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ORIGINAL RESEARCH ARTICLE

Emerging Technologies in PCM-Driven Hybrid Cooling Strategies for Lithium-Ion Batteries

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ABSTRACT

Global demand of electric vehicles and high-energy-density lithium-ion batteries has created a critical need for efficient battery thermal management systems (BTMS) capable to controlling battery cell temperatures between 20–40 °C and prevent the thermal run away in battery packs. The choice of phase change material (PCM)-based cooling has increased as passive technique that manage excess battery heat gained by absorbing and storing as latent heat without any external power. Despite their advantages, the low thermal conductivity of conventional PCMs (around 0.2–0.5 $W\ m^{-1}\ K^{-1}$) restricts their capability to effectively remove heat during charging and discharging with high C-rate. To mitigate this limitation, current research has focused on hybrid PCM-based BTMS, where PCMs are combined with liquid cooling channels, heat pipes, metal foams, thermal fins, or nano-enhanced PCMs (NePCMs) to enhance heat transfer. Reported research studies suggest that such hybrid systems can lower the peak temperature by 10–25 °C and improve temperature uniformity by 30–60 % compared with conventional cooling approaches. In upcoming years, among the various BTMS investigated, the combination of PCM with liquid cooling or heat pipe technologies, along with high-conductivity enhancements shows strong potential for electric vehicle battery packs. This article provides a detailed assessment of BTMS using PCM and hybrid PCM-based systems. In addition, use of Machine learning, digital twin structures, and advanced optimization techniques for predictive Battery thermal management are also discussed.

Keywords: electrical vehicle; btms; pcm; process innovation

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1. Introduction

The rapid shift to electrified transportation worldwide and the integration of renewable energy sources into power grids have increased demand for reliable, efficient advanced energy storage technologies. Lithium-ion batteries are considered the dominant choice for electric vehicles, hybrid vehicles, portable electronics, and grid stabilization applications because they offer superior energy density, a prolonged cycle life, and a relatively low self-discharge rate. However, electrochemical reactions within LIBs (refer **Figure 1**) are very sensitive to temperature variations. Even moderate departures from the optimal operating window can severely impact safety, performance, and lifespan. This would imply that developing robust BTMS has become one of the paramount engineering challenges in recent times due to increased electric vehicle adoption and expanded energy storage capacity[1,2].

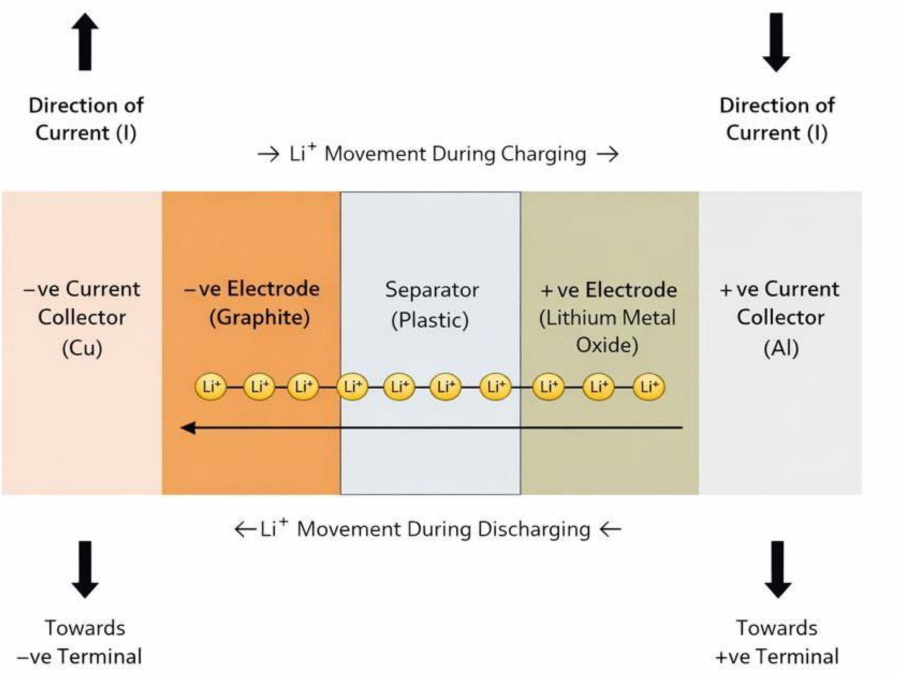
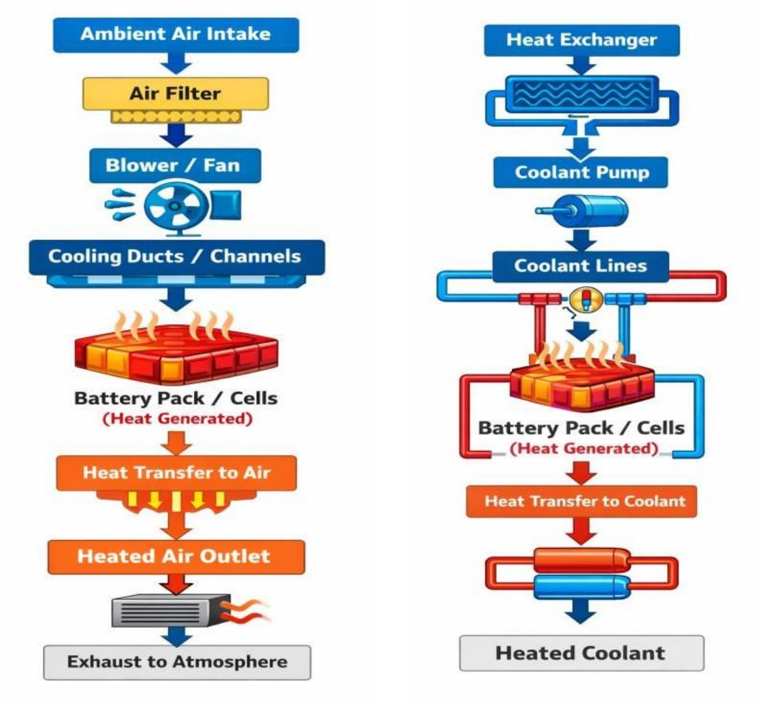


Figure 1. Internal Electrochemical Processes in Lithium-Ion Batteries[3].

Temperature has a twofold impact on battery behaviour. Elevated temperatures induce rapid electrolyte decomposition, increased growth of the Solid electrolyte interphase (SEI) layer, gas generation, and high internal pressure for lithium-ion cells. All these features reduce battery cycle life and may initiate thermal runaway-an unstoppable exothermic reaction that gives rise to huge fire and explosion risks[1,4]. On the other hand, at low temperatures, lithium-ion mobility is significantly reduced, leading to a loss in power capability, slower charge rates, and lithium plating when charging at high rates. It is thus necessary to keep the battery packs within an optimal temperature range, normally between 20°C and 40°C for most chemistries, for safety operation, durability, and efficiency[1,5]. The heat generation in lithium-ion batteries increases significantly with discharge rate due to ohmic and polarization losses. At higher C-rates, this leads to rapid temperature rise, non-uniform heat distribution, and potential thermal safety risks, thereby necessitating efficient thermal management systems.

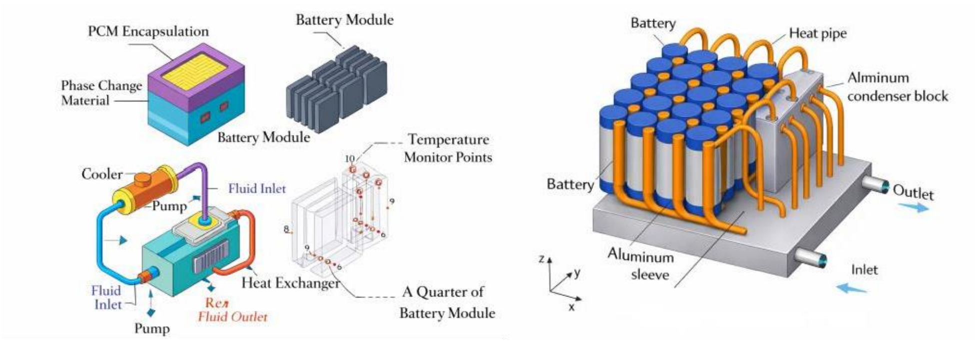
Traditional BTMS solutions for early electric vehicles were primarily air cooling or liquid cooling, as presented in **Figure 2**. While forced-air cooling is simple and cheap, it is unacceptable for the high-energy-density battery modules of modern times, which produce considerable heat fluxes[6]. Liquid cooling systems, using water–glycol mixtures or dielectric fluids, offer much higher thermal conductivity and better heat removal; thus, they are the preferred choice for most commercial electric vehicle manufacturers[7,8]. However, liquid cooling itself might be inadequate under extreme ambient conditions, during fast charging, or in compact battery configurations where the heat generation is highly intensive and localized. Furthermore, energy consumption by pumps, valves, and control units can deleteriously affect overall vehicle efficiency[6,7].



(a) (b)

Figure 2. BTMS Architectures (a) Forced Air Cooling, (b) Liquid Loop Cooling[9].

These issues are being addressed with the development of passive thermal regulation material, which can be used as a complement to the active cooling systems. **Figure 3** shows how such materials can be used.



(a) (b)

Figure 3. Schematic diagrams of (a) PCM Cooling[10], (b) Heat pipe Cooling[11].

Of these, phase change materials have been the topic of much attention because of their high latent heat capacity, which allows them to absorb much excess thermal energy during melting. PCMs store heat during phase transition and, thus, delay temperature increase and reduce thermal gradients inside the pack. Their silent operation, structural simplicity, and ability to function without external power make them appealing for Electrical Vehicles.

(EV) applications. However, PCMs have some drawbacks, such as low thermal conductivity, slow heat dissipation in post melting conditions, and dependence on ambient cooling for regeneration[12,13]. In this regard, keeping in mind the limits of stand-alone cooling methods, the hybrid BTMS concept has emerged as an ingenious engineering solution, as depicted in **Figure 4** & **Figure 5**. Hybrid systems integrate passive cooling by PCMs with continuous heat removal employing an active method-electronic liquid cooling, air-cooling, heat pipes, or fin-assisted thermal pathways.

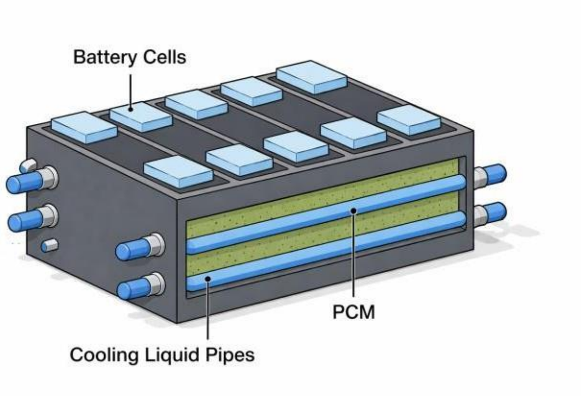


Figure 4. Schematic diagrams of Hybrid cooling PCM+Liquid[14].

The synergistic interactions between these components thus provide for effective heat absorption during sudden transient high loads and ensure efficient long-term dissipation while operating under steady load conditions. Therefore, a hybrid BTMS design can achieve enhancement in regulating temperature with much lower consumption of energy, reduced peak temperature, enhanced uniformity, and increased adaptability to transient load cycles[14,15]. Recent developments in hybrid PCM-based BTMS fall into several categories. The first category embeds PCMs in structural enclosures around battery cells and couples them with liquid-cooled plates. The phase-change materials buffer the sudden temperature spikes, while the absorbed heat is removed gradually by the liquid cooling loop to keep the PCM effective for many cycles[16]. Other approaches incorporate thermally conductive additives into PCMs, such as graphite, carbon nanotubes, or metal foams, which improve their conductivity. Such as NePCMs increase the pace of heat transfer significantly and, therefore, might be more appropriate for high-power applications. Combined with micro-channel liquid cooling or cold plates, NEPCMs can help maintain safe operation of cells in aggressive fast-changing conditions[12,17,18].

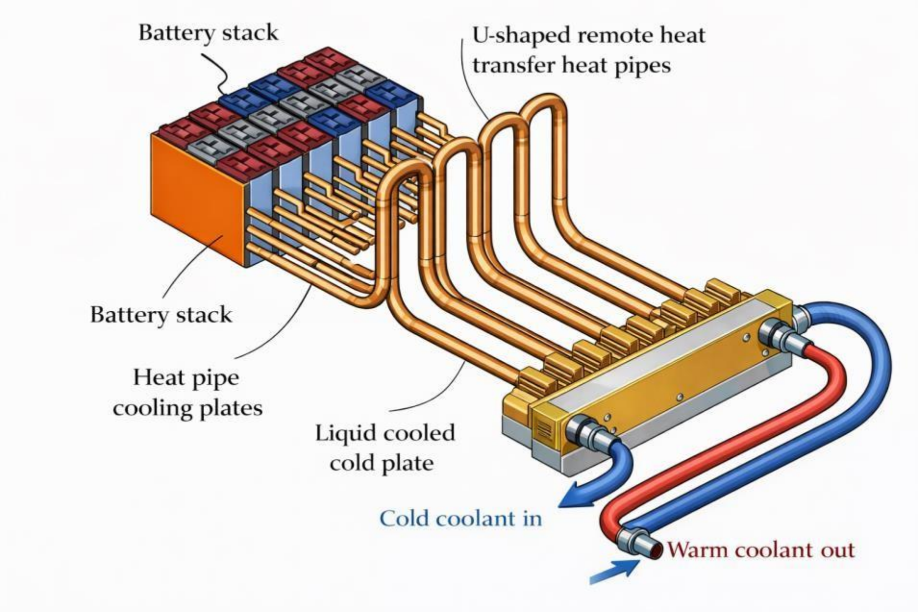


Figure 5. Schematic diagrams of BTMS using Heat pipe[19].

Researchers also studied the potential of Heat pipes along with PCM-based therma management systems as shown in **Figure 5**. Heat pipe helps in effectively transport the heat from the battery surface thorough evaporation and condensation cycles. In hybrid BTMS, heat pipes quickly transfer heat to cooler regions or to liquid-cooled interfaces, while PCM acts to stabilize transient temperature variations. Hybid BTMS is helpful as latent heat storage using PCMs, quick heat spreading using heat pipes, and a continuous heat removal with the help of active liquid systems. Study on hybrid BTMS with metallic fins embedded into the PCM from cooled surface also shows notable control of battery temperature. These extended surface increase the contact surface area, hence accelerating heat transfer and assuring uniform melting of PCMs. Nowadays 3d printing makes possible to create complex fin geometries which can enhance heat transfer performance with negligible change in mass[20,21]. Recent research has shown that using copper fins battery cell can be reduced by 8 °C. Coupling fin structures with thermally conductive or nano-modified PCMs leads to hybrid BTMS with enhanced responsiveness and better control of transient heat surges. These systems are therefore particularly effective for fast-charging and high-power applications, without significantly compromising mass or packaging.

Within the framework of increasing interest in high-power batteries for fast-charging EVs, hybrid BTMS research has also recently focused on systems with dynamic behaviour under extreme conditions. The study shows that hybrid PCM-liquid systems, depending on battery load, type of selected PCM, and coolant flow rate, are able to reduce peak temperatures from 5°C up to 15°C. They also improve temperature uniformity which is a critical parameter influencing battery aging and cell-to-cell variation. Enhanced uniformity minimizes differential aging, reduces mismatch in state-of-charge among cells, and improves overall pack reliability[22]. The actual performance of hybrid systems strongly depends on the selection of PCMs. The organic PCMs, including paraffin, have chemical stability and adjustable melting points, though they have low conductivity.

The advantages of hybrid PCMs based on foam materials, expanded graphite, and encapsulation design lie between conductivity and mechanical strength. The recent emerging trend in the development includes nano-enriched PCMs that help facilitate fast heat transfer and biodegradable PCMs, which ensure green energy solutions for batteries. This work was done by Zhao[23,24]. Advanced simulation software has also contributed significantly to hybrid BTMS design. Applications related to partial differential equations or complete flow dynamics simulations have been done by Pal[25] for heat generation and flow rate, phase transitions, and transitions analysis. Recent studies have also explored advanced thermal enhancement techniques such as hybrid nanofluids, mini-channel configurations, and biomimetic turbulator designs to further improve heat transfer performance and temperature uniformity in lithium-ion battery packs[26-28]. Work done by these authors gives an opportunity to evaluate hybrid designs for different strategies, optimize PCM location, improve geometrical designs for cooled channels, and estimate performances during realistic driving. Zhang[29] also explores the impact of machine-learning software integrated with algorithms in advancing the functionality of hybrid BTMS designs. Globally design of electric vehicles consider greater energy density, faster charging rates, and longer driving range. Therefore, the role of hybrid BTMS becomes more crucial. So in next generation battery pack most demanding BTMS is having combination of active and passive cooling systems. In next genersation Electrical Vehicles, hybrid PCM-based BTMS becomes most effective system due to advancement in the materials science, heat transfer technologies. Over time, these stresses lead to particle fracture, electrode delamination etc. at the cell level.

Another challenge with thermal challenge is the mechanical stress due to repeated cyclic lithiation and delithiation, and inherent structural in-homogeneities in the electrode materials may cause the mechanical degradation across the battery cell length. With time these stresses lead to particle fracture, electrode delaination and overall structural distortion. Due to that the movement of charge within the battery is get disturbed, causing shorter operational life, causing capacity decline[30]. The combined effect of mechanical stress and electrochemical reactions intensifies battery degradation, underscoring the importance of design strategies that address both mechanical integrity and thermal control.

High-nickel cathodes enhance energy density but make the material more prone to instability, leading to accelerated degradation mechanisms like micro cracking, surface reconstruction, oxygen evolution, and electrolyte side reactions under high voltage and thermal stress[31].

To address these issues, recent material engineering efforts focus on compositional tuning, surface coatings, gradient designs, and microstructural optimization, which collectively enhance mechanical integrity, reduce side reactions, and improve durability and thermal stability. To achieve long-term reliability and performance, advanced thermal management systems need to be designed alongside material-level stabilization approaches. This review highlights recent progress in PCM-based hybrid BTMS design. The objective of this review is to systematically analyze and compare different PCM-based hybrid battery thermal management architectures, with particular emphasis on thermal performance, energy consumption, and system complexity. The study aims to identify the most effective hybrid cooling configurations for improving temperature control and safety in electric vehicle battery systems.

2. PCM Materials and Enhancement Strategies

2.1. PCM Selection Criteria

Phase change materials (PCMs) used in BTMS are commonly grouped into three categories: organic materials such as paraffins and fatty acids, inorganic materials including salt hydrates, and eutectic compounds formed by combining two or more components. Because these materials differ significantly in thermophysical properties, their selection for hybrid battery cooling systems requires careful evaluation. As illustrated in **Figure 6**, several parameters must be considered simultaneously when identifying a suitable PCM. These parameters influence not only the effectiveness of heat absorption but also the operational safety, durability, and reliability of lithium-ion battery packs[32]. In hybrid BTMS designs, the chosen PCM must also work efficiently alongside active cooling components such as air flow channels, liquid cooling plates, or heat pipes.

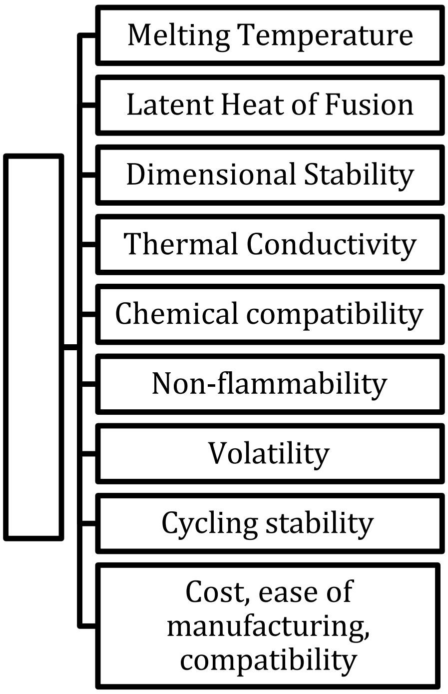


Figure 6. Factor need to consider for selecting PCM.

Among all properties, the melting temperature is one of the most decisive factors. In electric vehicle batteries, the PCM should ideally begin to melt within the typical operating temperature range of lithium-ion cells, usually between 35 °C and 45 °C. As most lithium-ion cells exhibit optimal performance within a temperature window of approximately 20–40 °C, beyond which degradation mechanisms such as SEI layer growth, electrolyte decomposition, and internal resistance increase significantly. A PCM with a melting point slightly above the normal operating range (≈35 – 45 °C) ensures that latent heat absorption is activated precisely when the battery approaches critical temperatures, thereby preventing thermal runaway and performance degradation. However, this range may vary depending on battery chemistry, discharge rate, and cooling configuration, and therefore should be considered as a design guideline rather than a fixed criterion. When the melting point lies within this interval, the material can start absorbing heat exactly when the battery temperature approaches levels where electrochemical degradation and internal resistance begin to increase. If the melting temperature is too low, the PCM may melt prematurely and lose its capacity to store heat during high-power operation. Conversely, a PCM with an excessively high melting temperature may not activate in time to prevent temperature escalation[33]. Organic materials such as paraffins and fatty acids often possess melting points within this preferred range, which explains their frequent application in EV battery cooling studies.

Another important parameter is the latent heat of fusion, which indicates the amount of thermal energy that can be absorbed during the phase transition. Materials with large latent heat values can store significant quantities of heat while maintaining nearly constant temperature. In many BTMS applications, PCMs with latent heat values exceeding 200 J/g are considered desirable. Such materials are capable of managing sudden increases in heat generation, for example during fast charging, rapid acceleration, or regenerative braking. A high latent heat capacity allows the PCM to delay the temperature rise of the battery pack and thereby supports the performance of hybrid cooling systems.

The structural stability of PCM during repeated phase transitions is another critical consideration. When a PCM repeatedly melts and solidifies, volume changes or phase separation may occur, potentially weakening the mechanical stability of the battery module or reducing the contact area between the PCM and the cells.

Organic PCMs generally show stable cycling behavior with minimal segregation. However, salt hydrate PCMs may experience issues such as phase separation or super cooling during solidification. Super cooling delays the release of stored heat and limits the material's ability to recover its thermal storage capacity between operating cycles. To overcome these limitations, salt hydrates are often combined with encapsulation techniques or nucleating agents.

The thermal conductivity of the PCM also plays an important role because it controls how quickly heat can be transferred from the battery surface into the thermal storage material. Many organic PCMs exhibit relatively low thermal conductivity, which may slow down heat dissipation and cause uneven temperature distribution. To improve this property, researchers frequently introduce conductive additives such as graphite particles, carbon fibers, metal foams, or nanoparticles, thereby forming composite PCMs with improved heat transfer characteristics. In comparison, inorganic PCMs such as salt hydrates typically possess higher thermal conductivity, which can promote faster heat spreading in battery modules operating at high power levels. Nevertheless, their application may be restricted by problems including corrosion, phase instability, and compatibility with containment materials.

Another essential factor is chemical compatibility with battery pack components. The PCM must remain stable when in contact with structural materials such as aluminium housings, steel casings, polymer separators, and insulating layers. Ideally, it should not corrode metals, degrade protective coatings, or react with electrolytes in the event of leakage. Organic PCMs are generally chemically inert and non-corrosive, whereas certain salt hydrates may accelerate corrosion unless protective encapsulation or corrosion inhibitors are used.

Safety aspects are particularly important for electric vehicle battery systems. A suitable PCM should have low volatility, minimal toxicity, and reduced flammability risk. Although organic PCMs are chemically stable, many paraffin-based materials are flammable and therefore may require fire-retardant additives or encapsulation techniques. Inorganic PCMs usually present lower fire hazards, although improper handling may introduce environmental or toxicity concerns. Eutectic PCMs, produced by combining two or more components, sometimes provide balanced thermal properties and improved stability, making them potential alternatives in certain applications.

Table 1. Applicability of Different PCM Types in Hybrid BTMS.

PCM Type	Advantages	Limitations	Suitable Hybrid BTMS
Paraffin (Organic PCM)	High chemical stability, negligible subcooling, good cycling reliability	Low thermal conductivity	PCM + air cooling, PCM + heat pipe, PCM + liquid cooling
Salt Hydrates (Inorganic PCM)	Higher thermal conductivity, high volumetric latent heat	Phase separation, corrosion risk	PCM + liquid cooling, PCM + immersion cooling
Eutectic PCM	Tunable melting temperature, balanced thermal properties	Limited long-term stability data	Advanced hybrid and multi-stage BTMS

The long-term reliability of the PCM during continuous operation must also be considered. A suitable material should maintain its thermal properties over many melting–solidification cycles without significant reduction in latent heat capacity or change in melting temperature. Organic PCMs generally demonstrate good repeatability and stable performance over extended cycling. Some inorganic PCMs, however, may suffer from issues such as dehydration, crystallization irregularities, or phase separation unless stabilization techniques are implemented.

In addition to these technical properties, economic and practical considerations also influence PCM selection. Cost, environmental impact, ease of manufacturing, and compatibility with hybrid cooling structures must all be evaluated. In hybrid BTMS configurations, PCMs are commonly combined with air cooling, liquid cooling plates, fins, or heat pipes to improve heat removal efficiency. The suitability of different PCM categories for hybrid battery thermal management configurations depends on their thermophysical properties and operational limitations. A comparative summary of the advantages, limitations, and typical hybrid BTMS applications of major PCM types is presented in **Table 1**. Most PCMs employed in hybrid BTMS are paraffin waxes, hydrated salts, and composite PCMs with melting temperatures typically ranging from 25–45°C, latent heat capacities of 100–250 kJ/kg, and thermal conductivities of 0.2–5 W/m·K depending on additives.

As shown in **Table 1**, organic PCMs such as paraffin are widely used in hybrid BTMS due to their stability and reliable cycling behavior, although their low thermal conductivity often requires enhancement through conductive additives or integration with active cooling methods. In contrast, salt hydrates provide higher thermal conductivity and compact thermal storage capacity, making them suitable for liquid-assisted hybrid cooling systems, while eutectic PCMs offer flexibility in tailoring melting temperatures for advanced thermal management designs.

Overall, selecting a PCM for hybrid battery thermal management requires balancing thermal performance, material stability, operational safety, and economic feasibility. The criteria summarized in **Figure 6** therefore provide a framework for identifying suitable materials and for designing hybrid BTMS architectures where PCMs function in coordination with active cooling components. This relationship between PCM characteristics and hybrid cooling design forms the basis for the hybrid BTMS configurations discussed in the following sections. Several early studies have investigated the use of pure PCM-based BTMS for controlling battery temperature without additional active cooling systems. These studies primarily focus on evaluating the ability of PCM to absorb transient heat loads and delay temperature rise during high discharge rates. A summary of representative studies on pure PCM-based BTMS is presented in **Table 2**.

Table 2. Summary Table: PCM-Based BTMS for Li-ion Battery Packs.

Author(s) & Year	Battery Type	PCM/NePCM	C-Rate	ΔT Reduction	Major Outcomes	Effect on Battery Life
Al-Hallaj & Selman (2000)[34]	Li-ion cylindrical cells (18650)	Paraffin wax	≤ 1C	reduced by ~5–10 °C	Delayed thermal runaway during high discharge	improved cycle life due to reduced temperature excursions
Kizilel et al. (2009)[35]	Li-ion battery module (cylindrical cells)	Paraffin wax	≤ 4C	Maintained module temperature below ~50 °C	Improved temperature uniformity	Indirect improvement in battery life due to minimized temperature gradients
Sabbah et al. (2008)[36]	Automotive Li-ion battery pack	Paraffin-based PCM	≤ 3C	~15–18 °C	Uniform cell temperatures achieved	Increase in service life due to stable operating temperature
Rao & Wang (2016)[37]	Li-ion pouch cell module	Paraffin wax	≤ 3C	<10 °C rise	Effective temperature control at high C-rates	Lower degradation rate suggested due to avoidance of high-temperature operation
Ling et al. (2015)[38]	Li-ion battery pack (prismatic cells)	Paraffin PCM	≤ 3C	~10–15 °C	Extended safe operating duration	Improved cycling stability inferred from reduced thermal aging
Kizilel et al. (2009)[35]	Prismatic Li-ion battery cell	Paraffin + expanded graphite (EG) composite PCM	≤ 4C	~10–12 °C (peak reduction) vs pure paraffin PCM	Improved heat spreading	Reduced degradation and improved cycle life
Ling et al. (2014)[39]	Cylindrical Li-ion battery pack	Paraffin-based Al_2O_3 NePCM	≤ 4C	~6–8 °C (peak reduction) vs base PCM	Thermal conductivity increased by ~40–60%; Tmax reduced by ~6–8 °C	Improved thermal uniformity reduces hotspot-induced aging
Sabbah et al. (2018)[36]	Li-ion battery module (numerical)	Paraffin + graphite composite PCM	≤ 3C	Not Reported	Composite PCM delayed temperature rise and stabilized battery temperature during high load	Stable temperature range enhances battery reliability and lifetime
Khateeb et al. (2004)[40]	Li-ion battery module	Paraffin-based composite PCM	≤ 1C	~10–15 °C (peak reduction) vs air/natural convection	Reduced peak temperature by ~10–15 °C vs natural convection	Lower operating temperature implies improved cycle life
Wang et al. (2016)[41]	18650 Li-ion battery pack	Carbon fiber–reinforced PCM	≤ 3C	<3 °C (temperature uniformity) at ~2–3C	ΔT reduced below 3 °C at 2–3C	Uniform temperature distribution slows degradation

2.2. Techniques for Boosting PCM Thermal Conductivity:

Practical application of conventional PCMs, especially paraffin-based materials, carries one well-known limitation: inherently low thermal conductivity. Paraffins have thermal conductivities ranging between 0.15 and 0.25 W/m·K, which restricts the rate at which heat may be transferred from the battery cells into the PCM region. Subsequently, extensive efforts have been under focus to enhance the heat transfer capacity of the PCMs while retaining their desirable latent heat characteristics. The application of advanced composite PCMs and nano-enhanced PCMs (**Table 3**) has emerged as one of the most successful approaches for improving hybrid BTMS performance[12]. The main aim of improving the thermal conductivity of PCM is to facilitate quicker heat spreading and to homogenize the temperature around the cells. The most popular approaches involve the use of graphite-based structures. Expanded graphite, graphite flakes, and graphene nanosheets exhibit excellent thermal conductivity-they create an interconnected network of conductive pathways within the PCM matrix that enables fast-spreading heat, preventing local hotspots and thus enabling the melting of PCMs in a more uniform manner. Expanded graphite has especially proven to be very porous, allowing it to hold considerable amounts of PCM. while still maintaining its structure, with conductivity enhancement by several orders of magnitude. According to the filler concentration and the compaction technique, values as high as 10–20 W/m·K have been reported[42]. Metallic foam reinforcement is another effective method of enhancing conductivity. Metallic foams, normally made from aluminum and copper, are chosen because of their high thermal conductivities, low densities, and easiness to be formed. When these metallic foams are impregnated with PCM, they give rise to a fully continuous metallic skeleton that rapidly removes heat from battery surfaces and distributes the heat throughout the PCM volume. The resulting hybrid material retains the latent heat capacity of the contained PCM but achieves much faster heat transport during charging and discharging cycles.

These composite structures have demonstrated excellent dimensional stability while undergoing melting-solidification cycles and thus prove very suitable for automotive environments subjected to frequent thermal cycles[43,44]. On a nanoscale level, the inclusion of low concentrations of nanoparticles, such as aluminum oxide (Al2O3), boron nitride (BN), copper oxide (CuO), and carbon-based nanomaterials, enhances conductive networks in the phase-change materials that promote heat conduction at higher rates. Concentrations of 1-5 wt% of these nanoparticles have been reported to significantly enhance the thermal conductivity of phase-change materials by establishing conducting paths across the PCM units[45]. In particular, hexagonal boron nitride not only improves conductivity but also enhances thermal and flame resistance properties. These nanoparticles reduce the total melting time required to melt the entire PCM block, thus allowing rapid absorption of heat with an equal temperature distribution in closely packed battery cells[46]. In one experiment, the introduction of h-BN nanosheets into paraffin wax increased the thermal conductivity of the composite material to 3.47 $W \cdot m^{-1} \cdot K^{-1}$, approximately 12 times more effective than pure paraffin wax ($\approx$0.29 $W \cdot m^{-1} \cdot K^{-1}$), which manifested the prominent rise in heat transfer properties during the melting and solidification processes.

Some methods not only try to enhance the conductivity properties but also try to increase the strength of the material. A prominent example of shape-stabilized PCMs is that where the PCM is encapsulated in an appropriate matrix like cross-linked polymers, elastomers, aerogels, and composite resins. In this way, leakage is avoided during the melting process, and it also maintains strong contact between the batteries and the PCMs. Shape-stabilized PCMs find major applications in EV batteries. The combination of CPCMs and NEPCMs in battery thermal management systems makes it possible to develop compact, light, high-performance coolers. The greater conductivity of these materials helps to achieve faster heat dissipation, lower maximum temperatures in cells, more uniform temperatures in the modules, and improved resistance to thermal runaway. As these materials continue to evolve, they are likely to have a growing impact on the next generation of hybrid thermal management of electric vehicles and energy storage systems.

3. Hybrid BTMS Architectures

As electric vehicles (EVs), portable robotics, and stationary storage systems continue to scale in size and performance, no single cooling strategy is capable of delivering the combination of high reliability, fast dynamic response, and minimal energy consumption required for safe and efficient operation. Hybrid battery thermal management systems (BTMS) as shown in **Figure 7**, which combine phase change materials (PCMs) with active or semi-active cooling mechanisms, have therefore gained considerable attention in recent years. These systems are specifically engineered to take advantage of the high latent heat absorption capacity of PCMs while simultaneously resolving their inherent drawbacks, such as low thermal conductivity and slow heat release. The resulting hybrid architectures offer enhanced temperature uniformity, lower maximum cell temperatures, and improved safety against thermal runaway.

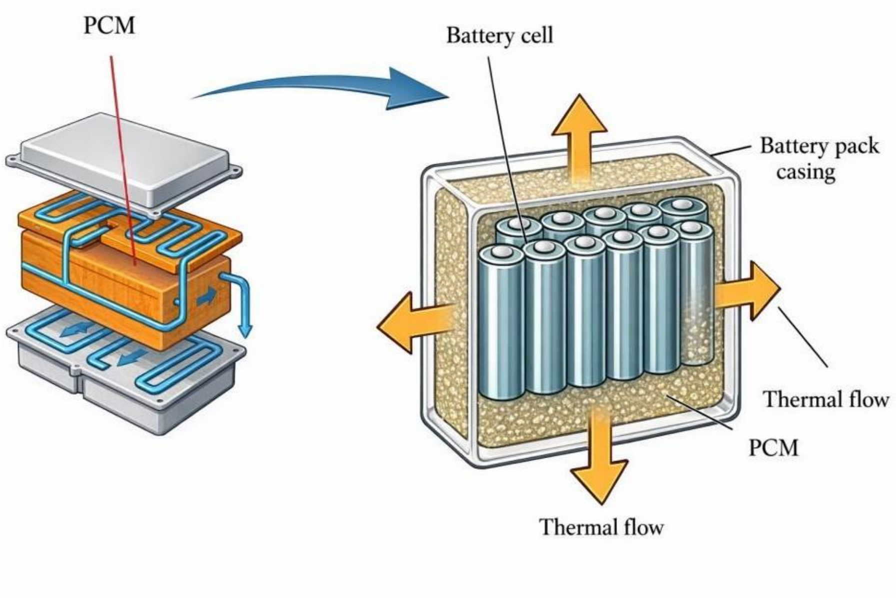


Figure 7. Schematic representation of a PCM-assisted hybrid BTMS[47].

At the heart of hybrid BTMS concepts is the integration approach of PCMs with other thermal control components such as liquid cooling plates, forced-air ducts, heat pipes, vapor chambers, metal foam structures, or dielectric coolants. Each architecture offers.

Special benefits based on the operating environment, space constraints, and heat generation characteristics of the battery pack. Multiple architectural variants have been envisioned and experimentally verified through simulations and laboratory experiments, which are followed by prototype EV pack development. This paper offers an overview of the functional principle and architecture of the widely used hybrid PCM-based architectures in depth.

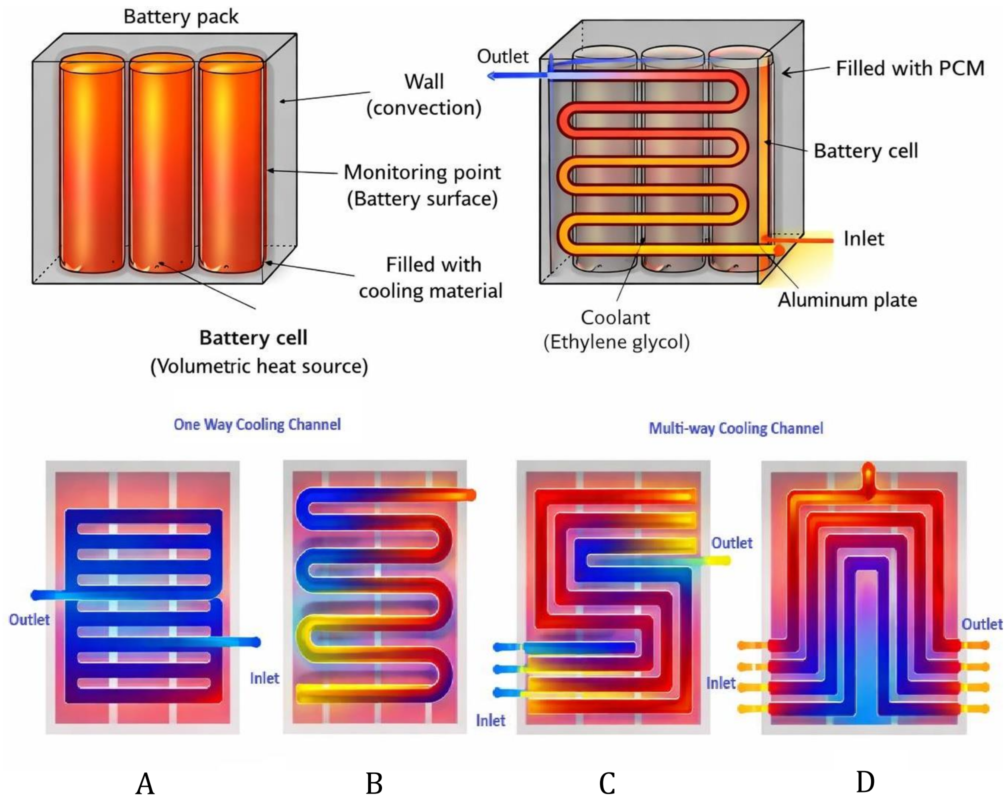


Figure 8. Schematic of PCM-Integrated Liquid Cooling BTMS[47].

Although PCMs are widely applied in battery thermal management systems due to their high latent heat storage capability, their long-term stability during repeated thermal cycling must be carefully considered. During continuous charging and discharging of lithium-ion batteries, the PCM undergoes multiple melting and solidification cycles. Over time, these repeated phase transitions can influence the thermophysical properties of the material, including slight reductions in latent heat storage capacity and thermal conductivity due to structural changes within the PCM matrix. Several studies have reported that composite PCMs used in battery thermal management may experience performance degradation after repeated thermal cycles, particularly when conductive fillers or additives are incorporated to enhance thermal conductivity[48,49].

In hybrid battery thermal management systems where PCM is integrated with additional cooling technologies such as air cooling, liquid cooling, or heat pipes, further reliability concerns may arise. Interactions between PCM additives and metallic components used in cooling structures may lead to material compatibility issues or corrosion during long-term operation. Additionally, composite PCMs containing graphite, metal foams.

Nanoparticles may experience particle agglomeration or interfacial deterioration after prolonged thermal cycling, which can reduce effective heat transfer within the system[49]. These degradation mechanisms may gradually affect the thermal regulation capability of the BTMS and influence the operating temperature of the battery pack.

Recent investigations have evaluated PCM durability through accelerated thermal cycling tests and reliability analysis. Results indicate that well-stabilized composite PCMs can retain most of their latent heat storage capacity after several hundred heating - cooling cycles; however, minor changes in thermal conductivity and phase stability have been observed[50]. These findings emphasize the importance of appropriate material selection, encapsulation strategies, and compatibility between PCM and structural components in hybrid BTMS design. Therefore, future studies should focus on long-term aging experiments and degradation modeling to better predict the reliability and durability of PCM-based hybrid thermal management systems used in electric vehicle batteries.

3.1. PCM-Integrated Liquid Cooling BTMS

One of the most efficient and widely used hybrid BTMS configurations combines the coupling of encapsulated or chambered PCMs with liquid cooling channels. This type of configuration is highly suited for high-performance EV battery modules facing fast charge-discharge operation cycles and high heat fluxes. Commonly, the PCM is placed near the cell, generally filling the interstitial gaps between the cells in prismatic or cylindrical form, while cold plates have coolant channels embedded and are placed next to the region filled with PCM.

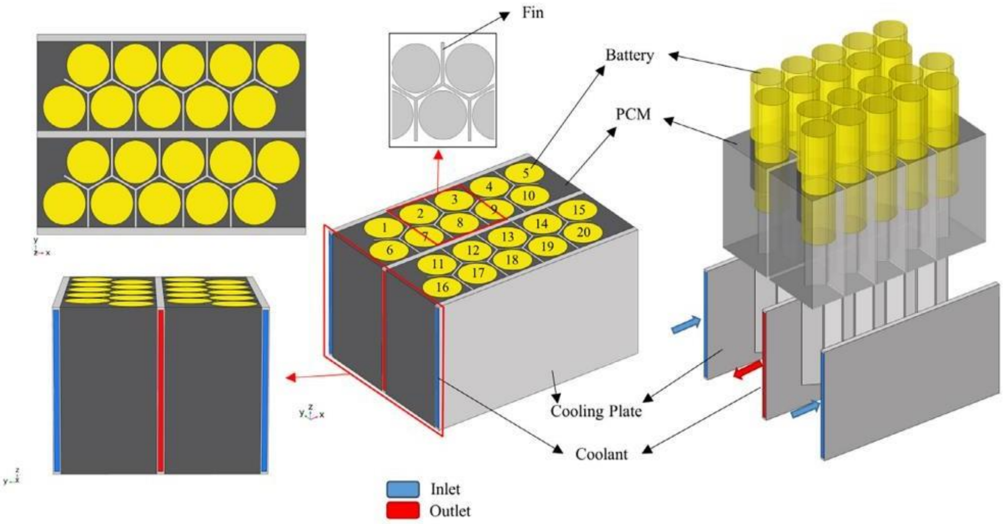


Figure 9. Schematic diagram BTMS model[51].

Table 3. Summary Table: Hybrid BTMS (PCM + Liquid cooling) for Li-ion Battery Packs.

Author(s) & Year	Battery Type	NePCM	C-Rate	ΔT Reduction	Major Outcomes	Effect on Battery Life
Rong et al. (2024)[52]	Li-ion battery module (single cell/cell arrangements in 3D model)	PCM layer around cells + liquid cooling cold plate with micro-channels	≤ 3C	~2 °C (temperature uniformity); additional ~26% reduction in ΔT with optimized PCM layou	strong uniformity control via geometric optimization	Improved uniform temperature distribution & lower T suggest enhanced battery reliability and slower degradation
Zhou et al. (2025)[53]	12 × 18,650 cylindrical cells	PCM around cells with liquid cold plates	3C	~2 °C	Hybrid PCM + liquid cooling maintains very tight thermal uniformity under high discharge	Lower operating temperatures imply improved safety and life stability
Mo et al. (2024)[54]	7 × 7 Li-ion module	Epoxy-enhanced PCM + water liquid cooling	≤ 3C	Not explicitly quantified	Focus on maintaining Tmax <48 °C; ΔT discussed qualitatively (no fixed value)	Stable thermal performance → better durability & reliability
Balasubramani an et al. (2025)[55]	Cylindrical Li-ion battery (18650 cells)	Nano-doped PCM (Al_2O_3 / high-conductivity additives) + liquid cooling	3C	Qualitative reduction (not given as a fixed value)	Strong peak temperature reduction (~10 °C vs baseline); ΔT improvement implied but not numerically specified	Reduced peak temperature and ΔT suggest significant improvement in battery aging resistance
Xiao et al. (2025)[56]	Cylindrical Li-ion battery module	Paraffin PCM integrated with micro-channel liquid cold plate	≈2–3C	~30% reduction in ΔT	ΔT refers to temperature gradient reduction vs conventional liquid cooling, not absolute value	Enhanced temperature uniformity minimizes hotspot-induced degradation, indicating better long-term durability

The transient and peak thermal loads are absorbed by the PCM as it undergoes phase transition, keeping cell temperatures within a narrow range. It is during such conditions that this latent heat buffer can become very important: when the vehicle is charging quickly or experiencing sudden high-power demands, local heat generation spikes momentarily. Once in their fully molten state, the active cooling subsystem-a water-glycol or dielectric liquid loop-takes stored thermal energy away from the PCM and the surrounding cold plate (**Figure 8**). This removal process "resets" the PCM for the next cycle, making its latent heat capacity available again.

Liquid cooling integrated with PCM offers many engineering benefits. First, it alleviates the risk of the saturation of PCMs under longer high-power operations-a common limitation in purely passive PCM-based BTMS. Second, it ensures fast heat removal from critical hotspots to reduce cell-to-cell thermal variability. Third, the design minimizes the coolant pumping power, since the PCM reduces the need for high-flow continuous cooling.

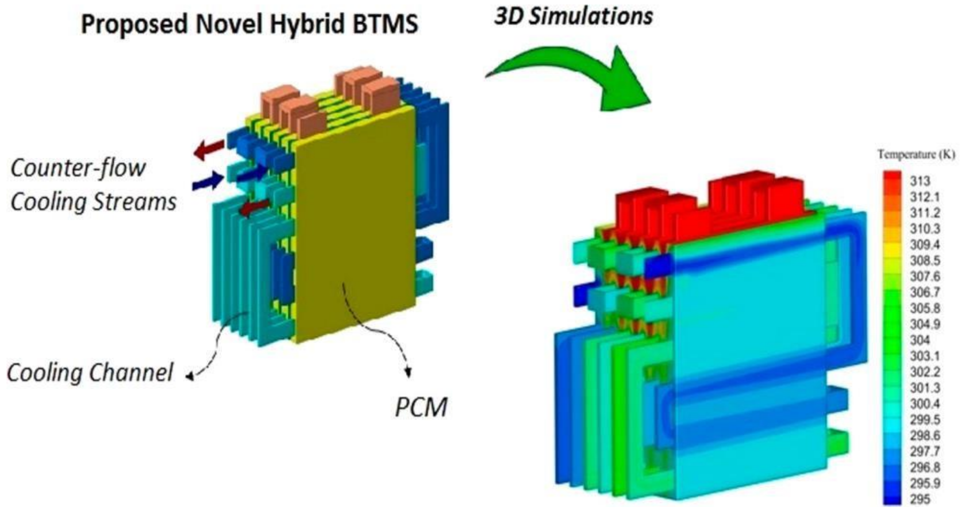


Figure 10. phase change material (PCM) and liquid cooling channels[57].

Advanced designs include embedded heat spreaders like aluminium fins, copper meshes, or graphite sheets inside the PCM to help in lateral heat transfer. Structured fins lead to enhanced conductive pathways, thus allowing uniform melting of the PCM and thereby reducing thermal gradients across the pack, as seen in **Figure 9**.

Various configurations for multiple cooling channels within a PCM-based battery pack were numerically studied by Hyun[58]. Hekmat[57] to enhance thermal performance, as shown in **Figure 10**.

It finds widespread acceptance as one of the most promising solutions for next-generation EV platforms due to its capabilities for rapid response, passive buffering, and continuous heat removal. PCM-integrated liquid cooling systems combine the latent heat storage capability of PCM with the continuous heat removal provided by coolant circulation. This hybrid approach effectively reduces peak temperature and improves temperature uniformity during high-rate operation. A summary of recent research on PCM–liquid cooling BTMS is presented in **Table 4**.

3.2. Air–PCM Synergistic BTMS

Air-assisted hybrid cooling systems represent a low-cost and lightweight solution for smaller-sized electric applications like e-bikes, electric scooters, portable energy systems, and drone platforms. Forced-air cooling alone has proved to be inadequate for high-power lithium-ion packs because of its low heat capacity and poor heat transfer coefficients; however, coupled with the help of PCM, its performance could be much better.

In a typical design for such PCM + air-cooled architectures, the PCM modules are placed around cells, while air channels are placed to direct flow across the PCM surfaces or fins, as illustrated in **Figure 11**. During operation, the PCM absorbs the short-term heat pulses and suppresses peak temperatures, while the air stream gradually takes heat away from the PCM, allowing it to resolidify. This hybrid approach enhances thermal resiliency against intermittent high-power bursts-a common occurrence with lightweight electric mobility and aerial systems.

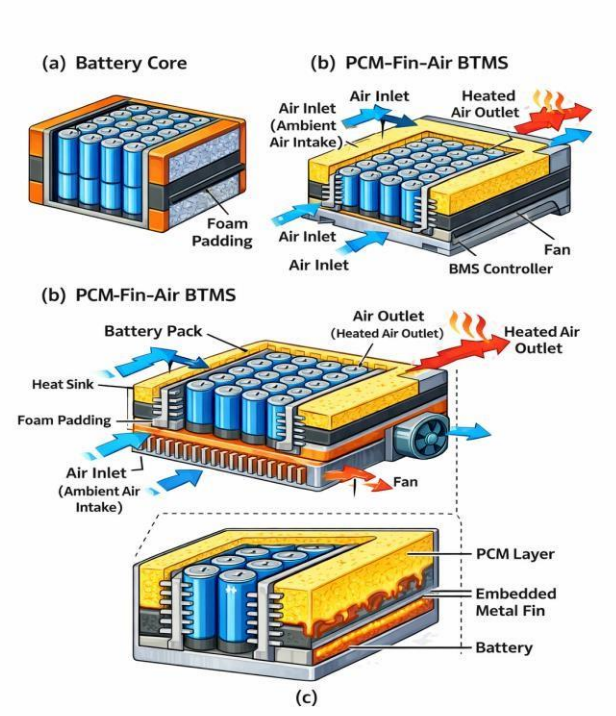


Figure 11. Schematic diagrams of (a) battery core, (b) the PCM-Fin-Air BTMS and (c) zoomed-in-view of the PCM layer around the battery and embedded metal fin[45].

To improve contact area and heat transfer efficiency, fin arrays or metal inserts are often embedded inside the PCM region, creating extended surface structures that enhance convective heat removal. Designs may include pin fins, longitudinal fins, honeycomb fin structures, or perforated plates. These enhancements reduce the dependency on high airflow rates and allow compact fan units to achieve acceptable cooling performance.

Table 4. Summary Table: Hybrid BTMS (PCM + Air cooling) for Li-ion Battery Packs.

Author(s) & Year	Battery Type	NePCM	C-Rate	Major Outcomes	Effect on Battery Life
Ling, Wang & Fang (2015)[38]	5S4P Li-ion battery pack (cylindrical cells)	RT44HC/EG PCM composite around cells	≤ 3C	Kept max temperature <50 °C across cycles	Lower thermal stress suggests improved cycle life and reliability
Huynh & Lee (2023)[58]	25-cell cylindrical Li-ion module	PCM layer (1 mm, RT series)	≤ 3C	Max temp significantly (~30–45 °C reduction depending on discharge and air velocity)	Reduced peak temperatures and ΔT implies reduced aging and better performance consistency
Chen et al. (2023)[59]	Li-ion pack with biomimetic fins	PCM with variable fins	≤ 3C	Reduced temperature & ΔT	Improvements imply *slower degradation* from uniform temps
Huynh & Lee (2023)[58]	3-cell Li-ion module	Generic PCM	≤ 3C	Lowered temperature	Balanced cooling suggests *potential life benefit under optimal air speed*
Zhang et al. (2024)[29]	Li-ion battery modules	RT35 & RT35HC PCM	4C	Held *T_max ≈ 308.4 K & ΔT≈1.64*	Low T & ΔT → *better long-term performance*
Hassan et al. (2025)[60]	5S4P Li-ion battery pack (cylindrical cells)	PCM with extended copper fins	≤ 3C	Kept *T_max & ΔT* much lower than air alone (up to ~62 % ΔT reduction)	Improved thermal stability → *less thermal ageing*
Mo et al, (2024)[54]	25-cell cylindrical Li-ion module	CPCM (composite PCM module)	≤ 3C	Improved cooling	Superior cooling & stability → *enhanced battery health*

Maintaining low system mass. Although this architecture cannot match the cooling capacity of liquid-based systems, its simplicity, low cost, and minimal maintenance requirements make it an attractive solution for low-to-moderate power battery modules. Several studies have demonstrated that integrating PCM with forced air cooling can significantly improve thermal uniformity and reduce peak battery temperature compared with air cooling alone. A comparative summary of recent PCM–air hybrid BTMS studies is provided in **Table 5**.

3.3. PCM–Heat Pipe Integrated Thermal Management System

In battery modules where localized hotspots or significant radial temperature gradients occur particularly in cylindrical cell arrangements integrating PCMs with heat pipes provides an efficient hybrid solution as shown in **Figure 12**. Heat pipes operate on two-phase heat transfer principles, transporting thermal energy at very high effective thermal conductivities through evaporative and condensative cycles.

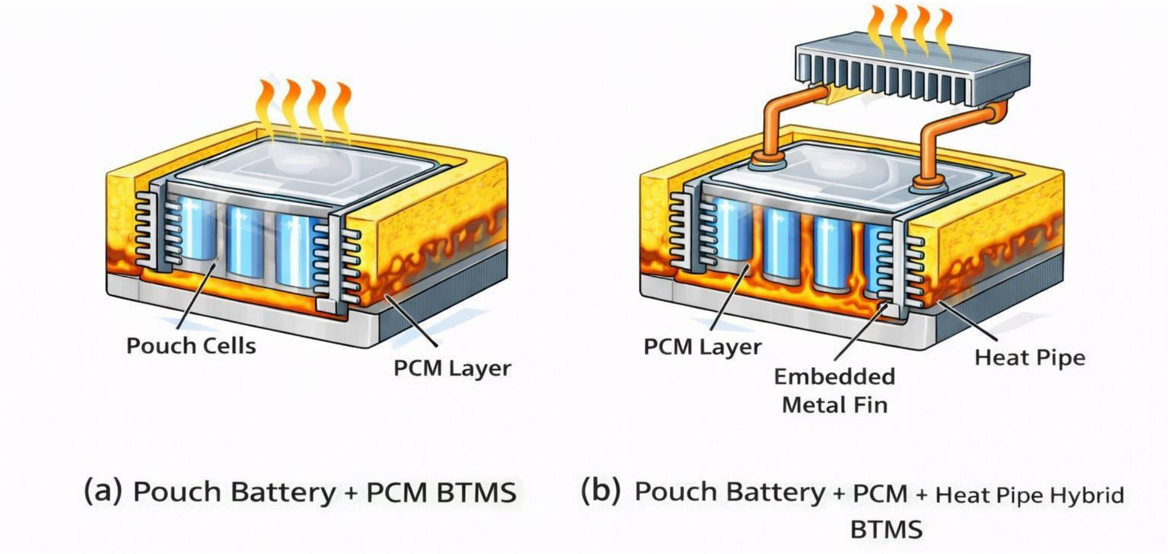


Figure 12. PCM–Heat Pipe Integrated Thermal Management System[61].

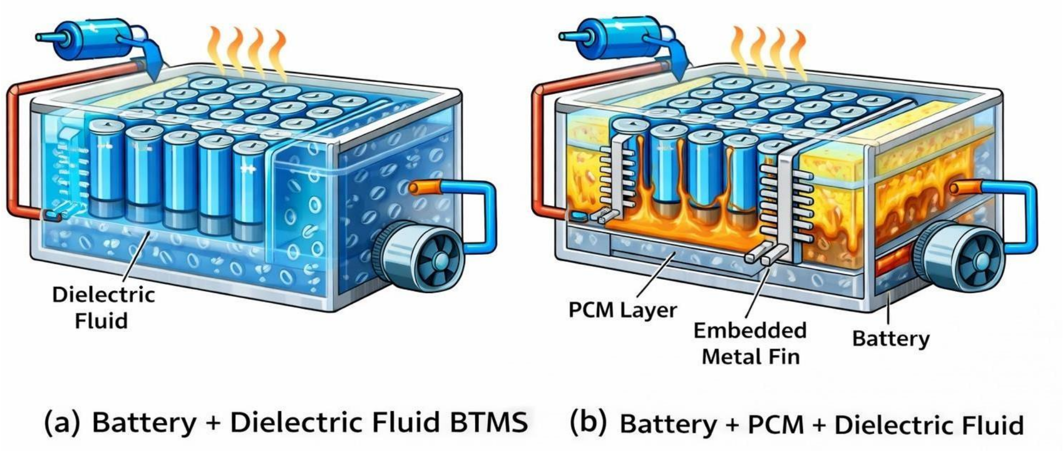
In PCM + heat pipe systems, heat pipes are strategically embedded either within the PCM region or in direct contact with cell surfaces. When the cell temperature rises, heat is rapidly transported by the heat pipe to remote heat sinks or to areas embedded in the PCM block. This mechanism ensures that heat is redistributed before it accumulates at localized hotspots. The PCM then absorbs the redistributed thermal load through melting, preventing temperature spikes in the immediate vicinity of the cells.

The synergy between PCM and heat pipes enhances overall BTMS efficiency by combining fast heat transport, large latent heat storage, and improved spatial temperature uniformity.

3.4. PCM–Dielectric Immersion Integrated Thermal Management System

A more recent, further advanced hybrid architecture consists of integration of PCM microcapsules or PCM granules within a dielectric immersion cooling environment.

Illustrated in **Figure 13**. In such an arrangement, the battery cells are fully immersed in a dielectric coolant like fluorinated fluids, silicone oils, or ester-based liquids providing continuous convective heat transfer. Dispersed within this coolant are the PCM capsules that float or remain suspended depending on density[62,63].



(a) Battery + Dielectric Fluid BTMS (b) Battery + PCM + Dielectric Fluid

Figure 13. Schematic of PCM–Dielectric Immersion Integrated Thermal Management System[64].

The PCM capsules absorb high-intensity heat pulses instantaneously, acting like a localized thermal regulator, while the immersion fluid is continuously transporting heat toward an external heat exchanger. This ensures that the PCM does not stay in its molten state for extended periods of time because the convective currents and also the external cooling loops will be actively promoting re-solidification. A combination of this dual-function approach yields in extremely fast heat dissipation, high spatial uniformity, and significant protection against thermal runaway.

Hybrid immersion+ PCM systems have indeed shown great promise for ultra-fast-charging applications, as they are able to manage extremely high heat fluxes without inducing severe temperature spikes. Their ability to surround the cell with coolant uniformly eliminates thermal dead zones, while PCM capsules act to flatten peak temperatures during transient loads. Although this approach is still an active area of research, it will no doubt play a key role in next-generation fast-charging EV platforms.

3.5. PCM–Refrigerant Cooling Integrated Thermal Management System

Refrigerant-based battery thermal management systems have emerged as an attractive cooling solution for electric vehicles because they can be integrated directly with the vehicle air-conditioning and thermal management system. In such systems, refrigerants such as R134a, R1234yf, or CO_2 circulate through evaporator plates or cooling channels placed adjacent to battery modules. The refrigerant absorbs battery heat through phase change evaporation and subsequently rejects the heat through the condenser section of the vehicle thermal management loop as shown in **Figure 14**.

The integration of PCM with refrigerant cooling creates a hybrid thermal management architecture that combines the latent heat storage capability of PCM with the high heat removal capacity of refrigerant evaporation as shown in **Figure 14**.

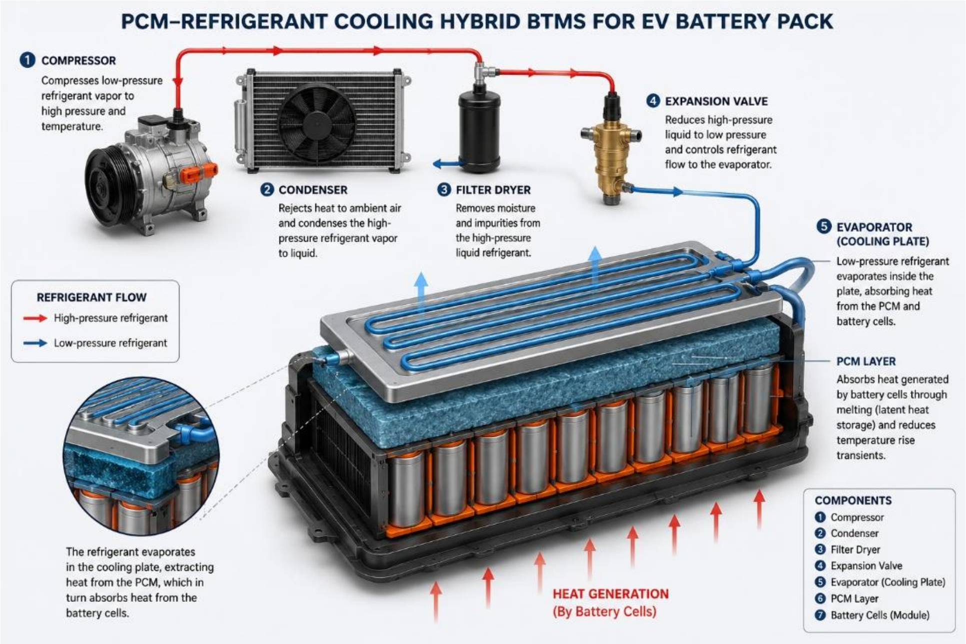


Figure 14. Schematic of PCM–Refrigerant Cooling Hybrid BTMS for Electric Vehicle Battery Packs.

During transient high-power operation or fast charging, the PCM absorbs sudden thermal spikes and delays temperature rise. Simultaneously, the refrigerant continuously extracts heat from both the battery cells and the melted PCM, thereby regenerating the PCM for subsequent thermal cycles.

Compared with conventional liquid cooling systems, refrigerant cooling can provide lower battery temperatures and improved integration with existing vehicle HVAC systems. Studies have reported significant reductions in peak temperature and improved temperature uniformity under high C-rate operation refer **Table 5**. However, refrigerant leakage, system complexity, compressor power consumption, and environmental concerns associated with certain refrigerants remain important design considerations. Consequently, PCM–refrigerant cooling systems represent a promising direction for future high-performance electric vehicle battery thermal management, particularly in fast-charging applications.

3.6. Comparative Results of Hybrid PCM based BTMS

Experimental studies indicate that hybrid PCM–liquid systems can maintain peak temperatures near ~36–38°C under high loads, while PCM-only systems may reach 44-50°C depending on configuration and PCM material. NEPCMs demonstrate BTMS improved melt rates and temperature uniformity. While maximum temperature (Tmax) and temperature difference (ΔT) remain primary indicators of thermal effectiveness, direct comparison across studies is challenging due to variations in operating conditions, battery formats, and discharge rates. To provide a more systematic evaluation, a normalized performance assessment is introduced.

Table 5. Summary Table: Hybrid BTMS (PCM + Refrigerant Cooling) for Li-ion Battery Packs.

Author(s) & Year	Battery Type	PCM/ Refrigerant	C-Rate	ΔT Reduction	Major Outcomes	Effect on Battery Life
Qian et al. (2025)[65]	EV Li-ion battery pack	Composite PCM + R1234yf	≤ 4C	≈ 3–5°C	PCM absorbed transient thermal spikes while refrigerant continuously removed heat, improving temperature uniformity	Enhanced battery safety and slower capacity degradation
Hyun et al. (2025)[47]	Hybrid PCM–Liquid/Refrigerant Inspired BTMS	Composite PCM + R1234yf	4C	Up to ~18°C	Demonstrated that hybrid cooling systems incorporating PCM with active cooling significantly improved temperature uniformity and reduced peak battery temperature.	Improved thermal uniformity and reduced peak temperature are expected to suppress thermal degradation, minimize hotspot formation, and enhance long-term battery reliability and cycle life
Kang et al. (2024)[66]	Li-ion battery module	PCM + Refrigerant Cooling Review	Up to 5C	Reported in literature: 5–18°C	Comprehensive assessment showing superior cooling performance compared with air cooling	Better thermal regulation reduces aging rate
Zhao et al. (2022)[49]	Cylindrical Li-ion battery module	Paraffin PCM + R134a	3C	~8–12°C	Significant reduction in peak temperature under high load conditions	Reduced thermal degradation and improved cycle stability

A dimensionless thermal performance index (TPI) can be defined as:

$$TPI = \frac{(T_{Baseline} - T_{Hybrid})}{(T_{Baseline})} + \frac{(\Delta T_{Baseline} - \Delta T_{Hybrid})}{(\Delta T_{Baseline})}$$

where:

$T_{Baseline}$ and $\Delta T_{Baseline}$ represent values for conventional air cooling,

T_{Hybrid} and ΔT_{Hybrid} represent hybrid BTMS performance.

This approach enables relative comparison of cooling enhancement independent of absolute experimental differences.

In addition to thermal indicators, practical deployment requires consideration of Added system volume, Cooling power consumption, Manufacturing complexity, Material cost, Maintenance requirements.

Although PCM-immersion cooling consistently demonstrates superior peak temperature suppression and thermal uniformity, it introduces increased material volume, sealing complexity, and higher implementation cost compared to PCM–air or PCM–liquid plate systems. The comparative thermal performance results of hybrid PCM-based BTMS are summarized in **Table 6**, which also incorporates a cost–performance trade-off analysis to enable a more comprehensive assessment.

The comparative study shows that integrating PCM with active or semi-passive cooling methods significantly enhances battery thermal management by reducing peak temperature and improving temperature uniformity. Among the studied systems, PCM dielectric immersion cooling provides the best thermal performance due to direct fluid cell contact, followed by PCM + liquid cooling, which offers a good balance between efficiency and technological maturity. PCM + heat pipe systems effectively improve heat spreading with low energy consumption, making them suitable for passive or compact applications. In contrast, PCM + air cooling, while simple and cost-effective, is thermally limited and more appropriate for low-to-moderate power applications.

Table 6. Comparative Results of Hybrid PCM based BTMS.

Author(s) & Year	BTMS Type	T_{max} Reduction and Temperature Uniformity (ΔT)	Overall Thermal Performance	Cost / System Complexity
Kang et al. (2024)[66]	PCM + Air Cooling	T_{max} reduction: PCM lowers T_{max} vs. air alone, e.g., ~12–15 °C reduction vs. natural convection; fin enhancements further improve ΔT. ΔT: Better than air alone but typically larger than liquid or HP hybrids. ΔT is typically 4–8°C.	Moderate improvement	Low – simple structure, low cost, easy integration
Chen et al. (2022)[67]	PCM + Liquid Cooling	T_{max} reduction: Typically, lower than PCM alone; liquid cooling yields ~3 °C lower battery temperature than air cooling under equivalent conditions; liquid + PCM *can* reduce T_{max} by ~7–14 °C in hybrid models. ΔT: Often reduced to a few °C with proper flow. ΔT is generally 1–4°C.	High performance	Medium – requires pump, coolant loop, and sealing Medium
Yu et al. (2023)[68]	PCM + Heat Pipe	T_{max} reduction: Higher effective heat transfers than PCM + air; HPs accelerate latent heat removal; ΔT reduced vs. PCM alone. ΔT is typically 2–5°C. ΔT: Generally lower than PCM + air, approaching passive liquid levels in some designs.	High performance	Medium–High – added manufacturing complexity and component cost
Liu et al. (2025)[18]	PCM + Dielectric Immersion	T_{max} reduction: Direct immersion yields *highest heat transfer*; can maintain uniform T within tight bounds (<5 °C) even at high C rates. ΔT: Very low due to full surface contact; excellent temperature uniformity. ΔT is typically <3–5°C.	High performance	High – expensive dielectric fluids and complex sealing requirements

So, among the evaluated configurations, PCM combined with dielectric immersion cooling demonstrates the highest thermal performance and temperature uniformity, although it involves higher system complexity and cost. In contrast, PCM–air cooling offers a simpler and more economical solution with moderate thermal improvement. Hybrid configurations such as PCM–liquid cooling and PCM–heat pipe systems provide a balanced trade-off between cooling effectiveness and implementation complexity, making them attractive for practical applications. requiring efficient yet scalable thermal management. Therefore, optimal BTMS selection depends not solely on thermal metrics but also on application-specific economic and packaging constraints.

Overall, hybridization with PCM is essential for meeting the thermal requirements of high-performance lithium-ion battery systems.

The literature reviewed in this study suggests promising opportunities for the development of triple-hybrid battery thermal management systems (BTMS) that integrate several cooling mechanisms within a single architecture as shown in **Figure 15**. Systems combining PCM, heat pipes, and liquid cooling, or PCM, dielectric immersion, and heat pipes, can take advantage of the strengths of each individual technology. It is important to note that the proposed triple-hybrid configurations (PCM + heat pipe + liquid cooling) are presented in this review as a forward-looking conceptual framework rather than a fully validated design. Due to the absence of dedicated experimental or high-fidelity numerical studies in the existing literature, detailed performance quantification or thermal resistance network analysis is not included. Instead, this concept is introduced to highlight a promising research direction where synergistic integration of latent heat storage, high-conductivity heat transport, and active liquid cooling may potentially enhance thermal regulation in next-generation battery systems. Future studies involving experimental prototyping and numerical modeling are required to evaluate feasibility, optimization, and real-world applicability. In these arrangements, phase change materials serve as a temporary heat storage medium that absorbs excess heat during high load conditions through latent heat absorption. Heat pipes provide a highly conductive pathway for rapid heat transport away from the battery surface, while liquid or immersion cooling removes the accumulated heat through continuous convective heat transfer.

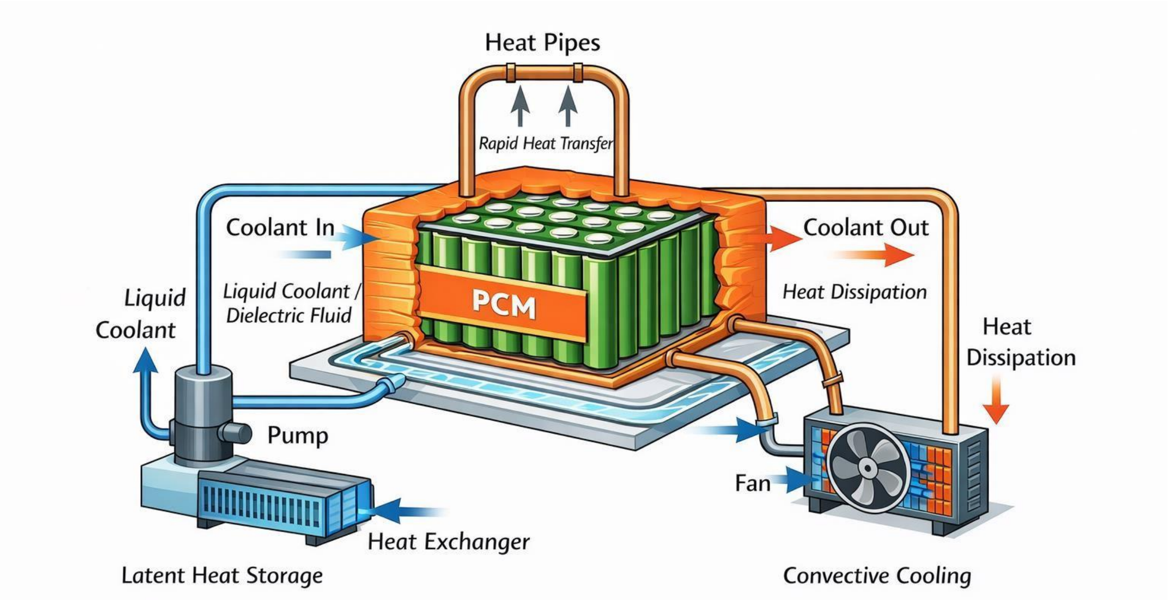


Figure 15. Conceptual Image of Triple Hybrid BTMS Architecture.

The cooperative operation of these mechanisms can lead to improved peak temperature suppression, better temperature uniformity within the battery pack, and enhanced operational stability, particularly for high-power applications such as electric vehicles and rapid charging systems.

However, the implementation of triple-hybrid BTMS also introduces several technical and practical challenges. Incorporating multiple cooling components inevitably increases system structural complexity, overall weight, and packaging requirements, which may restrict integration in compact battery modules. Additional elements such as coolant circulation systems, heat pipes, and PCM containment structures may raise manufacturing costs and maintenance demands. Efficient interaction among the different thermal pathways is also critical, as poorly designed interfaces can introduce additional thermal resistance and reduce the overall cooling effectiveness. Furthermore, the durability of PCM materials remains an important concern, particularly with respect to leakage, phase separation, and performance degradation during repeated melting and solidification cycles.

In configurations involving immersion cooling, further issues such as the cost of dielectric fluids, sealing reliability, and compatibility with battery materials must be addressed. Therefore, future work should focus on optimizing integrated system design, minimizing volume penalties, and developing coordinated control strategies to ensure reliable and efficient operation of triple-hybrid BTMS in practical energy storage applications. Also further research can focus on Combining PCM with two-phase dielectric immersion cooling (boiling/condensation) presents a promising pathway for ultra-fast charging application.

4. Integration of Machine Learning, Digital Twins, and Advanced Optimization in BTMS

Recent research has increasingly explored intelligent and data-driven techniques to enhance BTMS beyond conventional passive and active cooling methods. By combining machine learning (ML), digital twin frameworks, and advanced multi-objective optimization approaches, modern BTMS can achieve better prediction, control, adaptability, and lifecycle optimization, particularly in PCM-based hybrid cooling architectures.

4.1. AI-Driven BTMS Optimization

Recent advancements in data-driven modeling have significantly influenced the design and control of PCM-integrated hybrid BTMS. Machine learning techniques are now being adopted to overcome the high computational demand associated with detailed electro-thermal and CFD simulations. By learning complex nonlinear relationships from simulation or experimental datasets, ML algorithms can predict temperature evolution and system performance with considerably reduced processing time.

In hybrid configurations combining PCM with liquid cooling, data-driven surrogate models have shown strong potential for rapid thermal performance evaluation. For example, Xie[69] demonstrated that neural network-based predictive frameworks can accurately estimate temperature response under varying discharge conditions while substantially decreasing simulation time compared to conventional numerical approaches. Their study further highlighted the ability of ML models to assist in optimizing key design variables such as PCM layer thickness and coolant flow rate to achieve lower peak temperatures and improved energy efficiency during high C-rate operation.

Similarly, Zhang[29] reported the application of ML-based surrogate modeling for PCM–air hybrid cooling systems. Their approach enabled precise estimation of maximum cell temperature and transient thermal behavior without repeated high-cost numerical simulations. Such predictive tools are particularly beneficial during the preliminary design stage, where multiple parametric combinations must be evaluated to identify optimal system configurations.

More recently, advanced neural architectures have been explored to enhance prediction robustness. Gu[70] proposed deep learning structures incorporating self-attention mechanisms and Convolutional Neural Networks (CNN) based feature fusion to capture intricate heat transfer interactions within PCM–air and PCM–liquid systems. These models demonstrated high predictive accuracy and strong generalization capability, suggesting their suitability for real-time monitoring and adaptive thermal regulation.

Overall, ML enabled frameworks support simultaneous optimization of multiple design and operating parameters including PCM geometry, cooling channel dimensions, flow rate, and cell arrangement without relying on exhaustive CFD-based parametric sweeps. The integration of such intelligent prediction tools into hybrid BTMS design workflows not only improves computational efficiency but also contributes to enhanced thermal uniformity, reduced peak temperature, and more energy-conscious system operation.

4.2. Digital Twins for Real-Time Monitoring and Predictive Control

Digital twin (DT) technology is emerging as a transformative approach for next-generation battery thermal management systems. A digital twin represents a dynamic virtual counterpart of a physical battery system, continuously updated using real-time operational data. Unlike traditional physics-based models that operate offline, DT frameworks integrate sensor measurements, reduced-order electro-thermal models, and data-driven analytics to enable continuous monitoring, predictive diagnostics, and adaptive thermal control.

Recent literature highlights the growing role of artificial intelligence–enhanced digital twins in intelligent battery management systems. Madani[71] provide a comprehensive review of AI-integrated DT architectures capable of real-time estimation of critical battery parameters, including state of charge (SOC), state of health (SOH), and temperature distribution. By combining live data streams with predictive modeling, such frameworks support proactive decision-making, predictive maintenance, and lifecycle optimization.

From a thermal management perspective, digital twins offer significant advantages for PCM-based hybrid systems. They allow synchronization between the virtual model and the physical cooling configuration, enabling dynamic regulation of PCM melting and solidification processes under varying load conditions. Rather than relying solely on reactive cooling strategies, DT-enabled systems can anticipate thermal excursions and adjust liquid flow rates, airflow intensity, or auxiliary cooling mechanisms accordingly. This predictive capability enhances temperature uniformity and mitigates thermal runaway risks.

Practical implementations further demonstrate that digital twin models can achieve near real-time simulation accuracy, facilitating virtual prototyping and optimization of hybrid PCM–air or PCM–liquid architectures prior to physical experimentation[72]. Such capability significantly reduces development time and experimental cost while improving system reliability.

Overall, digital twin–based BTMS frameworks contribute to enhanced safety, improved thermal regulation, and greater operational adaptability. When integrated with PCM-driven hybrid cooling architectures, DT technology enables a shift from conventional passive or semi-active thermal buffering toward fully intelligent, predictive thermal management systems.

4.3. Smart BMS Integration and IoT-Enabled Adaptive Strategies

The incorporation of artificial intelligence techniques into advanced Battery Management Systems (BMS) has enabled more responsive and adaptive thermal regulation in PCM-based hybrid cooling configurations. In such systems, the interaction between phase change materials and auxiliary cooling mechanisms such as liquid or air cooling can be dynamically managed according to real-time operating conditions. Through continuous data acquisition and predictive analytics, intelligent BMS platforms can regulate cooling intensity, flow rates, and thermal buffering capacity to maintain stable temperature profiles. In addition, IoT supported infrastructures allow remote supervision, centralized data processing, and cloud-based performance evaluation, which are particularly beneficial for large-scale fleet applications and predictive maintenance planning[29,65,71].

Recent developments in reinforcement learning (RL) and adaptive control strategies have further strengthened intelligent thermal management capabilities. RL-based controllers are capable of learning optimal cooling actions under variable load demands, enabling improved balance between thermal stability and auxiliary energy consumption, especially during high-rate charging and discharging conditions. These closed-loop control frameworks continuously respond to thermal deviations by modulating cooling effort in real time. As a result, PCM utilization is optimized, temperature gradients are minimized, and battery longevity is enhanced through more effective thermal regulation.

5. Future Scope of PCM-Based BTMS:

5.1. Future Applicability of PCM-Based BTMS for Emerging Battery Technologies

Although PCM-based battery thermal management systems (BTMS) have been extensively investigated for conventional lithium-ion batteries, their applicability to emerging battery technologies requires further consideration. Semi-solid-state batteries generally offer better thermal stability than conventional lithium-ion batteries due to their lower liquid electrolyte content. Even so, heat generation can still become significant during fast charging and high-power operation. In such cases, PCM can help absorb excess heat and reduce temperature fluctuations, thereby maintaining a more uniform temperature distribution within the battery pack.

Solid-state batteries are often considered safer because they use non-flammable solid electrolytes and have a lower risk of thermal runaway. Nevertheless, heat can still be generated because of interfacial resistance and high current densities during operation. Therefore, thermal management cannot be completely neglected. PCM-based cooling may still be useful for controlling local temperature rise and minimizing thermal stresses, although the cooling demand may be lower than that of conventional lithium-ion batteries. Sodium-ion batteries have recently attracted considerable attention as a cost-effective alternative for energy storage and electric vehicle applications. Their operating temperature requirements are generally similar to those of lithium-ion batteries, but thermal behaviour can vary depending on cell chemistry and design. PCM can provide passive temperature control and improve thermal uniformity, especially in large battery packs subjected to varying operating conditions.

Overall, PCM-based BTMS is expected to remain a viable option for next-generation battery technologies. However, future designs may require customized PCM materials and hybrid cooling solutions that match the specific thermal characteristics of different battery chemistries. Further research on advanced PCM materials, integrated cooling systems, and intelligent thermal management strategies will help improve the performance, safety, and durability of future battery packs.

5.2. Challenges of PCM-Based BTMS under Low-Temperature Conditions

Most PCM-based battery thermal management systems have been developed to control excessive heat generation during high-rate charging and discharging. Their primary objective is to reduce peak battery temperature, improve temperature uniformity, and enhance safety under high thermal loads. However, battery operation in cold climates presents a different thermal management challenge.

At low temperatures, lithium-ion batteries experience increased internal resistance, reduced ionic conductivity, lower charge acceptance, and decreased available capacity. These effects can lead to significant performance degradation and reduced energy efficiency. In such situations, conventional PCM-based cooling systems may provide limited benefits because the PCM remains largely in a solid state and therefore cannot effectively supply thermal energy to the battery.

To overcome this limitation, researchers have explored hybrid thermal management approaches that combine PCM with active heating technologies such as electrical resistance heaters, heat pumps, and liquid-based heating systems. In these configurations, the PCM can act as a thermal energy storage medium, storing heat generated during operation and releasing it when ambient temperatures decrease. Such hybrid systems can help maintain batteries within their optimal operating temperature range while reducing auxiliary energy consumption.

Therefore, while PCM-based BTMS remains highly effective for high-temperature management, its application in extremely cold environments requires additional heating support. Future research should focus on multifunctional PCM materials and integrated heating–cooling thermal management systems capable of maintaining battery performance across a wide range of operating temperatures.

5.3. Bio-PCMs

In addition to developments in hybrid cooling systems, future research can also focus on creating more sustainable phase change materials (PCMs) for battery thermal management. Bio-based PCMs, which are made from renewable natural sources, are gaining more attention because they are environmentally friendly and can help reduce the overall environmental impact of thermal energy storage systems. Although this review mainly focuses on hybrid PCM-based battery thermal management systems rather than PCM material selection, combining bio-based PCMs with advanced hybrid cooling methods is an important area for future study. Recent research also shows that eco-friendly and bio-based PCMs can work effectively in battery thermal management systems when they are used with high-thermal-conductivity additives and hybrid cooling techniques, helping to improve both cooling performance and sustainability[73].

6. Conclusion

Following conclusions can be drawn from this research study:

- The comparative analysis confirms that integrating PCM with active or semi-passive cooling techniques significantly enhances battery thermal management compared to single-mode systems. The inclusion of PCM reduces peak cell temperature (T_{max}) typically by ~8–15 °C under moderate operating conditions (1–2C), owing to its latent heat storage capability, which effectively dampens transient thermal spikes.

- Among the investigated configurations, PCM–dielectric immersion cooling achieves the lowest T_{max} (generally maintained below ~40–45 °C even at high discharge rates of 3–5C). However, this system exhibits relatively higher ΔT (temperature non-uniformity, typically ~4–7 °C) due to localized fluid–cell interactions. Therefore, while it provides excellent heat removal and is suitable for fast-charging and high-power applications, further design optimization is required to improve temperature uniformity.

- The PCM + liquid cooling system demonstrates a balanced performance with significant reduction in T_{max} (~10–18 °C reduction compared to air cooling) and relatively low ΔT (~2–5 °C) under moderate-to-high C-rate conditions (2–4C). This makes it highly suitable for large-format battery packs where both thermal uniformity and reliability are critical.

- The integration of heat pipes with PCM enhances heat spreading and delays PCM saturation. This configuration maintains T_{max} within ~45–50 °C at moderate C-rates (1–3C), with ΔT typically in the range of ~3–6 °C. Although its cooling capacity is lower than liquid or immersion systems, its passive operation, low energy consumption, and high reliability make it suitable for compact and auxiliary battery systems.

- PCM combined with air cooling improves thermal performance compared to standalone air cooling, reducing T_{max} by ~5–10 °C at low-to-moderate C-rates (≤2C). However, due to the low convective heat transfer coefficient of air, ΔT remains relatively high (~5 – 8 °C), limiting its applicability to low-power or cost-sensitive applications.

- The integration of machine learning, digital twin frameworks, smart BMS architectures, and sustainable PCM materials transforms conventional PCM-based hybrid BTMS from passive heat buffering systems into predictive, adaptive, and environmentally conscious thermal management solutions. Collectively, these advancements enable accurate thermal forecasting, real-time state monitoring, intelligent cooling control, optimized system design, and improved sustainability.

Conflict of interest

The authors declare no conflict of interest.

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