BATTERY THERMAL MANAGEMENT SYSTEM FOR GREATER LIFETIME AND SAFETY: MINI-REVIEW

SeyedSaeed Madani[1], Mojtaba Hajihosseini[2], Carlos Ziebert[1], Iris Nandhakumar[3]
[1]Karlsruhe Institute of Technology, Germany; [2]University of Zagreb, Croatia; [3]University of Southampton, United Kingdom
seyed.madani@kit.edu , mhajihosseini.eng@gmail.com

Abstract. In this review paper, we make a collective effort to enhance our comprehension of thermal control systems for lithium-ion batteries, focusing on various aspects including cooling techniques, design adjustments, temperature distribution, and energy efficiency. This compilation of research studies delves into the crucial field of thermal management systems for lithium-ion batteries, addressing a range of factors to boost their performance and safety. The updated analysis aims to critically evaluate these systems with a focused objective on assessing their reliability under various operational conditions. By examining different cooling methods and design modifications, we highlight their implications for enhancing battery safety and operational stability, providing insights into how these systems can be optimized to improve performance and reliability. This review underscores innovative approaches and critical findings that contribute to the reliability and efficiency of these systems, offering a foundation for future advancements in battery technology. Key findings suggest that advanced cooling configurations and design adjustments significantly contribute to battery stability, indicating directions for future research to optimize these systems further.

Keywords: thermal management system, lithium-ion batteries, greater lifetime and safety.

1. Introduction

Meeting the growing global demand for energy while minimizing environmental pollution has become a critical issue. The emission of carbon dioxide has surged, resulting in a rapid increase in its concentration in the atmosphere. To address these challenges, lithium-ion batteries have emerged as a key technology with the potential to provide solutions [1-6]. These batteries are suitable for use in both fully electric and hybrid electric vehicles due to their exceptional energy density and specific energy, which surpass those of other rechargeable battery technologies. However, the reliability and safety of these batteries under various thermal conditions remain pivotal concerns, directly influencing their adoption and performance. This paper focuses on the review of various thermal management techniques and their direct implications on the reliability and safety of lithium-ion batteries, which are critical for their long-term operational integrity. However, despite the numerous advantages these batteries offer, they have not been widely adopted in commercial fully electric and hybrid electric vehicles. The primary reasons for this limited adoption are concerns about their performance in cold temperatures, their cost, and safety issues, all of which are related to the thermal management systems used for lithium-ion batteries [7].

An examination of heat loss in lithium-ion batteries found that the highest temperature and heat losses occurred near the upper part of the battery pack, while the lowest temperature and heat losses were observed at the bottom of the lithium-ion battery pack. Based on these findings, it was concluded that the non-uniform distribution of temperature and heat loss across the lithium-ion battery pack could potentially be reduced by making changes and modifications to the battery pack design [8]. Figure 1a illustrates various applications of lithium-ion batteries, encompassing transportation, electric devices, grid energy, and industry. Figure 1b depicts the design of lithium-ion batteries at different levels, including material, electrode, cell, and system levels. The design of lithium-ion batteries, which can be addressed at multiple levels, may impact their lifespan. Each level can influence the lifetime of a lithium-ion battery in vehicle applications. Influential factors, such as heat dissipation, generation, and solid electrolyte interface formation, are closely interrelated, complex, and need to be considered at different levels [9]. Figure 1c presents the primary factors affecting the rapid charging of lithium-ion batteries. The behaviour of battery packs and cells during rapid charging depends on numerous factors across various scales, from the atomic level to the system level, as shown in Figure 1c. Additionally, the figure outlines the considerations for rapidly charging lithium-ion batteries [10].

In Figure 2a, a depiction of the different factors impacting the temperature of lithium-ion batteries is provided. Maintaining an appropriate operating temperature range is a substantial challenge for lithium-ion batteries, with thermal runaway being one of the most critical concerns. To tackle these challenges, the most frequently utilized method involves the application of cooling methods, which can be either active, passive, or a combination of both. One of the notable challenges associated with electric vehicles pertains to the thermal issues of their batteries. These thermal problems have restricted the widespread adoption of electric vehicles for high-energy-consuming applications. Consequently, addressing the cooling and management of this primary issue is of utmost significance.

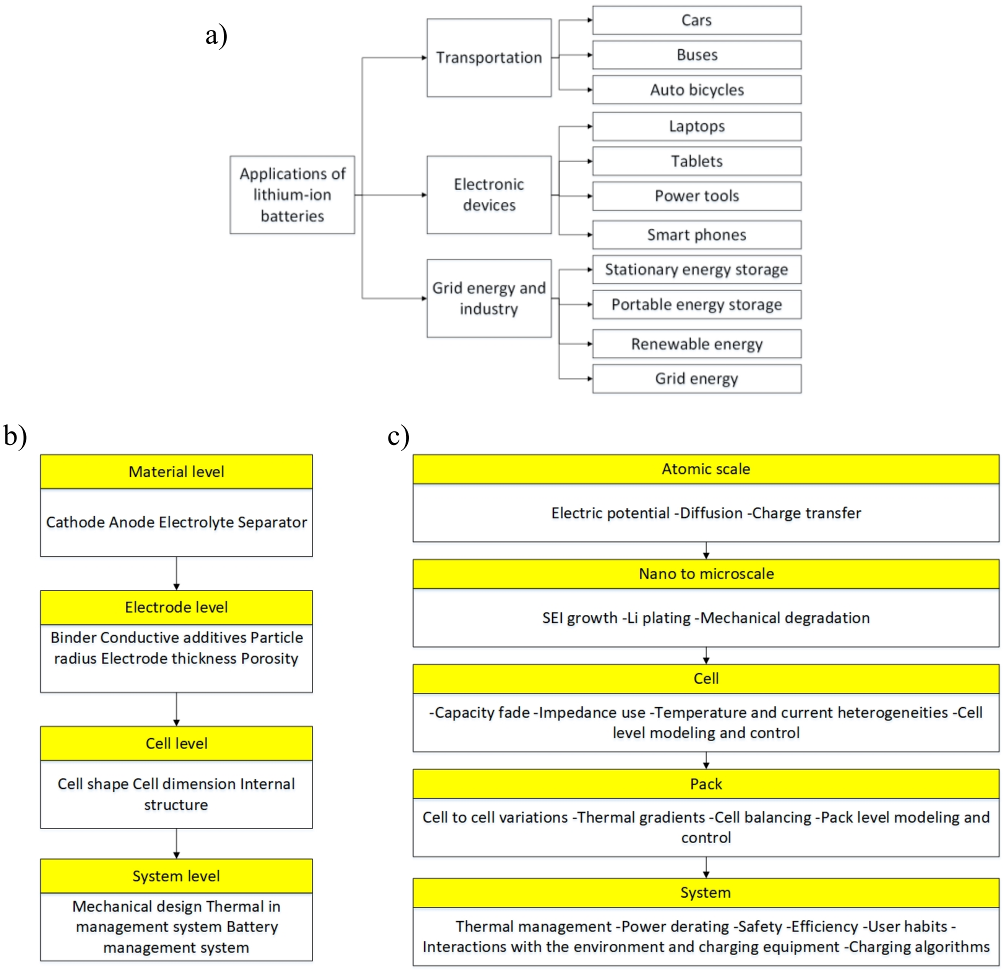

Fig. 1. **Applications of lithium-ion batteries (a); lithium-ion battery design on different levels [9] (b); principal factors influencing lithium-ion battery rapid charging [10] (c)**

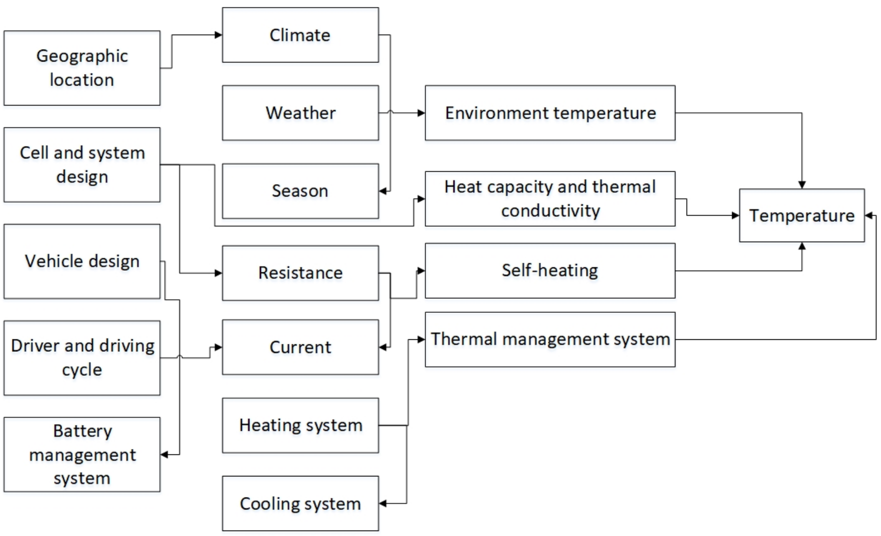

Fig. 2. **Factors affecting the temperature of lithium-ion batteries [9]**

2. Different methods for thermal management of lithium-ion batteries

This section offers a summary of diverse methods for managing the temperature of lithium-ion batteries. Various approaches can be employed to design the thermal control of lithium-ion batteries, such as indirect liquid cooling, air-cooling, phase change material, and direct liquid cooling. It is essential to ensure effective thermal management of lithium-ion batteries for their safe and efficient operation across different applications like hybrid electric vehicles and electric vehicles, regardless of the operating conditions. Madani et al. [11-16] applied several methods to achieve thermal management of lithium-ion batteries. Air cooling and direct liquid cooling exhibited similar temperature profiles, with air cooling having a more pronounced effect on the battery cell temperature. They used experimental data for heat generation from the lithium-ion battery and assumed an air cooling flow velocity of 20 $m \cdot s^{-1}$. Different arrangements were tested for managing the temperature of the lithium titanate oxide battery pack, with a 50 mm gap between lithium titanate oxide-based batteries, and a discharge current rate of 65 A. The amount of heat generated was directly related to the cooling flow velocity. Effective temperature management for lithium-ion batteries was achievable by using a high coolant flow velocity. However, pushing the cooling flow rate beyond specific thresholds (20 $m \cdot s^{-1}$ for air cooling, 0.01 $m \cdot s^{-1}$ for direct liquid cooling, and 0.05 $m \cdot s^{-1}$ for indirect liquid cooling) did not result in a substantial reduction in battery temperature. Among the various cooling methods, fin cooling demonstrated the least significant maximum temperature decrease, primarily due to its relatively high heat capacity. To enhance thermal management, one proposed solution was to relocate the current terminals to opposite ends of the lithium-ion battery. This change could potentially increase the electrochemical reaction rate, as it would create a more pronounced temperature gradient, particularly at different sections of the battery when operating at higher current rates. The rapid acceleration in electric vehicles necessitates high discharge rates, which can lead to the formation of concentration gradients and electrical currents within the battery. This phenomenon results in lower temperatures near the current collection point of the positive electrode compared to the negative electrode, primarily because of the significantly higher electrical conductivity of the negative electrode. Notwithstanding these discoveries, significant challenges persist in achieving a complete comprehension of the mechanisms governing heat generation and thermal control in lithium-ion batteries, primarily stemming from the absence of an all-encompassing analysis in this field. Additional research is imperative to address these challenges and cultivate a more profound insight into the thermal management of lithium-ion batteries.

While information regarding the assembly and chemistry of lithium-ion battery cells was somewhat limited, the methodology employed in this study could be extended to commercial lithium-ion battery cells. The investigation ultimately concluded that elevating the heat transfer coefficient or increasing the flow velocity led to a reduction in the maximum temperature observed in the lithium-ion battery at the conclusion of the discharge process [11-16]. Figure 3 provides a classification scheme outlining the diverse approaches employed for thermal management in cooling lithium-ion cells. It also illustrates the general structure of thermal management systems. It is crucial to emphasize that having a dedicated thermal control system is indispensable for mitigating the uneven distribution of temperature within lithium-ion batteries. By implementing effective thermal management techniques, it becomes possible to make substantial enhancements in the performance, safety, and overall lifespan of lithium-ion batteries. Figure 4 offers an overview of thermal management for lithium-ion batteries. Given the wide array of applications in which lithium-ion batteries are used, such as in electric vehicles, they regularly undergo charging and discharging cycles. To ensure optimal performance and safety, it is imperative to have efficient cooling systems like air or liquid cooling to dissipate the heat generated during these operational phases. Various simulations can be conducted to analyze thermal behavior under different charging and discharging scenarios. Additionally, considering the spacing between battery cells becomes important to enable efficient air or liquid cooling circulation, thereby facilitating the effective removal of heat from the system. This holistic approach to thermal management is critical for maximizing the lifespan and performance of the battery in a variety of real-world applications. Numerous researchers have explored different cooling techniques, configurations, and simulation methods for the thermal management of lithium-ion batteries. In most instances, the larger surfaces of the battery cells are utilized to effectively dissipate heat. Common methods include indirect liquid cooling and air-cooling, where the cooling fluid flows over the gaps between lithium-ion battery cells and directly contacts their surfaces. Another approach is direct liquid cooling, which involves the use of various liquids, including dielectric mineral oil, to cool the battery cells.

a)

b)

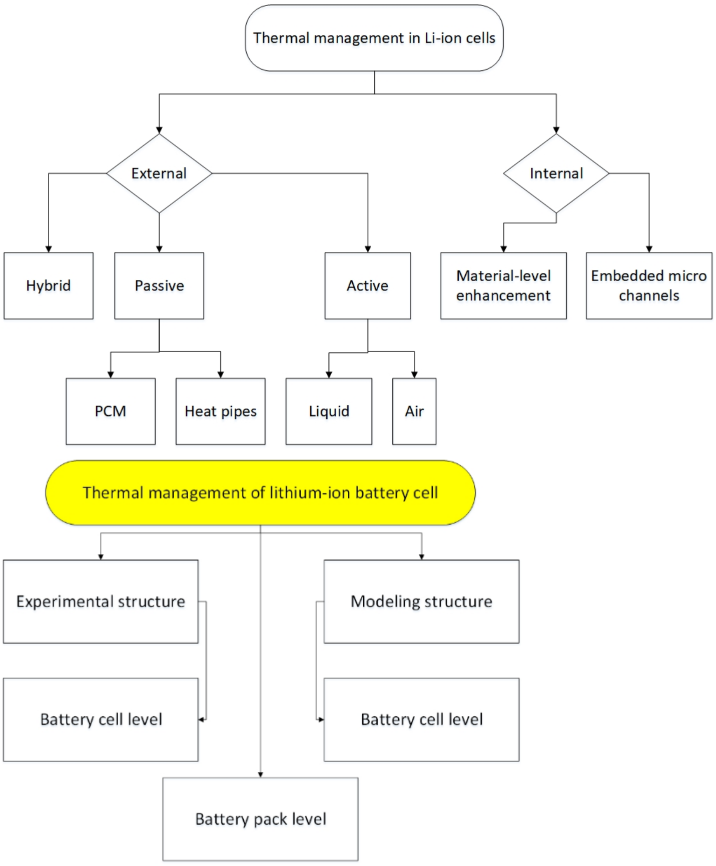

Fig. 3. **Classification of different thermal management approaches [17] (a); organization of thermal management systems (b)**

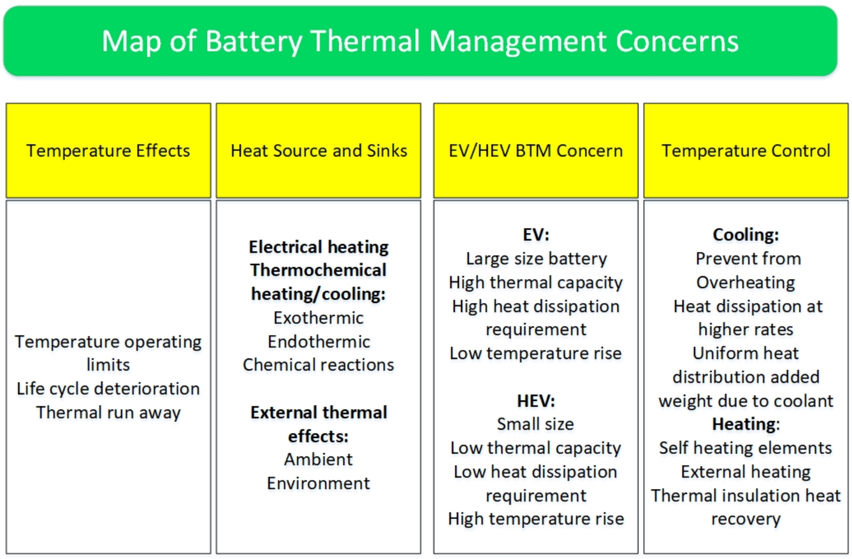

Fig. 4. **Outlining of battery thermal management [18]**

In the setup of indirect liquid cooling, a fin is positioned between two lithium-ion battery cells, and heat is conducted from the edges of the fin. Over the course of charging and discharging cycles, the heat generated within the battery is transferred to a cold plate. The accumulated heat in the cold plate can be effectively dissipated using methods such as air cooling, liquid cooling, or other cooling strategies to ensure that the battery temperature remains within safe operational limits. By delving into these cooling techniques and optimizing their configurations, it becomes feasible to enhance the thermal management of lithium-ion batteries, thereby improving their performance and safety across a wide range of applications.

Prior research studies [19-35] have proposed numerous advanced thermal management approaches for lithium-ion batteries, and these are summarized in Table 1. Substantial attention has been devoted to investigating various setups for regulating the temperature of lithium-ion batteries, especially under different current rate conditions. The majority of these investigations have centered on the thermal management of cylindrical lithium-ion batteries. Additionally, there have been thermal management studies conducted on commercially available pouch-type lithium-ion batteries. In these studies, numerical simulations have been employed to assess the thermal management of lithium-ion battery packs, utilizing both active cooling techniques like air cooling and passive cooling methods such as phase change materials. Diverse levels of heat source intensities were considered to simulate the heat generation within lithium-ion batteries. These simulations allowed researchers to evaluate the cooling efficiency under various discharge rates of lithium-ion batteries. Overall, these research efforts are aimed at enhancing the strategies for thermal management in lithium-ion batteries, ensuring their secure and effective performance in a wide array of applications. By comprehending and optimizing cooling methods, it becomes possible to elevate the overall performance and lifespan of lithium-ion batteries in practical, real-world scenarios.

In their research, C. Zhang and colleagues [19] employed a thermoelectric cooler heat pipe as part of their thermal management strategy for lithium-ion batteries. They conducted experimental tests and compared the results with the data generated from their modeling efforts. To assess the accuracy of their recommended and parameterized model for the specific lithium-ion battery cell they were investigating, they carried out a verification experiment. This step was crucial in validating the reliability and effectiveness of their proposed thermal management system for lithium-ion batteries. By comparing the experimental findings with the model predictions, the researchers could gauge how well their proposed approach aligned with the actual performance of the lithium-ion battery cell in real-world conditions.

In a study conducted by Teressa Talluri et al. [20], phase change materials were utilized to analyze the thermal characteristics of a battery pack. This investigation yielded valuable suggestions to improve the design of lithium-ion batteries. By implementing specific alterations in the battery structure, they discovered that it was possible to reduce the uneven surface temperatures and heat generation, ultimately leading to a lower peak temperature for the battery. One particular modification suggested in the study involved relocating the current tabs to opposite ends of the lithium-ion battery, a change that had the potential to create a more consistent temperature distribution within the battery and reduce heat generation, thereby enhancing thermal management. These design adjustments had the potential to improve the overall performance and safety of lithium-ion battery packs, making them better suited for a range of real-world applications.

Rui Zhao et al. [21] conducted research into various cooling methods and configurations for lithium-ion battery packs. Their study focused on numerically evaluating the thermal management of these packs using phase change materials (a passive cooling approach). They considered different heat source intensities for lithium-ion batteries and performed numerical simulations to assess the cooling effectiveness under various discharging and charging rates. They proposed a methodology that could be useful for understanding the cooling processes and thermal behavior of lithium-ion batteries, as well as displaying temperature variations during different charge and discharge cycles.

In their investigation, R.D. Jilte et al. [22] presented the temperature profile within a lithium-ion battery pack when employing air cooling. The researchers examined two distinct air cooling speeds, specifically 0.1 and 0.5 meters per second. They explored various setups to enhance the thermal control of the lithium-ion battery pack while maintaining a consistent spacing between the battery cells. The experiments involved a discharge current rate of 25 amperes. The study findings revealed that as the heat transfer coefficient or flow velocity increased, the maximum temperature within the lithium-ion battery did not decrease proportionally. In simpler terms, increasing the cooling flow velocity beyond a certain threshold did not significantly lower the battery maximum temperature. Consequently, there exists a limit to the advantages of higher flow velocities in terms of temperature reduction. Additionally, the research underscored that employing higher flow velocities for cooling would lead to a significant increase in energy consumption. This implies that even though higher flow velocities may not result in substantial temperature reductions, they would consume more energy, a factor that may not be practical or cost-effective in real-world applications. To sum up, this study offered valuable insights into the constraints associated with employing higher flow velocities for air cooling in lithium-ion battery packs. It emphasized the importance of achieving a balance between cooling efficiency and energy consumption to attain the optimal thermal management for lithium-ion batteries.

In their research, Hamidreza Behi and their colleagues [23; 24] introduced an innovative idea for regulating temperature and explored how heat is distributed in various thermal management systems, such as heat pipes and air cooling. During the discharge process, they observed that the area near the tabs of the lithium-ion battery cell experienced the most significant heating. Furthermore, they noticed an uneven temperature distribution within the battery pack. Their investigation showed that when high current rates were applied, it took longer to reach a thermal equilibrium. Despite substantial current passing through both the positive and negative electrode tabs, the negative electrode active material exhibited significantly higher electrical conductivity than the positive electrode. The research also demonstrated that increasing the heat transfer coefficient or the flow velocity during the cooling process reduced the battery maximum temperature at the end of the discharge. As a result, effective thermal management in the upper portion of the lithium-ion battery is critical for efficiently dissipating heat, especially in comparison to the lower part. In summary, this study offered valuable insights into how temperature behaves and is distributed within lithium-ion batteries under various thermal management systems. Understanding these thermal characteristics is vital for devising and implementing effective thermal management strategies to enhance the performance and safety of lithium-ion batteries in diverse applications. In exploring various thermal management techniques, this paper examines a range of experimental validations and modeling efforts. Air cooling techniques were evaluated by Zhang et al. [25], who demonstrated their effectiveness in reducing temperature peaks and prolonging battery life in high-load conditions. Similarly, liquid cooling strategies have been linked to enhanced safety profiles, particularly in preventing thermal runaway scenarios, as noted by Madani et al. [26]. These studies provide a strong empirical foundation, showing how different cooling techniques directly contribute to lithium-ion battery reliability.

Tao Deng and their team [27] undertook a multi-objective optimization study concerning the thermal management system of a lithium-ion battery pack. Their investigation revealed that an uneven distribution of fluid within the cooling channels could result in localized hot spots within the configuration. This non-uniform temperature distribution, in turn, could lead to an uneven voltage distribution across the battery pack. To address this challenge, the researchers proposed a solution that involved cyclic fluid flow and periodic adjustments of the entry and exit points for the cooling fluid. By periodically altering the positions of fluid entry and exit, the researchers aimed to establish a more consistent distribution of both fluid and temperature within the battery pack. This strategy could effectively mitigate hot spots and ensure a more uniform voltage distribution. The research highlighted the significance of the frequency at which the entry and exit points of the cooling fluid are adjusted, as it significantly influenced the performance of the thermal management system. Consequently, identifying the optimal frequency for each flow arrangement is crucial. Achieving this optimization requires the development of a suitable model for the thermal management system, accounting for various factors and objectives. Through multi-objective optimization and considering the dynamic behavior of the cooling fluid, the study aimed to enhance the thermal performance and overall efficiency of the lithium-ion battery pack thermal management system. This approach has the potential to result in improved battery performance and an extended lifespan, making it advantageous for various applications, including electric vehicles and other energy storage systems.

In the study led by M.A. Bamdezh and their colleagues [28], the primary focus was on assessing how the arrangement of a thermal management system impacts the performance of a lithium-ion battery module. The researchers measured the surface temperature of the lithium-ion battery cell at different locations on its surface, taking into account the rate of heat generation. The research brought to light that the heat generation rate is not consistent across the entire surface of the lithium-ion battery. This variance in heat generation results in an uneven distribution of temperature on the battery surface. In essence, the study revealed that heat is not uniformly generated across the lithium-ion battery surface. Given these findings, the researchers suggested that modifying the design of the lithium-ion battery could potentially alleviate the non-uniformity in surface temperature and heat generation. Such design enhancements could lead to a more uniform dispersion of heat and temperature within the battery module. Consequently, the battery maximum temperature could be reduced, resulting in improved thermal management and overall performance. Recognizing the non-uniform heat generation and temperature distribution is vital for developing effective thermal management strategies for lithium-ion batteries. By addressing these issues through design alterations and optimizing the thermal management system, the researchers aimed to enhance the safety, efficiency, and lifespan of lithium-ion battery modules across various applications.

In the research led by Shashank Arora and their team [29], they explored a pioneering approach to cooling lithium-ion batteries. The researchers focused on leveraging the two largest surfaces of the battery cells to effectively dissipate heat. They achieved this by using phase change materials placed in the gap between lithium-ion battery cells, making direct contact with the battery cell surfaces. Various phase change materials were tested within the thermal management system to optimize cooling efficiency.

In this setup, the phase change materials were strategically positioned between two adjacent battery cells. During charge and discharge cycles, the heat generated was transferred through these phase change materials, where it was absorbed and stored. Subsequently, the accumulated heat in the phase change materials could be dissipated using various cooling methods, such as air or liquid cooling. This innovative cooling technique, which involves the use of phase change materials, offers significant advantages in effectively regulating the thermal behavior of lithium-ion batteries. By utilizing these materials to absorb and store heat, the researchers aimed to enhance the effectiveness of the thermal management system and ensure safer operation of the battery pack. This study contributes to the ongoing research endeavors aimed at developing inventive thermal management strategies for lithium-ion batteries, with the ultimate goal of enhancing their performance, safety, and reliability across a wide range of applications.

In the study carried out by Chunjing Lin and colleagues [30], they investigated the thermal performance of a lithium-ion battery pack equipped with a passive thermal control system. The researchers examined the three-dimensional temperature distribution within the lithium-ion battery cell under different conditions. Various setups were constructed in a modern simulation laboratory to analyze how the temperature changed in lithium-ion batteries over time. Their investigation revealed that, in most instances, the rate of heat transfer was notably higher within the inner portion of the lithium-ion battery, particularly in its central region. This phenomenon is likely due to more efficient heat conduction in this specific area. Consequently, the temperature across the surface of the lithium-ion battery was uneven, indicating non-uniform heat generation on the battery surface. By studying the temperature distribution, they deduced that the highest-temperature region corresponded to the area with the most substantial heat generation. This observation also applied to the region with the most pronounced temperature non-uniformity. These findings underscore the significance of comprehending the thermal behavior and heat generation patterns within lithium-ion batteries. By understanding the non-uniform temperature distribution, researchers can formulate effective thermal management strategies to ensure the safe and efficient operation of lithium-ion battery packs across a range of applications. This research contributes to the advancement of knowledge and technology related to thermal management systems for lithium-ion batteries.

In the research conducted by Suman Basu and collaborators [31], a thermal regulation system was specifically developed for lithium-ion batteries. The study emphasized the critical role of the initial temperature of the cooling fluid in determining the effectiveness of the thermal management system. The researchers observed that there should be a limitation on how much the cooling fluid initial temperature can increase to ensure optimal thermal efficiency. As anticipated, the hottest area within the lithium-ion battery pack was identified near the cooling fluid exit, where the highest temperatures were recorded. In contrast, the coldest region was situated near the point where the cooling fluid entered, exhibiting the lowest temperatures. This non-uniform distribution of heat was evident within the battery pack. During the cycling process, where the battery underwent charging and discharging cycles, temperatures near the cooling fluid entry remained relatively lower, while higher temperatures were observed near the cooling fluid exit. This temperature variation during the cycling process emphasized the importance of effective thermal management in preserving the battery safety and stability. The study underscores the significance of meticulously controlling the initial temperature of the cooling fluid to enhance the performance of the thermal management system for lithium-ion batteries. Proper thermal management is crucial for achieving a consistent temperature distribution and preventing hotspots within the battery pack, ultimately enhancing the battery overall safety and longevity.

In citation [32], the scientists introduced an innovative thermal management system by merging data from a calorimeter with a thermal model. They utilized heat generation information obtained from an isothermal calorimeter to construct a dynamic heat source model. This dynamic heat source model was subsequently used to simulate how heat behaves in a lithium-ion battery. By monitoring the surface temperature of the lithium-ion battery cell at four distinct points on its surface and taking into account the heat production rate from the dynamic heat source model, the researchers noticed that the heat generation rate was not consistent across the entire surface of the lithium-ion battery. This discovery indicated that heat was not uniformly generated across the battery surface. The irregular distribution of temperature observed in the surface temperature measurements of the battery provided evidence of non-uniform heat generation on the surface of the lithium-ion battery. These observations underscore the importance of accurately characterizing heat generation and temperature distribution within the battery to implement effective thermal management. By combining the calorimeter data with the dynamic heat source model, the researchers gained a more comprehensive understanding of how heat behaves in a lithium-ion battery. Such insights are invaluable for developing efficient and targeted thermal management strategies to ensure the safe and optimal operation of the battery across a range of applications.

Table 1

Different techniques found in literature employed for the thermal management system (W, L, and T: width, length, and thickness)

Battery	Category	Description	Reference
TAFEL-LAE895 52,148, 96 W, L, T	Experimental Validation and Modeling	-An investigation of a thermal management system for lithium-ion batteries was undertaken. -The cooling medium employed in this study included a thermoelectric cooler and heat pipe. -The research utilized a combination of thermoelectric cooler and heat pipe to regulate the thermal behavior of lithium-ion batteries. Experimental tests were carried out, and the results were compared with the outcomes predicted by the model. A verification experiment was vital to confirm the reliability and efficiency of the proposed thermal management system.	C. Zhang et al. [19]
Lithium polymer 3.7V/16 Ah 220,132,7.8 mm W, L, T	Battery Design Modification	-Examination of a lithium-ion battery pack performance in the elevated temperature settings of an electric car. -Utilization of a phase change material as a cooling agent. -Phase change materials were utilized to assess how the battery pack manages heat. Recommendations for enhancing temperature consistency and minimizing heat production were made, including adjustments to the battery design, such as relocating current tabs.	Teressa Talluri et al. [20]
18650 cylindrical lithium-ion battery	Numerical Simulation and Cooling Procedures	-An examination was conducted to assess how the cooling efficiency of a system is influenced by the specifications and arrangement of lithium-ion batteries. -Cooling was achieved through a passive thermal management system. -The research concentrated on numerical simulations and configurations for cooling lithium-ion battery packs with the application of phase change materials. Different discharge and charge rates were taken into account, and the objective of the study was to gain insights into cooling processes and thermal performance.	Rui Zhao et al. [21]

Table 1 (continued)

Battery	Category	Description	Reference
3.6 Ah lithium-ion battery cathode: $LiMn_2O_4$, anode: Carbon	Air Cooling Velocity and Energy Consumption	-An examination was conducted on the cooling effectiveness of a thermal management system for lithium-ion batteries. -Operating under the condition of a substantial galvanostatic discharge. -This investigation employed numerical methods. -The study delved into the temperature distribution within a lithium-ion battery pack when subjected to air cooling at varying velocities. It revealed that increasing the cooling flow rate beyond a certain point did not significantly decrease battery temperature and resulted in higher energy consumption.	R.D. Jilte et al. [22]
2.2 A/3.6 V lithium-ion battery	Temperature Distribution and Thermal Equilibrium	-An examination was conducted to evaluate the thermal management system of a lithium-ion battery. -The cooling medium used was air. -Cooling and heat pipes were implemented for electric vehicles. -This research explored the temperature distribution within lithium-ion batteries when subjected to different thermal management systems. It underscored the significance of efficient thermal management, particularly in the upper section of the battery, and emphasized variations in electrical conductivity between the electrodes.	Hamidreza Behi et al. [23]
30 Ah lithium-ion battery, 3.7 V	Thermal Management System Design;	-Utilization of the non-dominated sorting genetic algorithm in designing a lithium-ion battery pack. -A design approach focused on multi-objective optimization.	Tao Deng et al. [24]
Lithium-ion battery	Multi-Objective Optimization and Cooling Channel Design	-A novel 3D vapor chamber was used. -Investigation of the thermal management system for lithium-ion batteries in an electric vehicle. -A feasibility analysis was successfully completed. -Scientists carried out multi-objective optimization for creating a thermal management system for lithium-ion battery packs. They stressed the significance of achieving even fluid distribution in cooling channels to alleviate hotspots.	Jingren Gou et al. [27]
Six $LiCoO_2$ 18650 lithium cells	Hybrid Thermal Management System	-An examination was conducted to understand how the performance of a hybrid thermal management system is affected by its configuration.	M.A. Bamdezh et al. [28]
Commercially available 20 Ah pouch cells	System Arrangement and Non-Uniform Heat Generation	-Enhancements in discharge/charge cycles were achieved. -An analysis of the performance of lithium-ion battery packs when subjected to abusive conditions was carried out. -The study investigated the influence of system configuration on the thermal management within a lithium-ion battery module. It uncovered non-uniform heat generation on the battery surface, indicating the need for design adjustments to enhance temperature consistency.	Shashank Arora et al. [29]
A commercial rectangular $LiFePO_4$ 100,32,180 mm (W, L, T)	Novel Cooling Method with Phase Change Materials	-A passive thermal management system was implemented, employing a cooling medium consisting of a composite phase change material and graphite sheets. -Both experimental and simulation methods were utilized to assess a lithium-ion battery pack. -This study introduced a cooling technique that incorporates phase change materials to regulate the heat of lithium-ion batteries. This method is designed to enhance the efficiency of the thermal management system by absorbing and storing heat.	Chunjing Lin et al. [30]

Table 1 (continued)

Battery	Category	Description	Reference
2.3 Ah $LiFePO_4$ battery and 1.8 Ah $LiCoO_2$ battery	Passive Thermal Management and Temperature Evolution	-Multi-objective optimization of the lithium-ion battery model was successfully conducted using a genetic algorithm approach. -The study examined the thermal performance of lithium-ion battery packs equipped with a passive thermal management system. It highlighted variations in the heat transfer rate within the battery and non-uniform surface temperature distribution.	Liqiang Zhang et al. [31]
Commercially available Li-NCA/C 18,650 cells	Coupled Electrochemical and Thermal Modelling;	-An innovative thermal management system for lithium-ion battery packs.	Suman Basu et al. [32]
Sixty-four 2.2 Ah BAK 18650-type cylindrical lithium-ion batteries	Coolant Fluid Entrance Temperature Control	-A thermal management system for lithium-ion batteries was devised. -A combined arrangement integrating electric vehicle cabin air conditioning was also designed. -The research focused on temperature control for high-power lithium-ion batteries. -The study aimed to create a thermal management system for lithium-ion batteries, with a particular emphasis on regulating the coolant fluid inlet temperature to optimize thermal performance.	Jiwen Cen et al. [33]
Three 20 Ah capacity prismatic lithium-ion cells	- Experimental and Numerical Methods	-A novel passive thermal management system was created for a lithium-ion battery pack. -The cooling medium utilized in this system was a phase change composite material.	M. Malik et al. [34]
35-Ah $LiMn_2O_4$ 200*170*14.5 mm (W, L, T)	Reciprocating Heating and Cooling	-A heating and cooling system based on reciprocating motion was developed for a lithium-ion battery pack. -Both experimental and numerical methods were employed in this project.	Xilong Zhang et al. [35]
Lithium Titanate Oxide Battery	Thermal Management Simulation	A three-dimensional numerical simulation of a passive thermal management system designed for a battery pack.	S.S. Madani et al. [36]

Chen and colleagues [33] employed a mathematical model to perform a thermal evaluation of lithium-ion batteries during charging, discharging, and the potentially hazardous scenario of thermal runaway. Their primary focus regarding the thermal behavior of these batteries at room temperature was on the potential for a significant temperature increase that might lead to thermal runaway. Their research places particular emphasis on investigating how different design factors and operational conditions impact the temperature rise or pattern during regular battery use. Furthermore, it evaluates the likelihood of thermal runaway occurring due to battery misuse. Accurate knowledge of the precise composition of lithium-ion batteries is essential for the development of an effective thermal management system and the creation of a reliable thermal model. Unfortunately, at present, there is either limited or no comprehensive understanding of the exact composition, which makes the modeling process quite challenging.

Various researchers [34-41] have utilized different measurement methods to ascertain the effective thermal conductivity both across and within the battery components, as well as the specific heat capacities. However, due to the rapid advancements and the use of diverse electrode materials, there is a scarcity of data points available on the thermal properties.

3. Discussion

Table 2 provides an overview of various reviews on thermal control systems for lithium-ion batteries. Battery Thermal Management Systems (BTMS) are essential for maintaining optimal battery temperatures in a range of applications, such as electric vehicles (EVs), consumer electronics, and renewable energy storage systems. Efficient thermal management is crucial for improving battery performance, lifespan, and safety. Below, we describe several methods for implementing battery thermal management systems.

Table 2

Review of different thermal management systems for lithium-ion batteries

Method	Description	Reference
Air Cooling	They conducted an examination of heat generation in the batteries of electric vehicles (EVs) and hybrid electric vehicles (HEVs), with a specific focus on how this heat affects the powertrain systems. The study involved evaluating enhancements in the design of air-cooled Battery Thermal Management Systems (BTMS) by utilizing a combination of computational simulations and experimental methods. These enhancements were aimed at improving the cooling efficiency of the battery packs through innovative concepts, channel designs for cooling, and thermally conductive materials. The paper concludes by suggesting potential areas for future research aimed at further advancing air-cooled BTMS within the electric vehicle and hybrid electric vehicle industry.	Zhao et al. [50]
Liquid Cooling	The review encompassed an exploration of the historical context related to battery thermal management and liquid-cooling Battery Thermal Management Systems (BTMS). This was followed by an extensive analysis of recent advancements in design, which included aspects such as coolant channel modifications, refrigeration-based cooling, and hybrid cooling using liquid and Phase Change Materials (PCM). The advantages and disadvantages of these approaches were deliberated upon, with a particular emphasis on how they impact the cooling performance of liquid-cooling BTMS, especially within the electric vehicle (EV) industry. The paper additionally pinpointed areas of insufficient research and outlined potential future directions for this field.	Zhao et al. [51]
Phase Change Materials	The review centered its attention on thermal management systems that rely on Phase Change Materials (PCMs) for the regulation of temperature in electronic devices, lithium-ion batteries, and photovoltaic cells. It delved into the evaluation of these systems, including the various categories of PCMs employed and their thermal characteristics, such as phase transition temperatures and thermal conductivity. Furthermore, the paper delved into methods to improve the thermal conductivity of PCMs and introduced innovative heatsink configurations, as well as a combination of passive heatsinks with active cooling mechanisms to guarantee the secure and efficient operation of these devices.	Ling et al. [52]
Thermoelectric cooler	The review provided an in-depth examination of the existing body of knowledge concerning Battery Thermal Management Systems (BTMSs), with specific emphasis on two distinct types: Phase Change Materials (PCM), which are passive systems, and Thermoelectric Coolers (TEC), which are active systems. The information from various sources was synthesized and organized in a tabular format to offer a concise comparison of how these BTMSs perform in relation to one another. Moreover, the paper also addressed the constraints associated with batteries, PCMs, and TECs, with the goal of identifying potential directions for future research in the realm of BTMS for Electric Vehicles (EVs).	Siddique et al. [53]
Heat Pipes	The review sought to advance comprehension of potential Battery Thermal Management System (BTMS) technologies, with a particular emphasis on Heat Pipes as passive thermal devices. It examined different Heat Pipe types and their methods for removing heat from the condenser, consolidating research outcomes, and outlining prospects for future developments. These prospective advancements encompass addressing the impact of ambient temperature, the adaptability of Heat Pipe BTMS to battery modules, and the utilization of environmentally friendly working fluids in Heat Pipe BTMS research.	Bernagozzi et al. [54]
Microchannel	The review examined a range of strategies and improvements to enhance the thermal efficiency of both straight and wavy microchannel heat sinks. These enhancements encompass the utilization of nanofluids and modified designs featuring secondary flow. The paper also investigates the implementation of microchannels in the thermal management of lithium-ion batteries. Furthermore, it discusses the current obstacles and outlines prospective avenues for future research in this domain.	Hajialibabaei et al. [56]

Air Cooling: This method uses fans or natural convection to disperse heat from the battery pack. Air either circulates through or around the battery cells, and the heated air is released into the surroundings. While this approach is simple and cost-effective, it may not be adequate for high-power applications.

Liquid Cooling: Liquid cooling involves circulating a coolant (typically a water and antifreeze mixture) through a network of pipes or channels that are in direct contact with the battery cells. Liquid cooling is efficient and can handle higher heat loads compared to air cooling.

Phase Change Materials (PCMs): PCMs are substances that absorb and release heat during phase transitions, like going from solid to liquid. These materials can be integrated into the battery pack to absorb and store heat when the battery is hot and release it when it is cold, maintaining a stable temperature.

Thermoelectric Cooling: Thermoelectric materials create a temperature differential when electric current passes through them. In BTMS, thermoelectric modules can be used to move heat away from the battery or provide localized cooling.

Heat Pipes: Heat pipes are passive heat transfer devices that use a closed loop of a working fluid to transport heat from the battery cells to the cooler area. They are efficient and reliable but can be relatively costly.

Phase Change Cooling: This technique uses a two-phase system where a refrigerant evaporates at the heat source (battery) and condenses at a heat exchanger. This phase change cycle effectively removes heat from the battery.

Microchannels: Microchannel cooling involves using small channels or fins to enhance heat transfer. These channels can be integrated within battery modules to improve thermal performance.

Hybrid Systems: Some BTMS combine multiple methods, such as pairing liquid cooling with phase change materials or combining air cooling with heat pipes, to optimize thermal management across different temperature ranges.

Active Thermal Management: Active systems use sensors and control algorithms to continuously monitor and adjust cooling or heating of the battery based on its temperature. This approach optimizes performance and battery life.

Pack Design: The physical design of the battery pack itself can influence thermal management. Proper spacing between cells, optimizing airflow, and using materials with high thermal conductivity can effectively dissipate heat.

Battery Cell Design: Manufacturers continuously enhance the battery cell design to improve thermal performance. Some cells incorporate thermal management features, such as integrated cooling channels or materials with enhanced thermal conductivity.

Insulation: Insulating materials can be used to reduce heat transfer from the environment or neighboring components into the battery pack, helping maintain a stable temperature.

The choice of a BTMS method depends on various factors, including the specific application, power requirements, available space, budget constraints, and desired battery performance. Many modern battery packs combine multiple of these methods to achieve efficient and reliable thermal management.

Building upon the detailed analysis of various thermal management techniques, our review further underscores the profound impact of these strategies on enhancing both the reliability and safety of lithium-ion batteries. Notably, the adoption of phase change materials has been instrumental in stabilizing battery temperatures during peak operational loads, thereby bolstering battery reliability. This aligns with the findings from Talluri et al. [42], who demonstrated the effectiveness of phase change materials in maintaining optimal operational temperatures and enhancing the durability of battery systems under extreme conditions.

However, despite these advancements, our review identifies critical research gaps that need addressing to advance our understanding of long-term battery performance under varied thermal management regimes. Specifically, there remains a substantial need for empirical data that explores the long-term effects of hybrid cooling systems on lithium-ion batteries. Such studies are crucial for validating the scalability and sustainability of these thermal management solutions in real-world applications.

This gap highlights a critical area for further research, suggesting that future investigations should focus on longitudinal studies that monitor battery performance over extended periods under different cooling configurations. These studies will be vital in developing more robust thermal management systems that can significantly extend the lifespan and safety of lithium-ion batteries in commercial applications.

4. Numerical analysis to assess reliability of thermal management systems

4.1. Introduction to numerical analysis

In response to insightful feedback, this section introduces a numerical analysis aimed at evaluating the reliability of thermal management systems for lithium-ion batteries. Reliability assessment typically involves quantifying the likelihood that a system will perform its intended function without failure over a designated period. For thermal management systems in battery applications, reliability is influenced by both passive (e.g. insulation materials, heat spreaders) and active components (e.g. cooling fans, pumps) [43].

4.2. Methodology

To conduct a preliminary reliability analysis, we gather data on the failure rates (expressed as failures per million hours, FPMH) and meantime between failures (MTBF) of key components. These parameters serve as foundational inputs for calculating the system's overall reliability. The analysis assumes that the components are configured in a series system, where the failure of any single component could lead to the system failure, which is typical in critical safety systems like battery management [44].

Reliability calculations

For the purpose of this example, consider a thermal management system composed of the following components:

- **Component A (Active):** Cooling fan with MTBF of 300,000 hours;
- **Component B (Active):** Pump with MTBF of 250,000 hours;
- **Component C (Passive):** Heat spreader with MTBF of 500,000 hours.

The reliability of each component can be approximated by

$$R = \exp(-t/MTBF),$$

where t – operation time.

Assuming a standard operation time of 1000 hours (just over a month of continuous operation), the reliability calculations for each component would be as follows:

- $R\_A = \exp(-1000/300{,}000) \approx 0.9967$;
- $R\_B = \exp(-1000/250{,}000) \approx 0.9960$;
- $R\_C = \exp(-1000/500{,}000) \approx 0.9980$.

The overall system reliability R_system for a series configuration is the product of the individual reliabilities:

$$R\_system = R\_A * R\_B * R\_C = 0.9967 * 0.9960 * 0.9980 \approx 0.9907.$$

This calculation reveals an overall system reliability of approximately 99.07%, suggesting a high degree of dependability under the assumed conditions [45].

4.3. Discussion of findings

The numerical analysis illustrates how component reliability impacts the overall system performance. While the individual components exhibit high reliability, the aggregate effect in a series system slightly reduces the system total reliability. This analysis emphasizes the importance of selecting high-reliability components and possibly incorporating redundancy, especially in critical applications like electric vehicle batteries where failure can have significant safety implications [46].

4.4. Conclusion for the numerical analysis

This numerical approach to assessing the reliability of thermal management systems provides a quantifiable measure of system performance, offering valuable insights into component selection and system design. Future research could expand upon this preliminary analysis by incorporating more complex configurations and exploring the impact of parallel and redundant systems to enhance reliability further [47].

5. Conclusions

Establishing an efficient thermal management system is of paramount importance for lithium-ion batteries. It is essential to ensure their proper functioning within specified temperature ranges, particularly when subjected to high charge and discharge conditions. A primary objective in designing and managing the thermal aspects of lithium-ion batteries is to reduce heat generation and lower the maximum cell temperature, especially during intense usage. Achieving this objective can simplify the complexity of the thermal management systems for these batteries. This study delved into various investigations that aimed to comprehend and showcase the thermal behavior and cooling arrangements within lithium-ion battery packs, along with the different methods used to simulate and model their thermal management. The findings suggest that employing multiple inlet and outlet flows is more advantageous than using a single flow, as it helps prevent the concentration of the hottest region within the cooling system. The thermal management of lithium-ion batteries has been thoroughly examined, considering various cooling strategies and configurations. Different researchers have utilized various setups for thermal management, incorporating different coolant fluids such as water in fin cooling arrangements. However, it has been observed that indirect liquid cooling adds more weight due to its higher density compared to direct liquid cooling. A common observation is the non-uniform temperature distribution on the surface of lithium-ion batteries, which necessitates modifications to enhance the thermal behavior. To address these thermal challenges, researchers have suggested altering physical and material properties, as well as improving the thermal management system itself. Changing the layout of the battery pack, including the positions of inlet and outlet points, can shift the location of the hottest region within the pack. Increasing the number of air-cooling outlets and inlets can help distribute the hottest region more evenly. However, reducing the fluid flow around the hottest batteries may lead to temperature increases in those specific areas, indicating the need for careful optimization. The temperature of the coolant fluid as it enters the system has been identified as a critical factor in lithium-ion battery thermal management. Striking a balance to limit the rise of the coolant fluid inlet temperature is crucial to ensure optimal performance and safety. When selecting a cooling method, trade-offs between advantages and disadvantages should be considered for different applications and cooling performance. Prioritizing cooling performance may be necessary for safety-critical systems, even if it results in higher costs. Building on these critical observations, it is evident that while current strategies improve safety and efficiency, there is an urgent need to explore more advanced thermal management solutions. Future research should focus on integrating innovative cooling technologies and exploring their long-term impacts on battery performance and safety. Such efforts are essential to ensure that lithium-ion batteries can meet the increasing demands of modern energy solutions, particularly in high-demand applications. In conclusion, research on thermal management underscores the complexity and significance of developing efficient and reliable cooling solutions for lithium-ion batteries, ultimately maximizing their performance, safety, and longevity in diverse applications.

Author contributions

All authors have contributed equally to the study and preparation of this publication. Authors have read and agreed to the published version of the manuscript.

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