid dynamics. Coolant flow rate, coolant temperature, power consumption were the parameters changed. In both systems, it was found that increasing the coolant throughput led to a decrease in the maximum cell temperature. In addition, the increase in coolant throughput had a greater impact compared to the liquid-based BTMS. Table 2 lists studies on air-based cooling methods and highlights the key details of the study.

3.2. PCM based BTMS

Compared to air-based and liquid-based BTMS, PCM are promising materials that allow large amounts of heat to be stored and released during phase change and have become the focus of attention by researchers [35]. The classification of PCM is presented in Figure 2. PCMs have fast thermal responses [36]. PCM provides more uniform temperature distributions in the battery compared to air-based and liquid-based BTMS, but may not be as effective as liquid cooling at high discharge rates [37,38]. In addition, PCMs have good cooling performance without the need for extra energy consumption [39]. But, PCMs are easily and frequently integrated with PCM-liquid cooled or PCM-air cooled BTMSs to rapidly dissipate heat stored in the battery, forming a crucial component of hybrid cooling [10, 40]. However, besides these features, PCM has low thermal conductivity and leaks problem [41]. PCM's low thermal conductivity makes it harder for heat to build up in the battery and to conduct heat out of the battery pack. Therefore, combining PCM and other cooling methods becomes inevitable to improve cooling performance and efficiency. PCM-based BTMSs are more vulnerable to ambient temperatures than air-based and liquid-based BTMSs, therefore their adoption is constrained [16]. Considering all these features, PCMs are not yet widely used in commercial EVs [42]. Numerous studies have been conducted on the temperature behavior, cooling performance and cost effectiveness of using PCM in BTMS. Studies on this topic, which has moved to the centre of scientific attention, continue unabated. Patel and Rathod [43] added fins to improve the multiple cycle cooling performance of PCM-based BTMS. And when the rest time is taken into account in the analysis, it was seen that the fins and 20 minutes rest time for multiple cycles were close to the expected results. Deng et al. [44] used composite phase change material (CPCM) to improve the leakage and poor thermal conductivity problem of PCM. As a result, it was concluded that the optimization of the use of CPCM in EVs and HEVs would yield broadly effective and beneficial results. Bais et al. [45] surrounded a 1.2 Ah, 3.7V single battery cell with 4 mm PCM layer. They performed discharge experiments in the presence and absence of PCM. As a result of the study, they measured temperature behavior and electrical changes separately for 1200 seconds in both cases. It was revealed that when PCM was integrated into the system, the battery cell thermal behavior was provided more perfectly and was more durable compared to the one without PCM in the same experimental environment. Li et al. [46] proposed a BTMS design using PCM. The aim of the research was to reduce the weight of the PCM by keeping it within reliable working temperature under favorable operating conditions. The study with a variable number of battery cells was compared and discussed experimentally and numerically. It is clearly seen that as the PCM radius and the heat generation rate of the battery grow, the peak temperature difference and the battery temperature increase, respectively. Zhang et al. [47] presented BTMS with various fin configurations depending on the PCM to reinforce heat transfer, which is a major phenomenon. The number of fins, thickness, angle, length, area and variable heat transfer coefficient were the parameters investigated. The computational fluid dynamics analysis results were validated by experimental studies. Finally, the novel fins designed possessed outstanding performance characteristics compared to the traditional flat fins. Huo et al. [48] introduced a PCM-based BTMS method to study temperature uniformity, which is a crucial point in the research and improvement of battery technologies. Table 3 presents recent studies on PCM-based cooling methods, discusses the working method and purpose of the study, and classifies the conditions under which the study is conducted.

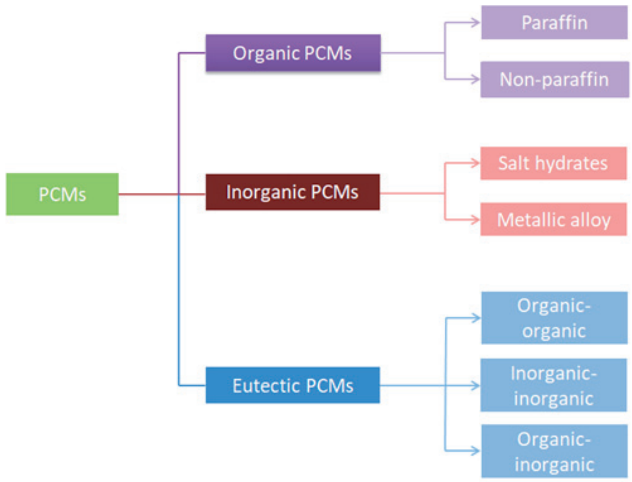

Fig. 2. Classification of PCM [49].

Table 2. Summary of studies on air-based BTMS.

Author	Method	Battery		Tmax	Remarks
		Type	Number		
Wang et al. [26]	Sim.	Cylindrical	24	304.27K	Channel distance and air inlet velocity optimization
Yu et al. [52]	Sim.	Cylindrical	16	NA	Investigation of the effects of air inlet and outlet cross section on the temperature of the battery pack
Li et al. [53]	Sim.	Cylindrical 2230 mAh	32	41.07 °C	Economic optimization of BTMS, investigation of the relationship between battery temperature and cycle life, determining the relationship between BTMS thermal efficiency increase and cycle cost
Mao-Sung Wu [54]	Sim.	Prismatic	12	NA	Effect of air cooling type on battery thermal performance and energy efficiency, optimization study

Table 3. Summary of studies on PCM-based BTMS.

Author	Method	Type	Battery Number	Load	Tmax	Remarks
El Idi et al. [55]	Exp. +Sim.	Cylindrical 2500 mAh	1	NA	NA	Investigation of cell temperature during charge/ discharge cycles
Wu et al. [56]	Exp.	Prismatic	5	1C 3C 5C	53.47 ◦C at 3C	Design criteria of shape memory composite phase change material and testing its applicability on BTMS, investigation of performance characteristics, temperature distribution and heat dissipation capacity of BTMS at different charge/discharge rates
Verma et al. [57]	Sim.	Pouch	1	2C	305 K at the end of 1200 s at 3 mm thickness	Comparison of the effects of capric acid and commonly used paraffin on BTMS at different thicknesses and different ambient temperatures, observing the effect of PCM on BTMS at high discharge rate
Kadam and Kongi [58]	Exp.+ Sim.	Cylindrical	12	1C 2C 3C	NA	Discussing the effect of PCM thickness on battery temperature distribution, cooling performance and weight at different charge/discharge rates.

3.3. Liquid-based BTMS

Liquid-based BTMS is one of the most frequently used methods to secure the safe operation of batteries in EVs. Although it requires a more complex structure and more energy consumption compared to air-based BTMS, it provides a very effective cooling performance thanks to the high specific heat capacity of the liquid [50]. However, liquid-based cooling is costly and increases the mass of the battery system considerably [51]. This technique is commonly utilized in leading EVs such as the BMW i3 and Tesla due to its superior cooling ability [38]. Water and glycol are frequently used in these systems. A mixture of water and glycol can also be used according to cost analysis and ambient conditions [59]. Vikram et al. [60] used a mixture of water and different concentrations of Ethylene Glycol and Propylene Glycol as coolant in BTMS. Temperature change, energy need, and ambient temperature were the analyzed parameters. The battery pack is set to operate at a constant temperature of 25°C. Considering the conditions of India, where the study was conducted, the ambient temperature was started from 30°C and increased by 5°C, up to 50°C. The load on BTMS, cumulative energy consumption value, and temperature profile results were evaluated together. It has been revealed that it takes more time and requires more cumulative energy to reduce the fluid entering the system to 25°C at high ambient temperatures. When water and other fluid concentrations were examined, it was observed that adding 25% propylene glycol and 50% ethylene glycol to the coolant provided effective results.

Liquid-based BTMS is divided into two groups: indirect contact and direct contact. In direct contact cooling, the battery pack has a more effective cooling performance than the indirect cooling because it is in direct contact with the dielectric liquid surrounding its surface [61]. In this way, more heat is removed from the battery pack, but since the dielectric liquid used has a high viscosity, more energy is required to circulate the liquid in the system [61, 62].

In indirect liquid-cooled systems, a cold plate, jacket, and heat pipes are used to remove the heat from the battery pack and keep the vehicle running in safe conditions [62]. Although it provides a more uniform temperature distribution and significantly reduces the temperature difference, the direct contact cooling method is not preferred except for fast charging [63]. While the indirect liquid cooling method is utilized in vehicles such as the Mercedes EQS, Tesla Model Y, Porsche Taycan, the direct liquid cooling method continues to be applied in the McLaren Speedtail model [64]. In Table 4, current studies on liquid-based cooling methods are presented, the key points of the study are highlighted, and the conditions under which the study was conducted are reported.

3.4. Heat pipe based BTMS

The heat pipe is one of the effective methods used to remove the heat generated in the battery. It can significantly reduce the thermal imbalance between battery cells [65]. Heat pipes with a compact structure, flexible geometry, and high cooling performance working with the phase change principle have been developed and studied by scholars recently [66, 67]. Heat pipes possess low thermal resistance, and act as heat exchangers that transmit heat from high temperature to low temperature by using phase changes [68]. They are outstanding components capable of transferring heat despite relatively low temperature differences [69]. Guo et al. [70] developed BTMS with heat pipe and micro heat pipe to enable efficient and high performance operation of batteries. In this way, they compared battery aging, the electrochemical structure of the battery, its service life, and the heat production in the battery. As a result, although a few cycles gave effective results, they could not obtain a satisfactory thermal management result after 1250 cycles owing to the formation of solid electrolyte interphase in the battery. In addition, micro heat pipes offered better results than heat pipes in the management of the peak temperature in the battery pack and the peak temperature difference in the battery cells. Jouhara et al. [71] experimentally studied the effects of a heat mat, which can be easily incorporated into the system, on the peak temperature and temperature uniformity of the battery on prismatic battery cells, using heat pipe-based BTMS. The results were very impressive and at the same time a useful approach model. The heat mat provided a very high performance in absorbing and removing the heat produced in the battery cells, thus reducing the energy requirement from the pump. Ren et al. [72] experimentally studied a BTMS with a preheated U-shaped micro heat pipe to prevent the battery from being affected by low ambient temperature. Variable energy input to the system, the presence or absence of heat pipes surrounded by an insulating material were the parameters tested. The results indicate that heat pipes surrounded by insulating material subjected to preheating undergo a remarkable temperature increase and enable a satisfactory preheating process. It is also concluded that cooling and heating processes can be carried out together. In addition to these studies, research on HP-based cooling methods is presented in Table 5.

3.5. Hybrid cooling

Although researchers are constantly developing battery systems, the proposed systems may be inadequate if used alone. When a single method is insufficient for cooling in battery systems and efficient and desired results cannot be achieved, more than one method is used together, and higher cooling performances are achieved by emphasizing the superior features of these methods. Thus, hybrid BTMSs have been proposed and have become the focus of researchers. Hybrid BTMSs are used for different purposes depending on the application area and expectations [73].

Table 4. Summary of studies on liquid-based BTMS.

Author	Method	Type	Battery Number	Load	Tmax	ΔT	Remarks
Li et al. [76]	Exp. +Sim.	Prismatic 64 Ah	12	1C 1.5C 2C 2.5C 3C	313 K	5 K at <3C	Analysis of the effects of operating conditions and battery pack design on the pressure drop, temperature and cooling performance of the BTMS, effect of coolant flow direction on temperature gradient
Wang et al. [77]	Sim.	Pouch battery 50 Ah	9	0.8C	311.2592 K	13.1092 K	Investigation of cooling performance of coolant flow rate and direction on BTMS
Wang et al. [78]	Exp. +Sim	Cylindrical	20	3C	53.48 °C	18.72°C (flow rate is 40 ml/min, serial cooling mode)	Improving pressure drop, energy consumption and temperature uniformity discussing the effects of coolant flow rate and serial or parallel design of the cooling system on BTMS.
Tousi et al. [79]	Sim.	Cylindrical	12	3C 5C 7C	305.59 K	1.07 K	Analyzing the effects of the inlet speed and amount of nanofluid-added liquid cooling at different discharge rates on BTMS performance and efficiency.
Chen et al. [80]	Exp.	Prismatic	8	0.5C 1C 1.5C 2C 2.5C	33.35°C	NA	Development of the regression model of the most effective and efficient BTMS in the fast charge-discharge

Table 5. Summary of studies on HP-based BTMS.

Author	Method	Type	Battery Number	Load	Tmax	Remarks
Zhang and Wei [81]	Exp.+ Sim.	Prismatic	5	4C 6C 8C	54.3 °C	Discussion of experimental and analysis results of flat heat pipe design and temperature distribution, cost and performance at different discharge rates.
Behi et al. [82]	Exp.+ Sim.	Prismatic	15	8C	43.8 °C at 0.2 m/s	Experimental and numerical discussion of different types of cooling, Investigation of battery pack temperature change by changing input speed
Liang et al. [83]	Exp.	Prismatic	2	NA	NA	Experimental discussion of the effects of coolant flow rate, coolant temperature, ambient temperature, heat generation per cell and BTMS start-up time on battery health and thermal performance.
Wang et al. [84]	Exp.+ Sim.	Cylindrical	12	3C 5C	31.55 °C	Comparing and discussing the analysis and experimental results of the effects of the design parameters of the conductive structural element in contact with the battery on the temperature distribution.

Active systems require excessive energy and cause temperature inequalities and require the support of passive systems. By using these two cooling strategies together, energy consumption decreases and battery temperature is distributed more evenly [74]. Ahmad et al. [75] enhanced a hybrid BTMS design with PCM and air cooling. They added fins to their system to improve heat transfer and comprehensively analyzed its contribution to cooling performance with and without PCM. It was observed that the wings added to the developed hybrid BTMS facilitated the air flow and yielded excellent results compared to the other analysis conditions tested. While the highest temperature value was obtained for Fin-Air BTMS, PCM-Fin-Air BTMS remained at a more controllable and reasonable level. There was a temperature improvement of 18.6% between PCM-Fin-Air BTMS and Fin-Air BTMS. The study offered a fresh outlook, particularly in the context of high charge and discharge environments, and was highly encouraging for the future of green energy initiatives. Mousavi et al. [85] designed a cooling system that combined PCM and liquid-based BTMS using prismatic battery cells to improve cooling performance.

They carried out the analysis with the help of ANSYS FLUENT at 1C, 2C, and 3C variable discharge rates. They concluded that the PCM plates integrated into the battery system provide a more significant cooling effect as the discharge rate increases. They discussed the cooling performance when 1 and 3 PCM plates were added to the system without using PCM by changing the speed of the refrigerant entering the mini-channel cooling plates at 3C discharge rate. When the refrigerant velocity was 0.01 m/s and a 100% increase in flow rate was made, a significant temperature drop of 9 K and 15 K occurred in the battery. Faizan et al. [86] developed a new cooling design by combining PCM and cooling plate with 3 mm diameter in different channel structures.

Isfahani et al. [88] proposed a new approach by combining PCM and microchannels to alleviate the extreme temperature and temperature inequality that pose a major threat to the battery. As a result, PCM/metal foam shows the highest temperature, although it is more excellent in terms of temperature uniformity and temperature standard deviation. In contrast, microchannels exhibit the opposite behavior. Therefore, the utilization of these two techniques together ensures that the battery operates within the desired operating temperatures. Additionally, an analysis of the response characteristics of battery cells and packs has been conducted, highlighting that the effect of surrounding battery cells is substantial and should not be underestimated. Zhao et al. [89] created a hybrid system by integrating air-based BTMS with liquid-based BTMS to improve the cooling effect. Coolant flow rate, number of pipes used in the system, fan position, and distance between coolant and battery were studied on COMSOL software and results were discussed. As a result of the analysis, it was seen that the change in the number of pipes did not have much effect on the maximum temperature in the battery. Additionally, it was concluded that there was an improvement in the temperature uniformity of the battery pack when the liquid flow rate entering the system was increased. In terms of cooling performance and energy efficiency, it is recommended that the air entering the system must not exceed 0.4 m/s. Zhou et al. [90] created a novel approach by combining an air jet and a helical flow coil into the battery system. The results revealed that this innovative hybrid system achieved a lower peak temperature difference than the liquid-based one when air cooling is applied at the positive and negative ends of the battery cell. Air inlet velocity and temperature were the parameters investigated and it was observed that varying them did not cause a major improvement in cooling performance. Wang et al. [91] proposed a novel BTMS with different flow orientations by combining PCM and liquid cooling with wavy microchannel structure. Increasing the number of liquid microchannels utilized in the improved hybrid system and different oriented flow enhanced the cooling efficiency. In addition, by switching from a microchannel cooling plate system to a hybrid system, there has been a substantial decrease in weight, which is also very advantageous in terms of cost and energy savings. Zhao et al. [92] conducted an experimental and numerical study on ANSYS FLUENT by combining composite phase change material and liquid cooling using 20 cylindrical type batteries. The study was carried out separately with pure PCM and hybrid cooling method under different experimental conditions. They inferred that with the liquid cooling included in the system in addition to PCM, the heat produced in the battery is transferred more effectively, but as a result, the temperature difference and the required energy increase. In the study conducted under 0.5C, 1C, and 2C discharge rates and variable discharge depth, when the discharge rate was 2C, the change in Reynolds number from 0 to 112 caused a 6 K decrease in the peak temperature, 59W power requirement and temperature differences. Table 6 presents a summary of the comprehensive report, organized and ranked based on recent research findings.

Table 6. Summary of studies on hybrid BTMS.

Author	Method	BTMS Type		Battery		Remarks	Tmax	ΔT
			Type	Number	Load			
Wang et al. [87]	Exp.+ Sim.	PCM+Liquid cooling	Cylindrical	12	1C 2C	coolant flow and inlet temperature optimization, control of energy consumption	57.6 °C, 44.8 °C	4.1 °C, <2 °C
Liu et al. [88]	Exp.+ Sim.	PCM+Liquid cooling	Cylindrical	16	1C 2C 3C 4C 5C	ambient temperature, coolant inlet temperature, flow direction optimization	46.2 °C	4.2 °C
Peng et al. [89]	Exp.+ Sim.	PCM+Heat pipe	Cylindrical	40	0.5 C 1C 2C	investigation of the effect of PCMs with different properties on the thermal performance of the battery	47.7 °C at 2C	NA
Chen et al. [90]	Sim.	Air cooling+ PCM	Cylindrical	16	1C 2C 4C 8C	investigation of ambient temperature, inlet velocity and melting and solidification temperature of PCM	NA	NA
Li et al. [91]	Exp.+ Sim.	Air cooling + Liquid cooling	Pouch battery 16 Ah	1 and 5	1C 3C 5C	effects of air velocity, air inlet location, different number of fans, cold plate thickness on BTMS	64.3 °C at 5C	NA
Yuan et al. [92]	Exp.	Heat pipe + Liquid cooling	Prismatic 50Ah	1	0.5–2C	coolant flow rate, evaporation section and condensing section length of HP-CP, ambient and inlet coolant temperature, battery discharge rate	34.1 °C	1 °C
Wang et al. [93]	Exp.	Heat pipe + PCM	Cylindrical	40	2C	effect of PCM tube and HP hybrid system on BTMS	47.7 °C	2.5 °C
Jang et al. [94]	Exp. + Sim.	Heat pipe + Liquid cooling	Prismatic 40Ah	10	0.5–2C	determination of the effects of discharge rate, liquid mass flow rate, liquid temperature and ambient temperature on BTMS		

4. Conclusions

In this review, BTMSs of electric vehicles developed to cope with the increasing energy crisis, environmental pollution and global warming and to alleviate these problems are discussed and systematically addressed. Electric vehicles are designed to be more efficient than those powered by internal combustion engines, and they do not contribute to greenhouse gas emissions in the environment. To ensure that these vehicles operate within safe limits and with high performance, the battery must be kept in efficient operating conditions. Batteries are very sensitive to temperature, so they can be kept within safe temperature limits one of air-based cooling, liquid-based cooling, heat pipe-based cooling, PCM-based cooling or hybrid cooling methods. This also maintains battery health and chemistry and increases cycle life. The following conclusions have been formulated based on a thorough examination of the relevant literature:

- Air-based cooling is one of the most preferred basic methods with its uncomplicated structure, no risk of leakage, lightness and low cost. However, since the specific heat capacity of air is lower than that of liquid, the cooling performance is lower than liquid cooling. Additionally, due to the application strategy of this method and the thermophysical properties of air, significant temperature differences can occur between the cells in the battery pack. This can degrade the performance and lifespan of batteries. To enhance the cooling efficiency of air-based cooling, the air flow rate, ventilation channel and structure, battery type and arrangement can be improved. Yet, when all these adjustments are insufficient, air-based cooling should be applied with other types of cooling techniques to maintain the battery within the range.
- Liquid-based cooling is one of the methods widely used in electric vehicles today to keep the battery in the optimum temperature range and provides high cooling performance. However, since liquid-based cooling has a complex system structure, energy consumption and cost can be relatively high. Today, many automotive manufacturers such as Mercedes, Tesla, Porsche, and McLaren have applied liquid-based BTMS instead of air-based BTMS due to its effective thermal management performance.
- PCM-based cooling is one of the BTMSs that is increasingly becoming the focus of researchers' attention and is constantly being developed. PCMs can absorb and dissipate large amounts of energy without needing extra energy. They have fast response times and a structure that can be easily integrated with other systems. However, PCMs have low thermal conductivity and leakage problems. Although various research studies have been conducted on the cooling performance, system compatibility and cost optimization of PCM, it has not yet been fully utilized commercially in EVs.
- Heat pipe-based cooling is one of the methods studied with great interest by researchers. Heat pipes with a compact structure and flexible geometry can remove the heat produced in the battery without needing extra energy. These systems, which work on the phase transformation principle, are sensitive to even low temperature differences and can operate efficiently.
- When a solely battery management system alone is insufficient for securing efficient run of batteries, more than one method can be employed simultaneously. In this way, systems that provide superior cooling performance can be created with hybrid cooling. Excess energy demanded by active systems can be compensated by the inclusion of passive systems. Furthermore, the control of the maximum temperature of the battery pack and the distribution of the cell temperature can be substantially improved.

5. Recommendation and future work

The numerical analysis of the battery is a complicated and extensive process in itself, and it is very essential that the results are consistent with the actual driving cycle. Deviation levels must be within acceptable limits and can be further improved. Although a variety of studies have been carried out regarding BTMS, several critical aspects still need to be examined. The majority of the weight of existing EVs consists of battery systems. This also leads to higher transportation costs. A key aspect of ongoing studies involves the replacement of the existing battery with a higher energy density variant to minimize weight. However, this creates certain problems, such as, under fast charge/discharge cycles, the higher energy density battery generates more heat. To dissipate this heat generated in the battery pack, a BTMS is necessary to maintain effective and safe conditions for continuous cycling. For variable battery types, cost analysis, weight, volume, and energy consumption values should be evaluated all together to reach optimum operating temperature range conditions. Although several parameters such as battery geometry and arrangement, ambient temperature, fluid inlet velocity, channel structures, number of channels, fluid type, and additives have been investigated for different BTMS types, it has been observed that there is a gap in cost effectiveness and energy efficiency studies. Therefore, it is thought to be beneficial for future studies to shift to this area, which is a key factor for BTMS. In addition, when the methods used in BTMSs are discussed separately, the following approaches may be valuable for potential research and can be focused on these issues.

- BTMSs for safe driving conditions: Advanced technology EV batteries have a higher energy density compressed into the battery and operate under continuous fast charge/discharge cycles. Without an appropriate control mechanism, this situation may adversely affect the battery, resulting in considerable destruction. In case of crash or collision, it may cause the release of poisonous gas, fire, explosion or even loss of life. BTMS is required to eliminate all these negativities and ensure the operation of the battery within a controlled temperature range. However, it is necessary to study in depth for different battery technologies to prevent the risk of thermal runaway, fire and explosion. Additionally, it is essential to consider the entire battery system, rather than just individual battery cells, when developing effective cooling strategies and thermal management solutions.

- During fast charge/discharge cycles, the cooling capacity required by the battery and the recommended cooling system must match each other. In order to choose the most appropriate cooling method, battery type and geometry, energy density of the battery, and discharge/charge conditions must be determined correctly. This approach is essential for preventing the battery from overheating.

- Air-based BTMSs: Air-based BTMS has significant restrictions that can lead to some problems. This method, in terms of its structure and applicability, may cause unequal temperature distribution between the cells in the battery pack, and it may produce undesirable levels of noise when operated at high levels. In terms of cooling efficiency, it is more suitable for use in light commercial vehicles. In order to enhance the cooling performance of air-based BTMS under safe and economic conditions, it is recommended to integrate air-based BTMS with other cooling strategies and to conduct deeper studies in this field in future studies. In addition, the distance between battery cells can be regulated within the allowed dimensions in order to control the battery temperature and ensure safe driving conditions. Moreover, this method can be further improved with the help of differently directed air flow and air duct with different geometry.

- PCM-based BTMSs: PCM-based cooling, which promises great potential, has not yet been fully commercialized. More research and development work are needed on these materials, to be utilized in EVs. System feasibility and material characteristics can be further enhanced by incorporating composite PCMs into BTMS. It is expected that the improvement of the flammability issue of PCMs, optimization of system size, and advancement of weight and thermal performance values will facilitate the inclusion of PCM in the EV market. The problem of decreasing PCM latent heat in continuous cycle should be addressed, and studies should be carried out to prevent the risk of leakage. In addition, by integrating PCM and liquid-based BTMS under appropriate operating conditions to meet the requirements of the system, more effective thermal control can be achieved than using these methods alone.

- Liquid-based BTMSs: Liquid-based BTMS is capable of effectively managing battery temperature in systems where high cooling performance is demanded. However, if not designed properly, it can result in a high temperature difference between cells. When this situation repeats in a continuous cycle, the service life of the battery is shortened and battery chemistry may deteriorate. In liquid-based BTMS, the selection of the coolant that corresponds to the cooling capacity required by the battery and its compatibility with the system is crucial. Especially in liquid-based BTMSs, additives utilized to improve cooling performance and conductivity coefficients cause heterogeneity problems in the closed loop. In the long term, efforts to ensure the flow of liquid cooling in homogeneous and appropriate conditions should continue. Additionally, studies should be developed to increase heat transfer by increasing the contact area of the battery component and the cooling interface. A major drawback for liquid-based BTMS is the leakage problems and the risks associated with it. This challenge can be mitigated by the development of a design that works in harmony with the requirements of the system and the inclusion of suitable sealing components. When all these complicated constraints and challenges are fully investigated and addressed with innovative solutions, liquid-based BTMS can be transformed into a safe and secure system.

- HP-based BTMSs: For thermal management, enhancing the heat transfer properties of the HP is the primary focus, considering that the battery is in constant operation. It is preferable to start research by developing heat pipe design, battery-heat pipe layout and material properties. Aluminum HPs are expected to be preferred to provide an advantage when weight is taken into account.

- Hybrid cooling: Hybrid cooling systems are created by integrating these methods together when air-based BTMS, PCM-based BTMS, liquid-based BTMS, and HP-based BTMS are insufficient alone. Hybrid method, which includes advanced and new technologies, requires more space, and increases weight as it involves different cooling methods. Additionally, the real-time thermal performance of this method on lithium-ion batteries needs to be improved. Especially by combining HP and PCM, various thermal management combinations can be designed that provide superior cooling compared to other approaches. However, studies should be carried out to determine the most optimal strategy considering different aspects such as cost, volume, weight, and time management. In addition, when the current researches in the literature are investigated, it is noticed that initially the cooling performance of the battery is aimed to be improved. However, there are very limited efforts on the response and sustainability of all these management technologies in the long term. This is a huge gap in the literature and the focus of future studies should be concentrated on this field. The hybrid cooling method is considered a very promising approach for the EV market and future studies that transition to high-performance and fast charging conditions. However, since it incorporates versatile cooling strategies, design configurations and cooling equipment must be selected harmoniously.

6. References

[1] Kim, I., Kim, Y., Kwon, J., Lee, C., & So, J. J. Beyond concept: The viability of exclusive lanes for zero emission vehicles on expressways. Transportation Research Part D: Transport and Environment 121 (2023) 103803.

[2] Kothare, C. B., Kongre, S., Malwe, P., Sharma, K., Qasem, N. A., Ağbulut, Ü., ... & Panchal, H. Performance improvement and CO and HC emission reduction of variable compression

ratio spark-ignition engine using n-pentanol as a fuel additive. Alexandria Engineering Journal 74 (2023) 107-119.

[3] Shrinet, E.S., A. Mukherjee, and L. Kumar, A novel thermal management system design based on variable contact area to maintain uniform temperature in Li-ion battery module. Journal of Energy Storage 72 (2023) 108332.

[4] Wankhede, S. and L.V. Kamble, A novel battery cooling system using nanofluids on MATLAB Simulink. Energy Storage 5.3 (2023) e418.

[5] Gong, H. and T. Hansen, The rise of China's new energy vehicle lithium-ion battery industry: The coevolution of battery technological innovation systems and policies. Environmental Innovation and Societal Transitions 46 (2023) 100689.

[6] Wang, C., Xu, J., Wang, M., & Xi, H. Experimental investigation on reciprocating air-cooling strategy of battery thermal management system. Journal of Energy Storage 58 (2023) 106406.

[7] Aswin Karthik, C., Kalita, P., Cui, X., & Peng, X. Thermal management for prevention of failures of lithium ion battery packs in electric vehicles: A review and critical future aspects. Energy Storage 2.3 (2020) e137.

[8] Son, Y.W., D. Kang, and J. Kim, Passive battery thermal management system for an unmanned aerial vehicle using a tetrahedral lattice porous plate. Applied Thermal Engineering 225 (2023) 120186.

[9] Rao, Z., Y. Wen, and J. Zhao, Thermal performance of battery thermal management system using composite matrix coupled with mini-channel. Energy Storage 1.3 (2019) e59.

[10] Ebbs-Picken, T., C.M. Da Silva, and C.H. Amon, Design optimization methodologies applied to battery thermal management systems: A review. Journal of Energy Storage 67 (2023) 107460.

[11] Bhutto, Y. A., Pandey, A. K., Saidur, R., Sharma, K., & Tyagi, V. V. Critical Insights and Recent Updates on Passive Battery Thermal Management System Integrated with Nano-enhanced Phase Change Materials. Materials Today Sustainability 23 (2023) 100443.

[12] Chavan, S., Venkateswarlu, B., Prabakaran, R., Salman, M., Joo, S. W., Choi, G. S., & Kim, S. C. Thermal runaway and mitigation strategies for electric vehicle lithium-ion batteries using battery cooling approach: A review of the current status and challenges. Journal of Energy Storage 72 (2023) 108569.

[13] Ghaeminezhad, N., Z.S. Wang, and Q. Ouyang, A Review on lithium-ion battery thermal management system techniques: A control-oriented analysis. Applied Thermal Engineering 219 (2023) 119497.

[14] Murugan, M., Saravanan, A., Elumalai, P. V., Murali, G., Dhineshbabu, N. R., Kumar, P., & Afzal, A. Thermal management system of lithium-ion battery packs for electric vehicles: An insight based on bibliometric study. Journal of Energy Storage 52 (2022) 104723.

[15] Thakur, A. K., Sathyamurthy, R., Velraj, R., Saidur, R., Pandey, A. K., Ma, Z. & Ali, H. M. A state-of-the art review on advancing battery thermal management systems for fast-charging. Applied Thermal Engineering 226 (2023) 120303.

[16] Vikram, S., Vashisht, S., Rakshit, D., & Wan, M. P. Recent advancements and performance implications of hybrid battery thermal management systems for Electric Vehicles. Journal of Energy Storage 90 (2024) 111814.

[17] Kalaf, O., Solyali, D., Asmael, M., Zeeshan, Q., Safaei, B., & Askir, A. Experimental and simulation study of liquid coolant battery thermal management system for electric vehicles: A review. International journal of energy research 45.5 (2021) 6495-6517.

[18] Xiao, J., Zhang, X., Bénard, P., Yang, T., Zeng, J., & Long, X. Fin structure and liquid cooling to enhance heat transfer of composite phase change materials in battery thermal management system. Energy Storage 5.6 (2023) e453.

[19] Ranjbaran, Y.S., M.H. Shojaeefard, and G.R. Molaeimanesh, Thermal performance enhancement of a passive battery thermal management system based on phase change material using cold air passageways for lithium batteries. Journal of Energy Storage 68 (2023) 107744.

[20] Khaboshan, H. N., Jaliliantabar, F., Abdullah, A. A., & Panchal, S. Improving the cooling performance of cylindrical lithium-ion battery using three passive methods in a battery thermal management system. Applied Thermal Engineering 227 (2023) 120320.

[21] Luo, J., Zou, D., Wang, Y., Wang, S., & Huang, L. Battery thermal management systems (BTMs) based on phase change material (PCM): A comprehensive review. Chemical Engineering Journal 430 (2022) 132741.

[22] Sikarwar, S., Kumar, R., Yadav, A., & Gwalwanshi, M. Battery thermal management system for the cooling of Li-Ion batteries, used in electric vehicles. Materials Today: Proceedings 2023.

[23] Moosavi, A., A.-L. Ljung, and T.S. Lundström, A study on the effect of cell spacing in large-scale air-cooled battery thermal management systems using a novel modeling approach. Journal of Energy Storage 72 (2023) 108418.

[24] Wu, T., Wang, C., Hu, Y., Fan, X., & Fan, C. Research on spray cooling performance based on battery thermal management. International Journal of Energy Research 46.7 (2022) 8977-8988.

[25] Liu, L., X. Zhang, and X. Lin, Recent Developments of Thermal Management Strategies for Lithium-Ion Batteries: A State-of-The-Art Review 10.6 (2022) 2101135.

[26] Wang, Y., Liu, B., Han, P., Hao, C., Li, S., You, Z., & Wang, M. Optimization of an air-based thermal management system for lithium-ion battery packs. Journal of Energy Storage 44 (2021) 103314.

[27] Hua, Y., Zhou, S., Cui, H., Liu, X., Zhang, C., Xu, X., & Yang, S. A comprehensive review on inconsistency and equalization technology of lithium-ion battery for electric vehicles. International Journal of Energy Research 44.14 (2020) 11059-11087.

[28] Chen, K., Zhang, Z., Wu, B., Song, M., & Wu, X. An air-cooled system with a control strategy for efficient battery thermal management. Applied Thermal Engineering 236 (2024) 121578.

[29] Zhang, F., Zhang, L., Lin, A., Wang, P., & Liu, P. Multi-method collaborative optimization for parallel air cooling lithium-ion battery pack. International Journal of Energy Research, 46.10 (2022) 14318-14333.

[30] Li, C., Ding, Y., Zhou, Z., Jin, Y., Ren, X., Cao, C., & Hu, H. Parameter optimization and sensitivity analysis of a Lithium-ion battery thermal management system integrated with composite phase change material. Applied Thermal Engineering 228 (2023) 120530.

[31] Singh, L.K., R. Kumar, and A.K. Gupta, A novel strategy of enhanced thermal performance in air cooled lithium-ion battery by wavy walls. Thermal Science and Engineering Progress 43 (2023) 101964.

[32] Yang, R.Y., M.W. Wang, and H. Xi, Thermal investigation and forced air-cooling strategy of battery thermal management system considering temperature non-uniformity of battery pack. Applied Thermal Engineering 219 (2023) 119566.

[33] Ren, R., Zhao, Y., Diao, Y., Liang, L., & Jing, H. Active air cooling thermal management system based on U-shaped micro heat pipe array for lithium-ion battery. Journal of Power Sources 507 (2021) 230314.

[34] Akbarzadeh, M., Kalogiannis, T., Jaguemont, J., Jin, L., Behi, H., Karimi, D. & Berecibar, M. A comparative study between air cooling and liquid cooling thermal management systems for a high-energy lithium-ion battery module. Applied Thermal Engineering 198 (2021) 117503.

[35] Ismail, K. A., Lino, F. A., Machado, P. L. O., Teggar, M., Arıcı, M., Alves, T. A., & Teles, M. P. New potential applications of phase change materials: A review. Journal of Energy Storage 53 (2022) 105202.

[36] Wu, X., Wang, K., Chang, Z., Chen, Y., Cao, S., Lv, C. & Wang, Y. Experimental and numerical study on hybrid battery thermal management system combining liquid cooling with phase change materials. International Communications in Heat and Mass Transfer 139 (2022) 106480.

[37] Ni, R., Zhang, D., Wang, R., Xie, Z., & Wang, Y. Prevention and suppression effects of phase change material on thermal runaway in batteries. Case Studies in Thermal Engineering 48 (2023) 103160.

[38] Wang, R., Liang, Z., Souri, M., Esfahani, M. N., & Jabbari, M. Numerical analysis of lithium-ion battery thermal management system using phase change material assisted by liquid cooling method. International Journal of Heat and Mass Transfer 183 (2022) 122095.

[39] Lin, X.W. and X.L. Zhang, Research Progress of Phase Change Storage Material on Power Battery Thermal Management. Energy Technology 9.4 (2021) 2000940.

[40] Youssef, R., Kalogiannis, T., Behi, H., Pirooz, A., Van Mierlo, J., & Berecibar, M. A comprehensive review of novel cooling techniques and heat transfer coolant mediums investigated for battery thermal management systems in electric vehicles. Energy Reports 10 (2023) 1041-1068.

[41] Lee, S., U. Han, and H. Lee, Development of a hybrid battery thermal management system coupled with phase change material under fast charging conditions. Energy Conversion and Management 268 (2022) 116015.

[42] Bernagozzi, M., Georgoulas, A., Miché, N., Rouaud, C., & Marengo, M. Novel battery thermal management system for electric vehicles with a loop heat pipe and graphite sheet inserts. Applied Thermal Engineering 194 (2021) 117061.

[43] Patel, J.R. and M.K. Rathod, Novel approach for the performance augmentation of phase change material integrated battery thermal management system for number of charging/discharging cycles. Energy Storage, 5.6 (2023) e456.

[44] Deng, J., Li, X., Li, C., Wang, T., Liang, R., Li, S. & Zhang, G. Multifunctional flexible composite phase change material with high anti-leakage and thermal conductivity performances for battery thermal management. Journal of Energy Storage 72 (2023) 108313.

[45] Bais, A., D. Subhedar, and S. Panchal, Experimental investigation of longevity and temperature of a lithium-ion battery cell using phase change material based battery thermal management system. Materials Today: Proceedings 2023.

[46] Li, Y., Du, Y., Xu, T., Wu, H., Zhou, X., Ling, Z., & Zhang, Z. Optimization of thermal management system for Li-ion batteries using phase change material. Applied Thermal Engineering 131 (2018) 766-778.

[47] Z hang, F., Lu, F., Liang, B., Zhu, Y., Gou, H., Xiao, K., & He, Y. Thermal performance analysis of a new type of branch-fin enhanced battery thermal management PCM module. Renewable Energy 206 (2023) 1049-1063.

[48] Huo, Y., X. Pang, and Z. Rao, Investigation on the effects of temperature equilibrium strategy in battery thermal management using phase change material. 2020. 44.9 (2020) 7660-7673.

[49] Gu, H., Chen, Y., Yao, X., Huang, L., & Zou, D. Review on heat pump (HP) coupled with phase change material (PCM) for thermal energy storage. Chemical Engineering Journal 455 (2023) 140701.

[50] Rabiei, M., A. Gharehghani, and A.M. Andwari, Enhancement of battery thermal management system using a novel structure of hybrid liquid cold plate. Applied Thermal Engineering 232 (2023) 121051.

[51] Shen, X., Cai, T., He, C., Yang, Y., & Chen, M. Thermal analysis of modified Z-shaped air-cooled battery thermal management system for electric vehicles. Journal of Energy Storage 58 (2023) 106356.

[52] Yu, Q., Abidi, A., Mahmoud, M. Z., Malekshah, E. H., & Aybar, H. Ş. Numerical evaluation of the effect of air inlet and outlet cross-sections of a lithium-ion battery pack in an air-cooled thermal management system. Journal of Power Sources 549 (2022) 232067.

[53] Li, W., Wang, N., Garg, A., & Gao, L. Multi-objective optimization of an air cooling battery thermal management system considering battery degradation and parasitic power loss. Journal of Energy Storage 58 (2023) 106382.

[54] Wu, M.-S., Multi-objective optimization of U-type air-cooled thermal management system for enhanced cooling behavior of lithium-ion battery pack. Journal of Energy Storage 56 (2022) 106004.

[55] El Idi, M.M., M. Karkri, and M. Abdou Tankari, A passive thermal management system of Li-ion batteries using PCM composites: Experimental and numerical investigations. International Journal of Heat and Mass Transfer 169 (2021) 120894.

[56] Wu, T., Wang, C., Hu, Y., Zhou, L., & He, K. Research on novel battery thermal management system coupling with shape memory PCM and molecular dynamics analysis. Applied Thermal Engineering 210 (2022) 118373.

[57] Verma, A., S. Shashidhara, and D. Rakshit, A comparative study on battery thermal management using phase change material (PCM). Thermal Science and Engineering Progress 11 (2019) 74-83.

[58] Kadam, G. and P. Kongi, Battery thermal management system based on PCM with addition of nanoparticles. Materials Today: Proceedings 72 (2023) 1543-1549.

[59] Altuntop, E. S., Erdemir, D., Kaplan, Y., & Özceyhan, V. A comprehensive review on battery thermal management system for better guidance and operation. Energy Storage 5.8 (2023) e501.

[60] Vikram, S., S. Vashisht, and D. Rakshit, Performance analysis of liquid-based battery thermal management system for Electric Vehicles during discharge under drive cycles. Journal of Energy Storage 55 (2022) 105737.

[61] He, L., Jing, H., Zhang, Y., Li, P., & Gu, Z Review of thermal management system for battery electric vehicle. Journal of Energy Storage 59 (2023) 106443.

[62] Alnaqi, A.A., Numerical analysis of pressure drop and heat transfer of a Non-Newtonian nanofluids in a Li-ion battery thermal management system (BTMS) using bionic geometries. Journal of Energy Storage 45 (2022) 103670.

[63] Zuo, S.G., S.P. Chen, and B. Yin, Performance analysis and improvement of lithium-ion battery thermal management system using mini-channel cold plate under vibration environment. International Journal of Heat and Mass Transfer 193 (2022) 122956

[64] Maiorino, A., Cilenti, C., Petruzziello, F., & Aprea, C. A review on thermal management of battery packs for electric vehicles. Applied Thermal Engineering (2023) 122035.

[65] Wang, J., Lu, S., Wang, Y., Ni, Y., & Zhang, S. Novel investigation strategy for mini-channel liquid-cooled battery thermal management system 44.3 (2020) 1971-1985.

[66] Wang, Y., Mu, X., Xie, Y., Li, W., Dan, D., Qian, Y., & Zhang, Y. A coupled model and thermo-electrical performance analysis for flat heat pipe-based battery thermal management system. Applied Thermal Engineering 223 (2023) 121116.

[67] Han, U., Lee, S., Jun, Y. J., & Lee, H.Experimental investigation on thermal performance of battery thermal management system with heat pipe assisted hybrid fin structure under fast charging conditions. Applied Thermal Engineering 230 (2023) 120840.

[68] Shailesh, K., Y. Naresh, and J. Banerjee, Heat transfer performance of a novel PCM based heat sink coupled with heat pipe: An experimental study. Applied Thermal Engineering 229 (2023) 120552.

[69] Weragoda, D. M., Tian, G., Burkitbayev, A., Lo, K. H., & Zhang, T. A comprehensive review on heat pipe based battery thermal management systems. Applied Thermal Engineering 224 (2023) 120070.

[70] Guo, Z., Xu, Q., Wang, Y., Zhao, T., & Ni, M. Battery thermal management system with heat pipe considering battery aging effect. Energy 263 (2023) 126116.

[71] Jouhara, H., Serey, N., Khordehgah, N., Bennett, R., Almahmoud, S., & Lester, S. P. Investigation, development and experimental analyses of a heat pipe based battery thermal management system. International Journal of Thermofluids 1 (2020) 100004.

[72] Ren, R., Zhao, Y., Diao, Y., & Liang, L. Experimental study on preheating thermal management system for lithium-ion battery based on U-shaped micro heat pipe array. Energy 253 (2022) 124178.

[73] Zhao, C., Zhang, B., Zheng, Y., Huang, S., Yan, T., & Liu, X. Hybrid Battery Thermal Management System in Electrical Vehicles: A Review. Energies 13 (2020) 6257.

[74] Liu, L., X.L. Zhang, and X.W. Lin, Recent Developments of Thermal Management Strategies for Lithium-Ion Batteries: A State-of-The-Art Review. Energy Technology 10.6 (2022) 2101135.

[75] Ahmad, S., Liu, Y., Khan, S. A., Hao, M., & Huang, X. Hybrid battery thermal management by coupling fin intensified phase change material with air cooling. Journal of Energy Storage 64 (2023) 107167.

[76] Li, M., Ma, S., Jin, H., Wang, R., & Jiang, Y. Performance analysis of liquid cooling battery thermal management system in different cooling cases. Journal of Energy Storage 72 (2023) 108651.

[77] 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. Journal of Energy Storage 40 (2021) 102771.

[78] 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. Applied Thermal Engineering 178 (2020) 115591.

[79] Tousi, M., Sarchami, A., Kiani, M., Najafi, M., & Houshfar, E. Numerical study of novel liquid-cooled thermal management system for cylindrical Li-ion battery packs under high discharge rate based on AgO nanofluid and copper sheath. Journal of Energy Storage 41 (2021) 102910.

[80] Chen, S., Bao, N., Garg, A., Peng, X., & Gao, L. A Fast Charging–Cooling Coupled Scheduling Method for a Liquid Cooling-Based Thermal Management System for Lithium-Ion Batteries. Engineering 7.8 (2021) 1165-1176.

[81] Zhang, Z. and K. Wei, Experimental and numerical study of a passive thermal management system using flat heat pipes for lithium-ion batteries. Applied Thermal Engineering 166 (2020) 114660.

[82] Behi, H., Karimi, D., Behi, M., Jaguemont, J., Ghanbarpour, M., Behnia, M. & Van Mierlo, J. Thermal management analysis using heat pipe in the high current discharging of lithium-ion battery in electric vehicles. Journal of Energy Storage 32 (2020) 101893.

[83] Liang, J., Y. Gan, and Y. Li, Investigation on the thermal performance of a battery thermal management system using heat pipe under different ambient temperatures. Energy Conversion and Management 155 (2018) 1-9.

[84] Wang, J., Gan, Y., Liang, J., Tan, M., & Li, Y. Sensitivity analysis of factors influencing a heat pipe-based thermal management system for a battery module with cylindrical cells. Applied Thermal Engineering 151 (2019) 475-485.

[85] Mousavi, S., Zadehkabir, A., Siavashi, M., & Yang, X. An improved hybrid thermal management system for prismatic Li-ion batteries integrated with mini-channel and phase change materials. Applied Energy 334 (2023) 120643.

[86] Faizan, M., S. Pati, and P. Randive, Effect of channel configurations on the thermal management of fast discharging Li-ion battery module with hybrid cooling. Energy 267 (2023) 126358.

[87] 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. Applied Thermal Engineering 232 (2023) 121080.

[88] Liu, Z., Wang, B., Tan, Y., & Li, P. Thermal management of lithium-ion battery pack under demanding conditions and long operating cycles using fin-enhanced PCMs/water hybrid

cooling system. Applied Thermal Engineering 233 (2023) 121214.

[89] Peng, P., Y. Wang, and F. Jiang, Numerical study of PCM thermal behavior of a novel PCM-heat pipe combined system for Li-ion battery thermal management. Applied Thermal Engineering 209 (2022) 118293.

[90] Chen, F., Huang, R., Wang, C., Yu, X., Liu, H., Wu, Q. & Bhagat, R. Air and PCM cooling for battery thermal management considering battery cycle life. Applied Thermal Engineering 173 (2020) 115154.

[91] 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. Applied Thermal Engineering 146 (2019) 866-880.

[92] Yuan, X., Tang, A., Shan, C., Liu, Z., & Li, J. Experimental investigation on thermal performance of a battery liquid cooling structure coupled with heat pipe. Journal of Energy Storage 32 (2020) 101984.

[93] Wang, Y., Peng, P., Cao, W., Dong, T., Zheng, Y., Lei, B., ... & Experimental study on a novel compact cooling system for cylindrical lithium-ion battery module. Applied Thermal Engineering 180 (2020) 115772.

[94] Jang, D. S., Yun, S., Hong, S. H., Cho, W., & Kim, Y. Performance characteristics of a novel heat pipe-assisted liquid cooling system for the thermal management of lithium-ion batteries. Energy Conversion and Management 251 (2022) 115001.