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Review

Recent Advancements in Battery Thermal Management Systems for Enhanced Performance of Li-Ion Batteries: A Comprehensive Review

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Abstract: Li-ion batteries are crucial for sustainable energy, powering electric vehicles, and supporting renewable energy storage systems for solar and wind power integration. Keeping these batteries at temperatures between 285 K and 310 K is crucial for optimal performance. This requires efficient battery thermal management systems (BTMS). Many studies, both numerical and experimental, have focused on improving BTMS efficiency. This paper presents a comprehensive review of the latest BTMS designs developed in 2023 and 2024, with a focus on recent advancements and innovations. The primary objective is to evaluate these new designs to identify key improvements and trends. This review categorizes BTMS designs into four cooling methods: air-cooling, liquid-cooling, phase change material (PCM)-cooling, and thermoelectric cooling. It provides a detailed analysis of each method. It also offers a unique examination of hybrid cooling BTMSs, classifying them based on their impact on the cooling process. A hybrid-cooling BTMS refers to a method that combines at least two of the four types of BTMS (air-cooling, liquid-cooling, PCM-cooling, and thermoelectric-cooling) to enhance thermal management efficiency. Unlike previous reviews, this study emphasizes the novelty of recent designs and the substantial results they achieve, offering significant insights and recommendations for future research and development in BTMS. By highlighting the latest innovations and providing an in-depth analysis, this paper serves as a valuable resource for researchers and engineers aiming to enhance battery performance and sustainability through advanced thermal management solutions.

Keywords: battery thermal management systems; Lithium-ion batteries; air cooling; liquid cooling; PCM-cooling; thermoelectric-cooling

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1. Introduction

Due to the global energy crisis and environmental pollution, there is an urgent need to shift to safer, cleaner, and more efficient renewable energy sources, which necessitates effective energy storage solutions. Transportation is a major contributor to the global energy problem since it mainly depends on fossil fuels, resulting in excessive energy consumption and the emission of greenhouse gases [1]. This highlights the importance of moving towards cleaner and more sustainable transportation options. Electric vehicles (EVs) powered by Lithium-ion (Li-ion) batteries present a promising solution to the energy crisis by reducing dependence on fossil fuels and lowering greenhouse gas emissions in the transportation sector. The operating temperature and internal heat generation of Li-ion batteries have a significant impact on their performance, lifespan, and safety [2]. Hence, a battery thermal management system (BTMS) is crucial to protect batteries from the negative impacts of increased temperatures and internal heat generation.

The present review provides the basic concept of experimental and numerical works conducted in 2023 and 2024, including air-cooling, liquid-cooling, PCM-cooling, and thermoelectric-cooling base hybrid BTMSs.

1.1. Importance of BTMS

A battery thermal management system (BTMS) is vital for maintaining the optimal performance and longevity of lithium-ion battery packs, which consist of multiple cells arranged in various configurations. The efficiency of these batteries is highly temperature-dependent, as internal heat generated during charge and discharge cycles can cause uneven temperature distribution, reducing the battery's lifespan and effectiveness [3]. Studies have shown that hotspots often form near the electrodes, leading to temperature non-uniformity [4]. To address these challenges and enhance battery performance in electric and hybrid vehicles, effective BTMS is essential, as highlighted by numerous researchers in the field.

1.2. Recent Advances and Critical Analysis of BTMS

In recent years, significant advancements have been made in the field of battery thermal management systems (BTMS), driven by the need to enhance the performance, safety, and longevity of lithium-ion batteries, particularly in electric vehicles and renewable energy storage systems. This section provides a comprehensive analysis of these advancements, critically evaluating the latest research and technological innovations.

Air-Cooling: Air-cooling methods have evolved with various modifications to enhance performance. Recent designs, such as honeycomb structures and multiple inlet/outlet air cooling systems, have shown substantial improvements in cooling efficiency and temperature uniformity.

Liquid-Cooling: Liquid-cooling systems, particularly those with advanced cold plate and cooling channel designs, offer superior thermal management capabilities. Studies on bionic spiral fins and liquid cooling plates have demonstrated significant enhancements in heat dissipation and temperature control.

PCM-Cooling: The use of PCM in BTMS provides passive thermal management, effectively absorbing heat during phase transitions. Hybrid PCM systems that combine PCM with air or liquid cooling have shown improved thermal performance and energy efficiency.

Thermoelectric Cooling: Recent advancements in thermoelectric cooling (TEC) have focused on integrating TEC with other cooling methods for precise temperature control and enhanced efficiency. Studies have highlighted the potential of TEC to maintain battery temperatures within optimal ranges, even under high thermal loads.

1.3. The Motivation for This Work

The current study presents new, innovative BTMS ideas in various categories. Figure 1 shows the battery pack cooling classification used in this study. The reason for this review is that, during 2023 and 2024, more innovative ideas have been presented by researchers as simulation software and methods have been developed at a rapid pace.

This study provides a pioneering and comprehensive analysis of the most recent advancements in battery thermal management systems (BTMS) for lithium-ion batteries, focusing on the innovations developed in 2023 and 2024. Unlike previous reviews, this study not only categorizes BTMS into traditional methods such as air-cooling, liquid-cooling, PCM-cooling, and thermoelectric cooling, but also emphasizes the groundbreaking hybrid systems that integrate multiple cooling technologies for superior thermal management. This work stands out by critically analyzing the performance improvements achieved through novel design modifications, such as the implementation of biomimetic structures, advanced materials like graphene-enhanced PCM, and optimized geometric configurations. By presenting a detailed comparison of the techno-economic aspects of these innovative cooling methods, this study offers significant insights that can drive future research and development, ultimately enhancing the efficiency, safety, and longevity of lithium-ion batteries in electric vehicles and renewable energy storage systems. The thorough evaluation and unique categorization of the latest BTMS designs underscore the importance of this study as a valuable resource for researchers and engineers dedicated to advancing battery technology.

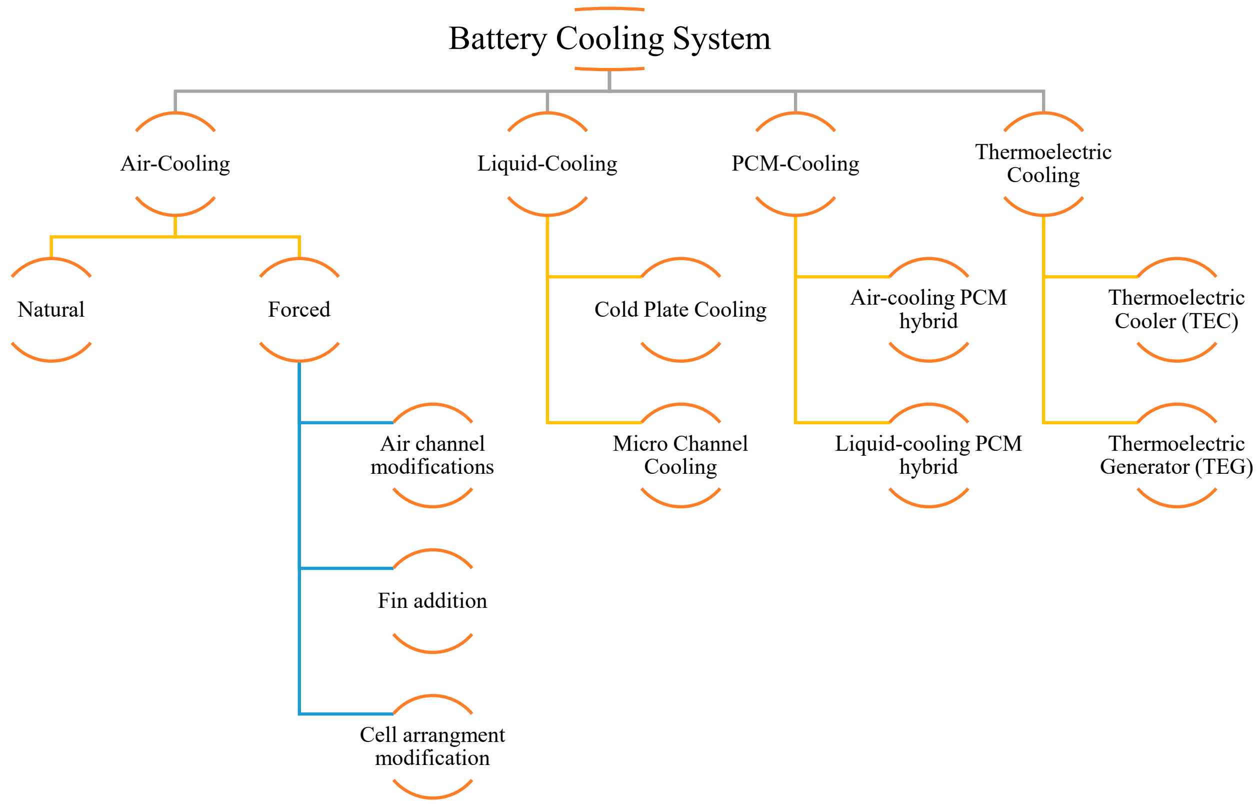


Figure 1. The battery pack cooling classification used in this study is based on the reviewed papers in this study.

2. Recent Progress in BTMS Studies

There have been many documented studies that have extensively explored various forms of battery thermal management systems (BTMS) through experimentation and numerical analysis. Scientists have carried out experiments at many levels, including cell, module, and pack to examine how batteries operate in terms of temperature under various conditions. Additionally, many researchers have utilized Computational Fluid Dynamics (CFD) for the purpose of mathematical modelling. Experimental research is essential for determining the relationships between dependent and independent variables, and for comprehending the effects of parameters. This section emphasizes the efforts of researchers in advancing computational and experimental methods to effectively control the thermal performance of lithium-ion batteries in different categories.

2.1. Air-Cooled BTMS

The air-cooling method, which is the natural method of BTMS cooling, can be categorized by free and forced convection. Many advantages are reported for this method, including: its simplicity, low cost, no leakage concern, and easier maintenance. The air-cooling method cannot respond to the demand of battery-pack cooling in high ambient temperatures, especially in natural air cooling. Thus, many modifications have been suggested by researchers, such as modifying air-flow channels, using fin structures, and modifying cell arrangements. Electric vehicles such as the Nissan Leaf, Volkswagen e-Golf, Chevrolet Spark EV, and early models of the BMW i3 utilize air cooling in their battery thermal management systems. Table 1 shows the recent, documented studies on air-cooling BTMS in 2023 and 2024. As detailed in Table 1, experimental and numerical studies have been conducted on air-cooled BTMS with different modifications. A summary of each modification type is presented in this section. The presented data in Table 1 show that, among different methods used to modify the air-cooling method, modifying the air channel can have more impact on the performance of BTMS.

Air-channel modifications: This method of air cooling, which involves altering the patterns of airflow to cool batteries, has been extensively researched and examined by several scientists in the last few years [4]. Continuing their idea, Luo et al. [5] developed an innovative X-type double inlet and outlet, symmetrical, air-cooled battery thermal management system (BTMS) designed to address issues of high temperature, temperature differences, and power dissipation in battery packs. The study showed that the proposed X-type BTMS significantly improves performance by reducing the maximum temperature, temperature difference, and power dissipation by 4.33 K, 74%, and 62.9%, respectively, compared to symmetrical air-cooling BTMS. The optimization and heat transfer correlations provide valuable insights for future BTMS design and improvement. Based on the optimization process, a modified X-type channel was designed, which decreased the maximum temperature by 2 K in comparison with the basic design. Furthermore, Yang et al. [6] investigated the thermal performance of a honeycomb-type, cylindrical lithium-ion battery pack incorporating an air-distribution plate (ADP) and bionic heat sinks. Their study demonstrated that the ADP significantly reduces maximum temperature and temperature differences within the battery pack by 1.7 K and 7.0 K, respectively. The addition of bionic heat sinks further enhances thermal performance and maintains temperature differences within 2 K, thus providing valuable insights for the design of efficient battery thermal management systems (BTMS). Duan et al. [7] developed a novel design method for a multiple inlet/outlet air-cooling frame for pouch lithium-ion batteries using thermal–fluid coupling topology optimization. Their research demonstrated that the optimized cooling frame significantly enhances cooling efficiency and temperature uniformity, reducing the maximum temperature by 4.79% and the temperature difference by 36.40%, compared to traditional frames, making it highly applicable to electric vehicles and hybrid electric vehicles.

Cell-arrangement modification: Cell arrangement is another field of interest among scientists for improving the efficiency of air-cooling BTMS [8]. As an innovative idea, Shen et al. [9] designed a modified Z-shaped, air-cooled battery thermal management system (BTMS) with a non-vertical structure to enhance the thermal behavior of lithium-ion power batteries in electric vehicles. Their study showed that this new system reduced the maximum temperature from 38.15 °C to 34.14 °C, and the temperature difference from 2.59 °C to 1.97 °C. This modified design improves cooling performance and temperature uniformity, offering significant engineering value for the advancement of BTMS in electric vehicles. Furthermore, Kashyap et al. [10] presented an optimized design for a staggered-arranged battery thermal management system (BTMS) using physics-based simulations and evolutionary algorithms. Their research showed that this integrated approach reduced maximum temperature by 0.627%, maximum temperature difference by 49.18%, increased pressure drop by 102.379%, and volume by 6.804%, compared to traditional configurations. This work provides significant improvements in thermal management for lithium-ion battery packs, offering valuable insights for future BTMS designs.

Adding fin structure: Adding metal fins to an air-cooled battery thermal management system (BTMS) significantly enhances cooling efficiency by increasing the surface area for heat dissipation, which improves heat-transfer rates and reduces the maximum temperature and temperature gradients within the battery pack [11]. Chaudhari et al. [12] conducted an experimental and computational analysis of a lithium-ion battery thermal management system (BTMS) using radial fins for air cooling. Their study revealed that forced convection with radial fins significantly enhanced cooling efficiency, reducing the maximum battery temperature by up to 39.23%, compared to natural convection. This research highlights the effectiveness of radial fins in improving the thermal performance and safety of lithium-ion battery packs in electric vehicles. Luo et al. [13] proposed a direct flow cooling battery thermal management system (DFC-BTMS) with bod baffles and a lipid organic liquid coolant to enhance thermal performance in electric vehicles. Their experimental and simulation study showed that the optimized DFC-BTMS achieved a maximum average surface temperature of 24.789 °C and a maximum temperature difference of 2.734 °C, providing an innovative solution for efficient battery thermal management.

Table 1. An outline of the work that has been done on air-cooled BTMS.

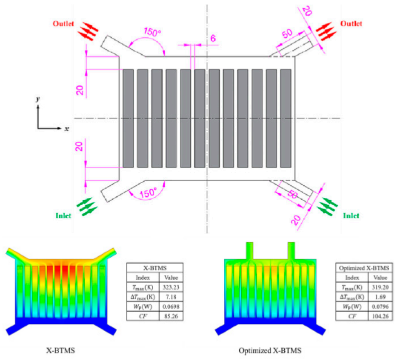
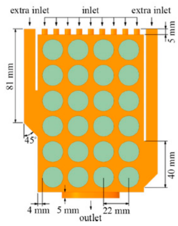
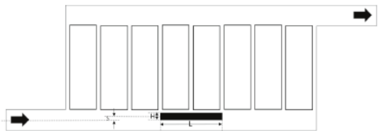
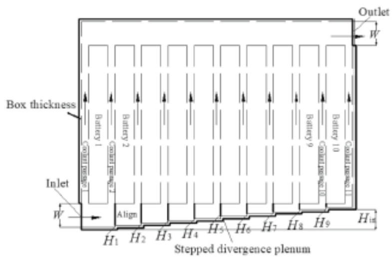
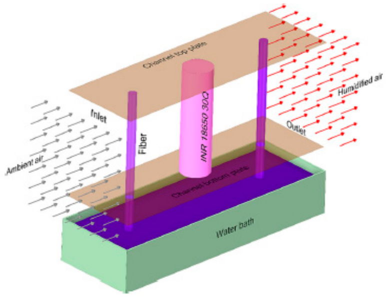
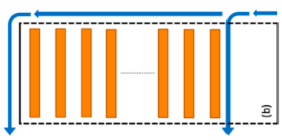
No.	Modification/ Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
1	X-type double inlet and outlet BP is used.	CFD	T_{max} and ΔT_{max} are deceased 4.33 K and 74% respectively. A heat transfer correlation is obtained.		[5,13]	Air channel
2	A new design with two extra inlets is used.	CFD	Maximum temperature and temperature difference are decreased by 17.93% and 12.22%, respectively.		[14]	Air channel
3	A spoiler is used in the air inlet manifold in U and Z-type BPs.	CFD	Maximum temperature and temperature difference are decreased by 2.97 K and 4.98 K, respectively.		[15]	Air channel
4	A Z-type BP with a new stepwise divergence plenum is suggested.	CFD	Maximum temperature and temperature difference are decreased by 34.65% and 77.51%, respectively. The optimum height for each step and velocity is h = 0.125 mm and v = 3 m/s.		[16]	Air channel
5	A BTMS in dry-out condition is compared with a simple one.	Exp.	Maximum temperature and temperature difference are decreased by 0.31% and 0.48%, respectively.		[17]	Air channel
6	A bypass cold-air channel is added to BP.	CFD	Temperature difference in the BP is decreased from 31.2 °C to 3.2 °C, and maximum temperature is decreased from 30.5 °C to 24.7 °C.		[18]	Air channel

Table 1. *Cont.*

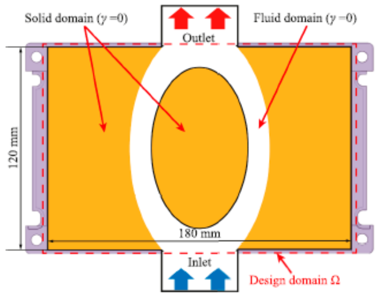
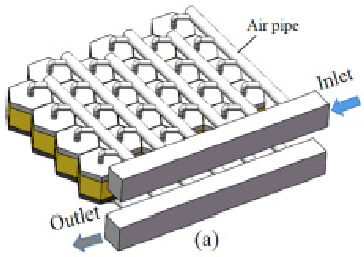
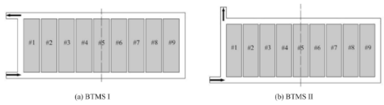
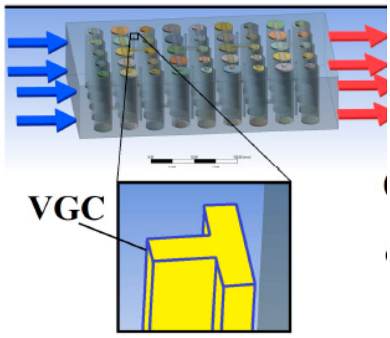
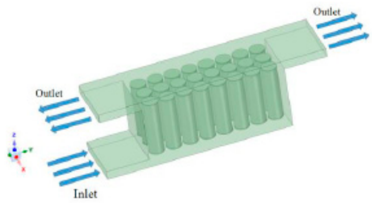
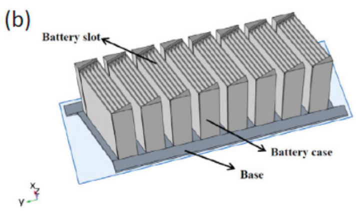
No.	Modification/ Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
7	A multiple inlet/outlet air-cooling frame is used for pouch Li-ion BP.	Exp.	This method reduces the module maximum temperature Tmax and temperature differential ΔTmax, which will be beneficial for the cost of small logistical vehicles, thus improving the cooling performance of the LIB module.		[7]	Air channel
8	A honeycomb-type, cylindrical BP air distribution design.	CFD	Maximum temperature and temperature difference are decreased by 1.7 K and 7.0 K, respectively.		[6]	Air channel
9	Air-flow pattern is changed, based on Z-type and U-type BPs.	CFD	Maximum temperature and temperature difference are decreased by 0.8 K and 2.4 K, respectively.		[19]	Air channel
10	A vortex generator is placed in the air channel.	CFD	Maximum temperature and temperature difference are decreased by 0.85 K and 0.77 K, respectively. Pressure drop in air channel is increased by 17.88 Pa.		[20]	Air channel
11	A J-type BP is proposed	CFD	Maximum temperature and temperature difference are decreased by 1.57 K and 0.80 K, respectively.		[21]	Air channel
12	A modified Z-type BP is proposed, which tilts the arrangement of battery packs.	CFD	Maximum temperature and temperature difference are decreased by 10.5% and 23.9%, respectively.		[9]	Air channel

Table 1. *Cont.*

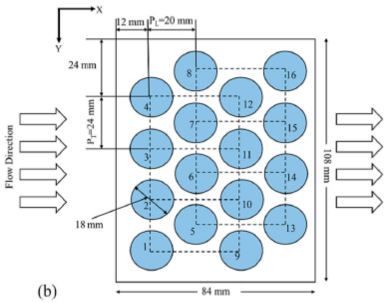
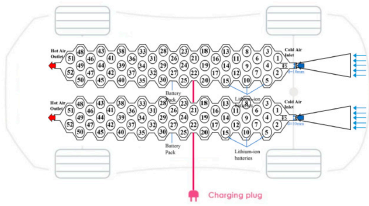
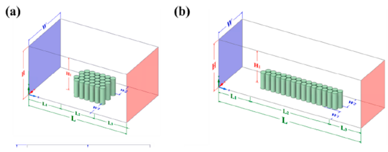
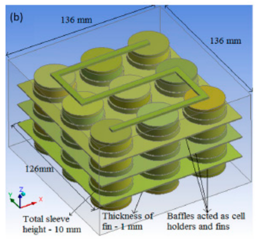
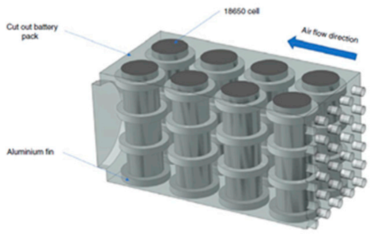
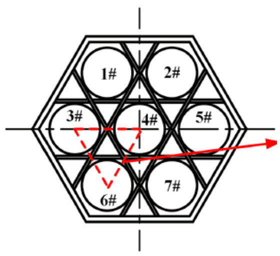
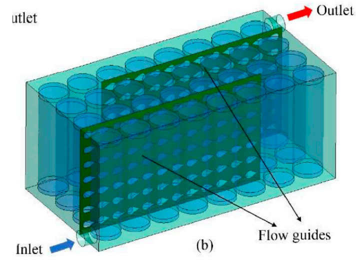
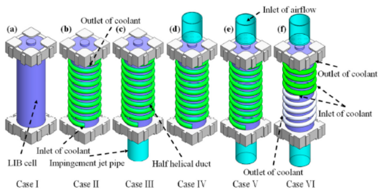
No.	Modification/ Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
13	A staggered-arranged BTMS	GA optimization CFD	The optimum architecture is found, which decreases maximum temperature by 49.18% and temperature difference by 102.37%.		[10]	Cell arrangement
14	An innovative cell arrangement for an EV is proposed.	CFD	The average temperature drop of lithium-ion batteries' cell surface temperature is 5.6% to 7.8% when cold fluid is flowed through them.		[22]	Cell arrangement
15	The effect of different cell arrangements is evaluated for a 30-cell battery pack.	CFD Exp.	The 5 × 6 BP works better than 15 × 2 BP, and offers better heat dissipation.		[23]	Cell arrangement
16	Innovative cell holders are used to act as a fin	CFD	Maximum temperatures for the basic model are 301.5, 303.9, and 308.8 K; for the modified model, they are 300.6, 302.1, and 304 K.		[24]	Adding fin
17	An innovative circular fin is used around cells.	Exp.	Maximum temperature is decreased by 27.26%.		[12]	Adding fin
18	Innovative bod baffles for EV are used.	CFD	For 3C discharge, the new design results in a maximum temperature of 24.7 °C and temperature difference of 2.7 °C.		[13]	Adding fin

Table 1. *Cont.*

No.	Modification/ Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
19	A separator plate with fish-shaped holes is used between batteries.	CFD	The new design results in a maximum temperature drop of 9.2% and temperature difference drop of 12.2%.		[25]	Adding fin
20	A helical coil is coupled with air jet in LIB.	Exp.	The new design results in a maximum temperature drop of 5.7 °C and temperature difference drop of 4 °C.		[26]	Adding fin

2.2. Liquid-Cooled BTMS

Liquid cooling battery thermal management systems (LC-BTMS) are a very efficient approach for cooling batteries, especially in demanding applications like electric vehicles. LC-BTMS may be classified into two types: liquid indirect cooling battery thermal management systems (LIDC-BTMS) and liquid direct cooling battery thermal management systems (LDC-BTMS), which are also referred to as immersion cooling systems. LIDC-BTMS employ a liquid-cooling plate that meets the battery module, facilitating the absorption and dissipation of heat produced during charging and discharging cycles. This approach capitalizes on a well-established manufacturing process and has a high capacity for transferring heat efficiently. However, its effectiveness may be limited by the thermal resistance that occurs when the cooling plate meets the battery. On the other hand, LDC-BTMS facilitate direct interaction between the coolant and the battery, resulting in a significant decrease in thermal resistance and an improvement in cooling effectiveness. This technology is very efficient at maintaining ideal battery temperatures, hence extending battery lifespan and reducing thermal runaway. However, the design of LDC-BTMS must be precise to successfully tackle the concerns of coolant containment and system sealing. LC-BTMS have exceptional thermal management capabilities, making them ideal for applications that need reliable and effective cooling solutions.

Electric vehicles such as Tesla's Model S, Model X, Model 3, General Motors' Chevrolet Bolt, and Jaguar's I-PACE use liquid cooling in their battery thermal management systems (BTMS) to effectively regulate heat and improve battery performance and safety. Many innovative designs were reported by researchers in 2023 and 2024, and some of the designs are presented in Table 2. The provided designs in Table 2 can be categorized into modifying cold plate and modifying cooling channels.

Cold plate modification: Optimizing the cold plate in a liquid-cooling system is essential for improving thermal efficiency. To enhance heat transfer, one should choose materials with high thermal conductivity, optimizing surface finishing and increasing the surface area in contact with the heat source. In addition, the heat dissipation can be further improved by designing the internal channels to optimize fluid flow and utilizing high-quality thermal interface materials. Yao et al. [27] introduced an innovative hybrid Battery Thermal Management System (BTMS) that integrates phase change materials (PCM) and a liquid cooling channel inspired by a spider web. This system effectively dissipates heat and keeps the battery module temperature below 40 °C even during high discharge rates. As a result, it greatly improves the efficiency of thermal management. The spider web pattern in the BTMS is employed to maximize heat distribution, enhance surface area for improved heat transfer, and ensure the efficient flow of cooling fluid, thereby enhancing the overall efficiency of thermal management. Li et al. [28] used the same idea and designed a diamond-type cold plate to increase the efficiency of liquid-cooled BTMS.

Cooling channel modification: Modifying cooling channels in battery thermal management systems enhances heat dissipation, ensures uniform temperature distribution, reduces energy consumption, and optimizes overall system performance, thereby improving battery efficiency and longevity. Improving battery thermal management requires implementing changes to the shape of the cooling channels, increasing the amount of exposed surface area, optimizing the paths through which the coolant flows, choosing materials with high conductivity, adjusting the rate at which the coolant flows, and designing effective locations for the coolant to enter and exit. These modifications aim to enhance heat dissipation, ensure consistent temperatures, and improve the system's efficiency. Yates et al. [29] analyzed the performance of liquid cooling designs in cylindrical lithium-ion batteries, focusing on two specific designs: a mini channel cylinder (MCC) and a channel-cooled heat sink (CCHS). Their study investigated the effects of channel number, hole diameter, mass flow rate, and inlet locations on the thermal management performance of these designs. They found that, while the MCC provided superior cooling performance, it also resulted in greater temperature variation and higher manufacturing complexity compared to the CCHS, which offered a more uniform temperature distribution across the battery pack. A novel BTMS that integrates bionic spiral fins inspired by natural vines and spirulina, with an embedded, integrated cold plate, was proposed by Chen et al. [30]. They used a set of numerical experiments to find the optimum structure design and showed that the optimum design can improve cooling and preheating proficiency. They also compared different cold plate designs. These findings provide valuable insights into the design and optimization of BTMS, offering potential improvements in battery performance and lifespan, particularly under high-temperature operating conditions. Furthermore, an innovative parallel sandwich cooling structure improving thermal uniformity and reducing pressure loss in lithium-ion battery packs was designed by Zhao et al. [31]. The study investigated three different cooling water cavities: the series one-way flow corrugated flat tube-cooling structure (Model 1), the series two-way flow corrugated flat tube cooling structure (Model 2), and the parallel sandwich cooling structure (Model 3). Compared to the series cooling systems, Model 3 decreased the average temperature by 26.2% and the maximum temperature by 26.9%. Furthermore, it reduced the temperature difference within the battery pack by 62%.

Table 2. An outline of the work that has been done on liquid-cooled BTMS.

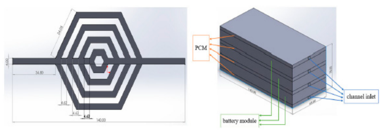
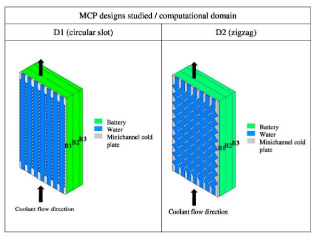
No.	Modification/Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
1	A spider web liquid channel is designed. This innovation increases the area surface in contact.	CFD	The novel design maintains the maximum battery temperature below 40 °C, even under high discharge rates.		[27]	Cooling channel
2	A novel mini channel cold plate (MCP) with circular slot and zigzag channel is designed.	Exp.	Using this design can decrease maximum temperature by up to 5 °C.		[32]	Cooling channel

Table 2. *Cont.*

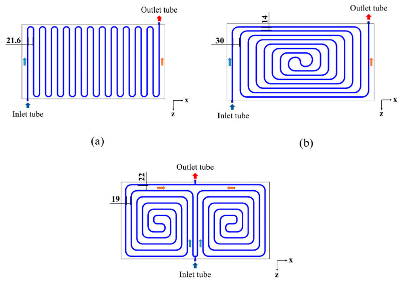
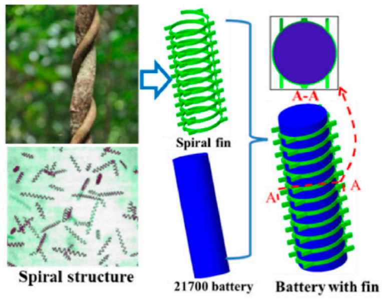
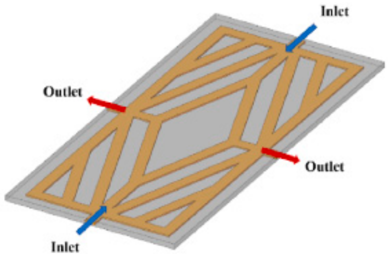
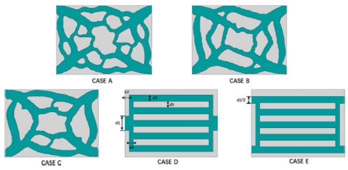
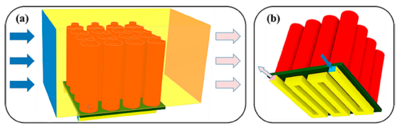
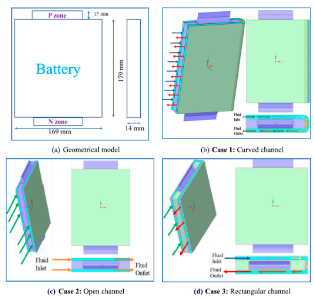
No.	Modification/Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
3	A new inlet/outlet layout is proposed.	CFD	An optimal BTMS scheme that utilizes aluminium cooling plates with a serpentine flow channel and an inlet flow velocity of 0.5 m/s achieves the best cooling performance, energy efficiency, and material cost-effectiveness.		[33]	Cold plate
4	A novel BTMS that integrates bionic spiral fins wrapped with phase change material (PCM) and embedded in a liquid cooling plate is designed.	CFD	This design significantly reduces the maximum battery temperature by 3.1 °C and increases preheating efficiency by 5.6 °C, compared to BTMS without fins		[30]	Cooling channel
5	A diamond flow-type channel cold plate is designed.	CFD	In comparison with usual cold plates, maximum temperature decreases from 313.33 K to 308.98 K, and pressure loss decreases from 1708 Pa to 1180 Pa.		[28]	Cold plate
6	Five different cold plates are compared, and the optimal one is found.	CFD Topology optimization method	The optimum design can decrease maximum temperature and temperature difference by 51% and 42%, respectively.		[34]	Cold plate
7	A composite battery thermal management system that integrates both air-cooling and liquid-cooling methods is presented	CFD	The composite thermal management system reduced the highest battery temperature to 317.38 K. It minimized the temperature difference to 3.73 K, and significantly decreased entropy production. This improvement was achieved with increased air and liquid flow rates.		[35]	Cold plate
8	The paper investigates various cooling configurations' impact on LIB temperature behavior and heat transfer, advancing optimal BTMS for EVs.	CFD	The study demonstrates that liquid cooling significantly enhances the thermal performance of the battery pack (BP). Curved channels showed the most promising results, achieving a temperature reduction to 317.38 K and a minimum temperature difference of 3.73 K among the configurations tested.		[36]	Cold plate

Table 2. *Cont.*

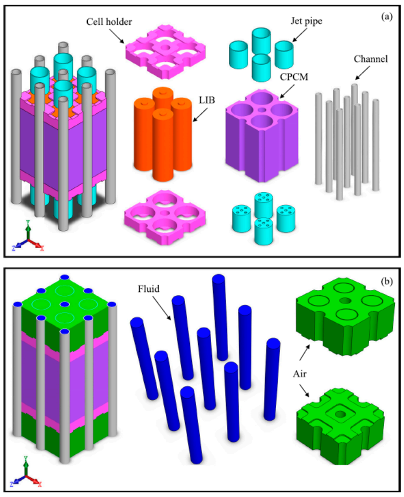
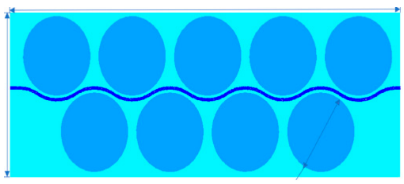
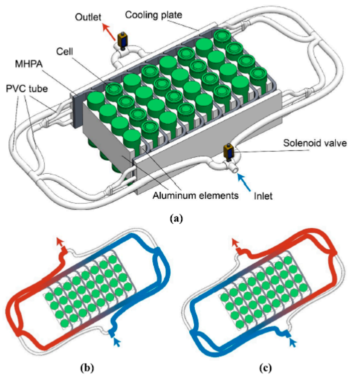
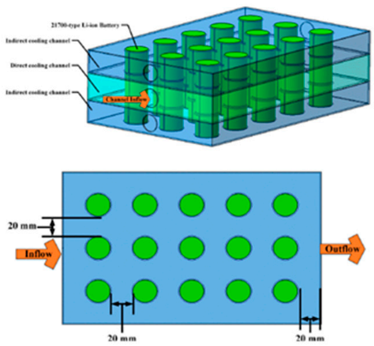
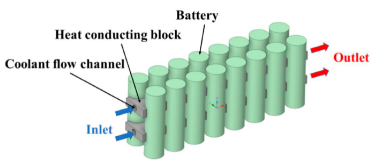
No.	Modification/Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
9	This study investigates a hybrid battery thermal management system (BTMS) that integrates phase change material/copper foam with air jet pipe and liquid channel to enhance the thermal performance of cylindrical lithium-ion batteries (LIBs).	Exp.	The BTMS reduces the maximum temperature and temperature difference of LIBs by 14.6% and 64.7%, respectively,		[37]	Cooling channel
10	A hybrid battery thermal management system combining phase change material and copper foam with air jet pipe and liquid channel is designed.	CFD	The indirect liquid cooling microchannel BTMS with nanofluids achieves superior temperature uniformity and rapid cooling, significantly enhancing the thermal performance of the battery module.		[38]	Cooling channel
11	Many liquid circulation types are compared to minimize energy consumption.	CFD	The reciprocating flow approach reduces the temperature differential and energy consumption by 55.3% and 15.6%, respectively.		[39]	Cooling channel
12	Innovative Hybrid Nano/Dielectric Fluid Cooling System for Cylindrical Li-Ion Batteries: Enhanced Thermal Management Across Operational Conditions	CFD	This system exhibits excellent thermal efficiency at high discharge rates, particularly when using a 4% Alumina nanofluid and high input velocities. Thermal management was further improved with the addition of curved cooling channels and separator plates. These enhancements effectively lowered both maximum and non-homogeneity temperatures.		[40]	Cooling channel
13	Hybrid BTMS for Cylindrical Lithium-Ion Batteries: Optimizing Thermal Performance and Ensuring Cell Temperature Uniformity	CFD Exp.	Three heat-conducting blocks (HCBs) and 6 mm cooling channels for excellent cooling efficiency and lightweight construction were used. Periodic air cooling might save energy and preserve battery safety.		[41]	Cooling channel

Table 2. *Cont.*

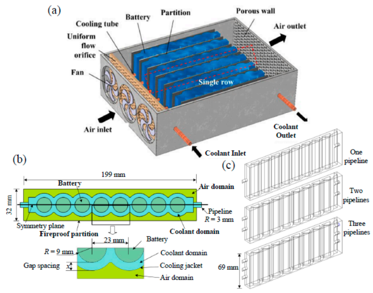
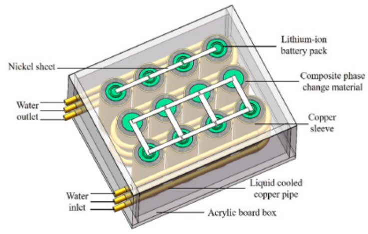
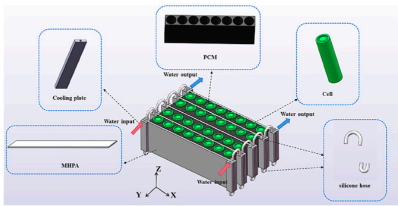
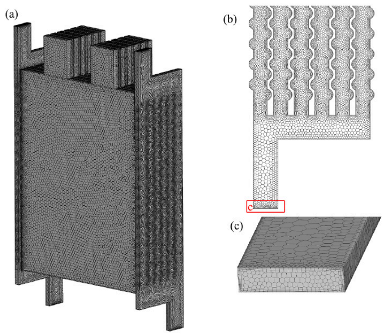
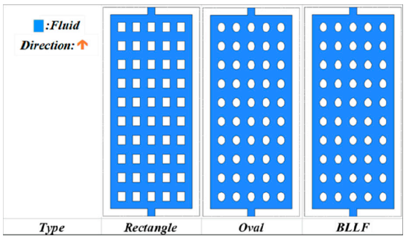
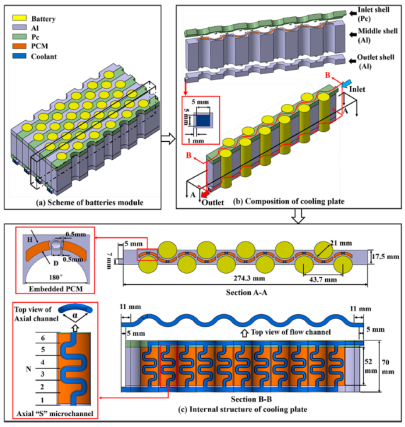
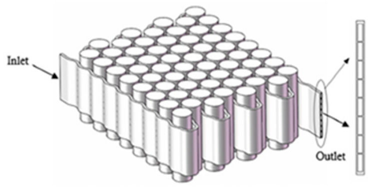
No.	Modification/Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
14	Battery Pack with 6 × 8 Cell Configuration: Cooling Jacket with Aluminum Plates and Transformer Oil for Direct Liquid Cooling	CFD	A two-pipeline liquid-cooling structure provides the best balance of cooling performance and energy consumption. This structure achieved effective temperature reduction and improved uniformity under high-rate discharge conditions with the hybrid system.		[42]	Cooling channel
15	BTMS with Hollow Copper Sleeves and Bent Liquid Copper Pipes for Cooling: Micro-Controller Optimization for Enhanced Performance	Exp.	the novel Battery Thermal Management System (BTMS), combining CPCM and liquid cooling, effectively controlled battery temperatures. It maintained a maximum temperature below 44.8 °C and a temperature difference under 2 °C. The optimal coolant flow rate was identified as 250 mL/min, balancing cooling efficiency and energy use. The system's design is scalable, making it applicable to various battery types for enhanced thermal management.		[43]	Cooling channel
16	Hybrid BTMS for Superior Thermal Management: Integrating PCM Modules with Copper and Graphite, Micro Cooling Plates, and Interconnected Cooling Channels.	Exp.	The hybrid Battery Thermal Management System (BTMS) reduced the maximum battery temperature by 13.78%. It also maintained the temperature difference below 3.9 °C and increased energy density by 11.23%. The optimal cooling configuration combined PCM, MHPA, and liquid cooling. This combination outperformed single-method cooling systems in both thermal performance and energy efficiency.		[44]	Cooling channel
17	Comparative Study of Four Designs with Various Inlet/Outlet Positions: Design D Features Circular Slots for Enhanced Heat Transfer and Optimized Channels for Higher Discharge Rates.	CFD	It was found that Design D demonstrated superior comprehensive performance compared to other designs. This design significantly lowered the maximum temperature of the battery pack and improved temperature uniformity. These features make Design D particularly suitable for high discharge-rate conditions.		[45]	Cooling channel

Table 2. *Cont.*

No.	Modification/Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
18	Optimized Bionic Limulus-Like Fins for Liquid-Cooled Plates: Enhanced Heat Dissipation and Reduced Pressure Loss Compared to Conventional Designs.	CFD	The key finding of this work is that the optimized bionic limulus-like fin design significantly reduced the average temperature by 1.69 °C (4.61%). It also decreased the pressure drop by 6.81 Pa (54.26%). These improvements enhanced overall cooling performance compared to the initial model.		[46]	Cold plate
19	Innovative Battery Pack Cold Plates: Radial Inlet/Outlet Flow Channels and Axial Microchannel Shell with S-Shaped Metal Tubes for Enhanced Cooling and Heat Dissipation.	Exp. Multi objective optimization	The study optimized a hybrid cooling plate with axial S-shaped microchannels, which enhanced thermal management and energy efficiency in EV batteries. Key findings include improved temperature uniformity, reduced energy consumption, and effective performance in both high-temperature and cold environments. A delayed cooling strategy was also used to save energy. Increasing the delay time before activating liquid cooling significantly decreased energy consumption. A delay of 300 s reduced energy consumption by 46.3% while maintaining a maximum temperature below 40 °C and a temperature difference within 5 °C.		[47]	Cooling channel
20	Novel Parallel Sandwich Cooling Structure: Enhancing Thermal Uniformity and Reducing Pressure Loss in Lithium-Ion Battery Packs	CFD	The parallel sandwich cooling structure significantly enhanced thermal uniformity in battery packs. It reduced the average temperature by 26.2% and the maximum temperature by 26.9%, compared to series cooling systems. The new model also achieved a 62% decrease in temperature difference within the battery pack, demonstrating improved thermal uniformity over series cooling structures.		[31]	Cooling channel

2.3. PCM-Cooled BTMS

The concerns related to liquid cooling systems, such as the potential for coolant leakage and the proper disposal of coolant, have been effectively addressed during the commercialization step. Passive thermal management utilizing Phase Change Materials (PCMs) has emerged as an alternative to active cooling systems [48]. Phase Change Materials (PCMs) provide a promising solution as they can absorb and store significant quantities of thermal energy during phase transitions. This allows them to effectively regulate battery temperatures without requiring the use of active cooling components. This approach not only reduces the risks related to coolant management but also simplifies the thermal management system, potentially decreasing maintenance needs and improving overall system reliability. PCMs enhance battery performance, increase battery life, and enhance safety by maintaining consistent and optimal battery temperatures. This makes PCMs a feasible option for contemporary battery thermal management. PCM simulation is considered a complex flow simulation. Mesoscopic methods are used by researchers to model PCM in battery thermal management systems. Rahmani et al. [49] conducted a computational investigation of magnetohydrodynamic flow and the melting process of phase change material in a battery pack.

PCMs provide passive thermal management. They can absorb heat as they change from solid to liquid, but once fully melted they no longer absorb heat effectively. This can result in temperature spikes during long, high-power operation or in high-temperature environments. PCM-based systems often need to be supplemented with active cooling systems, such as liquid or air cooling, to effectively manage the heat generated by the batteries, especially during high discharge rates or rapid charging scenarios. Active cooling systems can ensure continuous thermal regulation, even after the PCM has fully melted. Table 3 shows some innovative PCM-based BTMS which were presented in 2023 and 2024.

Hybrid PCM-air cooling systems: The battery pack can minimize temperature gradients and hot spots by integrating phase change material (PCM) with air-cooling. The PCM serves as a thermal buffer, absorbing and retaining excessive heat during phase change to achieve this. The continuous air supply from the air-cooling system distributes the absorbed heat, which stops any specific areas from becoming overheated. The combined effect guarantees a more uniform distribution of temperature through all cells, which increases battery performance and safety. In addition, air-cooling systems offer advantages in terms of cost, weight, simplicity, and maintenance, compared to liquid cooling systems. When combined with PCM, they effectively handle high thermal loads, enhancing the efficiency and reliability of the hybrid system. Chen et al. [50] presented a new hybrid Battery Thermal Management System (BTMS) that combines phase change material (PCM) with air cooling. It incorporates biomimetic variable-section fins to enhance thermal performance. It is shown that by implementing a delayed air-cooling strategy, power consumption can be reduced by 59% while still maintaining maximum temperature and temperature difference within 40 °C and 3 °C, respectively. A similar study is conducted by Rahmani et al. [51]. They investigated the enhancement of heat storage cooling systems via the implementation of a honeycomb-inspired design, focusing on efficiency and performance. Suo et al. [52] proposed an innovative design in which PCM covers prismatic battery tabs, and air passes batteries through Z-type air channels. Four cases were compared, and it was found that when PCM directly contacts the battery box, the volume of the battery box reduces by 3.48% and thermal performance is enhanced.

Hybrid PCM-liquid cooling systems: Phase change materials (PCM) and liquid cooling together provide substantial benefits for battery thermal management systems (BTMS) in terms of thermal regulation and heat transfer efficiency. Without requiring constant energy input, PCM can efficiently regulate battery temperature during phase transitions by absorbing and storing thermal energy. Nevertheless, the PCM's capacity to absorb heat decreases as it completes its transition. Therefore, by offering both passive and active cooling techniques, integrating PCM with liquid cooling improves the overall thermal management [53]. Hybrid PCM-liquid cooling systems leverage the high thermal conductivity and specific heat capacity of liquid coolants to rapidly remove heat from battery cells. Liquid cooling systems provide superior heat transfer compared to air cooling, making them highly effective for high-power density applications such as electric vehicles (EVs). The integration of PCM into these systems ensures that temperature spikes are mitigated during periods of high thermal load, such as rapid charging or discharging cycles. Wang et al. [54] developed a novel hybrid system combining wavy microchannel cold plates with PCM, which significantly improved both active and passive cooling of cylindrical lithium-ion battery packs. This design not only enhanced the heat-dissipation capabilities but also maintained uniform temperatures across the battery pack, minimizing thermal gradients and hotspots. Li et al. [55] developed a novel passive thermal regulator for lithium-ion batteries, utilizing the volume change during phase transitions of composite phase-change materials (cPCM) to control cooling water flow. This regulator significantly reduced the maximum battery temperature by up to 7.94% at high ambient temperatures, maintaining it below 39 °C, and improved temperature uniformity and fluctuation control during dynamic cycling. This design highlights the potential of passive thermal management systems in enhancing battery performance and longevity under various operating conditions. Hybrid PCM-liquid cooling systems offer significant advantages, including enhanced heat transfer efficiency due to the high thermal conductivity of liquid coolants, leading to faster and more efficient cooling. They improve temperature uniformity across the battery pack, reducing temperature differences and preventing localized overheating. These systems also increase reliability by handling peak thermal loads passively, reducing the strain on the liquid cooling system. Moreover, they are energy efficient, as PCM can absorb peak thermal loads, minimizing the need for continuous liquid cooling. Additionally, these systems are scalable and customizable for various battery sizes and configurations, making them versatile for applications ranging from small electronics to large electric vehicle battery packs [56].

Table 3. An outline of the work that has been done on PCM-cooled BTMS.

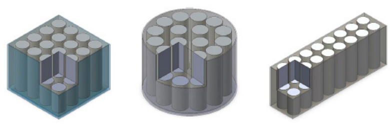
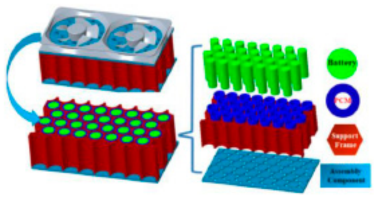
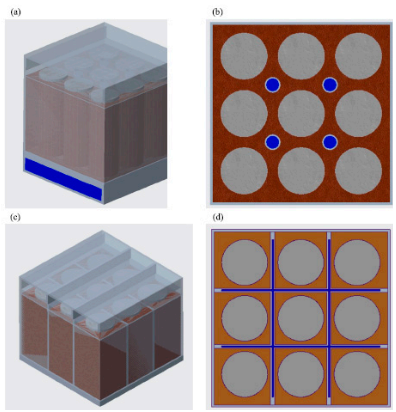
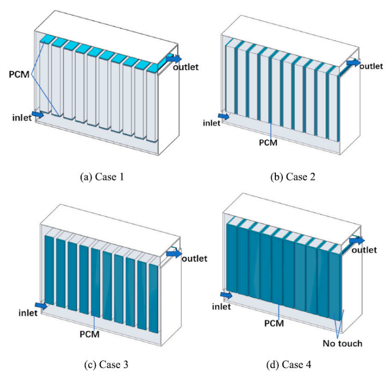
No.	Modification/ Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
1	Lithium-ion (LIB)-PCM Configurations: Square, Circular, Rectangular.	CFD	PCM-RT35 is ideal for temperatures of 20–30 °C. PCM-RT50 is optimal for 40 °C. Copper shells provide superior temperature control. Aluminium shells are more practical. Higher heat transfer coefficients improve temperature stabilization. Rectangular battery packs offer the best thermal management.		[57]	PCM-air
2	Biomimetic Fin with PCM and Delayed Air Cooling	Exp.	Maximum temperature reduced by 3.4 °C using fins. Power consumption reduced by 33% with beak fins. Optimal fin parameters: 75° angle, 40 mm length. Delayed air-cooling reduces power consumption by 59%.		[50]	PCM-air
3	Hybrid PCM with Secondary Air and Liquid Coolants	Exp.	With a discharge rate of 7C, the paraffin with copper foam showed a phase-change percentage of only 6.87%. This suggests effective thermal management without excessive phase change, resulting in reduced pumping power requirements and improved energy efficiency.		[58]	PCM-liquid
4	Optimized PCM Configurations for Prismatic Batteries	CFD	PCM significantly enhances thermal performance. Case 4 saves PCM while maintaining thermal efficiency. Optimized PCM proportion is 64%.		[52]	PCM-air

Table 3. *Cont.*

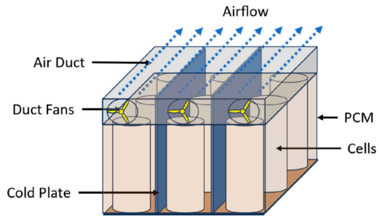
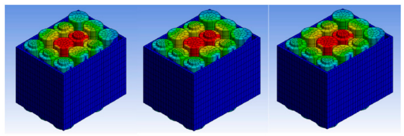
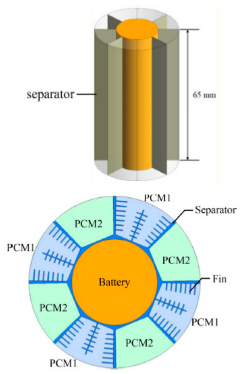
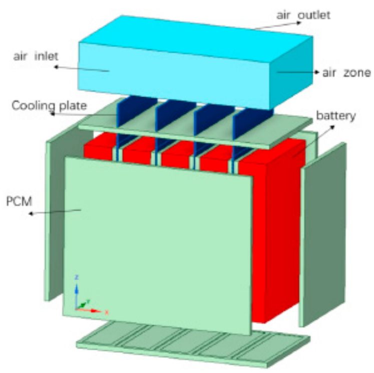
No.	Modification/ Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
5	Hybrid PCM-Air/Fluid Coolants for Enhanced Thermal Performance	CFD	Hybrid strategy with paraffin, air, and fluid coolants significantly improves thermal performance. Eliminates need for pumps. Achieves high temperature uniformity.		[59]	PCM-air
6	Graphene-Enhanced Paraffin PCM	Exp.	In higher temperature scenarios, researchers have found that a hybrid cooling system that combines phase-change material (PCM) with other cooling methods like forced-air or thermoelectric module cooling may be more effective. The inclusion of graphene-enhanced paraffin as a phase-change material (PCM) has a substantial impact on lowering the temperature of the lithium-ion battery pack. It was shown in the study that as the thickness of the PCM layer increases, the maximum temperature decreases.		[60]	PCM-air
7	Dual PCM System with Petal Design and Optimized Fins	CFD	The optimized solution with an asymmetric fin arrangement significantly decreases the maximum temperature difference (ΔT_max) by 5.53% at 30 °C. The optimized solution decreases the maximum temperature difference (ΔT_max) by 29.19% at 40 °C. It reduces the maximum temperature rise (ΔT_(m-rise)) by 36.15% at 30 °C. It reduces the maximum temperature rise (ΔT_(m-rise)) by 42.76% at 40 °C.		[61]	PCM-air
8	PCM-Based BTMS with Air-Cooling and Cold Plate	CFD	Throughout January, the battery temperature was carefully regulated with the help of a BTMS, staying consistently between 20–28 °C. The maximum temperature difference (ΔT) was only 2.6 °C. This demonstrates the successful implementation of efficient thermal management.		[62]	PCM-air

Table 3. *Cont.*

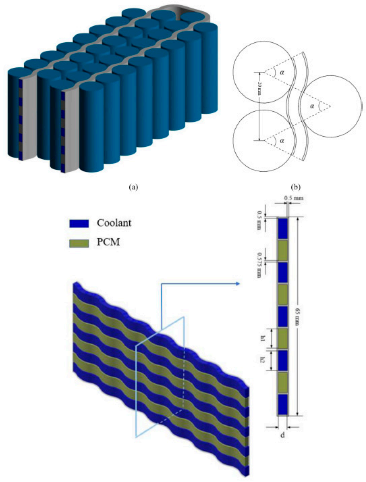
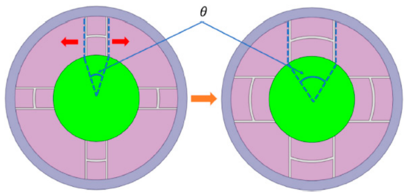
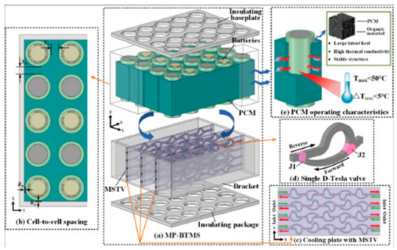
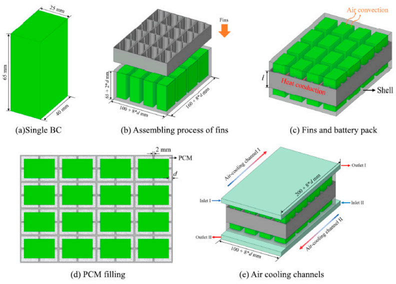
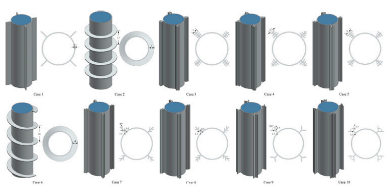
No.	Modification/ Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
9	Hybrid PCM with Wavy Microchannel Cold Plate (HWMCP)	CFD	In cold weather, HWMCP helps prevent battery temperature loss, allowing for longer battery temperature maintenance during short-term parking, compared to WMCP. By reducing the weight of HWMCP by 45%, the system's energy efficiency is significantly improved.		[54]	PCM-liquid
10	Nine Innovative Branch-Fin Designs for Enhanced PCM Thermal Management	CFD	The study presents nine new branch-fin designs for battery thermal management, showing superior thermal performance. These designs increase heat transfer efficiency by 14.98%. They extend operating time by 131.5%. The new designs reduce system weight by 10.28%, compared to conventional designs.		[63]	PCM-air
11	Hybrid PCM with Multi-Stage Tesla Liquid Valve-Cooling	Exp. CFD	The hybrid battery thermal management system with PCM and multistage Tesla valve-cooling significantly decreases energy consumption by 79.9%, compared to traditional systems. It also proves to be more efficient at maintaining battery temperature, especially during cold stops. This results in a doubling of warmth-retention time.		[64]	PCM-liquid
12	Novel BTMS with PCM, Air Cooling, and Fin Structures		Optimal BTMS parameters are d = 8.125 mm and l = 65 mm, with Tmax = 318.01 K, ΔT = 0.0135 K, and W = 5.13 kg. Increasing fin height from 5 mm to 65 mm enhances PCM utilization by 20.4% and reduces Tmax by 9.3 K. As d increases from 5 mm to 20 mm, PCM utilization decreases by 90.9% and BTMS weight increases by 146.7%. Fin addition improves thermal efficiency and compactness, significantly lowering battery temperature.		[65]	PCM-air
13	BTMS with PCM and Optimized Aluminium Fins	CFD	The identified optimal parameters are d = 8.125 mm and l = 65 mm, resulting in Tmax = 318.01 K, ΔT = 0.0135 K, and W = 5.13 kg. By increasing the fin height, the utilization of PCM is improved by 20.4% and the maximum temperature (Tmax) is reduced by 9.3 K. On the other hand, increasing the PCM thickness results in a significant decrease in utilization by 90.9% and a substantial increase in weight by 146.7%.		[66]	PCM-air

Table 3. *Cont.*

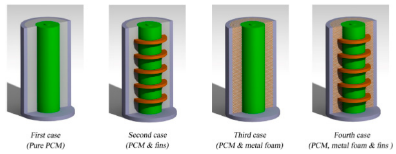
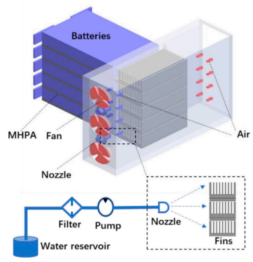
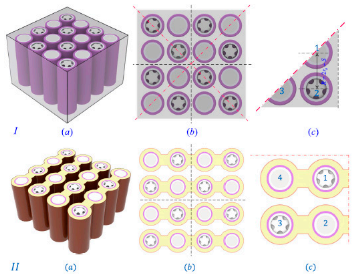
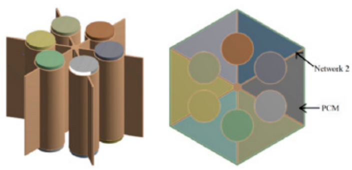
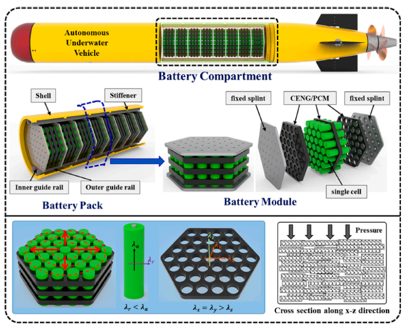
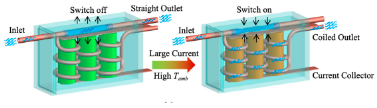
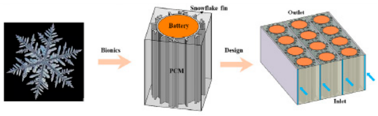
No.	Modification/ Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
14	Innovative BTMS with PCM, Metal Foam, and Fin Shapes	CFD	The fourth case of the BTMS, which combines PCM, metal foam, and fins, exhibited the best thermal performance, keeping the battery surface temperature at the lowest level. This design achieved a maximum reduction of 3 K in battery surface temperature compared to pure PCM systems. Different fin shapes (rectangular, triangular, trapezoidal, I-shape, and wavy) were analyzed. The results showed that, while the triangular fins were most effective before the PCM melting began, the I-shape fins provided the lowest battery surface temperature after the PCM started melting.		[67]	PCM-air
15	Hybrid BTMS with U-Shaped Micro Heat Pipe Array and Composite PCM	Exp.	The hybrid Battery Thermal Management System (BTMS), which combines a U-shaped micro heat pipe array (U-MHPA), composite phase change material (cPCM), and liquid cooling, significantly improves cooling performance. It effectively controls the maximum temperature and temperature difference within the battery module, even under extreme conditions. The system maintains the maximum temperature below 50 °C and the temperature difference below 5 °C.		[68]	PCM-liquid
16	Comparison of Hydrogel and PCM-Based BTMS	CFD	Hydrogel-based BTMS demonstrated superior cooling performance compared to PCM-based systems. It showed a significant decrease of 5.27 °C in maximum temperature under specific conditions.		[69]	PCM-air
17	Electrochemical–Thermal Modeling of Li-ion Batteries with Fin-Intensified PCM BTMS	CFD	Without any thermal management system (TMS), the peak temperature during a 4C discharge reached 336 K. The use of base PCM alone reduced the peak temperature increase by almost 71%. The finned designs further improved this, with Design D1 reducing the temperature increase by 72% and Design D2 by 75.58%.		[70]	PCM-air
18	High-Performance Anisotropic CPCM Composite for Thermal Management	Exp.	The CPCM showed excellent thermal management performance. Under a 2C high discharge rate, the maximum temperature of the battery module with CPCM decreased by 21.9 °C (29.9%). The temperature difference decreased by 7.8 °C (55.3%), compared to modules without CPCM.		[71]	PCM-liquid

Table 3. *Cont.*

No.	Modification/ Novelty	Type of Study	Remarks	Geometry	Ref.	Modification Method
19	Aluminium Nitride Enhanced PCM for Superior Passive Cooling	Exp.	Managing battery temperatures within the range of 25 °C to 45 °C is crucial for optimizing the performance of the thermal regulator. When the temperature is below 30 °C, the batteries can function without the need for active cooling methods, thanks to the use of PCM or cPCM. When the ambient temperature reaches 35 °C, it is important to use a thermal regulator with cooling water to ensure that the battery temperature remains below 38.13 °C. When the ambient temperature exceeds 40 °C, the thermal regulator equipped with cPCM can lower the battery temperature to 35.02 °C.		[55]	PCM-liquid
20	Snowflake Fin Design for Enhanced PCM Heat Transfer	CFD	With the addition of snowflake fins, the heat-transfer efficiency of PCM is greatly improved, resulting in a noticeable reduction in battery temperatures. With a 3C discharge rate, the Batteries–PCM–Fins design effectively keeps the battery module temperature below 45 °C, regardless of whether the ambient temperatures are 25 °C or 40 °C. The temperature difference remains less than 3 °C, ensuring optimal performance. These snowflake fins are designed to enhance thermal management efficiency, particularly during the initial cycles. They achieve this by minimizing the maximum temperature and temperature difference within the battery module.		[72]	PCM-liquid

2.4. Thermoelectric Cooler BTMS

Traditional cooling technologies such as air cooling and liquid cooling have reached their maximum cooling potential. TECs remain a favoured cooling technology for various applications due to their affordability and environmentally friendly features [73]. There are two main categories of thermoelectric devices: thermoelectric generators (TEGs) and thermoelectric coolers (TECs) [74]. Thermoelectric generators (TEGs) use the Seebeck effect to convert heat energy into electrical energy. The Seebeck effect is a fascinating phenomenon that occurs when there is a temperature difference between two electrical conductors or semiconductors, resulting in the generation of a voltage differential. It is truly remarkable how temperature can have such a profound impact on electrical properties. TECs utilize electricity to disperse heat from a medium through the Peltier effect. This effect occurs when an electric current passes across the interface of two materials, causing the absorption or dissipation of heat [75]. TECs offer several advantages, such as a lightweight design, compact size, minimal noise, straightforward operation, and a long lifespan. TECs are utilized in a wide range of industries, such as microelectronics, communications, laser diodes, superconductor systems, the aerospace industry, healthcare, and the food sector, among numerous others [76].

TEC-based BTMS was first proposed by Li et al. [77] for controlling a battery pack temperature. In this study, an innovative battery pack design was presented, incorporating an acrylic container and copper holders, combined with a thermoelectric cooling system integrated with liquid and air circulations, which demonstrated a significant thermal management improvement, achieving a reduction of approximately 20 °C under a 40 V input, compared to conventional liquid cooling, and maintaining battery temperatures below critical thresholds during extreme discharge conditions. Hameed et al. [78] introduced a novel TEC–TEG BTMS. In this study, a new hybrid battery thermal management system (BTMS) was developed, which combined thermoelectric cooling (TEC) and thermoelectric generation (TEG) with forced air. The system effectively decreased the maximum surface temperature of a single $LiFePO_4$ battery cell by around 7 °C. Table 4 shows the newest findings in thermoelectric cooling-based BTMSs.

Table 4. An outline of the work that has been done on TEC-cooled BTMS.

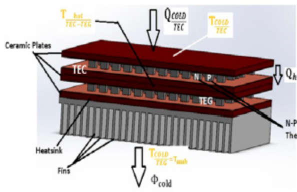
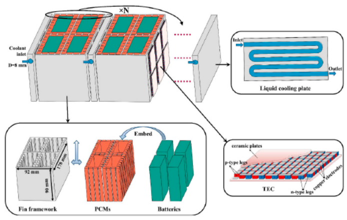
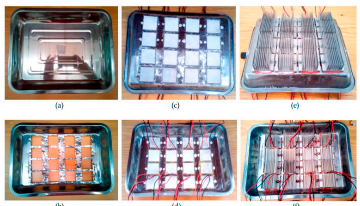
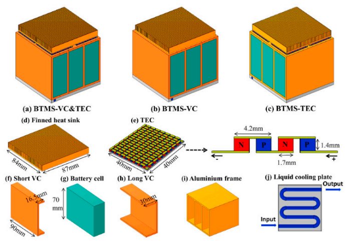
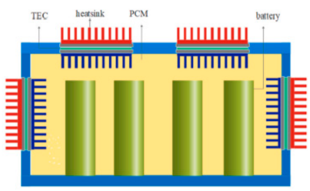
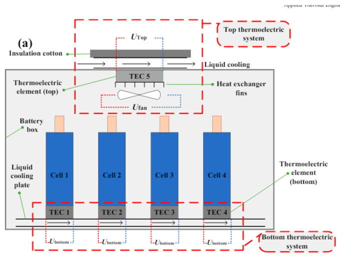
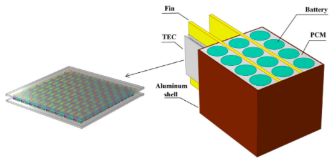
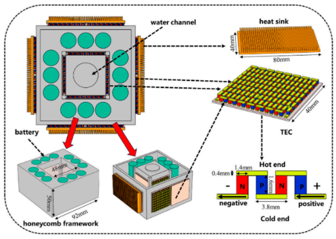
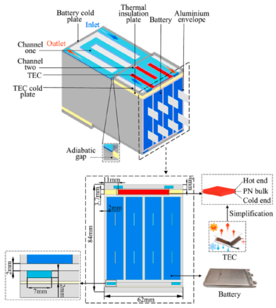
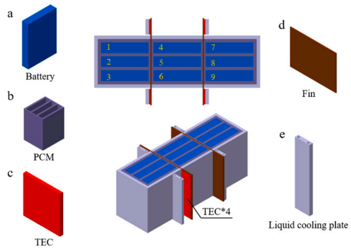
No.	Modification/ Novelty	Type of Study	Remarks	Geometry	Ref.
1	Enhanced BTMS Cooling: Using TEG to Power TEC for Improved Heat Management	CFD	To increase the heat dissipation of TEC–TEG, high-quality heat sinks are used to make the temperature of BTMS as close to ambient temperature as possible. The findings revealed that the maximum battery surface temperature decreased from 38 °C to 33.1584 °C with the introduced BTMS.		[78]
2	Novel BTMS: Integrating TECs and PCMs with Cooling Plate for Efficient Lithium-Ion Battery Temperature Control	CFD	Optimal fin length and thickness are 7 mm and 3 mm, respectively. At a 3 A TEC input current, the maximum temperature, temperature difference, and PCM liquid fraction were 315.10 K, 2.39 K, and 0.002 in Case 1. At a discharge rate of 5C, the maximum temperature, temperature difference, and PCM liquid fraction were 318.24 K, 3.60 K, and 0.181.		[79]
3	EV BTMS: Efficient Heat Transport from Battery Pack to TEC Cold Side and Release via Heatsink	Exp.	Forced air, and thermoelectric cooling (TEC) and -generation (TEG), are used to reduce the maximum surface temperature of a $LiFePO_4$ battery cell by approximately 7 °C.		[80]
4	Active–Passive Hybrid BTMS: Combining TEC and PCM with CFD Simulation for Optimal Thermal Performance	CFD	The findings reveal that, even under a high discharge rate of 3C, the system can maintain the maximum temperature of batteries below 45 °C, while ensuring that the maximum temperature difference during the discharge process remains within 3 °C.		[81]
5	Hybrid TEC–PCM BTMS with Circular and Axial Fin Arrangements: Evaluating Temperature in Middle and Top Sections of Battery	Exp.	The use of aluminium circular fins, PCM, and a thermoelectric cooling system significantly reduced battery temperature to 65 °C. Changing the fin configuration from circular to axial led to an average temperature of 48 °C. This study found that axial fins regulate LIB temperature better than ring fins. The battery body's top temperature is always higher than the middle, regardless of mode or time interval.		[82]

Table 4. *Cont.*

No.	Modification/Novelty	Type of Study	Remarks	Geometry	Ref.
6	BTMS for Battery Module Heating: Dual TECs (6 V Bottom, 9 V Top) and 10 V Fan with Cold Plate Integration	Exp.	The total power consumption of the system is 81.2 W, with the bottom TEC consuming 31.21 W, the top TEC using 47 W, and the electronic fan requiring 2.994 W. This demonstrates the overall effectiveness and energy efficiency of the system. The battery capacity increases by 9.1% as the ambient temperature rises from −5 °C to 5 °C. At a bottom TEC voltage of 6 V, it takes 1631 s to heat the battery from −5 °C to 5 °C without top TEC voltage, with a temperature difference normally below 5.5 °C.		[83]
7	BTMS with PC-Wrapped Cells in Aluminum Case: TEC and Fins for Enhanced Heat Transfer, Tested at High Discharge Rates	CFD	Increasing TEC current lowers battery temperature and decreases uniformity and cooling efficiency; a 2A current keeps the battery below 40 °C. Delaying TEC current at 80% PCM melting rate improves temperature homogeneity, while a 2A current maintains a temperature gradient under 5 °C and extends effective temperature-control time. While the transient PCM + TEC model maintains temperature control and uniformity during 4C discharge, pulsed TEC current improves cooling power and thermal performance.		[84]
8	Proposed Battery Pack: Four Heat Sinks, 12 TECs, Honeycomb Framework, and Water Channel-Integration	CFD	Thermoelectric coolers (TECs) improve the thermal management of batteries by providing the best cooling performance when a current of 5A is applied. However, the efficiency of TECs decreases when the current exceeds this value. Air and water cooling enhance the efficiency of TEC, with recommended values for optimal performance being 50 W/m^2K for air convection and 0.11 m/s for water flow. Optimizing thermal performance and energy efficiency requires precise control strategies to balance TEC input, air cooling, and water cooling-parameters.		[85]
9	Dual Active BTMS: Incorporating Thermal Insulation Plate, TECs, and Liquid Cold Plates for Enhanced Cooling	CFD Exp.	TEC helps batteries maintain a reasonable temperature range in harsh environments and at a 3C discharge rate. Dual active cooling reduces energy consumption more efficiently than pure TEC cooling. Pure liquid cooling uses less energy, but TEC ensures acceptable battery performance under challenging conditions.		[86]
10	Hybrid Active–Passive BTMS: PCM, TEC, Liquid Cooling, and Fins for Enhanced Heat Transfer	CFD	Increasing fin thickness from 2 mm to 8 mm extends temperature control by 12%, enhancing thermoelectric cooler (TEC) cooling power and COP. Fins improve cooling capacity and temperature uniformity, with 4 mm fins being particularly effective. TEC input currents from 1A to 6A boost temperature control by 87.42%.		[87]

3. Discussion and Conclusions

The importance of effective battery thermal management systems (BTMS) for Li-ion batteries cannot be overstated, especially given their critical role in electric vehicles (EVs) and renewable energy-storage systems. In this section, after presenting the main findings for each method, a techno-economic comparative analysis of the four primary cooling methods—air-cooling, liquid-cooling, phase-change material (PCM)-cooling, and thermoelectric cooling—is presented. Furthermore, the main advantages and disadvantages of each method are stated.

3.1. Summary of Key Findings

Air cooling: Air-cooling methods, categorized into free and forced convection, offer simplicity, low cost, and ease of maintenance. However, their efficiency decreases significantly at high ambient temperatures. Researchers have proposed various modifications, such as air-channel modification, adding fin structures, and changing cell arrangements to enhance the performance of air-cooled BTMS.

- Air channel modifications are the most impactful, with designs like the X-type, honeycomb structures, and multiple inlet/outlet air cooling significantly improving temperature management.
- Cell arrangement modifications also contribute to better thermal performance, with innovative designs such as the modified Z-shaped system and the staggered-arranged system.
- Adding fin structures greatly enhances cooling efficiency by increasing the heat-dissipation surface area using radial fins for air-cooling and direct cooling with baffles.

These findings emphasize that modifying air channels, cell arrangements, and adding fin structures can significantly improve the performance of air-cooled BTMS. These improvements help maintain battery temperatures within optimal ranges, thereby enhancing the overall performance and safety of Li-ion batteries in electric vehicles.

Liquid-cooling: Liquid-cooling methods, including liquid indirect cooling (LIDC-BTMS) and liquid direct cooling (LDC-BTMS), are highly effective for demanding applications like EVs. Liquid cooling offers superior heat-transfer capabilities compared to air-cooling, making it suitable for high-power density scenarios.

- Cold plate modifications show significant improvements in cooling efficiency, with designs like the spider web liquid channel, mini channel plates with circular and zigzag channels, and the diamond flow type channel maintaining optimal temperatures under high-load conditions.
- Cooling channel modifications enhance thermal management by optimizing fluid flow, wavy microchannels, increasing surface area for heat dissipation, and using advanced materials such as nanofluids and dielectric fluids.
- Hybrid systems combining PCM and liquid-cooling methods provide superior temperature control, ensuring consistent battery performance, even under extreme conditions.

These findings highlight that liquid-cooling methods, particularly with advanced cold plate designs and optimized cooling channels, offer superior thermal management for Li-ion batteries. Hybrid systems that integrate PCM with liquid cooling further enhance cooling performance, making them highly suitable for demanding applications such as electric vehicles.

PCM Cooling: PCM-based cooling provides passive thermal management by absorbing heat during phase transitions. This method is effective for maintaining consistent battery temperatures but requires supplementary active cooling systems for prolonged high-power operations.

- PCM configurations such as square, circular, and rectangular designs optimize thermal management for specific temperature ranges, with materials like copper shells providing enhanced temperature control.
- Hybrid PCM systems that integrate PCM with air- or liquid-cooling methods offer improved temperature regulation and energy efficiency. These systems are particularly effective at managing thermal loads during high discharge rates.
- Innovative PCM designs featuring advanced fin structures and optimized configurations significantly enhance heat-transfer efficiency, reduce temperature differences, and extend battery operating time.

These findings highlight the effectiveness of PCM-based cooling methods in providing passive thermal management for Li-ion batteries. By incorporating advanced designs and hybrid systems, PCM cooling can maintain optimal battery temperatures, improving performance and safety in various applications, including electric vehicles.

TEC cooling: Thermoelectric coolers (TECs) utilize the Peltier effect for efficient temperature control. TECs offer advantages such as compact size, low noise, and long lifespan, making them suitable for various applications, including BTMS.

- Hybrid TEC–TEG systems demonstrate substantial improvements in cooling efficiency by leveraging the benefits of both TEC and TEG. These systems are effective at significantly reducing battery temperatures.
- Active and passive hybrid systems that integrate TEC with PCM or fins show enhanced temperature regulation and energy efficiency. These systems are particularly effective at managing thermal loads during high discharge rates.
- Innovative TEC designs offer advanced solutions for thermal management, such as dual active cooling systems and TEC with cold plates. These designs provide efficient cooling, and maintain battery temperatures within optimal ranges, even under extreme conditions.

These findings highlight the potential of thermoelectric cooling methods for providing efficient and reliable thermal management for Li-ion batteries. By integrating TEC with other cooling technologies and optimizing system designs, thermoelectric cooling can significantly enhance battery performance and safety, making it a viable option for applications in electric vehicles and other high-demand scenarios.

3.2. Techno-Economic Comparative Analysis of Cooling Methods

To compare the four cooling methods (air-cooling, liquid-cooling, PCM-cooling, and thermoelectric cooling), several key terms are defined that will help to evaluate their performance, efficiency, and suitability for different applications:

- Cooling Efficiency (CE): measures how effectively a cooling method maintains the battery temperature within the optimal range.
- Temperature Uniformity (TU): assesses the ability of the cooling method to maintain a uniform temperature distribution across the battery pack.
- Maximum Temperature Reduction (MTR): the extent to which the cooling method can lower the maximum temperature of the battery.
- Energy Consumption (EC): the amount of energy required by the cooling method to maintain optimal battery temperatures.
- System Complexity (SC): the level of complexity involved in implementing and maintaining the cooling method.
- Response Time (RT): the speed at which the cooling method can adapt to changes in thermal load.
- Cost-Effectiveness (C-E): the overall cost of implementing and operating the cooling method, relative to its performance benefits.
- Scalability (S): the ease with which the cooling method can be scaled up or down to accommodate different battery sizes and configurations.
- Safety and Reliability (SR): the degree to which the cooling method enhances battery safety and operational reliability.

Table 5 summarises the comparison of these methods from various aspects.

Using the data presented in Table 5, the technical performance and economic feasibility of air-cooling, liquid-cooling, PCM-cooling, and thermoelectric cooling methods is evaluated.

Table 5. Summary table of comparative study.

	Air Cooling	Liquid Cooling	PCM Cooling	TEC Cooling
CE	Moderate	High	Moderate/High	High
TU	Good	Excellent	Good	Excellent
MTR	High	High	Moderate	High
EC	Low	Moderate	Low	High
SC	Low	High	Moderate	High
RT	Moderate	Fast	Slow	Fast
CE	High	Moderate	High	Moderate
S	High	Moderate	High	Moderate
SR	Moderate	High	High	High

Air-cooling systems are highly cost-effective due to their low initial and maintenance costs. They are suitable for applications where moderate cooling performance is acceptable, and system simplicity is desired. While liquid-cooling systems have higher costs associated with their complexity and energy consumption, their high cooling efficiency and reliability make them suitable for high-demand applications like electric vehicles. PCM-based cooling methods are cost-effective, with low operational costs and moderate system complexity. They are ideal for applications requiring consistent thermal management with minimal energy consumption. Thermoelectric cooling methods, while offering high performance and precise control, come with higher costs and energy consumption. They are suitable for high-end applications where precise temperature management is critical.

Using this techno-economic analysis, a summary is presented in Table 6 showing the advantages and disadvantages of each method as well.

Table 6. Techno-Economic Comparison of Cooling Methods.

Cooling Method	Advantages	Disadvantages
Air-cooling	Cost-effective, uncomplicated design and maintenance	Less efficient at high thermal loads
Liquid-cooling	Excellent performance, high cooling efficiency	Higher cost, complex design and maintenance
PCM-cooling	Satisfactory performance, low energy consumption and cost	Suitable for passive cooling, slower response time
TEC-cooling	Precise temperature control, quick response	More expensive, high-energy consumption

From a techno-economic perspective, each cooling method has distinct advantages and disadvantages. Air-cooling is cost-effective and simple but less efficient at high thermal loads. Liquid-cooling provides excellent performance but at higher costs and complexity. PCM-cooling offers a balance of good performance with low energy consumption and cost, suitable for passive cooling needs. Thermoelectric cooling provides precise control but is more expensive and energy-intensive.

Selecting the appropriate cooling method depends on specific application requirements, including performance, cost constraints, system complexity, and operational conditions. Hybrid systems that combine multiple cooling methods can leverage the strengths of each approach to achieve optimal performance and cost-effectiveness.

4. Future Directions and Recommendations

The future of Battery Thermal Management Systems (BTMS) looks promising, thanks to new trends and technological developments. The focus of research could be on innovative materials such as nanomaterials and Phase Change Materials (PCMs), hybrid cooling systems that combine several approaches, and intelligent–adaptive BTMS with real-time control. Innovations in microchannel designs, nanofluids, and thermoelectric and magnetocaloric cooling technologies aim to improve efficiency and reduce size. Highfidelity computational models and artificial intelligence integration are planned to improve BTMS operation. Sustainability and cost-effectiveness remain important factors, as do technical obstacles and regulatory demands. Multidisciplinary co-operation and long-term testing will be critical for the successful implementation of next-generation BTMS, which will provide dependable, efficient, and environmentally friendly thermal management for lithium-ion batteries.

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