J Ther Eng, Vol. 12, No. 2, pp. 830–841, March, 2026

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0001116

Review Article

A comprhensive review on aircooled battery thermal mangement system of electric vehicles

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ARTICLE INFO

Article history
Received:13 December 2024
Revised: 15 February 2025
Accepted: 25 February 2025

Keywords:
Electric Vehicles; Battery Thermal Management; Air Based Battery Cooling; Material Recovery; Hydrometallurgy; Pyrometallurgy; Plug-in EVs; Li-ion Battery; Battery Material Recovery

ABSTRACT

Battery-operated modern mobility systems are commonly referred to as Electric Vehicles. The transition from conventional internal combustion engines to modern electric mobility is progressing rapidly. Incorporating Electric Vehicles is a practical solution to addressing environmental pollution caused by the combustion of petroleum-based fuels. Among the various energy storage options, Lithium-ion batteries are the preferred choice due to their superior features, including high energy density, longevity, and efficiency. However, the performance, safety, and lifespan of Lithium-ion batteries are highly sensitive to operating temperature. Therefore, an effective battery thermal management system is essential. This review paper focuses on air-based thermal management systems. Compared to other cooling methods, air-based systems offer notable advantages, such as simplicity, lower cost, and ease of implementation. Despite these benefits, air-based systems often face challenges in efficiently managing higher thermal loads. Various techniques related to air-based cooling systems are discussed in detail. Additionally, the paper provides an overview of alternative cooling methods for comparison and context.

Cite this article as: S Kumar P, Krishnappa GB, Devegowda M. A comprhensive review on aircooled battery thermal mangement system of electric vehicles. J Ther Eng 2026;12(2):830–841.

INTRODUCTION

For the past few decades, world witnesses the exponential increase in demand of petroleum fuels. The excessive burning of these fuels in automobiles has caused severe environmental degradation. The vehicular pollution has crossed its acceptable level in major cities of the world. Government regulating bodies in various countries have been implementing stringent emission norms to deal with the pollution caused by vehicles. Many countries have been encouraging the research and development in the field of eco-friendly vehicles. This leads to a development of new-generation vehicles called Electric Vehicles (EVs). In EVs, the power required for the vehicle traction is supplied by a storage battery. There are three types of EVs: Battery Electric Vehicles (BEVs), Plug-in Hybrid Vehicles (HPVs) and Hybrid Electric Vehicles (HEVs). Currently, wide

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This paper was recommended for publication in revised form by Editorin-Chief Ahmet Selim Dalkılıç

Published by Yıldız Technical University Press, İstanbul, Turkey

varieties of storage batteries are available. Among the various options, Lithium-ion (Li-ion) battery shows better features in terms of energy-density, long-life and compactness [1-4]. Thus, Li-ion battery is widely accepted and employed in EVs. These batteries are also used in electronic devices [5]. To accommodate the required power in EV, more numbers of Li-ion batteries need to be connected in series and parallel. The life and performance of Li-ion battery are highly influenced by the working temperature [6-8]. The battery pack temperature should be maintained between 15 to 35 °C [9-11] and uniform cell temperature shall be within 5 °C [12-17]. Significant amount of heat is being generated while charging as well as discharging. The heat generation could be due to Joule's effect, called irreversible heat (Q_{ir}) and electrochemical reaction, known as reversible heat (Q_r) [18]. Bernardiet.al [19] developed a correlation (1) to find the total heat generation in a battery.

$$Q = Q_{ir} + Q_r = I2\ R_{in} - I\ T\ \frac{dT}{dE_o} \tag{1}$$

I is the current, R_{in} is the internal resistance, T is the temperature and $\frac{dT}{dE_o}$ is the entropy coefficient. To maintain the operating temperature of a Li-ion battery within acceptable limits, an effective Battery Thermal Management System (BTMS) is necessary. The safety, economic viability, and size of the BTMS should be carefully considered. At present, cooling is achieved using air, liquid, heat pipe, phase change materials (PCM) and thermoelectric cooling (TEC) technique. Alternatively, different cooling methods may be combined [20-22]. Each cooling method has its own pros and cons. Based on the cooling technique adopted, BTMSs are categorised into Active, Passive and Hybrid systems. In an active system, either free or forced cooling is achieved by air or liquid. Heat pipe or Phase Change Material (PCM) is employed in passive system. Hybrid system generally includes two different cooling methods.

Recent advancements in Battery Thermal Management Systems (BTMS) have garnered significant attention, particularly in the context of electric vehicles (EVs). Researchers have developed various BTMS solutions to enhance battery performance, safety, and longevity. This article provides a comprehensive review of the latest developments in air-based BTMS while also offering an overview of liquid, phase change material (PCM), and hybrid approaches.

NON-UNIFORM TEMPERATURE

Non-uniform cell temperature is one of the critical issues associated with Li-ion batteries. The key components of a Li-ion battery are the anode, cathode, electrolyte, and separator [23, 24]. During charging and discharging, lithium ions exchange between the two electrodes through the separator and electrolyte. During charging, lithium ions move from the anode to the cathode by absorbing energy from an external source. The same energy is then released as electricity when electrons flow from the anode to the cathode through an external circuit [25, 26]. The basic working principle of a Li-ion battery is illustrated in Figure 1. Various chemical reactions occur during these processes, and a significant amount of heat is also generated. As a result, a temperature gradient develops across the battery pack, which is often non-uniform.

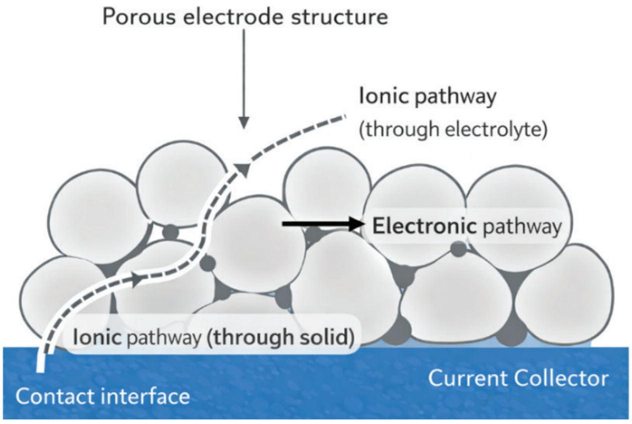

Figure 1. Electronic pathway at the interface.

Several factors contribute to the uneven temperature distribution across the battery pack and within each cell. A study by Hossein Maleki et al. [27] revealed that the structure of the electrodes changes due to repeated cycles. The variation in open-circuit voltage leads to changes in specific heat capacity, which causes de-lithiation. De-lithiation significantly impacts the structural changes in the battery. Moreover, the thermal conductivity of the electrode materials is affected by the changes in the specific heat of the battery.

An experimental study by Frank Richter et al. [28] explored the changes in the thermal conductivity of battery materials and the temperature profile. The thermal conductivity of the electrodes and separator is influenced by the electrolyte. The study showed that the thermal conductivity of the separator and electrodes was poor under dry conditions. Consequently, the decomposition of the electrolyte during aging reduces the thermal conductivity of these materials. The temperature profile of the battery pack is also highly influenced by the discharge rate. The temperature difference between the center and the edge of the battery pack increases with the discharge rate.

The internal resistance of battery materials increases with aging, leading to higher internal heat generation within the battery [30–32]. Additionally, the thermal conductivity of the electrodes varies with particle size [33]. Thermal contact resistance between the electrode and the current collector is another critical parameter that affects both the performance and fast charging capabilities of the cell. Often, the diffusion of ions in the electrolyte and the flow of electrons through the solid medium significantly contribute to the internal resistance of the cell. This contact resistance accounts for about 25% of the changes in the shape and structure (polarization) of the cell [34].

A microscopic view of the contact resistance and the paths of ions and electrons at a cathode (NMC5320) [35]. The cell current must pass through this interface during both charging and discharging [36–38]. Therefore, materials that offer minimal contact resistance are preferred to achieve better performance. Furthermore, microscopic properties such as the particle size of the current collector and binder, porosity, and the percentage of contact between the surfaces have a significant impact on the contact resistance [39–44].

AIR BASED SYSTEM

Atmospheric air is used as the working medium in an air based BTMS. In the EV sector, air based BTMS proven to be a better option over other systems due its advantages such as simple structural design, less weight, no leakages, and low cost [45, 46]. All other BTMSs except air-based system are still in developing stage. Major EV manufacturers preferred air-based system to match the supply and demand for EVs in the rapid growing market [47]. However, the challenges associated with air-based system are; low thermal conductivity of air, large volumes of airflow requirement, non-uniform cooling of the battery pack and vibration problems. Further, the air-based system alone is incapable of providing sufficient cooling due to the instant surge in heat generation from the battery at the higher vehicle speed [48,49]. Attempts have been made to improve the performance and reliability of air based BTMS. The structural designs and flow optimisations are the widely used techniques in this regard.

Mao LI et al., [50] have conducted a study modelling and optimisation in an air cooled BTMS. A U–Type Li-ion battery module with 36 cells and 37 cooling passages was considered for the analysis. The study focuses on the influence of important design parameters such as mass flow rate, heat flux and flow passage spacing. Increased mass flow rate results in decreased temperature differences and increased pressure drop between the cells' surface and air stream. However, increased pressure drop demands the higher power consumption. Increased heat flux causes significant increase in temperature difference and merely affects the pressure drop. Further, non-uniform temperature distribution within the battery module occurs due to the increased heat flux. Thermal performance reduces with increase in flow passage area. Further, uneven passages result in uneven temperature distribution. XiongbinPeng et al. [51] made an analysis of air-cooled cylindrical battery pack. A cylindrical battery pack of 20 modules was considered, and the dynamic model was created for the validation. The cooling performance was analysed for different battery layouts with various inlet and outlet air flow pattern as represented in Figure 2 and 3.

Analysis was done by considering the same rectangular inlet and outlet size (20 × 49 mm) for each module by blowing air at a constant speed in transverse and lateral directions. For each layout, lower temperature distribution was noticed near the air inlet than the outlet. However, better uniform temperature distribution was noticed in 4 × 5 layout. For the flow optimisation, 18 different patterns were attempted. Better flow distribution was observed in 3,4,12, and13. Experiments were conducted to check the validity of simulation results. Acceptable agreement between the simulation and experimental results was observed.

Kai Chen et al., [52] have developed various symmetrical air-cooled models for BTMS. The study was performed with different U and Z – type of flows. In symmetrical models, the higher cooling performance, and less energy consumption were reported. Further, the study has shown that the minimum number of battery cells results in a better uniform temperature distribution. Akinlabi A. A. Hakeem and DavutSolyali [53] performed a thermal performance

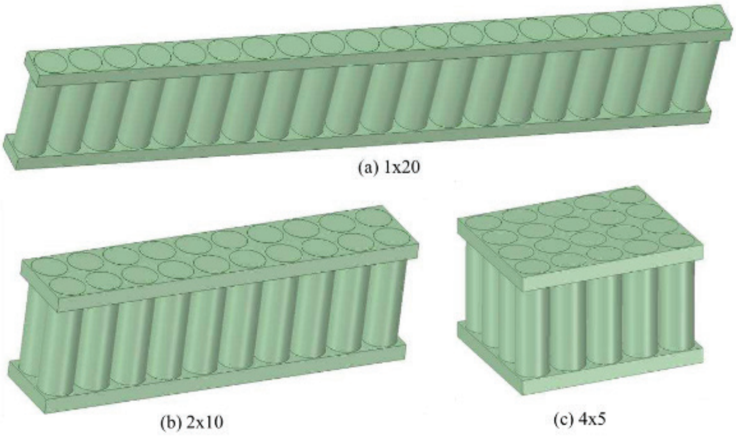

Figure 2. Different layouts of cylindrical Battery pack [From Akinlabi and Solyali [51], MDPI, licensed under CC BY 4.0].

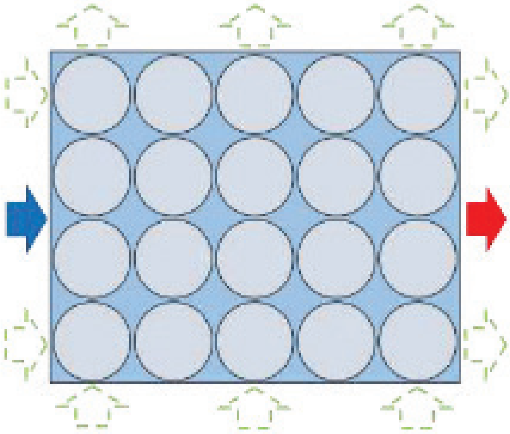

Figure 3. Flow positions [From Akinlabi and Solyali [51], MDPI, licensed under CC BY 4.0].

analysis under forced convection for a Li- ion battery. In this study, cell aligned cell optimisation technique was adopted. Experiments were carried out at variable air velocity. The results infer that improved cooling performance was attained at higher Reynolds numbers as a result of forced convention. Jiajun Zhang et al. [54] have done an experimental and numerical study of transient heat transfer analysis of air cooled BTMS. Parallel air cooled BTMS was considered for the study with, Z, U and I – type of flows. This study comprises of three analytical methods: Numerical analysis using CFD, Flow resistance network model, transient heat transfer model. Further, experimental work was also carried out. Transient model was formulated for I-Type flow by applying energy equations by considering four channels flow around the battery cell. In the experimental analysis, aluminium blocks were used to represent the battery cell. The blocks were heated uniformly by electricity. Thermocouples were placed on the blocks to continuously monitor the temperature. The results of numerical models were closely agreed with experimental results.

Thomas ImrerilleBuidin and Florin Mariasiu [55] proposed a modeling approach for the sports track conditions of 22 km travelling distance on the racetrack with battery temperature limit below 50 ^{0}C. The power train system consists of two motors of 15 kW each capacity. Battery pack was made into 22 segments with 8 modules. Maximum discharge current and voltage of battery pack were 464 Amps and 369 Volts respectively. Power required for the traction and current to be delivered by the battery as per the state of charge was determined by using energy efficiency graph.

To travel 22 km, the profile repeated for 23 times and time taken was 1960 seconds. CFD models were developed to determine the surface heat transfer coefficient between the air stream and surface of the battery cell. Initially, 1D transient heat transfer model was analysed. Further, it was used to develop the 3D transient heat transfer model. This makes the analysis simple. Simulation results depict that the heat transfer capacity decreases due to decrease in air flow coefficient in longitudinal direction. Higher temperature was recorded at the middle and lower region of the battery pack.

In most of the cases, non-uniformity of air flow causes the uneven temperature distribution within the battery pack. Researchers have tried to get uniform air flow pattern by different inlet and outlet positions, using air distribution fans [56, 57]. Few studies recommend adopting the change air flow direction within the battery pack to achieve uniform air distribution [58-61]. These studies also have shown considerable achievement in uniform air distribution. In this direction, Meiwei Wang [62] et.al, proposed a newer method to change air flow direction by using parallel plates. This study had taken Z-type BTMS for the analysis. Parallel plates were introduced at the bottom side of the battery. According to airflow pattern, nine BTMS models were developed.

The CFD analysis was made for these nine models. Simulation analysis shows that the minimum value of maximum temperature was noticed for model IX and minimum value of maximum temperature difference obtained for model VII. For the model IX, good flow distribution was achieved which leads to more uniform temperature profile than the other models. Introduction of parallel plates causes the decrease in maximum temperature difference initially and increase thereafter. Kai Chen et al. [63] developed parallel air cooled BTMS and done CFD analysis to know the influence of structural and operational parameters. The operational parameters taken for the studies were discharge rate, inlet air temperature and inlet airflow rate. Structural parameters focussed by this study were cell spacing, convergence and divergence plenum. CFD model was developed by considering turbulent flow conditions with k-ϵ turbulence model. The results obtained from the CFD analysis were validated by using Park's study [64]. Experimental data available in the study made by Wu [65] was taken for the validation. The inferences given by this study were: (i) reduced inlet air temperature reduces the battery temperature, however, could not restrict the rise in temperature effectively. (ii) Increase in inlet airflow rate decreases the maximum temperature in the battery pack. However, it increases the power consumption. (iii) Reduction in cell spacing results in lower cells' temperature, this also leads to increased power consumption. (iv) Often, reduction in maximum temperature and minimum cell temperature gradient can be achieved by optimizing the plenum angles.

The optimisation methods by using U and Z- type flow patterns were widely employed methods. To some extent I- type flow was also incorporated. Recently, researchers made attempts to study the cooling performance by obtaining J- type flow. This flow pattern was achieved by providing an inlet at the bottom and two outlets at the top of the battery pack. The experimental and simulation results proved that the cooling performance obtained by the J-type was satisfactory [66, 67]. However, discussion on J-type flow pattern is omitted due to lack of sufficient number of research papers. Few attempts were made to incorporate different controller like PID-controller for active control of cell temperature. The surface and core temperature of battery cell was continuously monitored by using temperature sensors. According to the pre-set temperature data, controller alters the air flow direction by actuating flip valves. Fan He, Lin Ma and XiaojingGao et al. [68, 69] made attempts in this direction. Reduced Ordered Method (ROM) was used in these studies to model the temperature distribution in the battery pack. Validation of ROM was also proved by comparing it with experimental results. Further, Computational cost of ROM is significantly less compared to CFD analysis. Results of the studies indicate that active cooling technique gives better uniform cell temperature which is much lower than the desired value. However, accurate real time temperature was not possible as the sensors were located at few cells only. Practically it is difficult to fix temperature sensors at all cells of a battery pack and it increases the cost also.

The staggered arrangement of battery cells is a geometrical optimization technique that focuses on the spatial configuration of cells. This approach enhances flow distribution and promotes a more uniform temperature profile [69]. Y. Wang et al. [70] studied the cooling performance of a staggered arrangement by incorporating non-uniform cell spacing. Their findings showed that this configuration improves cooling efficiency and results in a uniform temperature profile. However, significant energy consumption was reported. P. Kashyap et al. [71] attempted to optimize the staggered arrangement using a combined approach involving physical modeling, parametric optimization, and a sophisticated algorithm. In both models, the longitudinal pitch remained the same (24 mm), while the transverse pitch varied (24 mm and 20 mm). Under identical discharge and flow velocity conditions, the staggered pattern exhibited significantly lower temperatures compared to the conventional inline pattern. It was noted that the the staggered configuration outperformed the inline arrangement. Enhanced temperature uniformity was observed at higher Reynolds numbers due to increased convective heat transfer. Additionally, cells near the inlet had lower temperatures compared to those at the exit. Wenxu Yang et al. [72] incorporated a reverse flow mechanism with staggered battery cells and introduced a spoiler to induce turbulent flow. The results demonstrated significant cooling improvements achieved through this technique.

OTHER COOLING METHODS

This section provides a brief discussion of cooling techniques such as liquid cooling, PCM (Phase Change Material) cooling, and hybrid cooling. Liquid cooling offers superior performance and compactness compared to air-based systems [73]. A wide variety of fluids, including water, oil, nano-fluids, liquid metal, and refrigerants, are used in this method [74, 75]. Liquid cooling BTMS (Battery Thermal Management Systems) are divided into two main categories: direct cooling and indirect cooling.

Direct cooling involves submerging the battery pack in a non-conductive fluid, enabling efficient heat dissipation directly from the battery. In contrast, indirect cooling circulates a working medium through a cooling structure, such as plates or jackets, which surrounds the battery pack. The direct cooling approach provides direct contact between the battery pack and the coolant, resulting in better thermo-physical properties for heat dissipation [76]. Dielectric fluids, which are non-conductive, are the preferred choice as the working medium in direct cooling. These fluids prevent short circuits and reactions with battery materials. Studies on the direct cooling approach have used fluids such as terminal oil, mineral oil, water-glycol mixtures, NOVEC 7000, and refrigerants [77-85]. In these studies, both the battery pack temperature and cell temperature were effectively controlled within acceptable ranges. Additionally, these studies focused on fluid and flow optimization. However, challenges such as slow heat dissipation to the surroundings and leakage issues often limit the widespread use of this method.

Indirect cooling, on the other hand, offers better performance than direct cooling due to the continuous flow of the working fluid through cooling passages [86, 87]. Indirect cooling is further divided into single-phase and multi-phase cooling. In single-phase cooling, the working fluid remains in the liquid state throughout the entire cycle, whereas, in multi-phase cooling, the working medium undergoes a phase change between liquid and vapor states. Significant research has been conducted on indirect cooling in recent years, with various optimization techniques tested to improve cooling performance. The literature suggests that the highest priority has been given to structural modifications of the battery pack, fluid flow patterns, and the properties of the fluids used [88-96].

The use of Phase Change Materials (PCMs) in BTMS has gained considerable attention in recent years. The unique property of PCMs is their ability to absorb significant heat loads. These materials can absorb the thermal load of a battery pack through both sensible and latent heat. Studies have shown that PCM cooling can help achieve more uniform cell temperatures [97]. Desirable properties of PCMs include high latent heat, minimal subcooling, higher thermal conductivity, and chemical stability [98, 99]. Among these properties, thermal conductivity has the most significant impact on battery temperature.

The use of PCM for BTMS was first explored by Hallaj and Selman [100]. Literature reports various PCMs tested for this purpose, including decanoic acid, disaccharide, CnH2n+2, RT-35 PA, RT-42 PA, RT-55 PA, and sodium sulfate decahydrate [101-108]. However, the relatively low thermal conductivity of PCMs limits their extensive use in BTMS. To address this, efforts have been made to improve the thermal conductivity of PCMs by incorporating additives such as metal foam, graphene, hexagonal boron nitride (h-BN), and carbon fiber [109-114].

Furthermore, combined systems have been developed by incorporating both liquid and PCM cooling methods. In this combined approach, the liquid coolant typically flows through a cooling plate surrounding the battery pack, while PCM is placed between the battery cells. This configuration helps maintain the pack temperature within permissible limits and improves cell temperature uniformity. Studies have reported significant improvements in overall cooling performance using this combined system. Additionally, the effects of PCM mass fraction and liquid coolant flow rate have been studied [116-120]. However, this system becomes more complex and requires substantial power. Furthermore, it demands more space to house the components of the combined system, all of which contribute to an increase in the overall cost of an EV. Additionally, the slower melting and solidification properties of PCM must be addressed to further improve cooling performance. Priyadarsini et al. [121, 122] have conducted studies incorporating trapezoidal fins, which showed enhanced heat augmentation. However, this technique has not yet been applied in BTMS.

The selection of a BTMS for practical applications is influenced by various factors, including cost, safety, design, cooling performance, and reliability. Currently, air-based BTMS are widely used in EVs due to their simple design and low cost. However, the major drawback of air-based systems is their inability to handle higher thermal loads effectively. The liquid cooling approach offers more efficient cooling compared to air-based systems and can handle higher heat loads. Due to these advantages, liquid-based systems are also commonly employed in practical applications. PCM and hybrid cooling techniques show superior performance and are capable of managing larger thermal loads. However, the cost of these systems is much higher than that of air- and liquid-based methods. Moreover, PCM and hybrid systems require more complex structures to accommodate the various components of the BTMS. A comparative summary of different BTMS options is provided in Table 1.

FUTURE PROSPECTUS

It has been observed from the literature that structural and flow optimizations are the most common methods to enhance the cooling efficiency of air-based systems. Structural optimization focuses on the geometry of the battery pack, while flow optimization relates to the airflow pattern. The arrangement of battery cells and the spacing between them significantly impact cooling efficiency. Cylindrical and rectangular battery structures are commonly used in electric vehicles (EVs). Studies have been conducted by varying the number of cells in a battery pack, with the cylindrical structure generally yielding better performance than the rectangular structure. However, the design and production costs associated with each battery geometry need to be carefully considered. Even a small increase in these costs could result in a higher vehicle price. Computational Fluid Dynamics (CFD) analysis is the most widely used method in these studies as it allows for easy examination of the effects of structural and flow variables, with the flexibility to adjust boundary conditions. This flexibility enables a greater number of iterations before moving to experimental studies. Despite these advantages, none of the studies have managed to maintain a uniform cell temperature throughout the entire battery pack. In most cases, temperature uniformity is observed only near the inlet passage.

For next-generation EVs, a battery thermal management system (BTMS) must support features such as long driving range, quick charging, and safety. The air-based BTMS used in current EVs needs further improvement to meet these future demands. In air-based BTMS, the lower thermal conductivity of air and the need for large volumes of airflow are major concerns. The thermal conductivity of air affects the rate of heat dissipation, and the large airflow requirements consume significant pumping power. Research in this area suggests that incorporating evaporative cooling could significantly improve the performance of conventional air-based BTMS. Moreover, evaporative cooling can be integrated into the existing structure of air-based systems, thereby reducing the overall system cost. Lip Huat

Table 1. Comparison of different BTMS techniques

Type	Advantages	Disadvantages
Air based BTMS	· Less initial cost · Minimal operational cost · Easy to maintain · No risk of short circuit and leakages · System design is simple · Lower payload	· Air has poor thermal conductivity · Difficult to handle higher thermal loads · Lower cooling efficiency · Large volume air flow is required to take higher heating loads. This consumes significant blowing power
Liquid based BTMS	· System is compact · Capable to handle higher heating loads · Quick heat dissipation is possible · Better cooling performance than air-based system	· Overall system cost is high · Liquid storage facility is necessary · Prone to short circuit and leakages · Consumes significant pumping power
PCM based BTMS	· Low cost of PCM · Able to handle higher thermal loads · Better cooling efficiency than air and liquid based system	· Lower thermal conductivity of PCM · Possibility of PCM leakage · Chances of supercoiling · Change in volume of PCM during phase transition
Hybrid mode	· Features of different systems can be integrated as per the requirement · Offers highest cooling efficiency · Higher heating loads can be easily handled	· Complex system design · Higher cost of the system · Difficult to maintain the combined system

Sawa et al. [123] demonstrated an improvement in cooling performance by introducing fine water droplets into the air stream. This approach not only enhanced cooling efficiency but also reduced power consumption for the same rate of cooling. Similarly, studies have been made by incorporating heat pipes to improve the cooling performance of conventional air-based system. Heat pipe exhibit features; light weight, simple design, absence of moving parts, and low thermal conductivity which makes it suitable in combination with air-based system. The studies made in this direction gave improved performance of the combined system [124-128]. However, few studies depict that not much significant improvement was achieved at higher flow rates; even by introducing fins in the air stream [129-133]. Hence, further research has to be carried out to address these issues. Furthermore, significant advancements are needed in terms of battery material design and selection. Future research should focus on developing new materials and fabrication techniques to address challenges such as internal cell resistance, contact resistance, and premature material aging.

CONCLUSIONS

Battery Thermal Management Systems (BTMS) in electric vehicles (EVs) are designed to maintain battery packs within the ideal temperature range of 15–35 °C, safeguarding them from premature wear and degradation. Among various cooling methods, air-based systems are often favoured for their efficiency and straightforward design compared to liquid cooling or Phase Change Material (PCM)-based systems. Improvements in these systems typically involve structural and flow optimizations. Structural optimization includes modifying battery shapes and adjusting cell spacing, while flow optimization focuses on designing airflow patterns—such as I, U, Z, J, and staggered configurations—to enhance thermal performance, particularly at higher vehicle speeds. Additionally, the choice of battery materials plays a significant role. Internal and contact resistance within battery cells are responsible for approximately 25% of the heat generated. Future advancements in BTMS should aim to develop innovative materials and manufacturing methods to reduce these resistances and mitigate the early degradation of battery components.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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