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A Short Review of Recent Advancements in PCM-Air Hybrid Thermal Management for Batteries

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This comprehensive review paper provides an in-depth overview of Phase Change Materials (PCMs) and air-cooling technologies used for Battery Thermal Management Systems (BTMS). PCMs can be classified by their phase change and by their composition, and each class shows different advantages that respond to complex needs, dissipating the heat in a battery. Organic PCMs based on paraffin, such as 1-Tetradecanol, help improve the efficiency and sustainability of the cooling system. In contrast, paraffin wax offers the high thermal conductivity and stability needed for these applications. Eutectic and composite PCMs are a “made to measure” solution for these needs, and the addition of a PCM to the air cooling is highly advantageous for the optimization of the performance of the battery. It shows the validity of the air cooling in the BTMS, a system intrinsically, cost-effective, and practical in dissipating heat, thus minimizing the thermal stress in the battery. Besides PCM, the paper underscores the critical role of air cooling in improving battery lifespan, safety, and overall performance. The survey reports that air cooling is the leading BTMS configuration in addressing thermal challenges. Air cooling in combination with PCM is a significant approach in this thermal management arena. Among all existing configurations, the encapsulated PCM, metal fins, and the air-cooled hybrid system exhibited the best performance. Each resulted in an overall reduction in the battery’s maximum temperature and a uniform temperature distribution across the entire battery. This review mainly focused on the BTMS using PCMS and air cooling.

Keywords: Battery Thermal Management System; phase change materials; air cooling; hybrid cooling; energy storage materials

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With environmental concerns growing, it is more important than ever to find sustainable energy solutions [1]. The need for greener [2] and more sustainable energy sources are growing as the world is dealing with the effects of climate change [3]. Adopting sustainability is not only a choice; it is essential to preserving the future of our world and guaranteeing that humans and the environment coexist peacefully [4]. A major strategy in transportation is changing by contesting the historical hegemony of cars that create greenhouse gases. In the market for sustainable energy, electric cars (EVs) are becoming more and more commonplace, surpassing their initial novelty. This surge in popularity can be attributed to a combination of changing consumer tastes, technological developments, and environmental benefits. Since EVs produce no tailpipe emissions, as opposed to IC engines, they have a majorly reduced negative impact on air quality and favorably support efforts to mitigate climate change [5]. Additionally, the ongoing advancements in battery technology make EVs a more sensible option for lengthy trips [6].

In energy storage, batteries serve as power storage devices for cars and several gadgets. When batteries overheat, it can trigger a cascade of detrimental effects, ranging from reduced performance to potential safety hazards. In this scenario, the BTMS steps in as a crucial solution, regulating the battery temperature to prevent hazards [7]. Batteries generate heat during the charge and discharge cycles. If the generated heat isn't effectively managed, it leads to diminished lifespans, accelerated deterioration, and potential safety risks [8]. By upholding the battery within its optimal temperature range, the BTMS ensures peak performance, prolonged battery lifespan, and, most importantly, safe operation [9]. This system employs various techniques, including Phase Change Materials (PCMs), heat pipes, and air or liquid cooling, to maintain objects at desirable temperatures [10]. Functionality-based classifications

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that handle emergency, cooling, and heating systems are becoming more and more popular [11]. Concerning particular applications and research questions, this broad classification framework allows for focused comparisons and breakthroughs in BTMS design [12].

In this regard, air-cooled BTMS hold considerable appeal for Electric Vehicles (EVs) due to their cost-effectiveness and simple design. While forced air-cooled systems offer greater potential, traditional air-cooled alternatives often lack sufficient cooling capacity to meet the demands of EVs. This limitation underscores the need for innovative solutions to enhance the cooling capabilities of air-cooled BTMS to ensure optimal performance and longevity for electric vehicle batteries [13]. Studies have demonstrated that the most effective strategy involves maximizing the specific heat capacity of air through the optimization of airflow channels within battery packs. This approach is deemed paramount in enhancing the thermal management of battery systems, thereby contributing to their overall efficiency and longevity [14]. In cooling efficiency, it is noteworthy that parallel cell configurations exhibit superior performance compared to their serial configurations. Parallel arrangements demonstrate a heightened capacity for dissipating heat, thereby enhancing the overall efficiency of cooling systems [15].

In high-performance electric vehicles, liquid-cooled BTMS is emerging as the preferred choice. These systems manage the escalating temperatures generated by the robust lithium-ion batteries, owing to their superior heat transfer capabilities compared to air-based alternatives. While external coolant channels offer a cost-efficient solution, they may fall short of delivering peak cooling power. For optimum thermal management, air-cooling-coupled liquid-cooling systems stand out despite their higher cost. Balancing cooling performance with factors like volume, price, weight, and design complexity is crucial. Liquid cooling systems augmented with PCM, external channels, and air cooling systems emerge as the focal point in the current scenario. These integrated approaches offer exceptional cooling prowess while ensuring that costs and complexities remain manageable [16].

Besides this, refrigerant direct cooling is lacking in industrial applications due to temperature control limitations even though it has a simple design and high cooling efficiency. The two-phase zone excels at heat dissipation, maintaining low battery temperatures (28.3% lower than liquid cooling), and the superheated gaseous zone suffers, leading to substantial temperature spikes (12°C -14°C difference). This performance decline occurs when the refrigerant switches from two-phase to single-phase, highlighting a critical issue. Practical applications are hampered by the significant temperature changes caused by the low refrigerant temperature within the battery. This can be mitigated by raising the evaporation pressure, which will result in a 37.6% decrease in temperature differential. While refrigerant direct cooling initially offers faster cooling, because of the superheated zone's restrictions, its maximum temperatures are nevertheless comparable to those of liquid cooling. As a result, the battery's temperature inhomogeneity becomes more pronounced (16.0°C difference) [17]. Using the Peltier effect, thermoelectric cooling presents itself as a potentially environmentally benign and noiseless solution for controlling heat in EV batteries. These solid-state modules have some exciting features, like quiet operation, the use of no hazardous refrigerants, and excellent heat regulation at moderate temperatures. But their bulk comes at a high cost in terms of charm. Battery packs become much bulkier with the integration of thermoelectric cooling, with a 120% increase in volume and an 80% increase in weight. This results in a significant energy cost for the EV since it uses precious battery power to control heat. Under typical situations, they can maintain appropriate battery temperatures; however, in extreme cases, they struggle and consume as much as 4.8% of the battery's energy. A significant problem is striking a balance between their size and energy usage, even though thermoelectric cooling has the potential [18].

In addition to the above approaches, a potential replacement for BTMS in EVs and hybrids is heat pipes. Heat pipes provide high heat transfer rates without needing external power, in contrast to traditional fans or pumps. They can also be curved or flattened to fit the contours of battery packs, which maximizes heat dissipation even in small areas. Even though there are still issues with controlling non-uniform heat distribution and heat pipe layout optimization, research is working to find solutions. Heat pipes possess significant potential to revolutionize BTMS and facilitate the advancement of safer and more EVs owing to their passive operation, efficient heat transfer capabilities, and adaptable design [19]. Furthermore, the PCMs are another significant approach to passive cooling in BTMS, due to their distinct capacity to absorb and release heat at particular temperatures. PCMs absorb extra heat generated by Li-ion batteries when they are in use, preventing overheating and maintaining a stable temperature range. Reducing the potential for thermal runaway enhances security while maximizing battery efficiency. As PCMs don't need to be powered externally, they use less energy and are simpler to operate than traditional active cooling methods like liquid or air systems. Their lightweight design contributes very little weight to the battery pack in contrast to large cooling components [20].

The various approaches of BTMS are depicted in Figure 1 and the pros and cons of cooling technologies are listed in Table 1.

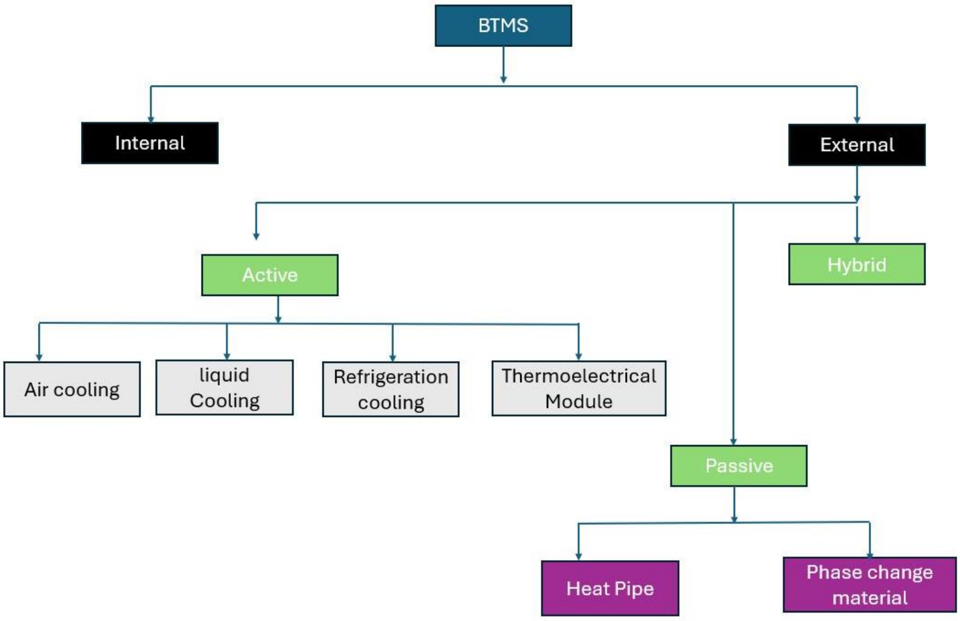

Figure 1. Classification of BTMS Technologies based on the Cooling system.

Table 1. shows the positives and negatives of all types of cooling technologies.

Type	**Positives**	**Negatives**
Air Forced Convection	➢ Affordable ➢ Lightweight ➢ Basic Design ➢ Simple to upkeep	➢ Low Heat Capacity ➢ It is challenging to achieve a consistent flow. ➢ Low efficiency
Liquid Cooling	➢ Good at letting heat flow through easily. ➢ Great at moving heat around quickly	➢ Heavy or as much mass. ➢ There is a problem with things leaking. ➢ Energy loss when pumping ➢ Chance of a short circuit happening
Refrigerant	➢ Cooling below the regular temperature might be achievable. ➢ It can transfer more heat efficiently	➢ We must design the refrigerant system to keep the cabin comfortable and cool the battery
Thermoelectric Cooler	➢ Long Life cycle ➢ Small and efficient design ➢ Silent operation ➢ Doesn't move or vibrate. ➢ Exact temperature control	➢ Uses much energy. ➢ Expensive ➢ Low efficiency
Phase Change Material	➢ Affordable ➢ Lasts a long time. ➢ Absorbs much heat. ➢ Evenly spreads temperature	➢ Issues with leaks ➢ It can only absorb a certain amount of heat after melting. ➢ Low thermal conductivity
Heat Pipe	➢ Small and portable ➢ Long Life cycle. ➢ Doesn't require any upkeep. ➢ Good at transferring heat	➢ High Cost

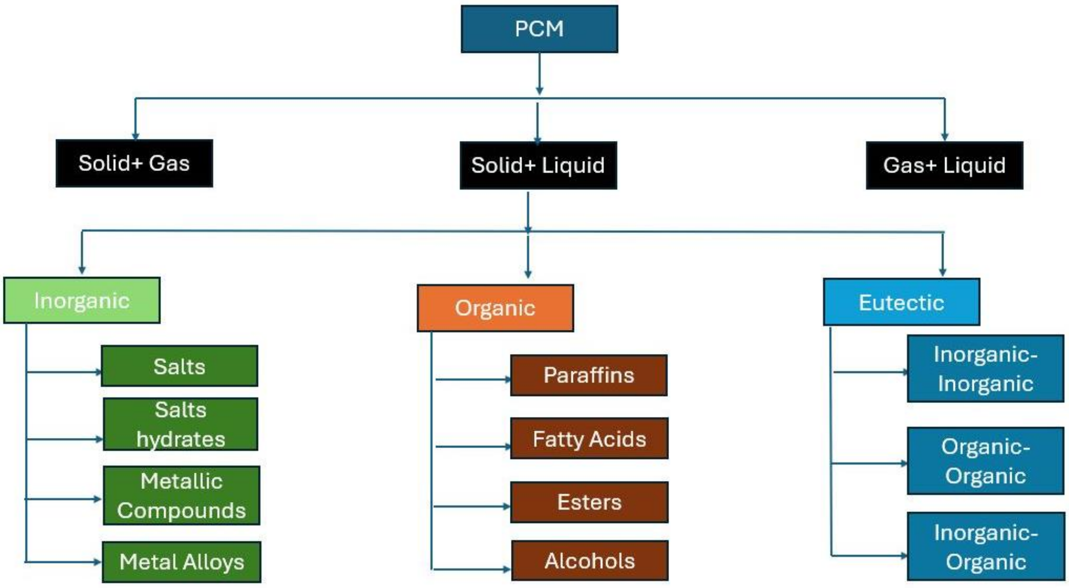

Figure 2. PCM Classification in Phase Change Category

From the recent literature, the integration of PCMs and air cooling leads to an innovative approach that leads to a delicate balance between practicality and efficiency, addressing the shortcomings of standalone PCM or air-cooling methods. In high-demand scenarios, relying solely on air cooling proves inadequate, while PCM alone lacks active heat dissipation capabilities. However, by harnessing the unique properties of PCMs to absorb and release heat within specific temperature ranges, this hybrid strategy passively mitigates temperature fluctuations. Moreover, the incorporation of air-cooling ensures active heat removal when necessary, maintaining optimal battery temperatures critical for longevity and performance efficiency [21].

The present review offers a comprehensive examination of PCMs, air cooling systems, and hybrid BTMS for EVs. This review endeavors with the necessary insights to make informed decisions regarding the selection of optimal configurations. The subsequent sections elucidate the various PCM and air-cooling approaches for effective BTMS in EVs.

PHASE CHANGE MATERIAL

Classification of PCM

During phase transitions, PCMs exhibit a remarkable ability to either absorb or release heat. This characteristic renders them adaptable for various applications, particularly in heating and cooling systems. Much like critical considerations in optimizing PCM usage in BTMSs, the selection of PCMs is paramount. PCMs must possess high latent heat and specific heat capacities to enhance heat absorption. These properties dictate the amount of energy absorbed or released during a phase change, thus influencing the efficiency of the system [22]. Factors such as corrosion, sedimentation, and overall costs should also be considered during the selection of material [23]. PCMs can be classified into different categories such as solid-liquid, solid-gas, solid-solid, and liquid-gas [24]. Solid-liquid is the most popular choice for BTMS. It can be further classified into organic, inorganic, and eutectic [25]. The classification of PCMs is pictorially depicted in Figure 2.

Organic PCM

Organic PCMs have a higher advantage over their other PCMs for BTMS. Organic PCMs show higher latent heat and higher specific heat. Joshwin et al. explored the application of 1-Tetradecanol as a PCM in BTMS for Lithium Iron Phosphate ($LiFePO_4$) battery-equipped EVs. Using ANSYS Fluent, a computational model assesses the thermal dynamics during 1-Tetradecanol PCMs melting within a cylindrical enclosure. While passive PCM systems face conductivity challenges, incorporating enhancing materials shows promise. Results indicate its potential as a lightweight and cost-effective alternative for maintaining EV battery temperatures within optimal ranges. The proposed BTMS design, featuring a uniform PCM layer around each $LiFePO_4$ cell, ensures temperature homogeneity within the battery pack [26]. Traditionally, cooling battery packs with an ethylene glycol and water mixture proves insufficient. Conversely, graphene nanoplatelets (GNPs) enhance heat transfer, reducing battery cell temperatures. Another study simulates a customized battery pack with coolants containing varying GNP concentrations (0.001 to 0.01 vol%). The discrete GNP particles' interaction with the continuous fluid phase is tracked using a Lagrangian approach. Results reveal a peak temperature reduction of 33.15°C with 0.003 vol% GNP, attributing this efficacy to higher thermal conductivity, increased surface area, and enhanced specific heat capacity. The study recommends avoiding GNP concentration increments beyond the optimum 0.003 vol% due to diminishing returns on heat transfer efficiency. While computationally limited, this research provides insights into future GNP experiments in active BTMS [27].

Effective cooling strategies are paramount for enhancing Li-ion batteries' lifespan, safety, and performance. This study investigates natural convection air and PCM-assisted cooling methods for a $5S_4P$ Li-ion battery module. Results indicate a notable reduction in the battery module's maximum temperature by 21.66% to 34.48% with PCM-assisted cooling across different discharge C-rates. Myristyl alcohol as a phase change material proves safe and efficient for high-current and high-energy-density Li-ion batteries. Additionally, an Adaptive Neuro-Fuzzy Inference System (ANFIS) model accurately predicts battery module temperatures, emphasizing the efficacy of PCM-assisted cooling for optimal Li-ion battery operation [28]. Another research delves into nine passive BTMSs utilizing paraffin wax as a PCM and copper foam as a conductive additive. The numerical simulations reveal that adding copper foam significantly impacts the evolution of the PCM liquid fraction. Introducing 6 vol% copper foam demonstrates the most effective cooling, maintaining the cell within the desired temperature range. Beyond this threshold, exceeding 6% compromises the BTMS's heat absorption capacity, rendering it unreliable. The study emphasizes the optimal addition of 6% copper foam for paraffin wax-based BTMSs, ensuring reliable thermal management with a 15 mm thickness [29]. They are focusing on pressurized polyethylene-glycol-1000 (PEG1000) for BTMSs. The Box-Behnken design assesses input parameters, revealing pressure's impact on the PCM's thermal performance in discharging a single cylindrical cell. Results indicate that at 7C discharge, applying 500 kPa pressure doubles discharge duration compared to atmospheric pressure, with a 10% increase in depth of discharge. High pressure effectively protects the battery from exceeding the safe temperature limit. The study showcases potential applications in high-pressure environments, offering insights into advanced thermal management systems [30].

Inorganic PCM

Inorganic PCM has a higher thermal conductivity and elevated temperature performance. These prominent properties will show domination over other materials while choosing the materials for BTMS [31]. The unique thermal performance and durability of inorganic PCMs underscore their pivotal role in optimizing the efficiency of BTMS across diverse settings [32]. Ping et al. introduced an encapsulated inorganic PCM (EIPCM) synthesized through nano-encapsulation, employing $Na_2HPO_4 \cdot 12H_2O$ as the inorganic core and silica for encapsulation. The EIPCM exhibits commendable phase change properties and thermal stability. Practical tests demonstrate a 23.7% reduction in peak battery temperature at a 3°C discharge rate. EIPCM effectively delays thermal runaway (TR) occurrence by 495 sec, showcasing its ability to rapidly suppress TR and extinguish the fire. This nonflammable EIPCM presents promising prospects for safe and efficient battery applications, emphasizing its potential to enhance energy storage [33]. Another study addresses challenges in the practical use of inorganic PCMs, precisely the supercooling issue with $CaCl_2 \cdot 6H_2O$. Flake graphite is introduced as a nucleating agent to reduce supercooling, while a super absorbent polymer prevents segregation during phase transition. The innovative combined method of thermos-gravimetric analysis/differential thermal analysis (TGA-DTA) assesses PCM segregation. Results reveal that 0.5 wt.% flake graphite eliminates supercooling and enhances thermal conductivity. Additionally, 25 wt.% SAP improves segregation resistance. Numerical simulations demonstrate the economic feasibility of using modified $CaCl_2 \cdot 6H_2O$ for building walls in Hong Kong and Changsha, with payback periods of 18.3 and 8.4 years, respectively. The proposed modified PCM proves economically viable for diverse applications, including solar energy and building energy conservation [34]. A flame-retardant inorganic composite PCM using sodium acetate trihydrate. The PCM, featuring a thermal conductivity of 4.27 W/(m·K) and a latent heat value of 154.5 J/g, is enhanced with a soft polyurethane coating for improved cycle stability. In battery thermal management experiments, the PCM effectively disperses and conducts heat from lithium-ion batteries (LiBs), controlling the battery temperature even at 40°C discharge and 40°C ambient temperatures. This flame-retardant PCM exhibits significant potential for EV BTMS, ensuring both safety and performance [36]. Figure 3 represents the no. of publications published on inorganic PCMs for effective thermal management and Figure 4 shows the publications on inorganic PCMs published from various counties.

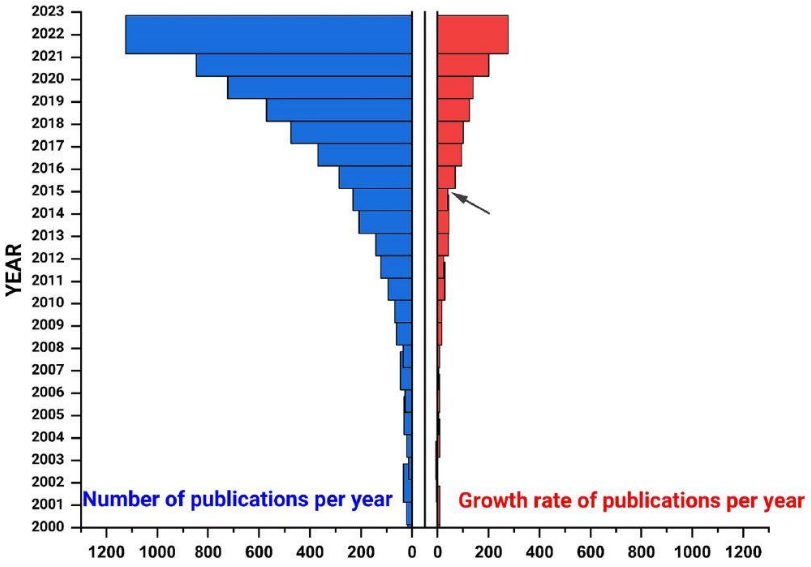

Figure 3. No publications throughout the different years [35].

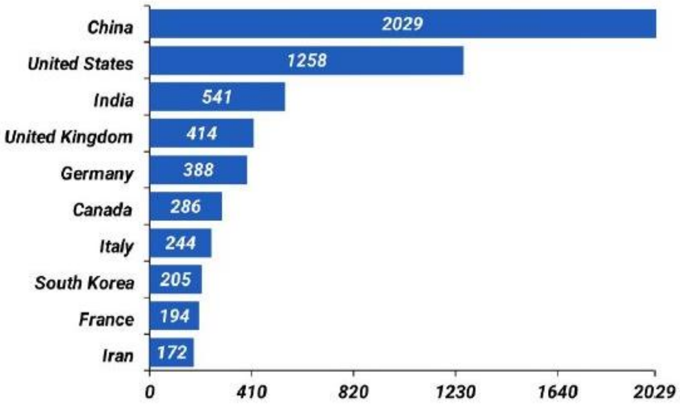

Figure 4. No of publications from different countries [35].

Eutectic PCM

Eutectic PCM shows unique properties, such as a fixed melting point and supercooling in nature. Eutectic PCMs have an advantage over other PCM choices due to their unique characteristics, which make them an appealing option for applications requiring accurate and reliable temperature control [37]. Kadir et al. investigated the possibility of adjusting the melting points of lauric acid (LA) and palmitic acid (PA) for low-temperature solar applications. Differential scanning calorimetry shows that a eutectic combination with 69.0 wt.% LA and 31 wt.% PA has a melting temperature of 35.2^{0}C and a latent heat of fusion of 166.3 J/gK. Experimental findings have validated the potential of a concentric pipe-in-pipe system for energy storage in low-temperature solar heating applications. Through meticulous analysis conducted over a prolonged duration, the favorable thermal properties exhibited by the LA–PA eutectic mixture suggest its viability for utilization in both solar applications and agricultural heating [38]. Diverse cooling methods for a 5000 mAh Li-ion battery pack under different charging and discharging rates. Methods include natural cooling, heat transfer fluid cooling, eutectic PCM cooling (LA and stearic acid with a melting point of 33.29°C), and hybrid cooling. Results reveal natural cooling reaching maximum temperatures of 66.9°C, 57.9°C, and 45.6°C at 2C, 1.5C, and 1C rates. Compared to natural cooling at 2C, heat transfer fluid cooling reduces maximum temperature by 22.42%, eutectic PCM cooling by 40.90%, and hybrid cooling by 46.18%. Hybrid cooling, reducing both maximum temperature and temperature gradient, suggests its efficacy for Li-ion battery packs, particularly in high-temperature conditions [39]. a novel eutectic hydrated salt (EHS), $Na_2SO_4 \cdot 10H_2O$-$Na_2HPO_4 \cdot 12H_2O$, Nano-α-Al_2O_3 is added to inhibit supercooling and enhance thermal conductivity. Employing a multi-factor orthogonal test method, the study demonstrates that 4.5 wt.% nano-α-Al_2O_3 effectively reduces supercooling by

7.8°C to 1.6°C and improves thermal conductivities by up to 61.3%. The modified EHS maintains thermal stability after 200 cycles [40]. Another research focuses on designing binary eutectic PCMs using 1-dodecanol and fatty acids, targeting low melting temperatures (15-20°C) and substantial latent heat. Lauric (LA), myristic (MA), and palmitic (PA) fatty acids with 1-dodecanol yield eutectic compositions experimentally validated through calorimetric measurements. Computed and measured values align well, with melting temperatures of 17°C, 18.43°C, and 20.08°C and latent heat of fusion of 175.3, 180.8, and 191 kJ/kg for LA-DE, MA-DE, and PA-DE, respectively. The designed eutectic PCMs, boasting suitable melting temperatures and substantial latent heat, show promise for solar thermal applications like building climate control and phase change clothing [41]. Composite PCMs offer distinctive advantages over traditional PCM systems. Composites can tailor properties such as thermal conductivity and phase change temperature by combining different materials to suit specific applications [42]. The key characteristics of various PCMs are tabulated in Table 2.

Composite PCM

The study introduces innovative fin structures in a PCM, showing superior thermal performance compared to traditional PCM and pure battery systems. The novel PCM-Fin system forms an efficient thermal conductive network within the PCM, significantly enhancing battery working time. Optimal configurations include one cylindrical ring, eight longitudinal fins, and a recommended dimensionless distance of 0.2 mm between the ring and the battery. The proposed system effectively controls battery temperature rise even under a 20 W heat generation rate. The study acknowledges the need for further investigations using genuine LiBs for comprehensive understanding and practical application [43].

Table 2. Shows Key Characteristics of Various PCM.

Type of Material	Key Properties	Reference
1-Tetradecanol	Lightweight, cost-effective, potential for optimal EV battery temperature	[26]
Nanoparticles (GNPs)	Peak temperature reduction (33.15°C), higher thermal conductivity, increased surface area	[27]
Myristyl alcohol	21.66% to 34.48% reduction in battery module temperature, ANFIS model for temperature prediction	[28]
Paraffin wax, Copper foam	Optimal addition of 6% copper foam, reliable thermal management	[29]
Polyethylene-glycol-1000 (PEG1000)	Doubles discharge duration at 500 kPa pressure, effective in high-pressure environments	[30]
paraffin wax	High thermal conductivity, stability during thermal cycling, resilience to degradation and corrosion	[31]
$Na_2HPO_4 \cdot 12H_2O$ (core), Silica (encapsulation)	23.7% reduction in peak battery temperature delays thermal runaway	[33]
$CaCl_2 \cdot 6H_2O$ with flake graphite and super absorbent polymer	It eliminates supercooling, enhances thermal conductivity, and is economically viable for various applications	[34]
Sodium acetate trihydrate	Thermal conductivity (4.27 W/(m·K)), latent heat (154.5 J/g), flame-retardant	[36]
LA-PA	Fixed melting point, minimal supercooling, stable performance	[37]
LA (69.0 wt.%), PA (31 wt.%)	Melting temperature (35.2°C), latent heat of fusion (166.3 J/gK)	[38]
LA and stearic acid	Hybrid cooling reduces maximum temperature by 46.18%	[39]
$Na_2SO_4 \cdot 10H_2O$-$Na_2HPO_4 \cdot 12H_2O$	Reduces supercooling improves thermal conductivities by up to 61.3%	[40]
1-dodecanol with fatty acids	Melting temperatures and latent heat suitable for solar applications	[41]
Composite PCM with tunable properties	Versatility in properties, suitable for diverse industries	[42]
Composite PCM with fin structures	Superior thermal performance, the efficient thermal conductive network	[43]
Composite PCM pouch with copper foam	Effective heat dissipation, significant reduction in liquid cooling system operating time	[44]
Paraffin (core), Methanol-modified melamine-formaldehyde (shell)	High thermal conductivity (0.50 W/(m K)), latent heat (139.64 J/g), enhanced heat storage and dissipation	[45]

A compact BTMS utilizing a Composite PCM pouch with copper foam for efficient heat dissipation during fast charging and preheating in low temperatures. Under 3C charging conditions, the system achieves a maximum temperature of 39.3°C with a 3°C difference, and after preheating at -10°C, the final temperature is 29.2°C with a 2.5°C difference, outperforming existing methods. The proposed BTMS significantly reduces liquid cooling system operating time by 35.2%, ensuring effective heat recovery. Future research should explore PCM shape optimization for enhanced heat transfer performance in diverse applications [44]. Another study introduces a core-shell microcapsule, synthesized via in-situ polymerization, using paraffin as the core and methanol-modified melamine-formaldehyde as the shell for improved thermal stability. Three heat-conductive fillers-nano-Al_2O_3, nano-ZnO, and carbon nanotubes (CNT)—were added to create composites. The CPCM with 10 wt.% CNT exhibited the highest thermal conductivity (0.50 W/(m K)) and latent heat (139.64 J/g). Battery charge/discharge experiments revealed enhanced heat storage and dissipation, making the CPCM@CNT a promising material for BTMS and energy storage applications. The study emphasizes its potential in high-conductivity environments, highlighting CNT's superior performance over other fillers [45].

Air Cooling

Air cooling is a formidable solution for BTMS, surpassing alternative methods. This approach leverages efficient heat exchange through convection, ensuring optimal temperature regulation. Its inherent simplicity and cost-effectiveness make it an attractive choice for diverse applications. The efficacy of air cooling lies in its ability to dissipate heat swiftly, mitigating thermal stress on batteries [46]. This method not only enhances overall system reliability but also minimizes maintenance complexities. Compared to competing technologies, air cooling emerges as a pragmatic and reliable solution, showcasing its prominence in advancing BTMS [47]. The classification of air-based systems for battery thermal management involves two key aspects: convection type and airflow source. While natural convection, despite its simplicity, induces large thermal gradients and environmental dependency, forced-air systems prove essential despite higher costs. Another classification is based on the air source, which can be external, cabin pre-conditioned, or pre-conditioned by an auxiliary heat exchanger. Ongoing research endeavors are focused on optimizing the inlet and outlet configurations of air for different battery setups. These investigations have unveiled that elongated fluid flow paths lead to a more uniform distribution of temperature across the battery unit. Moreover, there's a growing interest in exploring bidirectional airflow systems to enhance thermal efficiency. Symmetrical designs and reciprocating airflow strategies have emerged as promising avenues for achieving improved thermal performance [48]. Another study chose a different approach to find the role of LiB cycle life in EVs. Active air cooling will outperform passive PCM cooling at higher temperatures despite temperature non-uniformity at lower air velocities for developing BTMS to enhance LiB cycle life and reduce operational costs [49].

Forced Convection

The forced convection method quickly transfers or releases heat generated within it to the surrounding environment. In the pursuit of enhancing BTMS, researchers are focusing on optimizing forced convection types [50]. The synergistic coupling of forced convection and phase change material not only improves thermal efficiency but also addresses the challenges posed by traditional systems [51]. Akinlabi A.et al. studied LiB performance, which is crucial for electric vehicle drivetrains, through a BTMS. Analyzing a 100-cell NCR18650 LiB pack, the research employs a complete factorial Design of Experiment to explore the impact of varying air flow and current rates. Increasing air flow rates notably demonstrated a consistent improvement in BTMS performance, evidenced by a 54.28% reduction in temperature difference between cells. The findings suggest an optimal cooling-air flow rate for minimizing power consumption in dynamic BTMS operations. Higher air flow rates exhibit reduced cell temperatures, validating literature-based conclusions on convective heat transfer coefficients [52]. Another research delves into the numerical investigation of an air-cooled battery module, focusing on heat removal during discharge. The study employs a coupled electrochemical-thermal model, considering air-flow velocity, cell configuration, and the number of cells. Results reveal that the arrangement of cells has minimal impact on the thermal field beyond a critical number of cells. Forced convective air cooling demonstrates enhanced heat removal with increased air inflow. Still, efficiency declines with a higher number of cells, emphasizing the critical role of BTMS in maintaining battery temperature uniformity [53].

U-type Forced Convection

A specialized U-type design enhances heat transfer efficiency by promoting fluid flow in a manner that optimally dissipates thermal energy. Kai Chen et al. focus on improving the cooling efficiency of a parallel air-cooled BTMS with U-type flow through structural optimization. The study employs a flow resistance network model to calculate airflow rates, optimizing plenum angles and inlet/outlet widths. Results demonstrate that while adjusting plenum angles has limited impact, optimizing widths significantly improves cooling efficiency. After optimization, a 70% reduction in temperature difference among battery cells during a 5C discharge is achieved, coupled with a 32% power consumption reduction. Compared to a previous study, the optimized BTMS shows a 43% lower temperature difference and a 50% power consumption reduction. The improvements hold across various inlet airflow rates [54]. A three-dimensional thermal model is developed to understand battery cell thermal behavior in simulated driving cycles. This approach integrates a Computational Fluid Dynamics (CFD) pack-level sub-model, a one-dimensional battery pack network sub-model, and a three-dimensional thermal and electrochemical coupled cell/module level sub-model. It predicts non-uniform heat generation, temperature distribution, and variations across a battery pack. The flow profiles in individual battery cooling channels are calculated using the CFD sub-model. Results show that cooling duct geometry significantly influences temperature uniformity. A tapered upper cooling duct improves battery temperature variation by around 70%, validated by physical tests. The model also highlights cell temperature variations due to non-uniform convection heat transfer rates [55]. A similar study focuses on enhancing the efficiency of air-cooled systems for EV battery packs. A parallel air-cooled system with a designed control strategy is developed to investigate different flow types (J-type, U-type, L-type). Numerical simulations, validated by experiments, reveal the limitations of a J-type system. An innovative system is proposed to integrate J-type, U-type, and L-type flows featuring narrowed parallel channels to address this. The developed system, guided by a responsive control strategy, reduces the temperature difference among battery cells by over 67% [56].

Z-Type Forced Convection

This specialized approach outperforms conventional methods by optimizing the system's airflow patterns and heat dissipation. The distinctive Z-type configuration facilitates enhanced heat transfer, presenting a superior alternative for BTMS over traditional counterparts. Kai et al. focused on improving the cooling efficiency of an air-cooled BTMS by optimizing its flow pattern. Using CFD, various BTMSs with different inlet and outlet positions are assessed. The symmetrical BTMS denoted as BTMS IX, is positioned with inlets and outlets in the middle of the plenum, demonstrating superior cooling efficiency. An optimization strategy based on temperature distribution is proposed and applied to BTMS VII-opt, resulting in a 4.5 K temperature reduction compared to typical BTMS with Z-type flow. The optimized BTMS shows promise across various inlet airflow rates, offering an effective method for cooling efficiency improvement [57]. Another study presents a method to enhance the cooling strategy of an air-cooled lithium-ion pouch cell battery pack in hybrid EVs. Through a three-dimensional thermal model and analytical design of experiments, a "Z-type" flow pack is identified as optimal. Simulations reveal the critical role of duct geometries, and using tapered inlet and outlet ducts, along with additional secondary ducts, significantly improves flow rate uniformity and reduces temperature variations. Further enhancements involve incorporating corrugations between cooling plates and using copper for improved heat conduction. These modifications effectively minimize temperature variations, showcasing a robust cooling design for increased durability and driving range [58]. To enhance the heat distribution of the BTMS, a spoiler is introduced to the air-cooled BTMS, exploring its impact on Z-type (BTMS I) and U-type (BTMS II) structures. Novel configurations, BTMS III and BTMS IV, incorporating spoilers at the air inlet manifold, are proposed and optimized based on structural parameters. Results reveal improved cooling efficiency, with BTMS III-opt decreasing T_{max} by 2.56 K (48.61%) compared to BTMS I. Similarly, BTMS IV-opt, compared to BTMS II, achieves a T_{max} reduction of 2.79 K (80.68%). Spoiler integration proves effective in enhancing BTMS heat distribution despite a minor increase in pressure drop [59]. Various types of air cooling methods are listed in Table 3.

PCM with Air Cooling

The significance of PCMs combined with air cooling techniques in BTMS arises from their unparalleled effectiveness. By combining these two methods, researchers capitalize on their complementary strengths while mitigating their weaknesses, resulting in superior performance compared to using either method alone. Lalan et al. delve into the efficacy of an innovative BTMS that integrates PCM with air cooling, demonstrating a substantial reduction in average cell temperature and thereby enhancing overall thermal performance. Furthermore, they establish a predictive equation, providing a valuable tool for predicting performance in future applications [60]. Another study proposes a hybrid BTMS incorporating metal fins and air cooling, addressing PCM limitations. Numerical investigations explore PCM thickness, fin parameters, and airflow variables. Results reveal that the hybrid system outperforms alternatives, reducing maximum battery temperature by 18.6%. Optimal design parameters include 1.0 mm PCM thickness, 162 fins, and 3.0mm fin diameter. The novel BTMS effectively maintains battery temperature below 40°C with minimal power consumption, offering insights for advanced BTMS in high-performance battery systems [61]. Hybrid BTMS, employing PCM and active cooling, shows promise, but ensuring uniform temperature distribution in irregular-shaped LiBs remains challenging. This team introduces a novel hybrid BTMS integrating PCM/copper foam (PCM/CF), air jet pipe (AJP), and liquid channel (LC) for cylindrical LiBs. Numerical simulations reveal that conventional battery holders hinder heat dissipation, but incorporating thermally conductive polymers mitigates thermal accumulation. The proposed hybrid BTMS, optimizing T_{max} and ΔT, significantly enhances temperature uniformity, providing valuable insights for BTMS designers in improving LiB heat dissipation [62]. Another research team tried to combine active and passive methods using PCM. Nine case studies explore various cooling duct structures and air stream pressures. Results show that the hybrid BTMS effectively maintains cell temperatures within a safe range, with a maximum of 314 K. Increasing air stream power or duct length through PCM reduces battery surface temperature and ensures uniform temperature distribution.

Table 3. Types of convections used for different materials in air cooling.

Type of Convection	**Cooling Efficiency**	**Temperature Difference Reduction**	**Power Consumption Reduction**	**Additional Features**	**Reference**
Natural	Outperforms PCM Cooling extends cycle life	Lower cyclical cost	-	Advanced models for LiB cycle life in EVs	[49]
Forced Convection	Enhanced heat transfer mechanisms	Improved thermal efficiency	Addresses challenges of traditional systems	Integration with phase change material and heat pipes	[50]
Forced Convection	Improved BTMS performance with increased airflow rates	54.28% reduction in temperature difference	-	Complete factorial Design of Experiment	[52]
Forced Convection	Enhanced heat removal with increased air inflow	Efficiency declines with a higher number of cells	-	Numerical investigation, coupled electrochemical-thermal model	[53]
Forced Convection	Enhanced cooling efficiency through structural optimization	70% reduction in temperature difference	32% power consumption reduction	Flow resistance network model, plenum angle optimization	[54]
Forced Convection	Influences temperature uniformity	-	-	CFD pack-level sub-model, one-dimensional battery pack network sub-model, three-dimensional thermal and electrochemical coupled cell/module level sub-model	[55]
Natural Convection, Forced-Air	-	-	-	Optimization of air inlet/outlet schemes, bidirectional airflow	[48]
J-type, U-type, L-type Flows	Effective thermal management under varying conditions	Over 67% reduction in temperature difference	-	Innovative control strategy narrowed parallel channels.	[56]
Z-type Forced Convection	Improved cooling efficiency with optimized flow pattern	4.5 K temperature reduction compared to typical BTMS	-	CFD, optimization strategy based on temperature distribution	[57]
Z-type Forced Convection	Optimal cooling strategy for lithium-ion pouch cell battery pack	Significant flow rate uniformity, reduced temperature variations	-	Three-dimensional thermal model, analytical design of experiments, corrugations between cooling plates, copper for improved heat conduction	[58]
Z-type, U-type	Improved BTMS heat distribution	T_{max} reduction of 48.61% to 80.68%	The minor increase in pressure drop	Spoiler integration in BTMS III-opt and BTMS IV-opt	[59]

However, higher air stream power or longer ducts result in a more significant temperature gradient. The study suggests that optimizing these parameters enhances the overall performance of the proposed hybrid BTMS [63]. Four PCM configurations are proposed, with Case 4 standing out for superior thermal performance and reduced PCM usage. The optimized PCM proportion is found to be 64%, significantly lowering temperature differences, energy consumption, and PCM volume [64].

DISCUSSION

In BTMS, the utilization of organic PCMs presents a promising approach for enhancing efficiency while adhering to eco-friendly principles. Organic PCMs, such as 1-Tetradecanol, offer distinct advantages in BTMS. Their high latent heat capacities and specific heat ensure efficient heat absorption, aligning with eco-friendly practices. In contrast to inorganic counterparts, organic PCMs exhibit enhanced thermal conductivity, stability, and a broader phase transition temperature range. Joshwin et al. explored 1-Tetradecanol as a PCM in BTMS for $LiFePO_4$ battery-equipped EVs, demonstrating its potential for lightweight, cost-effective temperature regulation. Meanwhile, research on air cooling highlights how it might improve the performance, safety, and lifespan of Li-ion batteries. Myristyl alcohol-based PCM-assisted air-cooling techniques demonstrate significant drops in battery module temperatures, demonstrating its effectiveness.

Research examining forced convection air cooling technology demonstrates considerable advantages over competing solutions, particularly in extending the cycle life of LiBs. The use of sophisticated models and numerical simulations demonstrates how forced convection works better than passive PCM cooling to increase battery module cycle life. In U-type forced convection designs, plenum angles, and inlet/outlet widths are tuned to increase cooling efficiency. Similar to this, Z-type forced convection has exceptional advantages with CFD optimization, such as improved cooling efficiency and temperature control.

It seems that combining PCM with air cooling is a popular strategy in BTMS. The effectiveness of forced convective air cooling and encapsulated PCM is confirmed by research that demonstrates notable reductions in average cell temperature. Furthermore, by integrating PCM with active cooling strategies, hybrid BTMS solves the challenges of maintaining a constant temperature distribution in LiBs with irregular shapes. The incorporation of innovative ideas such as air conditioning and metal fins enhances thermal performance even more. In high-performance systems, this reduces the maximum battery temperature and provides data for sophisticated battery temperature monitoring systems.

CONCLUSION & FUTURE SCOPE

In conclusion, it should be noted that PCM-based BTMS variants can operate quietly and absorb large quantities of heat throughout their phase shift cycle. Nevertheless, the system's low thermal conductivity and limited temperature range allow for the high latent heat capacity. PCMs can increase their thermal conductivity in several ways, such as encasing them in a material that conducts heat well, adding metallic or carbon-based fillers, or adding heat sinks. Although air-cooled systems are inexpensive to install, low maintenance, and energy-efficient, they are not effective enough to cool battery packs with large thermal loads. Integrating PCMs, air cooling, and their combined methods can improve battery temperature management. Therefore, it works better with EVs that are made for short trips and have low heat load needs. Despite obstacles, ongoing research shows a promising trend toward optimizing heat transmission and improving the system's overall performance. The path ahead entails improving these methods, exploring new materials, and leveraging cutting-edge cooling approaches. As technology evolves, these innovations will likely contribute significantly to the efficiency and sustainability of battery systems. The advantages of two or more BTMS types can be combined with hybrid BTMS, although this would further raise the BTMS's complexity and expense. Therefore, before being deployed, the hybrid BTMS combination of choice should weigh the benefits and drawbacks of each system.

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