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Review Article

Heat transfer performance of Li-ion battery pack using composite phase change material: A review

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ABSTRACT

Electric Vehicles (EVs) rely on Li-ion batteries (Li-ion), which perform best in an operating temperature range of 15°C to 40°C. However, in regions where ambient temperatures are higher, EVs can catch fire even with thermal management systems. To address this issue, researchers are exploring the use of phase change materials (PCM) in battery thermal management systems (BTMS). PCM-based BTMS can maintain operating temperatures within the standard range for a long time without additional power, thus improving battery lifespan. Various types of PCM, such as Composite phase change material (CPCM) and Flexible phase change material (FCPM), have been proposed for BTMS to address existing issues like overheating, internal heat generation, and optimization. Battery Thermal Management Systems (BTMS) in Electric Vehicles (EVs) have issues like overheating during running and charging, internal heat generation, optimization, and battery life. The maximum temperature difference (ΔTmax) is achieved between 2°C to 20°C for different discharge rates. This reduces the battery surface temperature by 24% to 70% and improves battery lifespan.

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INTRODUCTION

Electric vehicle (EV) adoption is a positive step toward energy security and carbon footprint reduction. An appropriate energy storage system is required for EVs to have a long road trip range, rapid charging, and proper functioning. Due to the benefits of Li-ion batteries are the most beneficial power source for EVs. They also have long service lives and high energy densities. Additionally, LIBs are composed of environmentally friendly materials and do not

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emit any hazardous gases. They also offer a high level of safety. LIBs have been extensively used for energy storage in numerous applications, including power packs of electric devices, electric vehicles, and medical equipment. EV technology is necessary for today's society due to its low operating costs, pollution-less operation, and goodwill towards the environment [1].

The performance of the Li-ion battery cell is affected by its temperature. The temperature of the batteries rises over the working temperature range due to the fast charging and discharging rates and the extreme ambient conditions, causing battery capacity to decline and chances of catching fire arise. BTMS controls the temperature of the Li-ion batteries to avoid such incidents.

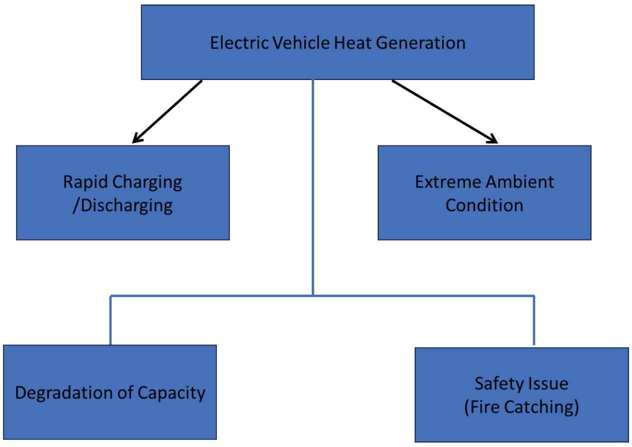


Figure 2. Problem description.

LITERATURE SURVEY

In this paper, research articles published from 1994 to 2023 in the domain of heat transfer performance of Li-ion battery packs using PCM are reviewed. Various categories of PCM cooling based on the material used such as Pure PCM, CPCM, FPCM, and metal fins are discussed. The future development of PCM-based BTMS based on evaluation and analysis is emphasized. This paper intends to provide an overview of the battery temperature management system. Additionally, it clarifies experimental and numerical work with various Li-ion battery cooling mediums that should have been extensively addressed in the prior review publications. The number of research papers that have been reviewed for this review paper is shown in Figure 1.

Literature Gap and Motivation

The average cost of the batteries and BTMS used in EVs is nearly 40 to 55% of the total cost of the vehicle [1]. Even though several BTMS systems are employed to regulate the temperature of the Li-ion battery pack in EVs, specific instances of EVs catching fire have been reported globally. There are estimated to be 2825 electric cars catching fire each year, based on the data collected from the IEA and KBB. Several researchers have studied the BTMS and their issues, such as overheating of batteries during running and charging conditions, characteristics of batteries, internal heat generation in batteries, and optimization. Figure 2 expresses the problem with Li-ion batteries in EVs in the present scenario. Certain limitations exist in the literature. Extensive reviews on solutions to resolve the above issues are not available in the literature or the EV industry, and researchers must have such reviews for further design and development activities of BTMS. Therefore, this study addresses the aforementioned issues by proposing a PCM-based BTMS. PCM-based BTMS keeps the batteries from catching fire and takes up less space, which is essential for electric two-wheelers. Therefore, the present study focuses on PCM, CPCM, and FPCM-based BTMS.

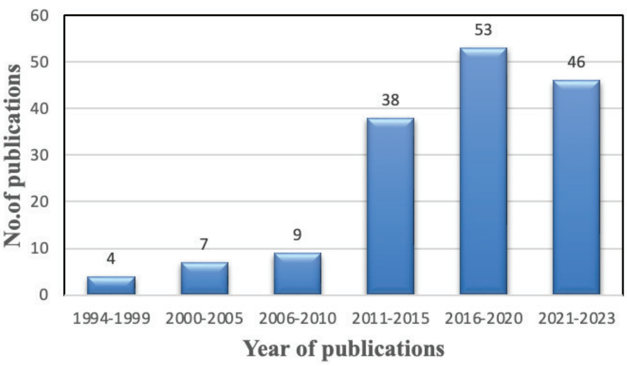


Figure 1. Year-wise publication reviewed.

Challenges and Contribution in the Field of Thermal Management of Li-Ion (Li-Ion) Batteries for EVS

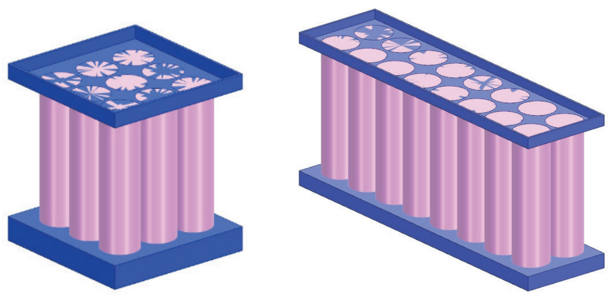
It has been observed that as temperatures increase, the cycle life of Li-ion batteries decreases. The cycle life which is 3323 cycles at 45°C falls to 1037 cycles at 60°C [2]. This shows that the battery's cycle life and energy capacity are significantly influenced by temperature. The main challenge is to maintain the temperature of batteries within the specified limit (15°C to 40°C) [2]. Many researchers contributing to better thermal management systems for EVs. The BTMS of EVs uses a variety of cooling techniques, including air-cooled, liquid-cooled, and PCM-based BTMS.

In the case of air-cooled BTMS different arrangements are used by researchers, air-cooled + metal-foam-based heat exchanger plates, forced Air-cooling, air-cooling + pin-fin heat sink, air cooling +embedded metal foam, parallel air-cooled BTMS, air cooling + pin fin heat sink + porous metal foam, U-type parallel air-cooled BTMS, reverse layered air flow, reciprocating air flow cooling, forced air cooling (Z-type flow structure), forced-air cooling (U-type duct) and many more [3, 4].

Liquid cooling gives better results as compared to air cooling but the cost of the system and space requirements increase. The leakage of liquid in liquid-cooled BTMS is a major issue. In liquid cooling, most researchers use water as the base liquid. Results are improved in liquid-cooled BTMS when ethylene glycol and nanoparticles are used in combination with water [5].

Researchers used different combinations of PCM and performed experimental as well as numerical analyses on different types of batteries with different types of loads on them. Mostly, the PCM used for this purpose are paraffin wax, paraffin wax + Al Foam + Al Fins, PCM/Graphite matrix, paraffin/EG, n-octadecane wax, copper foam + paraffin wax, Graphene + Paraffin wax, EG Flakes + Molten wax, Nickel foam-paraffin wax, Pure paraffin (PCM1), EG 20% + paraffin 80% (PCM2), EG 3% + epoxy 47% + paraffin 50% (PCM3). To improve the heat transfer rate, nanoparticles are mixed with paraffin wax.

This review examines the existing literature on various aspects of the heat transfer performance of LIB packs using PCM. Furthermore, the review identifies the challenges in the implementation of the systems in Section 1. Classification of PCM cooling as per material used is discussed in detail in Section 2. The scope for future research is given in Section 3. Finally, the conclusion of the review is given in the last section. LIBs come with several significant unique benefits, including a high energy density and a comparatively low price. However, the metal's high reactivity continues to have an impact on its general use. Batteries that most frequently use a carbon electrode in place of lithium metal were developed to address this flaw [6]. EVs require the most energy while being as light as feasible. Hybrid electric vehicle (HEV) batteries are more expensive because they offer the most power in the smallest possible package. LIBs are the only option being researched for Plug-in HEV (PHEV) power due to their definite energy and energy density [7]. The design and simulation of a phase change material (PCM)-based passive thermal management system (TMS) for a LIB pack for a laptop, a commercial 186502 LIB's heat generation rate was experimentally measured [8]. For an electric scooter, a LIB with a new PCM temperature management system was developed. PCM can regulate temperature extremes and maintain temperature uniformity in LIBs without active cooling components.



(a) (b)

Figure 3. Battery pack design shape (a) cube, and (b) rectangular parallelopiped.

Researchers perform a thermodynamic analysis of the LIB pack and optimize the heat dissipation structure.

The effect of airflow channel spacing and air inlet angle on the battery pack's temperature distribution is studied using a fluid-solid conjugate heat transfer mechanism. [9, 10]. Figure 3 shows the battery pack design shape for cube and rectangular parallelopiped.

Due to their improved performance, LIBs are frequently utilized in EVs. The problem of overheating can have an impact on the efficacy of batteries. For the dissipation of the heat, the from LIB pack, a water-cooling approach combined with a mini-channel is designed and further enhanced [11]. For a thoughtful LIB battery thermal management system (BTMS) to minimize the operating temperature and strain, thermal and strain management is essential. In this study, the temperature and strain of an 18650 LIB pack are simultaneously monitored using non-destructive temperature equipment and strain gauges [12]. To prevent excessive temperatures and uneven temperatures inside the LIB pack, thermal management is crucial. Despite much research on the subject, this problem still presents a hurdle. The proposed technique tries to minimize both the highest cell temperature and the uniformity of the cell temperature [13].

Argonne National Laboratory has been working on lithium-alloy/metal sulfide batteries since 1972. Lithium/iron sulphide bipolar stack production is now feasible because of novel stable sealant materials that create high-strength connections between a range of metals and ceramics [14]. The tabs in a battery should be rationally designed to have the highest fluctuations of the characteristics in the transition region between both the electrodes and electrode plates. The anode is more crucial to the overall overpotential of this $LiFePO_4$/Graphite battery than the cathode [15]. Also, ALIB intended for use in electric scooters. The aluminium foam is used in the spaces among the cells to minimize temperature rise. Additionally, it offers a consistent temperature throughout the battery module, which is necessary for the effective operation of the cells utilized [16, 17]. The lifespan of LIB packs has grown in significance in the development of electric cars. Researchers also suggested to combine the electrochemical, thermal, solid electrolyte interface (SEI) cell formation model, fluid dynamics, and the series-parallel circuit model to provide a more accurate and general modelling approach [18]. Commonly used LIBs and their internal structure is shown in Figure 4 [19].

LIB pack thermal simulation for the newest cars. At operating temperatures >16°C, the pack satisfies power assist mode pulse power goals when controlled to minimum/maximum voltage limitations, but falls short of the available energy target. At 25°C, the pack produces heat at a rate of 320 W on a US06 driving cycle, with lower temperatures producing greater heat [20]. The LIB has become a crucial energy source for mobile technology and EVs. A LIB needs a suitable operating temperature range and a little temperature variance to function properly. Discussions are had regarding systematic battery heat management and advancements

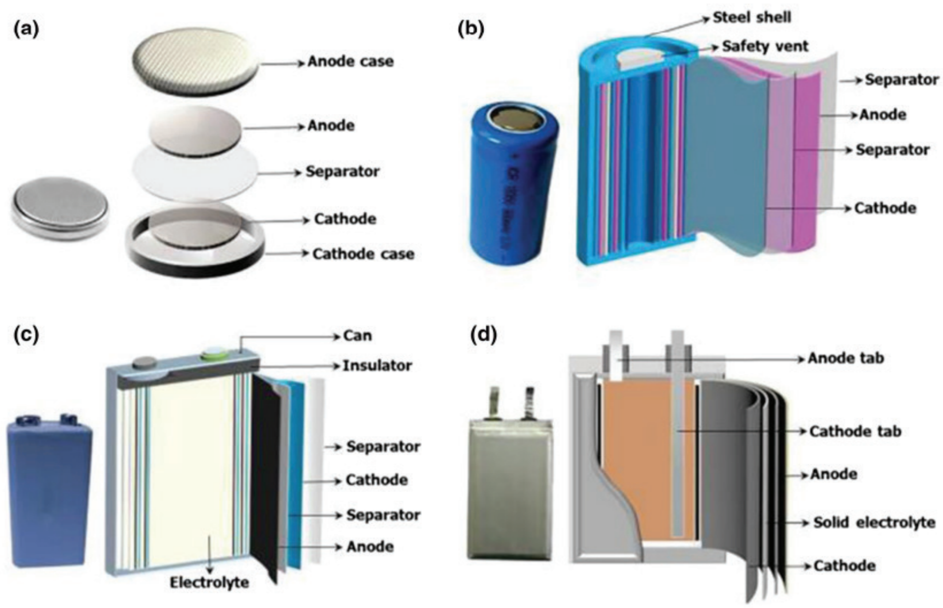


Figure 4. Applications of CPCM in power systems (a) fabricated PCM matrix, (b) PCC with cylindrical cells, and (c) PCC plates with prismatic cells [From Chen et al. [19], open access Springer].

in electrode modification [21]. At 50°C after 800 cycles, the battery cells lost more than 60% of their initial power, and at 55°C after 500 cycles [22, 23]. A LIB can be cycled 3323 times at 45°C, but only 1037 times at 60°C [3]. The thermal management of LIB packs has been compared using internal and external cooling techniques. Investigations were carried out to determine the way the techniques affected the internal temperature of the battery as well as temperature uniformity. The bulk temperature within a LIB is lowered more by internal cooling than by external cooling [4]. This shows that the LIB's performance, longevity, and safety are all significantly impacted by the temperature at which it is being stored or used, as well as by the surrounding environment. The discharge performance, discharge capacity, and battery life cycle of a LIB battery are all dramatically reduced when it works at low temperatures, while at high temperatures, the deterioration process is accelerated [23]. Using sinusoidal alternating current, LIBs can be heated from -20°C to 5°C in about 15 minutes (AC). The rate of heating is directly increases with increase in amplitude and decreases in frequency. Repeated AC preheating tests reveal no capacity loss, showing this procedure causes no harm to the battery's health [5]. An important factor in a LIB's temperature change is reversible heat (RH). RH inclusion or exclusion is often decided on the basis of discharge rate. To account for the RH, a more accurate electrochemical-thermal coupling model was created [24]. In this study, researchers investigated the usage of a particular HEV LIB module as a heat pipe cooling device. They observed that, combining heat pipes with a limited ventilation system is an effective approach to maintain cells' temperatures within their ideal range even while natural convection and the chimney effect are insufficient to do so [25].

Hexamethylenetetramine has been used to create Co_3O_4 in a straightforward manner that can be produced in large quantities. The samples were calcined at various heats between 30°C and 60°C. An increase in calcination temperature hampered Li-ion conduction within the SEI layers and charge transfer at the electrode/electrolyte interface [26].LiPF6-based electrolyte's thermal stability was investigated using in-situ Fourier transform infrared (FTIR) spectroscopy and C80 calorimetry. Polymerization and breakdown processes took place in the electrolyte. They found that the electrolyte's reactions are suppressed by the $LixFePO_4$ cathode [27]. Low temperature tungstate materials $Fe_2WyO_3(y+1)$ (y=1 and 3) have been synthesized, and galvanostatic and Electronic Voting Systems (EVS) measurements have been used to determine the materials' lithium insertion properties. All materials showed very high initial discharge capacities, with the y = 3 material heat treated at 50°C having the highest at 653.9 mAh g1 [28]. The preparation of electrode materials for lithium secondary batteries using sol-gel techniques shows promise. The structural stability of the obtained electrode materials is significantly better than that of those made using a conventional solid-state reaction. Sol-gel can be used to create novel electrode materials, as $LiCoO_2$ and V_2O_5 nanotubes and nanowires [29].

To protect batteries from the negative consequences brought on by temperature rise and internal heat generation, a BTMS is necessary. When batteries are exposed to extreme temperatures, the batteries self-discharge and their capacity begins to deteriorate over time. Thus, the battery should operate between 15 and 35°C [30], 20 to 40°C [31, 32], or 20 to 50°C [33, 34], with a extreme temperature difference (T_{max}) of no more than 50°C between

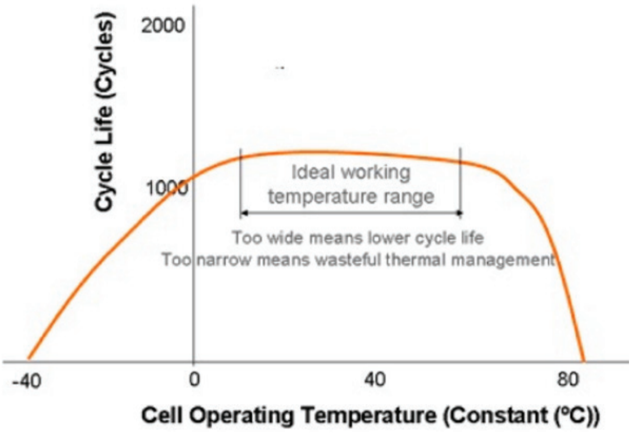


Figure 5. Effect of temperature on battery life [From Tete et al. [38], with permission from Elsevier].

modules to ensure a constant temperature distribution [35]. Under typical operating conditions, 60°C is regarded as the highest limit for safety [33]. To investigate the behavior of LIB with numerous and/or multi-dispersed active materials in each electrode, a quick computing electrochemical model has been created. It has been used to comprehend the internal operations of each electrode throughout constant current charges and discharges as well as the duty cycles of hybrid EVs [36]. Due to their excellent performance in terms of high energy density and long lifespan, LIBs are the best choice for use in EVs. However, a number of factors, including battery ageing cycles, noise effects, and temperature affects, have an impact on how accurately the level of charge is measured [37]. One of the debated topics of research in recent years has been the TMS of battery packs for EVs. Figure 5 shows the effect of temperature on battery life [38].

The concept of "thermal runaway" refers to a condition where a battery catches fire because of the rapid heat transfer from one damaged cell to another. The negatively charged anode's SEI layer begins to break down when the cell temperature rises to roughly 80°C. The electrolyte decomposes into exothermic processes between 100 and 120°C, producing a variety of gases inside the cell. An internal short circuit results from the anode and cathode coming into touch with each other as the temperature approaches 120°C–130°C and the separator melting down. A positively charged cathode starts to break down and release oxygen at roughly 130°C–150°C. The cell can ignite and catch fire due to the release of oxygen and other chemical processes. Thermal runaway can occur in less than 10 seconds and generates heat in the order of 107 W/m^3. The quantity of heat produced is on the order of, and thermal runaway can occur in less than 10 seconds [39, 40]. The performance and durability of a LIB are significantly impacted by thermal build-up. At a discharge rate of 5C, simulations show a temperature rise of nearly 50°C. Temperature fluctuations are not greatly affected by the current collectors' and separator's comparatively low heat output [41]. A single stack LIB cell's local heat generation as a function of the C-rate and state of charge (SoC)was studied. The inherent asymmetry of the reversible heat and the kinetic restrictions of the active materials combine to provide a clear asymmetry between charging and discharging [42]. LIBs have built-in heat restrictions (i.e., capacity fade and thermal runaway). On a compact, heat generation rates were assessed for commercially accessible C/$LiFePO_4$LIB made for high-rate applications. Researchers demonstrated that the heat rate rises as the temperature falls [43]. The transportation industry places a lot of attention on electrification, replacing some motor-powered engines with battery-powered ones. Specially crafted, high-quality goods are required for the materials used in battery applications. Although Li-ion batteries have some drawbacks, substantial advancements have been made recently. Battery material recycling at a greater rate while also extending battery life is crucial [44]. The susceptibility of LIBs to temperature is a significant problem. The various battery pack configurations and heat production techniques are reviewed by researchers. They also reviewed the application of nanomaterials to the battery pack's thermal problems [45]. Because every nation depends on logistics, the transportation sector serves as the global connection. For readers who are vehicle users, manufacturers, and scientists, this review can offer both general and technical information [46]. Lack of a properly sized battery is a major barrier to the development of commercially effective electric cars. If only LIB could be "scaled up safely," they would be the answer. PCM is being used to create a revolutionary thermal management system [2]. The longevity of LIBs is crucial to the dependability, economic competitiveness, and ultimately, consumer satisfaction of EVs. The effects of aging on car batteries are discussed by researchers. On many levels—material, cell, and pack—mechanisms and underlying reasons are examined. There are descriptions of test procedures and field data, modeling and simulation techniques, and diagnostic procedures. Also. methods and strategies to meet and surpass the lifetime objectives of car batteries are suggested by them [47]. LIB research has been intensively pursued to create new electrode materials that can meet the high energy density, high power, and exceptional cycling performance requirements of EVs. Technical challenges with high-performance materials for LIBs for cars were examined, and technical problems with batteries that need to be resolved soon for successful integration into transportation systems were also covered [48]. Understanding cell behavior makes it easier to forecast and enhance battery performance. It also influences the development of a battery pack's cost-effective thermal management system. A realistic driving cycle from the Artemis class is used to assess EV cells. Some important recommendations are proposed in response to the study's findings [49].

Table 1. LIB heat generation under various temperature ranges [3, 50]

Temperature range/°C	Chemical reaction	Heat generation/J
100-150	Li_xC_6+	350
130-180	Melting of PE diaphragm	-190
160-190	Melting of PP diaphragm	-90
180-500	Decomposition of $Li_{0.3}NiO_2$and electrolyte	600
220-500	Decomposition of $Li_{0.45}CoO_2$and electrolyte	450
150-300	Decomposition of $Li_{0.1}MnO_4$ and electrolyte	450
130-220	Solvent and $LiPF_6$	250
240-350	$Li_xC_6$and PVDF	1500
660	Aluminium melting	-395

CONCEPT OF BTMS

A BTMS is essentially a battery pack's brain. A battery pack is composed of several battery cells arranged in various series, parallel, and combination configurations. The most popular option for commercial use is LIBs because of their better performance than other battery types. EVs have emerged as one of the most promising modes of transportation due to their low operating costs, high speed, and energy-efficient battery technology. The BTMS is possibly the most crucial part of an EV. LIB heat generation under various temperature ranges is tabulated in Table 1.

By using appropriate and effective cooling measures, the negative effects of the high surface temperature of battery cells can be significantly reduced [51]. Working principles of BTMS using PCM are shown in Figure 6.

Researchers conducted an experimental investigation into the thermal management of battery modules with PCMs. To mimic the heat source of a battery cell, an electric heater is employed. The ability of two various PCM designs to keep the heater within a desired temperature range is examined [52]. The study by Taghilou and Mohammadi [53] examined the thermal control of a LIB during four charging and discharging cycles when phase transition material is present. They discovered that the battery's maximum temperature rose by 17% when this substance was absent, but only by 1.7% when the ambient temperature changed from -20 to 50°C [53]. LIB's thermal behavior is now essential for enhancing battery safety. The battery surface temperature increases above acceptable levels as charging currents and ambient temperatures increase simultaneously. Analyzing how much convection would be required to maintain its functionality and general health is essential [54]. Ajour et al. [55] simulated a two-dimensional battery pack with 27 Li-ion cylinder batteries. Airflow exists at Reynolds numbers between 100 and 400. The findings showed that the battery's temperature has a growing trend and is not controlled by the temperature of the surrounding air at Reynolds number = 100.

The ability of a cell to reject heat has been defined by the development of cell cooling coefficients (Cs). A 34% increase in tab thickness results in a 20% improvement in tab cooling efficiency at a mere 0.7% reduction in specific energy use. The evidence showed that the "sub-system optimization trap" has been exploited by cell designers [56]. An electrochemical reaction that ultimately depends on temperature determines how well the battery performs. According to the Arrhenius law, chemical reaction rates climb exponentially as temperature rises. Studies reveal that a battery cell's hotspot is located nearer the electrode than the rest of the battery surface [57]. The life cycle and cell performance are reduced because of the temperature distribution's unevenness, which also produces temperature non-uniformity. Due to internal heat production throughout the charging and discharging operation, battery temperature changes. Ohmic heat, mixing heat, enthalpy heating, and the entropy change of the electrochemical process all have an impact on the internal heat generation in batteries [58].

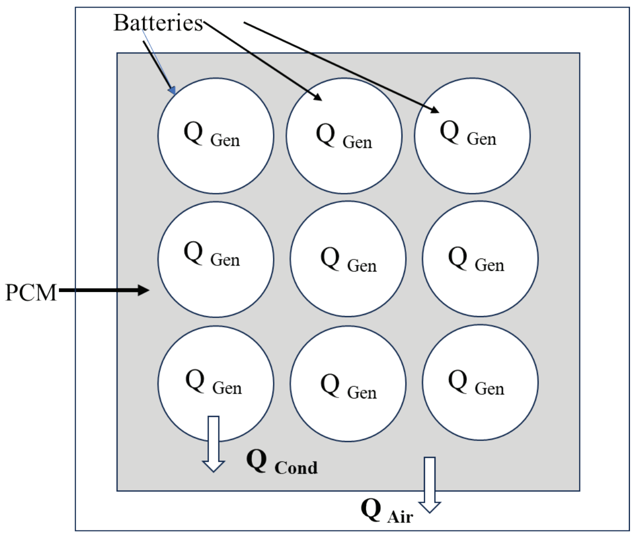


Figure 6. Working principles of BTMS using PCM.

An investigation of the thermal management of a new lithium-titanate-oxide battery pack for a Super Truck II Class 8 hybrid truck. The researchers examine the possibility of placing the battery pack inside the vehicle and cooling it by using fans that extract conditioned air from the inside [59]. Since low-temperature charging could result in significant performance deterioration for LIBs, it is a significant challenge. One trusted internal pre-heating approach with good temperature consistency is adopted: pulsed operation. EVs and stationary storage systems are just two possible application scenarios for such pulsed heating techniques [60]. The thermal environment in which batteries function has a significant impact on that environment. For better deployment and use, batteries must have proper temperature management. A bibliometric examination of battery heat management systems was presented by the researchers. It determines research gaps and evaluates the current state-of-the-art [61]. To preserve cell longevity and ensure vehicle safety, thermal control is crucial in EVs. The idea of a cold plate and heat pipe-based battery liquid cooling system is put forth with the understanding that the heat pipe won't be immediately submerged in coolant. The HP-CP structure offers the ability to cool batteries during rapid charging [62]. The triangular morphology of LiNiNi1/3Mn2/3O2 thin films can be used to create all-solid thin film batteries. All of the elements and their oxidation states are present, according to X-ray photoelectron spectroscopy experiments [63]. The battery pack's cells must operate within a suitable temperature range, which is where thermal management comes into play. By using the single-factor analysis method, various cooling structures, the quantity of mini-channels, and the inlet mass flow rate are examined. The study and optimization techniques may offer effective battery heat management system solutions [64]. The inter-cell connection resistances might result in uneven loads in battery packs with paralleled cells because of non-uniform interconnect overpotentials. This might cause a small-scale TR. These consequences could happen, as demonstrated by a simulation of a 12P7S pack under a genuine load cycle [65]. Researchers developed a new LIB pack design with a hybrid active-passive heat management mechanism. The battery pack can be used in electric and hybrid cars. To demonstrate the effectiveness of the battery pack, a comparison between the thermal and physical properties of the suggested battery pack and other recent studies is provided by them [66]. To maintain the LIB's thermal stability and long-term durability, thermal management is an essential technique. Two different types of air ducts with separate intake channels and fans make up the system. Through the improved thermal management system, the maximum temperature can be lowered to 33.1°C [67]. To study the thermal behaviors of a battery pack, a theoretical electrochemical thermal model and a thermal resistive network are suggested by investigators. According to simulation studies, the huge battery pack's temperature at the end of an EV driving cycle can reach 50 or 60°C in hotter environments [68]. Air cooling, liquid cooling, and PCM cooling are the different types of cooling for EVs. Natural air cooling and forced air cooling are subcategories of air cooling. To enhance heat dissipation performance for battery packs with bottom duct modes, double "U" type ducts are used in place of double "1" type ducts [69].

Rechargeable LIBs used in hybrid and electric vehicles are presented with a revolutionary design that includes a cooling medium. The battery pack relies on distributed natural convection and uses several thin, distributed ducts for cooling. The LIB pack has many advantages, including extremely uniform voltage and temperature distributions, the least amount of temperature dispersion within each battery unit, and great thermal performance [70, 71]. For the operation of EVs, a TMS for commonly used LIBs is necessary. The critical zone of the cell in terms of heat generation was determined by a novel thermal study of the single battery cell. Researchers were able to maximize heat dissipation with just one heat pipe installed in the crucial area [72]. Reducing the price of its battery systems is an important step in the direction of the widespread adoption of PHEVs on the market. Model-based and data-driven methodologies to explain the aging of battery cells have advanced the field of battery aging modelling and prognosis [73]. To manage the thermal surge of LIBs during high-rate operations, a heat pipe and wet cooling combined BTMS is designed. The system relies on incredibly thin heat pipes that effectively transport heat from the battery sides to the cooling ends, where it may be quickly dissipated by the process of evaporating water [74]. To better understand the thermal behavior of battery cells in a pack under simulated drive cycles, a three-dimensional thermal model has been created by researchers. The numerical approach allows for quick prediction of the heat generation rate, battery temperature distribution, and battery temperature change within a pack. The impacts of the battery pack's cooling flow on the inconsistency of individual battery cell temperatures were also investigated [75].

The electrochemical reaction is endothermic when charging and exothermic when discharging. One argument against using LIBs in EVs and hybrid electric vehicles (HEVs)is internal generation during charge-discharge cycles. Renewable energy is increasingly being used in EVs. On a wide scale, battery electric vehicles with zero emission characteristics are being developed. This document provides a summary of the research for enhancing the energy storage density, safety, and renewable energy conversion efficiency of LIBs. The performance of the battery management system's temperature regulation and estimation accuracy are examined by researchers [76]. Therefore, BTMS is essential to the longevity and general performance of the battery pack to resolve these conflicts are classified as air cooling, liquid cooling, direct refrigerant cooling, PCM cooling, thermoelectric cooling, and heat pipe cooling systems.

The power grid and the production of renewable energy both make extensive use of battery energy storage systems (BESS). A LIB module with an air-cooling thermal management system is examined using a thermofluidic model. The maximum temperature is lowered by 0.4 K when the fans are active for forced air convection cooling [77].

PCM Cooling

Any BTMS must have a cooling medium as its primary need. The only commercialized cooling mediums for EVs and HEVs are air and water, which are also the most widely used and traditional cooling mediums. The most researched coolants for liquid cooling are water and a mixture of water and ethylene glycol. However, new coolants can also be found. Although the thermal conductivity of the base fluid improves with the addition of nanoparticles, cooling efficiency is not significantly affected. For cooling reasons, suitable nanoparticles can be created and evaluated. Although extensively researched, PCM has not yet been used in any practical battery cooling systems, particularly in 2-wheeled electric vehicles. LIB thermal runaway is still an unsolved and difficult issue. One of the most efficient ways to keep the temperature of the battery pack under control is via BTMS based on PCM, however the challenges in applying PCM to automotive applications have not yet been investigated. There is much to learn about how to make pure PCM and composite PCMs (CPCMs) more thermally conductive.

Users are gravitating toward EVs due to rising pollution levels, growing environmental awareness of climate change, and other factors. A total increase of EVs were sold in the nation in FY22 compared to FY21 is 211.3%. Also, two-wheelers have seen the largest rise at 461%. According to Times of India, a total of 23,786 EVs were registered in Maharashtra in FY2021–22, including 2,633 vehicles and 19,396 two-wheelers. When a LIB cell is mechanically constrained, it charges more quickly and with a greater voltage. Cell capacity is drastically decreased in fast-charge conditions due to mechanical constraints. The outcomes demonstrate the potential of multi-physics methods to understand the electrochemical-mechanical coupling mechanisms [78].

Although fire mishaps involving vehicles are not unusual, the frequency of e-scooter fire incidents in India is somewhat concerning. After receiving the report of the expert panel that has been assembled to investigate the issue, the government decided to issue the required orders on defaulting organizations due to the rising number of accidents involving electric two-wheelers catching fire. One way to solve this issue is with CPCM, which are lightweight and inexpensive. Even though many researchers focus on CPCM, there is still much that can be learned about how to increase the thermal conductivity of pure PCM and create composite PCMs. Important point of PCM based cooling are as follows.

- PCM cooling is the passive TMS that demonstrates improved thermal management due to its high latent heat. This is an important point of PCM-based cooling.
- PCM with a melting temperature of 45°C offers superior thermal performance.
- Studies have proven that the PCM not only offers effective heat dissipation but also aids in warming LIBs in a cold environment.
- Utilizing PCM ensures efficient thermal energy storage.
- The most researched and best-suited PCM for BTMS is pure paraffin, but like most PCMs, it has the fatal flaw of having low thermal conductivity. To overcome this, pure PCMs are supplemented by metal foams, carbon nano powders, metal fins, porous materials, etc.
- The temperature of the battery surface drops as PCM thickness increases. But when PCM thickness increases, battery pack weight will also rise. Therefore, when developing BTMS, an ideal value of PCM thickness should be considered.
- The gap spacing between the cells lengthens the time that a phase shift lasts and slows the battery pack's rate of heating, but it also adds weight and volume, which is unfavourable for practical applications [79].
- By integrating the PCM-based BTMS with the other active cooling systems, it is possible to increase thermal conductivity while using less electricity [80].

Numerous researchers have written articles on the performance of the LIBs pack's heat transmission using PCM. Solving thermal safety issues brought on mostly by thermal runaway (TR) is necessary. Schematic of LIB TR mechanism under various abusive conditions is depicted in Figure 7.

Zhang et al. [81] studies of the literature outlines practical methods for improving PCM performance for high-density LIB BTMS. Another review paper by Rojas and Khan lists over 10 performance parameters along with experiments

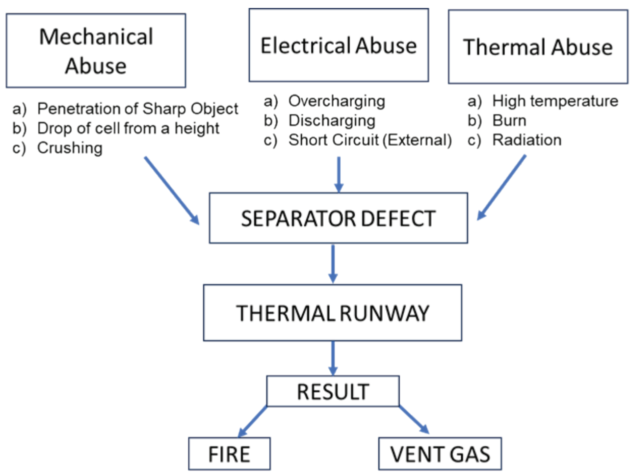


Figure 7. Schematic of LIB TR mechanism under various abusive conditions.

and theories developed to comprehend the impact on LIB packs' performance, integrity, and safety. They concluded that conducting research is essential to enhancing the performance and security of battery packs. Both an original academic contribution and an inventive technical solution for the automotive sector were put forth [82]. Zhao et al. [83] review attempts to shed light on the CPCM-based BTMS. They talk about how batteries generate heat and how temperature affects batteries. Future research should, according to the review, concentrate on creating assembly techniques that maximize the mechanical properties of CPCM while minimizing interfacial thermal resistance [83]. The reliability, safety, and lifespan of these batteries are significantly impacted by the cell temperature [84]. Ghaeminezhad et al. [85] give a review of the most recent BTMSs used on LIB packs. These fall into two categories: feedback-based methods and non-feedback methods. The paper's conclusion included a thorough examination of the methodologies under review's advantages and disadvantages [85]. For EVs with great performance, TMSs are essential. In comparison to passive air cooling, immersion cooling, which immerses the battery in a dielectric fluid, has the potential to increase the rate of heat transfer by 10,000 times. Fluids which have been considered included hydro-fluoro-ethers, mineral oils, esters and water-glycol mixtures [86]. The cell's anomalous temperature increase causes performance deterioration and safety concerns. Therefore, a sufficient BTMS is required to lower the battery's maximum temperature [87]. It has been suggested that PCMs be used in future energy vehicles to control the temperature of LIBs. The performance of thermal management has been improved with enhancement tactics, proving the viability and promise of PCM-based systems [88]. By using the latent heat created by PCM's phase transition to regulate temperature [89]. The PCM-based BTMS is a reliable cooling solution for extending the lifespan, performance, and dependability of LIBs. Future research might be directed at developing novel PCMs, increasing efficiency, and lowering volume, weight, and energy consumption [90]. For a 53 Ah LIB under a discharge rate, a hybrid cooling system with two-sided cold plates can lower the maximum temperature from 64°C to 46.3°C. In extreme situations, it can control both the maximum average temperature and the variation in temperature across cells [91]. The primary cause of the LIB fire and explosion, in which carbon elements are significant, is TR. Jiang et al.'s review [92] provided details on how carbon materials affect the safety of LIBs. Researchers also examined the actual process of heat production and its impact on each LIB component [93]. Jiang et al. [94] reviewed two types of phase transition-based BTMSs. The distribution of heating areas and the upward trend in temperature can be precisely predicted by thermophysical models. They also talk about the computer models' simulation times and calculating errors. PCM-based cooling has recently received a lot of attention for battery cooling applications. The researchers also investigated a combination of passive cooling (PCM) and active cooling techniques like PCM-air, PCM liquid, and PCM-heat pipe and came across that these hybrid systems performed better in terms of temperature uniformity and the highest temperature inside the battery pack in comparison with the baseline systems [95].

Classification of PCM

Phase Change material generally classified into organic material (like paraffin and alkanes) and inorganic phase change compounds including salts, hydrates of salt, metal, and alloys (Fig. 9).

Compared to organic PCMs, inorganic PCMs (like salt hydrates (M_nH_2O), nitrates, and metallics) have several

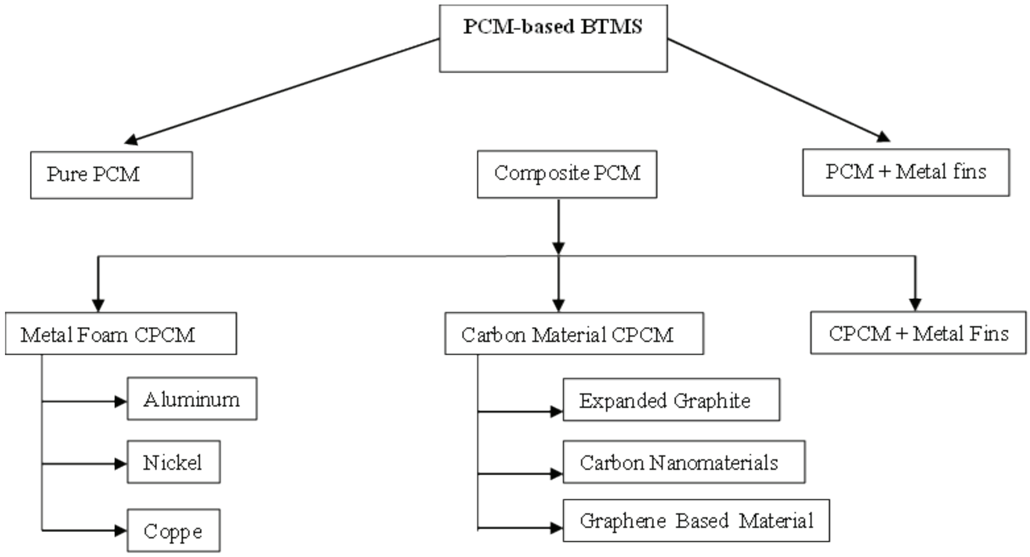


Figure 8. Methodology of literature review.

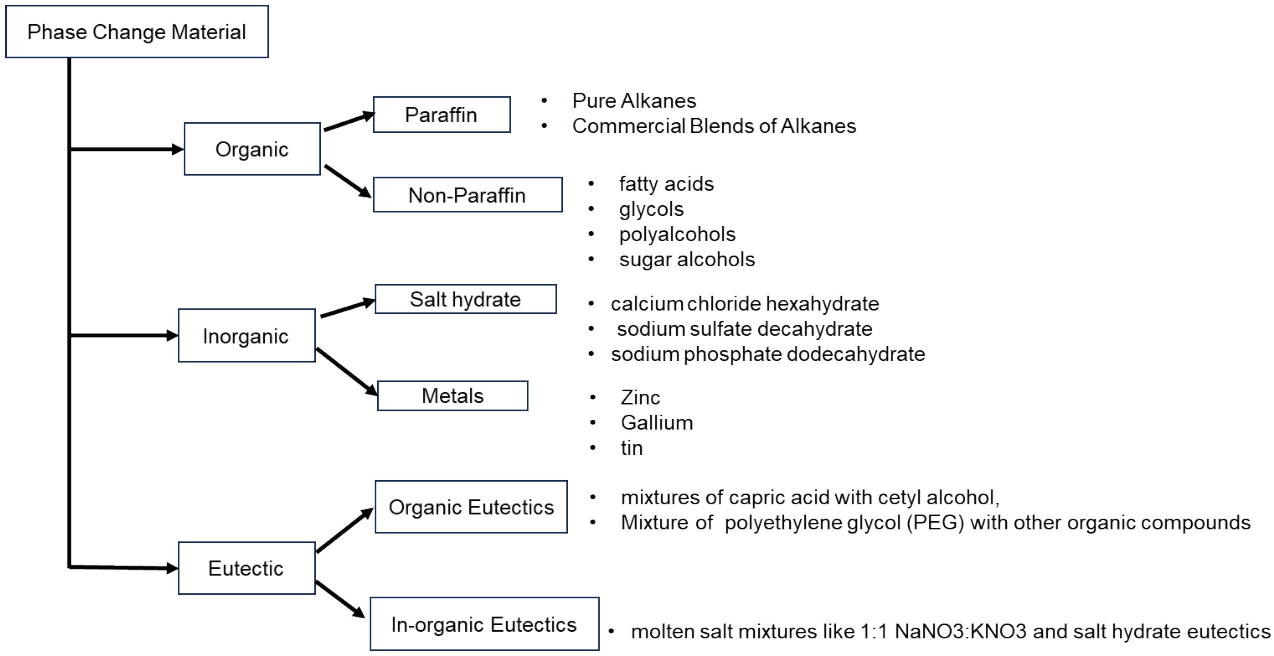


Figure 9. Classification of phase change materials.

disadvantages, such as a possibility for corrosion phase separation, improper re-solidification and advantages are having greater thermal conductivity, storage capacity, non-flammable, cheap, and readily available, which is required in medium to high temperature application of thermal energy storage field. Inorganic phase change materials have double heat storage capacity per unit volume as compared with organic materials. Inorganic PCM have higher operating temperatures, and lower cost relative to organic phase change materials, However, because inorganic PCMs corrode metals, they cause the system's service life to be shortened and its cost to increase [96]. Table 2 summarized the advantages and disadvantages of both organic and inorganic materials.

Comparison of latent heat storage of organic and inorganics phase change compounds are shown in Table 3.

Yana Galazutdinova et al. [97] developed the inorganic composite phase change materials s ($MgCl_2$ $6H_2O$/ $Mg(NO_3)_2 6H_2O$) and bischofite/ $Mg(NO_3)_2 6H_2O$) for passive thermal management of Li-ion batteries and compared with paraffin wax and observed that these mixtures can be safely used up to 100^{0}C. To address the inherent issues of the inorganic PCM-sodium acetate trihydrate (SAT)-Urea, a multiscale encapsulation technique is used by Ling et

Table 3. Comparison of latent heat storage

Property	Latent Heat storage	
	Organic PCM	Inorganic PCM
Density (kg/m^3)	800	1600
Specific heat (kJ/kg)	2	2
Latent heat (kJ/kg)	190	230
Latent heat (kJ/m^3)	152	368

Table 2. Comparison of organic and inorganic materials for heat storage [96]

	Organic PCM	Inorganic PCM
Advantages	• Non-corrosive, • Low or none under-cooling, • Chemical and thermal stability.	• Greater phase change enthalpy.
Disadvantages	• Lower phase change enthalpy, • Low thermal conductivity, • In flammability.	• Undercooling, • Corrosion, • Phase separation • Phase segregation, • lack of thermal stability.

al. [98]. This technique uses extended graphite (EG) on a microscale to encapsulate the PCM and increase its thermal conductivity to 4.96 W/mK and avoid the leakage problems. Although inorganic materials have very beneficial and promising qualities for their usage as PCM in BTMS, these materials still have a difficult time becoming a widely used commercial product.

Kumar Kurugundla et al. [99] focuses on measuring temperature flow analysis using a condition monitoring system for wind turbine generator (WTG) gearboxes, aiming to evaluate the thermal performance in relation to plant load factor. The effect of charging and discharging processes of phase change materials (PCM) with paraffin and Al_2O_3 additive at three temperature locations, aiming to elucidate their thermal behavior and performance characteristics [100]. The design and structural analysis of a liquefied cryogenic tank, windmill blades tailored for domestic applications subjected to seismic and operating loading conditions, aiming to ensure its structural integrity and safety in harsh environmental conditions is performed by Kumar et al. [101, 102].

Classification of PCM Cooling

This section discusses various categories of PCM cooling based on the material used such as Pure PCM, CPCM, PCM, and metal fins. In many energy-related applications, thermal energy storage (TES) has proven to have considerable potential. There has been a review of TES for cold energy storage using different liquid-solid low-temperature PCMs. Future low-charging rate recommendations and a design technique for devices are put forth by researchers [103]. PCM-based thermal management systems offer a practical remedy for LIB overheating. Failures of the thermal management system are caused by the accumulation of heat in PCMs because of ineffective air cooling by natural convection. For recovering PCMs' thermal energy storage capability, forced air convection is crucial. When compared to active (forced air) cooling, the efficiency of passive cooling using PCM is shown to be superior. While the active cooling mode blasts air through the spaces between the cells, the PCM cooling mode uses a micro-composite graphite-PCM matrix to surround the array of cells [104]. During high pulse power discharges, a compact and correctly engineered passive TMS using PCM dissipates heat more quickly than active cooling. It maintains a sufficiently consistent cell temperature to guarantee the pack's desired cycle life. Researchers also looked at the impact of nickel tabs and cell spacing [105].

Pure PCM

Heat transfer performance in LIB packs is crucial for maintaining safe and efficient operation. One way to improve heat transfer in these packs is by incorporating PCMs into the design. A pure PCM, such as a wax or a salt hydrate, can absorb and release large amounts of heat during its phase transition, such as solid-liquid or solid-gas, thus helping to regulate the temperature within the pack. This approach has been shown to significantly enhance the thermal performance of LIB packs, making them more stable and reliable. Some common examples of pure PCMs include:

- Waxes, such as paraffin wax, which can be used as a solid-liquid PCM.
- Salt hydrates, such as calcium chloride, which can be used as a solid-liquid PCM.
- Eutectic mixtures, which are mixtures of two or more substances that have a lower melting point than any of the individual components.

Other materials like fatty acids, amides, esters, and some metal alloys are also considered as pure phase change materials. These materials are typically used in various thermal energy storage applications, such as heating and cooling systems, buildings and vehicles, and LIB thermal management. The PCM based BTMS is highly effective due to its high latent heat and can also be used without any power consumption. Due to its high energy density and isothermal energy exchange, PCM based BTMS can be a desirable solution. Low heat conductivity, volume expansion, and phase change leakage are some disadvantages of pure PCM [106]. The performance of LIBs is restricted by their working temperature; the highest limit is set at 50°C. If batteries operate in a warm environment, this limit is easily exceeded. To combat this problem, sintered copper-powder heat pipes and water spray were used [107].

Various researchers investigated heat transfer performance of LIB pack using Pure PCM. The strategy adopted in improving the thermal energy storage characteristics of the PCMs through encapsulation and nanomaterials additives are discussed in detail by researchers [108]. Emerging heat transfer media include nanofluids. These materials have various advantages when used in electronic cooling applications. The battery heat management system for pouch LIBs modules is examined in the research. In the presence of copper foam with or without PCM, the maximum battery temperature differential is reduced by 77% [109]. Six commercially available PCMs are studied with the battery pack at three different charging rates and three different ambient conditions by Patel et al. [110]. Using the PCM of paraffin saturated in metallic copper foam, a two-dimensional transient model for a passive thermal management system for commercial square LIB was created. Foam-PCM composite thermal management has significantly lowered battery surface temperature when compared to the air convection and adiabatic modes of operation [111]. Due to the thermal effect of entropy changes, thermal cycling of the cell in combination with slow rate cyclic voltammetry enables the quick identification of phase transitions in electrodes. It is discovered that a cell held at the theoretical average temperature has a higher impedance than one held over a temperature gradient [112]. LIBs must operate within a specific temperature range in order to function properly and safely. To manage the heat surge that occurs when a

LIB pack is operating, a water-based PAAS (sodium polyacrylate) hydrogel TMS has been developed [113]. The main problem with thermal management of LIB systems is thermal modelling. The history of cooling techniques, particularly forced air cooling, is reviewed and summarized in the article by Wang et al. [114]. They introduced an empirical heat source model that may be used extensively in thermal modelling of battery modules and packs. A battery pack with constrained surface area can be effectively thermally managed using the heat pipes. Compared to forced convection cooling, the heat pipes' higher surface contact provides for better cooling control. The design of a heat pipe system in a distributed configuration was anticipated to reach a maximum temperature of 27.6°C and 51.5°C when paired with force convection [115].

EVs have a strong requirement for thermal strategy to control a high-powered LIB package within the necessary safe temperature range. The PCMs were designed into a copper metal foam layered cooling structure. Experimental analysis of the system's thermal efficiency and comparison to two control instances were performed by researchers [116]. Under varied cooling settings, the thermal performance of the flat heat pipe cooling system was compared to that of a traditional heat sink. According to the findings, introducing heat pipe decreased a common heat sink's thermal resistance by 30% under natural convection and 20% under low air velocity cooling [117].

The heat transport and thermal performance of the design are significantly impacted by the anisotropic properties of prismatic batteries. The high temperature region inside the battery module can be reduced by expanding the contact area. It can meet the system's need for heat dissipation when the PCM's phase transition temperature ranges from 311.15 to 313.15 K with a thickness of 6 to 8 mm [118]. The cooling system consists of a mini-channel cold plate with high latent heat PCM filled between the batteries at the bottom. The maximum temperature and temperature difference of the current hybrid cooling system (baseline case) are decreased by roughly 42.67% when compared to the single liquid cooling case without a PCM [119].

By pumping refrigerant through a cold plate, a thermal management system for a liquid-cooled battery enables the battery to go through quick, high-temperature recharging cycles. Based on the characteristics of the refrigerant, a cascade-change strategy with priority is recommended to account for the uniformity and temperature fall of the battery [120]. When using EV battery packs under conditions of ultra-rapid and extremely fast charging and discharging, thermal management is essential for their safety. Since liquid cooling uses so little power and has a high heat transfer coefficient compared to other battery thermal management solutions, it is particularly appealing [121]. The creation of lightweight batteries offers a significant potential benefit for mobile applications, such as electric cars and aeroplanes. Giving energy storage devices several uses is one way to reduce the weight of batteries. The term "structural batteries" is frequently used to describe this kind of battery [122]. Designing and producing an effective "Cooling System" for an FSAE automobile is the goal. Components were created and chosen with the manufacturing process, price, weight, ease of maintenance, and assembly in mind. The finished item was then put through testing to see whether it had any flaws and to determine its dependability [123].

The best option for the cooling system at 2C discharge is an N-type cold plate with a bottom inlet-top outlet arrangement, channel depth of 2.5, and mass flow rate of 8. To improve BTMS performance, apply the topology cold plate and optimization method suggested in this study [124]. The study by Lebrouhi et al. [125] is aimed at developing a low-cost lumped model for simulating a LIB pack with TMS under continuous charging/discharging cycles. Simulations were carried out at 3-C discharging/0.5-C charging rates and compared with three-dimensional computational fluid dynamic results. Using thermally enhanced water adsorbents, researchers create a passive battery temperature management system. The suggested passive cooling method lowers the battery temperature by 7.5°C when compared to natural cooling, air cooling, and cooling of solid-liquid phase change materials [126]. Most theoretical and practical studies on battery thermal management systems ignore the impact of vibration on the BTMS. This results from the addition of components with high heat conductivity, including graphene and carbon nanoparticles, to pure PCM [127]. One of the most urgent problems with LIB development is thermal safety, especially in large-scale battery packs. The internal increase in heat and pressure is not quickly addressed by conventional external measures. Internal control techniques could endow LIB with inborn thermal self-protective intelligence [128]. Even with a 4C discharge rate at 42°C, a TMS could maintain the battery temperature within a desirable range, and the enclosure could significantly increase its heat absorption capacity. Pure PCM could not satisfy the needs for battery cooling with an air flow rate of less than 200 m^3/h [129]. COMSOL software is used to perform thermal analysis on the batteries. Additionally, there is a reduction in the heat transfer coefficient (HTCT) between the PCM and the air. The effect of increasing the horizontal distance of batteries on battery temperature is also lessened (T-BT) [130].

Composite PCM

Heat transfer performance in LIB packs is crucial for maintaining safe and efficient operation. One way to improve heat transfer in these packs is by incorporating CPCMs into the design. A CPCM is a combination of a solid phase change material and a thermal conductive filler, such as graphite. These materials can absorb and release large amounts of heat during their phase transition, while also increasing the thermal conductivity of the pack. This approach has been shown to significantly enhance the thermal performance of LIB packs, making them more stable and reliable. Additionally, CPCMs can also mitigate the TR which is a critical safety concern in LIBs.

Metal foam CPCM

Metal foam CPCM is a type of material that is composed of a metal foam structure filled with a phase change material. These materials have a high thermal conductivity and a high heat storage capacity, making them useful in a wide range of applications, including building insulation, thermal energy storage, and TMSs. Additionally, metal foam CPCM have a unique combination of mechanical and thermal properties, making them suitable for use in areas where both high strength and thermal insulation are needed. These materials are being studied for usage in a variety of applications, including cold storage, building thermal management, and solar thermal energy storage systems. They may also be used in automobile and aerospace applications.

Rechargeable LIBs are a popular choice for EVs due to their effectiveness in thermal management. PCM is helpful for cooling such batteries because it offers a number of benefits, including low cost, ease of use, high latent heat, and temperature stability during the phase transition process. In this study, a new type of PCM made from hexagonal boron nitride (h-BN), paraffin, high density polyethylene, and diatomaceous earth was developed and tested. The thermal conductivity of this new PCM was found to be 12.49 times that of pure paraffin. When tested on battery packs, the new PCM was found to be more effective at cooling the batteries than natural cooling methods. The maximum temperature of the battery packs cooled by the new PCM was 48.6°C and the temperature difference between cells was controlled at 2.47°C. Overall, the new PCM was found to be an effective solution for controlling the temperature of battery packs [131].

The performance and longevity of battery packs will surely be enhanced by a successful BTMS. For battery modules, a brand-new flame-retarded CPCM has been proposed. According to the experimental findings, fire retardant PCMs have considerable cooling and temperature balancing benefits [132].

The range of the CPCM 1 to 7's thermal conductivity and latent heat is 0.2383-4.086 W/(mK) and 114.1-154.8 (J/g), respectively. Sanyo LIB's average maximum temperature when using CPCM cooling was 39.3°C and 28.6°C [133]. The durability and performance of batteries are impacted by their operating temperature. A unique BTMS built with aluminium boxes and CPCM was created by researchers. It can drastically lower the LIB pack's average temperature and increase temperature uniformity [134]. This study considers strengthening a LIB TMS by including both the flat heat pipe (FHP) and PCM modules. Even at a discharge rate of 3C, the FHP-PCM-BTM system's maximum temperature is lower than 313.15 K. It lessens "cold start," which shortens the battery's lifespan [135].

The research is focused on improving the performance of LIB packs by using a thermal management system that includes a PCM with a passive metallic connection. The battery packs were tested at different charge rates and in three configurations. The study found that typical pure PCM had poor thermal performance and an improved design with a metallic separator at the wall of PCM showed that the effective battery temperature did not exceed 55°C and allows for more temperature delay effect. Due to its increased thermal conductivity and improved heat transfer capability, it was found that extended graphene CPCM (EG CPCM) was superior to paraffin wax PCM during the investigation [136].

Carbon foam CPCM

Carbon foam CPCM is a type of material that is composed of a carbon foam structure filled with a phase change material. Carbon foam is a lightweight, porous material that is made from carbon, which is a highly thermally conductive material. This makes carbon foam CPCM ideal for use in thermal energy storage and thermal management systems. These materials have a high thermal conductivity, a high heat storage capacity, and a unique combination of mechanical and thermal properties. Additionally, carbon foam CPCMs have low thermal expansion coefficient and good chemical resistance. They are being researched for use in diverse range of applications such as in solar thermal energy storage systems, Building thermal management, Cold storage and batteries. They also have potential use in aerospace and automotive applications as well.

Researchers suggested to develop a product battery thermal cooling module (BCM) made of CPCM, a carbon foam skeleton support material, and a gasket made of thermally conductive carbon fiber. A extensive range of uses in battery materials, energy storage, and other areas are awaited for this material combination [137]. A large-capacity rectangular lithium iron phosphate battery with a wide temperature range underwent thermal management testing. The critical temperature for the preheating and heat preservation processes was established. Low temperature environments can have a significant impact on LIB performance, particularly battery durability and charge-discharge capacity [138]. It was examined how spacing between the each cell, content of EG (expanded graphite), direction or orientation of batteries ,flow rate of coolant and diameter of pipe affected the cooling performance of battery pack. The accumulation of inside heat can be lessened by the poles facing inward. It was discovered that the thermal performance of the pack can be maximized by employing an appropriate coolant flowing rate [139].

The best filler for creating extremely thermally conductive polymer composites has long been thought to be graphene. Researchers examined recent developments in the creation of high thermal conductivity graphene/polymer composites. They also pointed out a number of unresolved problems, fresh difficulties, and chances for future endeavors [140]. A brand-new BTMS was proposed that couples water cooling with CPCM using double s-shaped microchannels. Compared to other mass fractions, the BTMS with 20% EG/PCM has a greater heat dissipation effect [141].It is suggested to develop a brand-new battery thermal cooling module (BCM) made of CPCM, a carbon foam skeleton support material, and a gasket made of thermally conductive carbon fiber. A wide range of uses in battery materials, energy storage, and other areas are anticipated for this material combination. By successfully dissolving in an organic solvent, a novel flexible composite SBS@PA/EG is created and used in BTMS. Thermal conductivity measurements, scanning electron microscopy, and X-ray diffractometer analyses are used to examine the chemical composition and structure of the CPCM [142].

LIB pack's temperature is managed using two techniques. PCMs are used in the passive technique, whereas nanofluid flow is compelled inside it in the active method. Key factors including temperature and the heat transfer coefficient were studied using various nanoparticle shapes and velocities (HTCO) [143]. EV adoption is a positive step towards energy security and carbon footprint reduction. Due to their high energy density and prolonged cycle life, Li-ion batteries are widely used in EVs. The dependability, safety, and longevity of these batteries are significantly impacted by the cell temperature.

CPCM and metal fins

CPCM with metal fins is a type of material that is composed of a composite of PCM and metal fins. The PCM is typically encased within the metal fins to enhance thermal conductivity and increase heat storage capacity. This kind of material is beneficial in a variety of thermal management applications due to its strong thermal conductivity and high heat storage capacity. The metal fins also provide added structural support and help to increase the surface area of the material, which can enhance its thermal performance. Additionally, the fins help to dissipate heat more effectively, making this type of material particularly useful in high-heat applications, such as electronic cooling and solar thermal energy storage. It also has a potential use in building thermal management, aerospace, and automotive applications as well.

Due to their enormous capacity, LIB modules provide a very substantial fire risk. The complete LIBs modules could easily catch fire if a battery catches fire. The protection causes the TR occurrence time of nearby LIBs to grow from 1384 s to more than 6 h+ [144].

PCM and Metal Fins

Heat transfer performance in LIB packs is crucial for maintaining safe and efficient operation. One way to improve heat transfer in these packs is by incorporating PCMs and metal fins into the design. The PCMs, such as waxes or salt hydrates, can absorb and release large amounts of heat during their phase transition, helping to regulate the temperature within the pack. The metal fins, such as aluminium or copper, can increase the surface area available for heat dissipation. This combination of PCMs and metal fins has been shown to significantly enhance the thermal performance of LIB packs, making them more stable, reliable and also increases the heat dissipation rate. Furthermore, it assists in reducing thermal runaway, which a serious safety issue with Li-ion batteries.

During charging or discharging, LIBs generate considerable heat. The life of the batteries will be significantly decreased if they are not managed properly. In order to reduce the maximum battery temperature during the discharging process, Chen et al. [145] set out to determine the appropriate battery compartment size and fin count.

Flexible Phase Change Material (FPCM)

The drawbacks associated with phase change materials are liquid phase leakage, inherent stiffness, and easily brittle failure. For avoiding leakage of PCM, polymers which has flexibility are used and flexible form stable PCM are prepared, which improve the surface contact and reduce thermal contact resistance. Polymer with flexibility also has outstanding shape stability. Huang et al. [146] prepared two types of flexible form-stable CPCMs, one with Eicosane as phase change material and another with Tetracosane and observed 29.4°C and 34.2°C temperature drop is obtained in LI-ion battery packs. Wu et al. [147] prepared a thermal induced flexible composite phase change materials and observed 28.8°C maximum temperature difference when the battery is discharged from 100% to 0% charge state, with and without FCPCM. A novel thermal induced FCPCM contained SBS/PA/AlN has been successfully prepared by Huang et al. [148] and observed Tmax and ΔT were 48.4°C and 8.7°C at 3°C discharge rate in Li-ion batteries. Flexible and form-stable composite TPEE-SBS/EG/PA PCM successfully prepared by Huang et al. [149] and used for pouch lithium battery in EV and HE applications. The maximum temperature of the battery module was only 66.4°C, and it could still be maintained at about 66°C in 10 charge–discharge cycles without thermal accumulation. With the help of melt-mixing method, a novel FPCM with shape memory property and a wider flexible temperature range (-15 to 60°C) has been developed using paraffin (PA) as the PCM, thermoplastic polyether ester elastomer (TPEE) as the flexible support material, and expanded graphite (EG) as the heat transfer enhancement material. Then, using flexibility and the form memory characteristic, it was expertly put together on power batteries at room temperature. Based on this, the FPCM's flexibility may be used to lower thermal contact resistance during battery operation. The findings showed that the aforesaid BTM's thermal contact resistance was 0.27°C/W lower than that of previously reported thermally induced FPCM. Additionally, with the high discharge rate of 5°C and 40°C ambient temperature, the maximum temperature of the battery module with the passive BTM based on FPCM could be kept below 55°C, and the temperature differential was within 3°C [150]. Cao et al. [151] prepared FCPCM by mixing paraffin (PA), styrene ethylene

Table 4. Comparison of PCM-based thermal management systems [153]

Thermal Management system	Type of investigation	Melting Point	Cell Chemistry	Discharge rate	T_{max} (°C)	ΔT_{max} (°C)
PCM + Metal Foam + air	Numerical	27°C	LFP	2C.	28.1°C	5.2°C
PCM + liquid [72]	Numerical	42°C – 45°C 41°C – 43°C	LCO	0.5C, 3C,	20°C,44°C,47°C	1°C, 4°C, and 6°C
PCM-fin [73]	Numerical	44°C 50°C, 54°C	LFP	1C,1.5C,2C,3C	57.2°C	< 5°C
PCM + Water [74]	Numerical	27˚ C	NMC	0.5C, 1C 1.5C	35°C	8°C
PCM + Fin [76]	Numerical	42 to 44°C	LFP	2C	54.6°C	6°C
PCM-Air	Experimental	27 to 28°C	NMC	2.5C	40°C	2.4°C
PCM + graphene nanoparticles-Air	Numerical	29°C	LCO	1C, 4C	29.5°C	Single cell

butylene styrene (SEBS), and hexagonal boron nitride (h-BN) and observed even with a high discharge rate of 6 C and an ambient temperature of 38 °C, the prismatic battery pack's temperature and temperature differences can be maintained below 45°C and 4°C. The maximum temperature of the battery module with flexible CPCM is 2°C and 10.4°C lower than that of forced air cooling and natural air cooling, respectively, following six cycles of 2.5°C high-rate discharging. The battery module's temperature differential is less than 4.0°C [152]. Table 4 highlights the major research findings of PCM based cooling method [153].

APPLICATION AND CHALLENGES OF PCM IN BTMS

Application of PCM

This section provides an overview of the use of PCMs in BTMSs and thermal safety. PCM cooling is frequently used for BTMS due to its inexpensive cost, simplicity, and excellent cooling efficiency. The PCM-based BTMS has gained popularity due to its remarkable capabilities for temperature management and extending the temperature distribution without the need of additional energy (passive cooling). For instance, Karimi et al. [153] showed that the maximum temperature of a traditional cylindrical Li-ion battery was significantly reduced by up to 70% by employing PA-based PCM composites with a metal matrix and nanoparticles. Similar to this, Kizilel et al. [154] looked into the performance of the BTMS cooling system using PA/EG composite PCMs inside a Li-ion battery module, and the results showed that the maximum temperature remained constant at roughly 45°C. Even at 45°C ambient temperature, the PCM pack showed a 50% reduction in capacity recession rate and a 2.08C-high discharge rate (10 A). The design described above also resulted in a less compact pack space for the enhanced complex cooling system, which in turn led to a decrease in the total enormous power weight for application and an improvement in Li-ion pack energy density. Wang et al. [155] introduced three alternative PCMs to the typical 18,650 battery module: PCM 1 (pure PA), PCM 2 (EG 20%, PA 80%), and PCM 3 (EG 3%, ER 47%, PA 50%). According to the testing findings, the module for PCM 2 demonstrated its peak temperature at 1C, 3C, and 5C discharge rates, which decreased by 10%, 12%, and 20%, respectively. The battery module based on PCM 3 reported a maximum temperature after 30 continuous charging-discharging cycles that was 8.36% lower than the battery module based on PCM 2. Following the application of copper foam (CF) atop PCM as opposed to those solely using pure air cooling, Wang et al. [156] reported on improved power cell cooling capabilities, specifically 26,650, 42,110, and square cells. The findings pointed to improvements in temperature-controlling capability, as the peak temperatures of the 26,650, 42,110, and square batteries of CF/PCM-BTMS were kept below 44.37°C, 51.45°C, and 50.69°C for longer periods than those utilising pure PCM or air. The nickel foam-PA composite made by Hussain et al. [157] greatly reduced the PCM surface temperature. Particularly, at a discharge rate of 2C, temperature reductions of 31% and 24% were seen in comparison to pure PCM and spontaneous air convection. Applications of CPCM in power systems is shown in Figure 10 [158].

Khateeb et al. used an aluminium foam-PCM composite to a 13.2 Ah battery pack, which resulted in a temperature that was 5^0C lower than with pure PCM. In contrast, Wang et al. [159] showed that using aluminum foam-PA composites resulted in an 11.7 C lower battery surface temperature at a 2C discharge rate. A PA-based PCM composite matrix combined with CF was used by Zhang et al. [160] to manage the temperature of a cylindrical 42,110-type Li-ion battery module (36 V/20 Ah). The findings showed that the thermal conductivity had significantly improved, maintaining the module's peak temperature and maximum temperature difference at 50°C and 3°C, respectively. When Ling et al. [161] used CF-PCM composites to measure the surface temperature of a 10 Ah cell, they found that it was 29% and 12% lower than when using air convection and the pure PCM mode at a 1C discharge rate, respectively. In

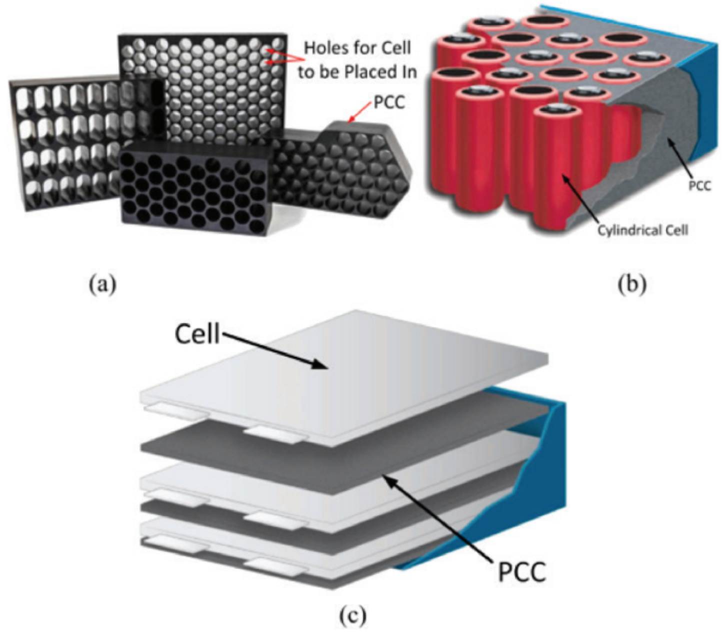


Figure 10. Applications of CPCM in power systems (a) fabricated PCM matrix, (b) PCC with cylindrical cells, and (c) PCC plates with prismatic cells [From Malik et al. [158], with permission from John Wiley and Sons].

order to study the passive thermal management of square Li-ion batteries, Qu et al. [111] used CF-enhanced PCM. According to the experimental findings, adding PCM/CF at discharge rates of 1C and 3C resulted in decreased battery surface temperatures of 17°C and 30°C, respectively. Numerous PA/EG composites have also been the subject of prior studies [161, 162]. A PA/EG matrix was specifically used by Somasundaram et al. [162] to study the heat dissipation performance using a thermo-electrochemical model, which resulted in an 18°C lower temperature at a 5C discharge rate. Ling et al. [161] examined various PA and PCM performances using PA/EG composites with BTMS. The best working temperature for batteries was offered by PA due to its 44°C melting point. Additionally, with larger composite densities and higher EG mass fractions, a constant temperature may be attained. Using PA/EG composites in a passive PCM cooling system, Fathabadi et al. [66] found that the PCM could regulate the maximum operation temperature below 60°C. In the battery module, Samimi et al. [163] employed a composite PA-based PCM with carbon fiber, and their testing data showed a reduction of 15°C. Under various environmental temperature settings, Zhang et al. [164] tested a 42,110-type LiFePO4 battery module (48 V/10 Ah) using PA/EG composites. The battery pack made up of the four aforementioned modules was also subjected to the practical loading test, and the results showed that it was capable of keeping the PCM cooling system's peak temperature under 42°C and maintaining a maximum temperature difference of 5°C. Even under extreme pulse discharge current conditions, the peak temperature was kept within 50°C. Using a PCM and aluminum wire mesh plate composite, Kizilel et al. [154] reported on the high-temperature LiFePO4 battery pack thermal management. At discharge rates of 1C, 2C, and 3C, respectively, a maximum temperature drop of 19%, 21%, and 26% was noted. A composite PCM was used by Wilke et al. [165] to delay the propagation of the TR in a Li-ion battery pack, lowering the maximum temperature by at least 60°C.

Challenges of PCM

Since the PCM cooling system provides good temperature control and equalization, it is typically used for battery thermal management. As is well knowledge, keeping a high-energy power Li-ion battery system density helps extend the driving range of EVs and HEVs. As a result, by reducing the system weight and increasing the energy density, a high-efficiency BTMS can be created.

The weight and volume of the entire power system were necessarily increased by conventional PCM modules, particularly those with large PCM blocks and matrices, which considerably decreased the energy density. The creation of novel shapes and new, lightweight PCMs and PCM-BTMSs is a vital concern in order to address the aforementioned issue. In addition, compared to more established air cooling and liquid cooling techniques, current research on PCM cooling systems is still in the experimental stage. The created battery packs with PCM functionality are still at the sample stage and have not been encouraged for actual EV use. The industrialization of PCM-based battery modules can be sped up by optimizing the PCM thermophysical parameters and PCM BTMS, particularly the performance optimization, structural design, weight, cost, space, and cooling efficiency. High-density power batteries have a heat dissipation need that cannot be met by a single PCM heat dissipation system. The more effective hybrid cooling systems based on PCMs that combine passive PCM and active cooling technologies are now the future development trend. Based on their key characteristics, the active and passive cooling methods within the composite cooling system each offer unique advantages. The complimentary system will effectively remove the heat that has built up in the PCM heat dissipation medium, enhancing the PCM's ability to store and release heat as well as extend its cycle life for improved overall performance and safety.

The benefits and drawbacks of various PCM-based hybrid BTMS techniques, such as PCM/air cooling, PCM/liquid cooling, PCM/HP cooling, and PCM/TE cooling, vary depending on factors including space accessibility, cost, weight, degree of integration, and service life. As a result, the creation of a logical design and the installation of a suitable thermal management system must consider the demands of heat dissipation under real-world loading situations.

CONCLUSION

Research articles published from the year 1994 to 2023 in domain of heat transfer performance of Li-ion battery pack using PCM are reviewed in the present paper. Temperature dependence, which can lead to temperature rise and irregularity, is a limitation of Li-ion batteries. The maximum temperature of the applicable PCM-based cooling systems must be reduced while preserving a uniform cell temperature distribution. The development of PCM-BTMSs has been hampered by low thermal conductivities, the poor combustion performance of organic PCM, structural instability brought on by leakage, and deformation or collapse. Prior to characterizing the heat generation/transfer mechanisms of Li-ion batteries, this study first examined and categorized common Li-ion batteries. The current research situation and performance promotion solutions to the low thermal conductivity, structural instability, and combustion characteristics were then illustrated while taking into account the practical application and security properties of PCM. The design strategy, cooling effectiveness, and benefits and drawbacks of the present BTMS that use PCM as the heat transfer medium for EVs/HEVs were then impartially assessed and examined. The present potential and problems relating to PCM and BTMS using PCM were also specifically discussed. Following the investigation mentioned above, the following findings were made:

1. According to their outward shape and appearance, the three primary types of Li-ion power batteries used in electrified cars are cylindrical, prismatic, and pouch. The battery module/pack is the most often used style of assembly for standard and typical cylindrical cells (particularly 18,650-type), as it increases temperature consistency among thousands of cells and regulates temperature. Because they have a wider contact surface than cylindrical cells, prismatic cells are more effective at dissipating heat. The prismatic cells should be used with enough room for the EVs/HEVs. The pouch cell's unique form allows for a reduction in weight, an increase in high-energy densities, and packaging efficiency, but this may also lead to more mechanical destruction and swelling. Due to the differences in the chemical makeup of lithium batteries, those with higher energy densities (like NCM811/C and NCM/SiC) may have higher potential safety risks as a result of the materials used in their electrodes, especially when subjected to harsh conditions (electrical, thermal, and mechanical abuses). These anomalies reduce battery life and could lead to TR. Consequently, a reliable BTMS is essential and required for Li-ion battery modules/packs.
2. The overall power system heat transfer efficiency is substantially impacted by the PCM thermal conductivity. However, just increasing the thermal conductivity coefficient by including high thermal conductive fillers (such metallic powers/foam, carbon-based foams, etc.) is insufficient when taking into account the practical application of PCM. The inherent feature of organic PCM can cause some PCM structure damage under continuous battery module charging and discharging cycles. As a result, it is anticipated that research would focus heavily on the structural stability and flame retardancy of PCM. It is critical that form-stabilized and flame-resistant composite PCMs be developed. It should be noted that while adding functional additives to PCM, the heat latent and melting point, which are key PCM properties, shouldn't be altered. A high-thermal conductive, sturdy, and excellent flame retarded composite PCM is acceptable and beneficial for boosting the system security when choosing the right composite PCM for a battery system.
3. Experimental and simulation techniques have demonstrated the impressive temperature-lowering and temperature-stretching capabilities of a PCM cooling system. A single PCM-BTMS is insufficient for power Li-ion battery systems with greater heat dissipation criteria. High-energy density battery systems are expected to increasingly rely on hybrid PCM-based systems, which are more effective options when combined with conventional air cooling, liquid cooling, HPs, and TE. The high PCM heat transfer efficiency and usage life can be preserved while removing stored PCM heat using a secondary cooling approach such active auxiliary measures. Additionally, the heating techniques of PCMs in extremely low temperatures have been studied through the combination of resistance wires, heating sheets, and other means in addition to the cooling performance of PCMs under high temperature conditions.
4. A compact and innovative version of PCM is an excellent way to retain the higher energy density of Li-ion

battery systems. Although PCM and PCM-based cooling systems have undergone extensive experimental and simulation research, these ideas are still in the laboratory since numerous technological problems must be resolved before they can be implemented in real EVs and HEVs. The final PCM-based cooling system must be integrated, lightweight, compact, efficient, secure, and have a low energy consumption. Each PCM-based heat dissipation technology has clear benefits and drawbacks. As a result, we must logically select the best BTMS based on criteria including heat generation, cooling requirement, area, weight, and cost.

Summarized Conclusion

The paper focuses on the effect of PCM thermal conductivity on total power system heat transfer efficiency. It emphasizes the importance of structurally stable and flame-resistant composite PCMs. Experimental and simulation methodologies indicate the capability of PCM cooling systems, as well as the possibility for hybrid PCM-based systems. It also focuses on the effect of PCM thermal conductivity on total power system heat transfer efficiency. It emphasizes the importance of structurally stable and flame-resistant composite PCMs. Experimental and simulation methodologies indicate the capability of PCM cooling systems and the possibility of hybrid PCM-based systems. In conclusion, while PCM and PCM-based cooling systems show promise, significant technological difficulties must be overcome before their practical application in EVs and HEVs. The most appropriate BTMS should be chosen after carefully evaluating a variety of criteria.

Scope for Future Research

The following research topics are emphasized as the future development of PCM-based BTMS based on the evaluation and analysis:

1. Ternary Li-ion power batteries have been recognized as one of the primary technical paths due to the high energy density, lightweight, and continuous driving range requirements of EVs/HEVs. It is important to note that the system's energy density cannot be greatly decreased by the PCM's involvement in the power battery module or pack. Excellent heat dissipation efficiency and strong safety performance has to be preserved at all times. Therefore, future research will concentrate on composite PCM with flexible, processable, high thermal conductivity and latent heat, flame retardant, and electrical insulation qualities. The important thing to remember is that in order to assure the composite PCM's superior comprehensive qualities, a good proportion and balance point for its physical property parameters needs to be found.
2. As a functional material, PCM's thermal conductivity and latent heat will have a direct impact on the effectiveness of heat dissipation. Due to its advantages, PA is the most often employed organic PCM in BTMS. The important issue in the future will be how to solve the precipitation issue during continuous high temperature cycles without noticeably lowering the thermal physical performance characteristics. It is essential to increase the mechanical strength of PCM to prevent collapse, cracks, and damage phenomena given the actual operating conditions of EVs/HEVs (climbing, accelerating, starting, collision, etc.). The suggested remedy for the issue is Micro-PCM. However, it is clear that the use of Micro-PCM in power battery modules and packages needs to be further investigated; if the temperature increase of power battery modules and packages is only managed by PCM after prolonged continuous high-rate charge-discharge cycles, the latter's heat storage capacity will inevitably degrade and won't be able to be restored in time. In order to increase PCM longevity and, ultimately, utilization efficiency, secondary heat dissipation is required. Consequently, one of the next research hotspots will be hybrid PCM-based BTMS. The coupling of PCM with liquid cooling plate will be the most promising technical option to reach industrial application in the future, especially in light of the present integrated CTP (cell to pack) and CTC (cell to chassis) technologies.
3. One of the primary uses of the BTMS is low temperature fast preheating. In terms of PCM-based BTMS, preheating technology is currently being researched less than heat dissipation system. Future research must focus on creating a quickly heating system that is safe, affordable, and high-efficiency.
4. Each BTMS that uses PCM has advantages and disadvantages. The research in this area has thus far concentrated on measuring the effect of heat dissipation, evaluating performance, and optimizing construction, but it lacks quantitative information on economy, environmental benefit, maintenance, system complexity, and weight. The researchers' focus in the upcoming study will be on the aforementioned future research paths.
5. In a nutshell, the goal of this effort was to comprehensively address the essential PCM thermophysical performances and security characteristics for use as a benchmark. Additionally, the PCM-BTMS cooling capabilities were examined and contrasted with real-world BTMS applications, which will help to speed up the commercialization of this ground-breaking cooling method.

NOMENCLATURE

ABS	Acrylonitrile butadiene styrene
Ah	Ampere hour
Al	Aluminium
Al_2O_3	Aluminum Oxide
ANN	Artificial Neural Network
AUVs	Autonomous underwater vehicles

BCs	Boundary conditions
BDS	Battery Design Studio
BTM	Battery Thermal Management
BTMS	Battery Thermal Management System
CCD	Central Composite Design
CCFSS	Cutting copper fiber sintered skeleton
CF	Copper foam
CFD	Computational Fluid Dynamics
CM	Copper mesh
CO_2	Carbon dioxide
COP	Coefficient of performance
CPCM	Composite phase change material
C-rate	Charge/discharge-rate
CuO	Cupric Oxide
CVM	Cell voltage measurement
DCM	Double copper mesh
DOD	Depth of Discharge
DoE	Design of experimentations
EG	Expanded graphite
ELP	Evaporative liquid pool
EVs	Electric Vehicles
Fe_3O_4	Ferrous ferric oxide
FOHP	Flexible Oscillating Heat Pipe
FPCM	Flexible phase change material
FPLHP	Flat plate loop heat pipe
GNP	Graphene Nanoplatelet
GO	Graphene oxide
HEVs	Hybrid Electric Vehicles
HP	Heat Pipe
HTMS	Hybrid thermal management system
IR	Infrared Imaging
IEA	International Energy Agency
ITMS	Integrated thermal management system
KBB	Kelly Blue Book
LCO	Lithium Cobalt Oxide
LB	Lattice Boltzmann's model
LCP	Liquid cooling/cold plates
LDPE	Low-Density Polyethylene
LHS	Latin Hypercube Sampling
LIBs	Li-ion batteries
$LiFePO_4$/LFP	Lithium-iron-phosphate
Li-ion	Li-ion
MHPA	Micro heat pipe array
NCM	Ni1− x− yCoxMnyO_2
Ni-Cd	Nickel–Cadmium
Ni-MH	Nickel-Metal Hydride
NMC	Nickel Manganese Cobalt
NPCM	Novel phase change material
NS	Nano silica
OHP	Oscillating heat pipe
PA	Paraffin
PCC	Phase change composite
PCM	Phase Change Materials
PCMP	Phase change material plate
PCS	Phase change slurry
PCT	Phase change temperature
PEG1000	Poly Ethylene Glycol 1000
ROM	Reduced-Order Model
RSM	Response Surface Methodology
S	Series
SEI	Solid Electrolyte Interface
SG	Silica gel
SiO_2	Silicon dioxide
SOC	State of Charge
SOE	State of Energy
SOF	State of Function
SOH	State of Health
SOP	State of Power
SOS	State of Safety
SOT	State of Temperature
TEC	Thermoelectric cooling
TME	Trimethylolethane
TR	Thermal Runaway
UD	Uniform Design
UMHP	Ultra-thin micro heat pipe
VCC	Vapor compression cycle
VG	Vortex Generator

Symbols

ΔT_{max}	Maximum temperature difference(°C)
T_{max}	Maximum temperature of battery (°C)
T_{avg}	Average temperature(°C)
T_{pcm}	PCM melting temperature (°C)
T_s	Battery surface temperature (°C)
T_{bf}	Temperature difference between inlet coolant and maximum temperature of battery (°C)
T_{amb}	Ambient temperature (°C)
ΔT_{nu}	Temperature non-uniformity factor
T_σ	Standard temperature deviation
Re	Reynolds number
Nu	Nusselt number
nc	Number of channels
Vc	Coolant velocity (m/s)
Q	Heat generation rate (W)
Tuni	Temperature uniformity
fd	Fluid flow direction
tc	Cold plate thickness (mm)
np	number of cold plates
$\dot{m}$ f	Inlet mass flow rate (kg/s)
L	Channel width (mm)
ΔP	Pressure drop of coolant (Pa)
H	Channel height (mm)

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

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

ETHICS

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

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