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A Comprehensive Review of Phase Change Materials and Their Application in Thermal Management Systems of Lithium-ion Batteries

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Lithium-ion batteries hold great promise for addressing environmental and energy challenges, driving their increased adoption in electric vehicles. Their advantages include stability, high energy density, low self-discharge, and long lifespan. However, both high and low temperatures pose significant challenges. High temperatures can lead to thermal runaway and safety hazards such as short circuits and explosions, while low temperatures can promote the formation of lithium dendrites, resulting in degradation and performance issues. To mitigate these thermal challenges, phase change materials (PCMs) have emerged as a promising solution for battery thermal management systems (BTMS). This review provides a comprehensive overview of PCMs and their application in BTMS. We categorize PCMs used in BTMS based on their modified filler materials and functionalities, including carbon-based (carbon fiber-PCM composites, carbon nanotube-PCM composites, and expanded graphite-PCM composites), metal foam, metal mesh, and organic and inorganic materials. Both inorganic and carbon-based materials can serve as highly thermally conductive encapsulants and fillers for PCMs. Finally, we present a thorough review of recent research on the thermal properties of modified PCMs and their impact on BTMS performance, including a detailed discussion of PCM performance metrics and selection criteria.

1. Introduction

The continuous increase in energy demand, coupled with the growing reliance on fossil fuels, [1] especially in developing economies, poses a serious global challenge [2].To address this challenge, the transportation industry is increasingly leaning towards electric propulsion and electric vehicles (EVs), with the ultimate goal of achieving zero emissions and reducing pollution [3]. Lithium-ion batteries, due to their significant advantages such as high energy and power density, suitable lifespan, and low self-discharge rate, are recognized as the primary energy storage option in these vehicles. Therefore, improving their performance and increasing their lifespan is crucial to ensure the efficiency of electric vehicles [4].The optimal performance of lithium-ion batteries is achieved within the temperature range of 15 to 40 degrees Celsius, and maintaining a temperature difference of less than 5 degrees Celsius between the various components of the battery is essential [5-6]. Long-term exposure to unsuitable temperatures or experiencing temperature fluctuations can lead to numerous problems in the performance and lifespan of these batteries [7]. Specifically, high temperatures increase the risk of thermal runaway and explosion

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[8,9]. In contrast to high temperatures, the performance of lithium-ion batteries significantly declines at low temperatures, leading to premature aging and a reduction in their usable capacity [10–12]. Therefore, the design and implementation of an efficient Battery Thermal Management System (BTMS) is of critical importance to ensure the safe and optimal performance of these batteries [13,14]. BTMS systems are typically designed to regulate temperature in two conditions: low-temperature heating and high-temperature cooling. Low-temperature heating in lithium-ion batteries is primarily achieved through two methods: external heating, which utilizes a preheated heat transfer medium, such as air, liquid, or phase change materials, to increase temperature; and internal heating, which employs the resistive (ohmic) heat generated by the battery itself to raise the temperature [15–17]. High-temperature cooling of batteries is also accomplished using various methods, categorized into three main types based on the cooling medium: air cooling, liquid cooling, and heat pipe cooling [18–20]. Lithium-ion batteries are gradually becoming the dominant energy source in diverse applications, particularly electric vehicles; however, efficient thermal management is indispensable to guarantee their optimal performance, safety, and lifespan. Conventional methods, such as liquid cooling and the use of fans, while offering benefits, are accompanied by limitations, including high costs, installation and maintenance complexities, and significant energy consumption [21–23]. Phase change materials (PCMs) have emerged as an ideal alternative for thermal management of lithium-ion batteries, as they offer advantages such as reduced energy consumption, simpler design, increased driving range, and improved battery performance. Further research and development in this field could lead to the introduction of these materials as a superior solution in diverse thermal management systems for lithium-ion batteries [24].

The absorption of latent heat during the phase change process, along with minor temperature and volume variations, enables temperature stabilization within a desired range and significantly enhances thermal management efficiency. However, phase change materials (PCMs) face challenges such as the potential for leakage, low thermal conductivity, and limitations in structural flexibility. Recent research has focused on optimizing the use of phase change materials in Battery Thermal Management Systems (BTMS), with an emphasis on the diversity of PCM types and efficient BTMS designs [43–61]. Furthermore, the encapsulation of PCMs and the improvement of their thermal conductivity play a vital role in the effectiveness of thermal management systems for lithium-ion batteries. This research, through the analysis of materials used in PCM encapsulation and thermally conductive fillers, serves as a valuable resource for temperature management in PCM-based lithium-ion batteries. This review specifically addresses two key aspects of PCM integration: structural arrangement and increasing thermal conductivity via the addition of fillers. This comprehensive evaluation is regarded as a fundamental reference for advancements in the field of thermal management for PCM-based lithium-ion batteries.

In this article, lithium-ion batteries and phase change materials are examined within the framework of Battery Thermal Management Systems (BTMS), and various BTMS designs for low-temperature heating and high-temperature cooling are classified and evaluated. Additionally, the phase change materials utilized in thermal management systems, particularly modified PCMs with functional fillers, are categorized into groups such as carbon, metal, minerals, non-elastic and elastic polymers, and modified and form-stable paraffin-based PCMs (Figure1). Carbon, metal, and mineral materials can serve both as high-performance thermally conductive fillers and as structurally stable encapsulating materials, whereas non-elastic and elastic polymers are primarily used as structurally stable encapsulating materials.

This study systematically reviews and assesses the latest achievements in the thermal properties of phase change materials and the characteristics of Battery Thermal Management Systems in their modified

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Figure 1: Principles of PCM applications in battery management systems

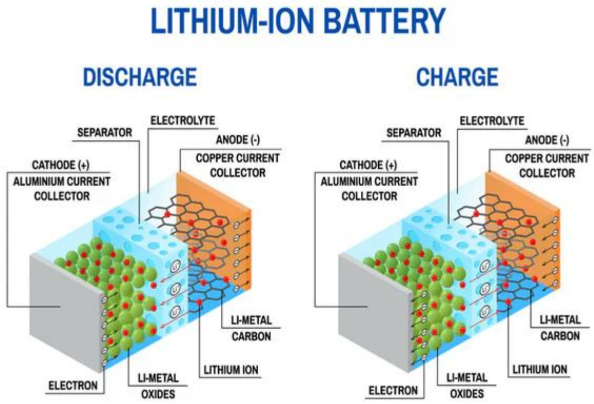

Figure 2: schematic representation of a lithium-ion battery during (a) charging and (b) discharging cycles.

forms. In this research, the selection criteria for PCMs and the performance evaluation metrics in BTMS applications are meticulously analyzed. Furthermore, the weaknesses and shortcomings in existing research are identified, and potential avenues for future studies in the field of PCMs are examined. This study presents phase change materials and lithium-ion batteries for application in Battery Thermal Management Systems (BTMS). The phase change materials (PCMs) used in these systems are categorized based on their modified filler materials and functions, encompassing carbon-based composites (such as carbon fiber-PCM, carbon nanotube-PCM, and expanded graphite-PCM), metal foam, metal mesh, and organic and inorganic substances. Carbon and mineral materials can simultaneously serve as high-efficiency thermally conductive fillers and structurally stable encapsulants. This study diligently analyzes recent research on the thermal properties of modified phase change materials (PCMs) and their impact on the performance of Battery Thermal Management Systems (BTMS), providing a comprehensive evaluation of selection criteria and performance metrics.

2. An overview of lithium-ion batteries

A standard lithium-ion battery consists of the following essential components: a positive electrode (cathode), a negative electrode (anode), an electrolyte, a separator, a current collector, and an outer case [16].

The fundamental operation of lithium-ion batteries is based on the transfer of lithium ions between the positive (cathode) and negative (anode) electrodes. During the discharge process, lithium ions detach from the cathode, migrate through the electrolyte to the anode, and consequently, an external electrical current is generated. Conversely, during the charging process, this trend occurs in reverse; that is, lithium ions detach from the anode and move towards the cathode [25]. The type of chemical reactions that occur during charging and discharging depends on the material composition used in the construction of the electrodes. For example, in lithium iron phosphate ($LiFePO_4$) batteries, the following electrochemical reaction takes place [26]:

$$Charge: LiFePO_4 - xLi^+ - xe^- \rightarrow xFePO_4 + (1-x)LiFePO_4 \quad (1)$$

$$Decharge: FePO_4 + xLi^+ + xe^- \rightarrow (1-x)FePO_4 + xLiFePO_4 \quad (2)$$

This chemical equation elucidates the critical role of lithium ions (Li+) in the charging and discharging processes of lithium-ion batteries. Lithium ions, acting as charge carriers, migrate between the electrodes throughout these cycles. The battery's capacity, which refers to its ability to store electrical energy, is directly correlated with the concentration of Li+ ions. Ambient temperature impacts the rate of transfer and the extent of diffusion of Li+ ions within the electrolyte and separator. Each battery operates within an optimal temperature range to achieve efficient Li+ ion transfer. Deviations from this range can negatively affect battery performance [27].

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3. Lithium-ion battery thermal effects

The thermal behavior of lithium-ion batteries during charging and discharging is influenced by two main factors. First, Joule heating, which results from the resistance of lithium ions as they move through the internal components of the battery. This includes ohmic heating in the electrodes, electrolyte, and separator, as well as polarization heating in the electrodes. Second, thermal energy generated by the exothermic chemical reactions during the charging and discharging process. For accurate modeling of heat generation in lithium-ion batteries, the comprehensive model provided in reference [28] can be used.

$$Q = Q_I + Q_J + Q_C \qquad (3)$$

The presented equation illustrates the total heat generated (Q) within a lithium-ion battery during its thermal activity. This equation encompasses ohmic heat (QI) resulting from internal resistance during charging and discharging processes, electrode polarization heat (QJ), and heat generated during the overall battery operation (QC) [29]. However, numerous factors beyond these primary mechanisms influence the battery's thermal behavior, including ambient temperature fluctuations, charge/discharge rates, and battery degradation levels. Electrolyte active materials exhibit high sensitivity to temperature variations; hence, extremely high and low temperatures intensify heat generation. At low temperatures, reduced internal resistance increases Joule heat generation, whereas exceeding the battery's safe operating temperature leads to rapid accumulation of chemical reaction heat, ultimately dominating the total heat output. Charge/discharge rates affect the balance between reversible and irreversible heat generation. At low rates, reversible heat from chemical processes and Joule heat are predominant. Conversely, high rates necessitate stronger currents between the positive electrode and separator, leading to a rapid increase in Joule heat and, consequently, a significant rise in battery temperature. Thus, the charge/discharge rate is the primary determinant of heat generation [30].

4. BTMS and Classifications

To ensure the safe and optimal performance of lithium-ion batteries, the use of Battery Thermal Management Systems (BTMS) is essential. The primary function of a BTMS is to precisely control the battery's temperature within a safe operating range and to reduce thermal fluctuations during charging and discharging processes. Modern thermal management methods can be categorized into active, passive, and hybrid systems, based on the type of external energy source required. Active BTMS systems employ fans and pumps with an external power supply to circulate a heat transfer fluid (typically air or liquid). However, the additional energy consumption in these systems can lead to a reduction in the range of electric vehicles. Conversely, passive BTMS systems, utilizing Phase Change Materials, control temperature through the inherent properties of the materials without requiring an external energy source. Hybrid BTMS systems aim to achieve optimal thermal performance by combining components of active and passive systems, such as using PCM alongside air or liquid cooling. BTMS systems based on PCM offer numerous advantages compared to other methods, including lower cost, ease of installation, smaller dimensions, and more uniform temperature distribution within the battery. Additionally, these systems offer higher thermal efficiency, require no external energy, and demand less maintenance. These characteristics make PCM-based BTMS a practical and efficient solution, which we will examine in more detail [31].

5. Systems based on phase change materials

Phase change materials (PCMs), by storing latent heat, are capable of absorbing or releasing a significant amount of energy during phase transitions at an approximately constant temperature. In other words, they absorb energy from their surrounding environment during the melting process and release that same energy back into the environment during the solidification process [32]. This capability makes PCMs an efficient tool for thermal energy storage, allowing energy to be stored at any time and place and released when needed. When heat is applied to a PCM, they first absorb energy in their solid state. Then, at the melting point, they absorb more heat to change phase from solid to liquid at a constant temperature. In the reverse process, with the solidification of the material, energy is released back into the environment, and the material's temperature rises. PCMs are mainly used in solid-liquid phase changes and are classified into three main categories: organic, inorganic, and eutectic. Organic materials include carbon-based compounds like paraffins and fatty acids, inorganic materials include hydrated salts and metals, and eutectic materials include mixed compounds of organic and inorganic materials. PCMs have extensive applications in thermal management and thermal energy storage, including storing solar energy and waste energy, cooling electronic components, regulating building temperatures, and managing battery temperatures.

The main feature of PCM-based systems is the ability to absorb and release latent heat during phase transitions. In battery thermal management, this feature helps reduce the maximum battery temperature during charge and discharge cycles. PCMs can effectively control battery temperature in various conditions, even with significant temperature fluctuations, and improve battery performance at low temperatures. A variety of commercial PCMs are available, facilitating their selection based on the needs of each application. Choosing the right PCM for thermal management is essential, and the optimal material should possess specific characteristics [33]:

1. High specific heat capacity and latent heat: To maximize the absorption of heat generated by battery cells.

2. Optimal thermal conductivity: To accelerate and optimize the process of heat absorption and dissipation from PCM.

3. Low density: To prevent an increase in the overall weight of the thermal management system.

4. Chemical inertness: No reaction with cell casings and adjacent components.

5. Cycle stability: The ability to maintain optimal performance after multiple battery charge and discharge cycles.

6. Easy accessibility and cost-effectiveness: For economical implementation of the system. [31].

In this system, battery cells are surrounded by a phase change material. As the charge or discharge process begins, the cells' temperature increases, and the PCM absorbs the generated heat due to the temperature difference. As the temperature continues to rise, the PCM melts and absorbs latent heat. This process leads to the creation of a natural convection current that intensifies heat absorption from the cells. Effective heat dissipation from the PCM to the surrounding environment plays a crucial role in maintaining the desired temperature [34].

6. Systems Utilizing Pure Phase Change Materials

Al-Hallaj and Selman [35] were pioneers in exploring the application of PCMs for thermal control in batteries. Their model, using paraffin wax, demonstrated that PCMs provide a more uniform temperature distribution compared to conventional cooling systems.

Duan and Naterer [36] compared PCM cooling systems in both cylindrical and jacket configurations and showed that both types can maintain battery temperature within a safe range. Hemery et al. [37] compared the performance of PCMs with natural and forced convection cooling systems. The results indicated that PCMs achieve a significantly more uniform temperature distribution, although forced convection can lower the maximum temperature in some conditions.

Somasundaram et al. [38] developed an electro-thermal model to analyze the impact

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of PCMs on battery performance and showed that PCMs can reduce the maximum temperature at high discharge rates.

Yang et al. [39] also created a computational model to examine the melting behavior of PCMs and showed that using a metal enclosure for PCMs performs better than an acrylic enclosure.

Wang et al. [40] using a numerical model, demonstrated that PCMs can effectively reduce temperature fluctuations during discharge and create a more uniform temperature.

Kizilel et al. [41] examined the performance of PCMs at high temperatures and very high discharge rates (conditions close to thermal runaway) and showed that PCMs, by using graphite to increase thermal conductivity, can effectively prevent temperature rise. Yan et al. [42] by developing a hybrid cooling system (thermally conductive-insulating-PCM), showed that increasing the latent heat of the PCM significantly extends the time to reach critical thermal conditions. This highlights the importance of selecting a PCM with appropriate latent heat. Research indicates that information regarding the precise impact of PCM thermophysical properties, such as thermal conductivity and phase change temperature, on battery thermal performance is limited. Hu and Rao [43] demonstrated that the latent heat of PCM has a significant effect on controlling battery temperature in various temperature conditions. Ling et al. [44] examined the influence of phase change temperature and proposed a temperature range of 40-45°C for optimal battery cooling. Yang et al. [45] by testing three types of paraffin, showed that choosing a PCM with phase change temperature and latent heat appropriate for operating conditions is essential. The geometric parameters of the PCM system, including the thickness and number of layers and contact area, play an important role in the performance of the PCM-based thermal management system. Javani et al. [46] demonstrated that increasing the PCM layer thickness, while improving temperature uniformity in batteries, does not have a significant impact on reducing the recorded maximum temperature. The results from tests on thicknesses of 3, 6, 9, and 12 mm showed minor changes in the recorded maximum temperature. In this context, studies by Malik et al. [47] on lithium iron phosphate battery packs indicated that greater PCM thickness leads to a reduction in temperature at low discharge rates (1C and 2C), but no significant effect is observed at high rates (3C and 4C). However, Javani et al. [48] through more detailed investigations, found that increasing PCM thickness up to 3 mm significantly improves temperature uniformity, and increasing it up to 12 mm leads to a 3.04°C reduction in the maximum battery temperature. Additionally, experimental research by Zhao et al. [49] on prismatic batteries showed that increasing PCM thickness up to 25 mm improves battery thermal management efficiency, but further increases beyond this point reduce heat dissipation.

Moraga et al. [50] by examining the impact of the number of PCM layers in a prismatic cell, found that using three layers compared to one-layer results in a more significant temperature reduction, and recommended that the layer with maximum thermal conductivity be placed in direct contact with the cell. Ramandi et al. [51] through an exergy study on four types of PCMs, demonstrated that while a single layer of capric acid has high efficiency, using a dual-layer combination of capric acid and $Zn(NO_3)_2 \cdot 6H_2O$ provides better efficiency. Furthermore, the structure of the PCM layers, in addition to their number, plays a crucial role in the overall effectiveness of the system. Wang et al. [52] by designing a vertically stratified system and using PCMs with different thermal conductivities, improved the system's performance and determined an optimal thickness of 10 mm for the PCM layers. Ultimately, PCMs, due to their ability to passively reduce and stabilize battery temperatures, are considered an effective solution, leading to an 8% to 28% reduction in cell temperatures. Paraffin wax, due to its suitable operating temperature range, is recognized as the most common PCM, but there is still a need to explore and develop alternative PCMs and improve the

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performance of battery thermal management systems.

Table 1: Summary of reviewed articles on pure phase change materials.

Authors	Battery Type	Numbe of Cells	Year	Research Method	Parameter Evaluated
X. Duan, G.F. Naterer [36]	Cylindrical	1	2010	Experimental	Battery module thermal management
C. Hemery, F. Pra [37]	Cylindrical	27	2014	Experimental	PCM amount reduction, PCM solidification
K. Somasundaram et al. [53]	Cylindrical	1	2012	Numerical	Spiral cell thermal management
H. Yang, H. Zhang [39]	Cylindrical	1	2017	Exp.-Numerical	Melting process investigation
J. Yan, Q. Wang [42]	Prismatic (book)	3	2016	Numerical	Latent heat increase, normal & thermal abuse conditions
Z. Ling, J. Chen [44]	Cylindrical	4	2014	Exp.-Numerical	Optimized PCM properties
J. Yan, K. Li [54]	Cylindrical	16	2016	Experimental	Phase change temperature effect, resting time effect
N. Javani, I. Dincer [46]	Prismatic (book)	1	2014	Numerical	PCM thickness variation
M. Malik, I. Dincer [47]	Prismatic (book)	3	2017	Experimental	Discharge rate & thickness variations
N. Moraga et al. [55]	Prismatic (book)	1	2016	Numerical	Multiple PCMs
J. Weng, X. Yang [56]	Cylindrical	1	2019	Experimental	PCM property optimization
R. Jilte, R. Kumar [57]	Cylindrical	24	2019	Numerical	PCM amount reduction, temperature effect, PCM melting

7. Composite phase change material systems

Phase change materials have limited thermal conductivity. Systems solely using PCMs may not adequately regulate battery cell temperature during extended operation. Thermal conductivity enhancers (TCEs) can address this limitation. High thermal conductivity facilitates heat transfer from PCM to the environment, prevents excessive temperature drops, and improves temperature control. Common TCEs include carbon-based and metal-based additives. PCMs incorporating these substances are termed "composites" or "enhanced PCMs" due to their improved thermal conductivity [58].

7.1 Composite PCM-based systems with carbon, graphene, and metal additives

Carbon-based additives are highly regarded in PCM-based thermal management systems due to their unique properties such as corrosion resistance, high thermal conductivity, and low density. These additives enhance the thermal performance of the system by increasing the heat absorption and dissipation rates in battery cells during charging and discharging cycles, and also help to reduce PCM leakage. Commonly used carbon additives include expanded graphite, graphene, and carbon fiber [59].

Xiao et al. [60] achieved a significant increase in the thermal conductivity of paraffin wax in 2020 by adding only 3 wt% expanded graphite, reducing the melting and solidification times by up to 40% and 22%, respectively. Subsequently, many researchers utilized expanded graphite to improve the thermal performance of various PCMs, including paraffin wax, fatty acids, and fatty alcohols [61–64]. Wang et al. [65] first used carbon nanotubes to enhance the thermal conductivity of paraffin wax in 2008 and found that increasing the concentration of nanotubes increases thermal conductivity but decreases the melting point and latent heat of the composite. For example, using 2 wt% carbon nanotubes increased the thermal conductivity by up to 40% compared to pure paraffin. Samimi et al. [66] demonstrated through computational analysis that using a paraffin/carbon fiber composite in cylindrical batteries increases thermal conductivity by up to 10.5% and reduces battery temperature by up to 2°C. Fathabadi [67] also showed through computational analysis of lithium-ion battery packs that using expanded graphite in PCM increases thermal conductivity from 0.22 W/mK to 16.6 W/mK and maintains the

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battery pack temperature below 60°C even at an ambient temperature of 55°C. Jiang et al. [68] using an expanded graphite composite and RT44HC paraffin in lithium-ion batteries, concluded that increasing the mass fraction of expanded graphite increases the convective heat transfer coefficient and decreases the latent heat of PCM. Therefore, the optimal mass fraction of expanded graphite is about 10 wt%, which leads to a 10°C reduction in the maximum battery temperature compared to a pure PCM system.

Investigations demonstrate that carbon and metal additives, due to their unique properties, play a significant role in improving the thermal performance of PCM-based battery thermal management systems. Babapoor et al. [69], through an experimental study of the effect of carbon fiber in PCM, concluded that a mass fraction of 0.46 wt% provides the best performance in reducing the maximum temperature and improving temperature uniformity, with 2 mm fibers being more effective in reducing temperature and 5 mm fibers more effective in improving temperature uniformity. Goli et al. [70], using graphene, showed that a 20 wt% fraction significantly increases the thermal conductivity of PCM and reduces the battery temperature by up to 14°C. Malik et al. [47], using graphene composite plates, achieved better performance than active fluid cooling and observed a 20-degree temperature reduction with a 6 mm thickness. In general, the addition of carbon significantly increases the thermal conductivity of PCM. On the other hand, metals, due to their inherent high thermal conductivity, are a suitable option for improving the thermal conductivity of PCM and, in addition, increase structural strength and reduce PCM leakage. Zhang et al. [72], using aluminum nitride, observed the largest increase in thermal conductivity at a 20 wt% fraction, which led to a 19.4% reduction in battery temperature. Pan and Li [73], by studying a copper fiber/paraffin composite, concluded that this composite performs better than other cooling methods, and a 47 wt% fraction of copper fiber provides the best balance between uniformity and temperature reduction.

Research indicates that the use of metals in phase change materials (PCM) is recognized as an effective method for improving the thermal performance of batteries. Pan and Zhong [74], by presenting a validated computational model, investigated the impact of using copper fiber in PCM. They found that increasing the number of holes per inch, due to the increase in heat exchange surface, leads to a reduction in battery temperature. Also, increasing the spacing between cells, despite reducing the temperature, increases the system's weight due to the use of a larger amount of PCM. Zhao et al. [75], by using copper microfibers in PCM, were able to improve the performance of lithium-ion batteries at high discharge rates (15C) and maintain the cell surface temperature below 48°C. Metal meshes are also widely used in PCMs due to providing structural support and increasing thermal conductivity and mechanical strength. Uniform distribution of metal mesh in PCM improves heat transfer compared to finned PCMs. Lazrak et al. [76], by examining the impact of copper mesh in PCM, observed a 10°C temperature reduction compared to pure PCM. Their three-dimensional model showed that increasing the thermal conductivity of PCM and adjusting its phase transition temperature to the optimal battery operating range are of great importance.

Figure 3: Schematic of a thermal management system based on a phase change material with a copper mesh [80]

Wu et al. [77] created a new composite phase change material by combining copper mesh, expanded graphite, and paraffin. Due to the presence of copper mesh, this composite exhibited enhanced structural reinforcement and thermal conductivity. The test results showed that this material performed well at a high discharge rate of 5C and was able to

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reduce the maximum battery temperature by 5 degrees Celsius.

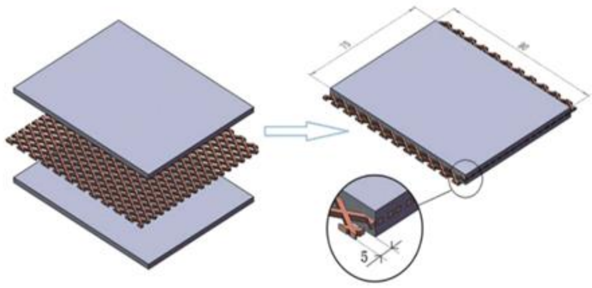

Figure 4: Another schematic of a thermal management system based on a phase change material with a copper mesh [77]

Khateeb et al. [78] experimentally evaluated four cooling solutions for a lithium-ion battery in an electric scooter (Figure 5), utilizing two modules of 18 18650 cells each: natural convection, aluminum foam, pure phase change material (PCM), and a combination of aluminum foam and composite PCM. The aluminum foam/composite phase change material reduced the temperature by approximately 50% compared to natural convection and ensured consistent temperature distribution throughout the battery.

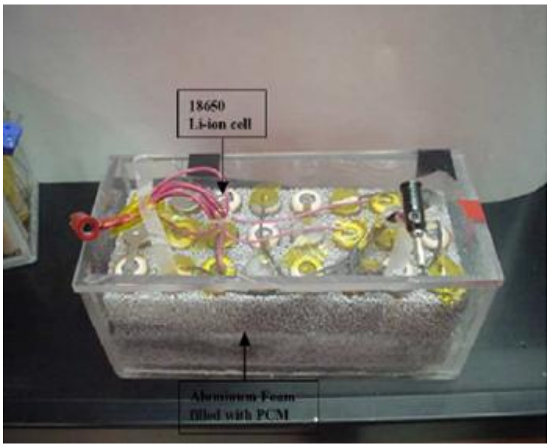

Figure 5: Lithium-ion battery covered with aluminum foam and phase change materials, laboratory model by Khatib et al. [78]

Azizi and Sadrameli [79] with the aim of improving the thermal management of lithium-ion battery packs, designed an innovative system. This system utilizes a combination of aluminum wire mesh and a polyethylene glycol composite phase change material. The experimental results showed that this combination reduces the battery surface temperature by 19, 21, and 26 percent at discharge rates of 1C, 2C, and 3C, respectively. Furthermore, this system was able to maintain the ideal battery temperature in the high-temperature range of 50 to 55 degrees Celsius for 6 hours.

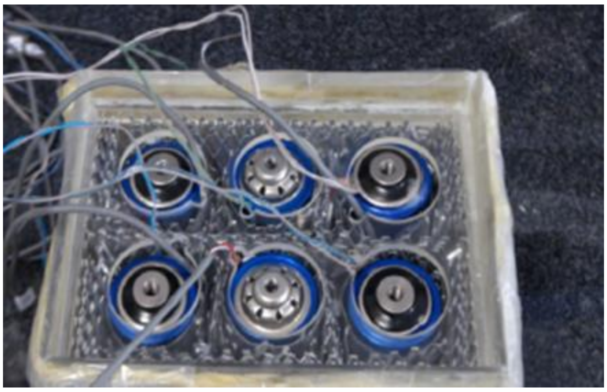

Figure 6: Battery pack with ethylene glycol and aluminum mesh in the research of Azizi and Sadramli [79].

The use of metal foams alongside phase change materials (PCMs) has garnered attention from researchers as an effective method in battery thermal management. Qiu et al. [80] by presenting a thermal-electrochemical model and comparing it with natural convection, demonstrated that the use of copper foam saturated in PCM significantly reduces battery temperature. Specifically, temperature reductions of 33% and 35% were achieved at discharge rates of 1C and 3C, respectively. Rao et al. [81] also confirmed the effectiveness of paraffin/copper foam in real-world driving conditions by conducting experimental tests on batteries of electric vehicles, observing a 31.4% reduction in peak temperature and a 66.3% reduction in temperature difference. Mehrabi Kermani et al. [82], by developing a system including copper foam, a heat sink, and PCM, showcased the significant impact of this combination in reducing both peak battery temperature and temperature gradient. In the presence of copper foam, the battery temperature reached 53.5°C after 100 minutes, whereas without copper foam, the temperature increased to 60°C after 40 minutes. Wang et al. [83] also increased the thermal conductivity of PCM by 218 times using aluminum foam, resulting in temperature reductions of 62.5% and 53% at discharge rates of 1C and 2C, respectively. Malou et al. [84] , by examining the effect of aluminum foam pore density, found that foam with a 40 PPI density results in a greater temperature reduction compared to 10 PPI foam, and compressed natural graphite foam, due to its superior properties, provides better performance than aluminum foam. Li et al. [85], by studying the influence of copper foam porosity and pore density, showed that reducing these two parameters leads to a reduction in battery temperature, and the PCM system based on copper foam achieves temperature reductions of 29% and 12% compared to a system without thermal management and a pure PCM system, respectively. Alipanah and Li [86] also concluded, by examining the impact of aluminum foam porosity and PCM thickness, that foam significantly increases the thermal conductivity of PCM.

Hussein et al. [87], by utilizing graphene-coated nickel foam alongside phase change material (PCM), achieved a 23-fold increase in thermal conductivity compared to uncoated nickel foam (6-fold increase). Using this improved nickel foam resulted in a 2°C temperature reduction in batteries, whereas uncoated nickel foam only achieved a 0.7°C temperature reduction. He et al. [88] formulated a composite PCM using expanded graphite and copper foam, evaluating battery performance at different discharge rates (1C, 3C, and 5C). They found that this composite, in addition to improving tensile and flexural strength, reduces compressive and impact strength, though this negative effect is mitigated by the copper foam. Moreover, this composite PCM decreased battery temperature by 8.37% compared to pure PCM. Li et al. [89] created a new composite phase change material by integrating paraffin wax, expanded graphite, and silica gel within an innovative aluminum honeycomb framework. This honeycomb configuration, by increasing thermal conductivity, was able to maintain an optimal battery temperature (45°C) at a 5C discharge rate. Karimi et al. [90], by adding metal nanoparticles (copper, silver, and iron oxide) to PCM, improved its thermal conductivity, with silver nanoparticles showing the best performance by reducing the temperature difference by 50%. Zhao et al. [91] also increased thermal conductivity by 41% and 61.5%, respectively, using multi-walled carbon nanotubes and graphene in PCM. Combining 30% carbon nanotubes and 70% graphene led to a 123% increase in thermal conductivity and stabilized the battery temperature around 46°C. Finally, Zhao et al. [92] evaluated battery performance using a composite PCM consisting of paraffin, expanded graphite, and carbon nanotubes in four different configurations.

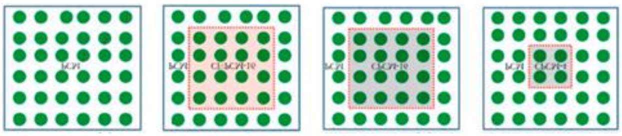

Figure 6: Four different arrangements of phase change material and composite phase change material within the battery pack [92]

In evaluating battery cooling systems, four distinct configurations were examined: 1) the use of pure phase change material (PCM), 2) copper foam around the central cells and pure PCM around it, 3) composite PCM around the central cells and pure PCM throughout the space, and 4) composite PCM only around the core cells and pure PCM in the remaining space. The results showed that configurations 2, 3, and 4 have similar peak temperatures, but configuration 4 offers a more uniform temperature distribution. The use of copper foam or composite PCM led to a 5 to 20 percent reduction in peak temperature and improved temperature uniformity. Research has extensively demonstrated the benefits of metal foam in PCM-based thermal management systems. To further improve thermal performance, increasing the heat transfer surface area through the use of fins has been investigated. Lu et al. [93], by combining PCM and fins, significantly reduced the temperature difference and kept the battery temperature below the safety limit of 50°C. Zhong et al. [94] also, by integrating metal fins in composite PCM, were able to keep the battery temperature below 45°C and maintain the temperature difference below 5°C, even under high discharge conditions

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(5C) and high ambient temperatures (40°C). Ping et al. [95] found that fins can keep the temperature of prismatic batteries below 65°C at a 3C discharge rate, and their numerical model showed that narrower fins with appropriate spacing and thicker PCM layers offer better thermal control. Sun et al. [96] concluded that 8 longitudinal fins provide a suitable balance between heat transfer surface area and heat absorption by PCM. Weng et al. [97], by examining different fin shapes, found that longitudinal fins are more suitable for natural convection and circular fins for forced convection. Also, a hybrid design with circular fins at the bottom and longitudinal fins at the top provides a greater reduction in battery temperature compared to rectangular fins.

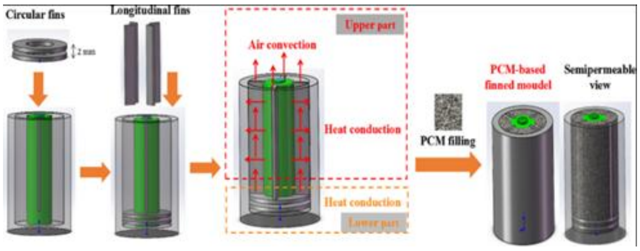

Figure 7: Use of rectangular, triangular, circular and combined longitudinal fins in the battery thermal management system [97].

Mohammadian and Zhang [98]], in their research, investigated the thermal efficiency of lithium-ion battery packs using a specific pin-fin heat sink configuration. The results of their three-dimensional transient thermal analysis showed that the incorporation of these pin-fins significantly reduced the overall battery temperature and also improved the uniformity of heat distribution within it.

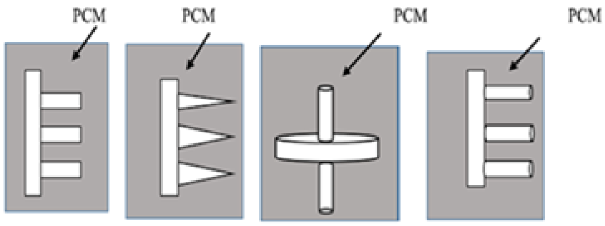

Figure 7: Different types of fins used in the thermal management system of a battery based on phase change materials [98]

Weng et al. [99] in their study, examined the efficiency of branching fins in the cooling of cylindrical cells. By comparing four longitudinal fin designs (shaped like the letters I, V, Y, and X), they found that the X-shaped fin achieved the best temperature reduction, successfully maintaining the battery temperature below 47°C even at an ambient temperature of 40°C. Heyhat et al. [100], using numerical analysis, evaluated the impact of the number of fins (1, 3, and 5) in PCM-based systems. The results indicated that increasing the number of fins does not necessarily lead to improved thermal performance. They also compared the effect of fins, nanoparticles, and metal foam and found that although fins performed better than nanoparticles, metal foam was the most effective method for enhancing heat transfer.

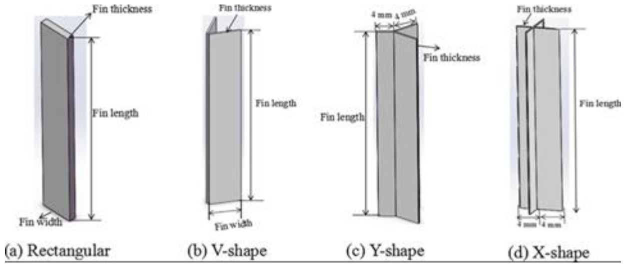

Figure 7: Four types of longitudinal fin shapes in the form of the English letters I, V, Y, and X [99]

Although fins improve the performance of PCM-based battery thermal management systems by increasing the heat transfer surface, most research has focused on longitudinal fins, overlooking the potential of circular fin configurations. However, PCM systems face challenges due to the inherently low thermal conductivity of PCMs. Adding conductive materials, while increasing conductivity, usually affects other beneficial PCM properties. Additionally, the limited heat storage capacity of PCMs leads to short-term thermal retention. Increasing the PCM volume can solve this issue but increases the system's weight. After the PCM completely melts, the system's ability to dissipate heat decreases, and there is a risk of increased battery temperature. Therefore, effective heat transfer from the PCM is crucial for proper thermal management.

Table 2: Summary of reviewed articles on phase change materials composed of carbon additives, graphene, and metals

Authors	Battery Type	Number of Cells	Year	Research Method	Parameter Evaluated
J. Selman, S.	Cylindrical	20	2009	Experimen	Cell

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Authors	Battery Type	Number of Cells	Year	Research Method	Parameter Evaluated
Al-Hallaj [41]				**tal**	**spacing, thermal runaway propagation prevention**
H. Fathabadi [101]	**Prismatic (book)**	**22**	**2014**	**Numerical**	**Ambient temperature**
G. Jiang, J. Huang [102]	**Cylindrical**	**1**	**2016**	**Experimental**	**PCM mass fraction variations**
A. Babapoor, M. Azizi [103]	**Cylindrical**	**3 nodules**	**2015**	**Experimental**	**Carbon fiber addition**
F. Samimi, A. Babapoor [104]	**Cylindrical**	**1**	**2016**	**Experimental**	**Carbon fiber addition**
P. Goli, S. Legedza [70]	**Cylindrical**	**7**	**2013**	**Experimental**	**Graphene addition**
J. Zhang, X. Li [72]	**Cylindrical**	**30**	**2019**	**Experimental**	**Aluminum nitride addition**
M. Pan, W. Lai [73]	**Cylindrical**	**15**	**2017**	**Experimental**	**Copper fiber addition**
M. Pan, Y. Zhong [74]	**Cylindrical**	**15**	**2018**	**Experimental**	**Copper fiber addition**
W. Zhu, H. Yang [105]	**Cylindrical**	**4**	**2017**	**Numerical**	**Microfiber addition**
A. Lazrak, J. Fourmigué [76]	**Cylindrical**	**15**	**2017**	**Exp.-Numerical**	**Fin effect, copper fiber**
W. Wu, X. Yang [77]	**Prismatic (book)**	**5**	**2016**	**Experimental**	**Copper fiber addition**
W. Situ, G. Zhang [106]	**Prismatic (book)**	**5**	**2017**	**Experimental**	**Dual copper fiber addition**
Y. Azizi, S. Sadrameli [107]	**Cylindrical**	**8**	**2016**	**Exp.-Numerical**	**High-temperature environment, Al fiber addition**
N. Javani, I. Dincer [46]	**Prismatic (book)**	**4**	**2014**	**Exp.-Numerical**	**Wet foam effect at different volume fractions**
Z. Qu, W. Li [80]	**Prismatic (book)**	**6**	**2014**	**Exp.-Numerical**	**Porous metal foam**
Z. Rao, Y. Huo [108]	**Cylindrical**	**24**	**2014**	**Experimental**	**Copper foam**
M. Mehrabi-Kermani et al. [82]	**Cylindrical**	**84**	**2019**	**Exp.-Numerical**	**Copper foam**
Z. Wang, Z. Zhang [83]	**Prismatic (book)**	**4**	**2015**	**Experimental**	**Aluminum foam**
O. Abdelaziz, S. Graham [84]	**Prismatic (book)**	**1**	**2018**	**Experimental**	**Aluminum foam**
W. Li, Z. Qu [85]	**Prismatic (book)**	**10**	**2014**	**Experimental**	**Metal foam, porosity, pores**
M. Alipanah, X. Li [86]	**Cylindrical**	**1**	**2016**	**Numerical**	**Metal foam**
Z. Luo, C. Chao [109]	**Cylindrical**	**6**	**2018**	**Experimental**	**Graphene and nickel coating**
J. He, X. Yang [88]	**Prismatic (book)**	**6**	**2019**	**Exp.-Numerical**	**Enhanced thermal conductivity with dual TCEs**
J. Huang, M. Cao [110]	-	-	**2018**	**Experimental**	**Heat transfer enhancement with silica & Al honeycombs**
G. Karimi, M. Azizi [90]	**Cylindrical**	**1**	**2016**	**Experimental**	**Metal matrix, nanoparticles**
D. Zou, X. Ma [91]	**Cylindrical**	**1**	**2018**	**Experimental**	**Graphene, carbon nanotubes**
D. Zou, X. Liu [92]	**Cylindrical**	**36**	**2019**	**Experimental**	**Copper foam, different temperature conditions**
Y. Lv, X. Yang [93]	**Cylindrical**	**24**	**2016**	**Experimental**	**Composite PCM, fins**
X. Yang, X. Li [94]	**Cylindrical**	**15**	**2017**	**Exp.-Numerical**	**Composite PCM, fins, preheating**

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Authors	Battery Type	Number of Cells	Year	Research Method	Parameter Evaluated
G. Chen, J. Wen [95]	Prismatic (book)	5	2018	Exp.-Numerical	Fins, fin & PCM thickness
T. Zhou, N. Zheng [96]	Cylindrical	1	2019	Exp.-Numerical	Fins, fin geometry
G. Zhang, J. Wang [97]	Cylindrical	1	2019	Exp.-Numerical	Fins, fin geometry
G. Zhang, J. Wang [99]	Cylindrical	1	2019	Exp.-Numerical	Fins, fin geometry
S. Mousavi, M. Siavashi [100]	Cylindrical	1	2020	Numerical	Metal foam, fins

8. Conclusions

In this study, a comprehensive review of the current status of lithium-ion battery thermal management systems based on phase change materials (PCMs) was presented. The examination of research findings revealed that the use of PCMs as an efficient method for regulating battery temperature, due to advantages such as negligible supplementary energy consumption, simple and compact design, ease of installation, and lightweight materials, has high potential. However, since most of the research conducted in this field has been carried out on a laboratory scale, further research is needed before widespread industrial application. In order to accelerate the transfer of PCM-based thermal management technology from the laboratory level to industrial applications, it is suggested that future studies focus on the following:

1. **Improving PCM Heat Transfer Efficiency:** To achieve uniform temperature distribution in batteries by leveraging the exceptional heat transfer characteristics of PCMs, it is essential to increase thermal conductivity and latent heat while reducing the melting point. These enhancements are especially beneficial for mitigating thermal runaway situations.
2. **Hybrid Thermal Management Systems:** Although PCMs offer significant latent heat capacity, their efficacy as a standalone passive thermal management solution is limited, particularly for devices with cyclic operation. Integrating PCM-based passive cooling with active thermal management techniques is a viable option. These hybrid systems provide uninterrupted operation and enhanced energy efficiency compared to exclusively active systems. Therefore, the advancement of PCM-based hybrid thermal management systems represents a promising avenue for further research.
3. **Development of Advanced PCMs:** A primary research focus is the advancement and refinement of phase change materials with superior thermal properties. Developing novel materials with high heat capacities and tailored phase transition temperatures for lithium-ion batteries would significantly improve thermal performance.
4. **PCM Integration with Battery Structure:** Effectively integrating PCMs within lithium-ion battery structures remains a significant challenge. Future research should prioritize developing improved integration methods for combining PCMs with battery cells, along with innovative designs that optimize heat transfer. This includes exploring the use of nanomaterials and advanced manufacturing techniques.
5. **Optimization of Thermal Management with Intelligent Systems:** Integrating PCMs with intelligent thermal management systems offers the potential to optimize energy consumption and extend battery lifespan. These intelligent systems can utilize sensors and algorithms to monitor and control battery thermal conditions in real-time.
6. **Economic and Environmental Evaluation:** Future research must also consider the economic viability and environmental impact of implementing PCMs in lithium-ion battery thermal management. These assessments will be crucial for informed decision-making regarding the broader adoption of this technology in the energy sector.

Future research and development in phase change material-based lithium-ion battery thermal management will be essential for improving battery performance and longevity.

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These improvements will enhance efficiency, reduce costs, minimize environmental impact, and bolster energy sustainability.

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