

Advanced Battery Thermal Management Systems: A Comprehensive Review of Performance Optimization Using Nano-Enhanced Phase Change Materials

Saad Hussain*

Mechanical Engineering Department, University of Management and Technology, Lahore, Pakistan

Safdar Ali

Department of Mechanical Engineering, School of Engineering, Glasgow Caledonian University, United Kingdom

Rana Mehmood

Department of Physics, University of Kotli, Azad Jammu and Kashmir, Pakistan

ABSTRACT

Electric cars (EVs) and other applications that require high battery capacities apply batteries that cannot be used without prior Battery Thermal Management Information Systems (BTMS) in order to ensure the battery content remains cool and safe enough to use in the long run. This review gives an extensive contrast of the various cooling techniques adopted by BTMS. The paper presents an analytical evaluation of 4 major cooling mechanisms including air cooling, liquid cooling, phase change material (PCM) based cooling, and thermoelectric cooling (TEC). It outlines the functioning of each strategy, design modifications, thermal capabilities as well as the applicability to different operating conditions. It is possible to greatly improve air cooling solutions through the optimization of cell layouts, incorporation of fins to enhance air distribution and temperature consistency and the alteration of air channels. The advantages of these methods are that they are cheap and easy to perform. High heat transfer capability provided by liquid cooling due to its innovative cold plate and channel designs as well as coolants like Nano fluids make it an excellent choice in high-load pursuits. With the processes with high-conductivity material added, or even hybridized with active systems, PCM-based systems can achieve greater performance, or passive thermal control can occur as a result of an absorption of latent heat. Besides the technical performance analysis, the review entails a techno-economic analysis of each method based on factors like cooling efficiency, temperature uniformity, and complexity of the system, energy and costs.

Air cooling is very inexpensive and easy to implement and works well on high thermal cases. A liquid cooling process will provide uniform and fast heat disposal, but a higher complexity level and higher operating expenses. The PCM-based systems are energy efficient and low-maintenance, operational especially during transient thermal conditioning, which is useful mainly as a thermal buffer of peak power requirements, but not designed to accommodate the constant high power. Although with great precision and rapid reaction speed, TEC-based cooling is limited by its power consumption and price. The drawbacks and limitations of each of the methods highlight the need of application-specific BTMS designs to achieve a trade-off between thermal performance, cost and system complexity. In the long run, the future of BTMS is the hybrid design, where proactive and passive approaches are coupled to enjoy the best of both worlds. Novel high-performance material developmental technologies, such as nanomaterial and magneto caloric materials have the potential to improve heat transfer and energy efficiency. Moreover, artificial intelligence, real-time monitoring, and adaptive control systems integration will allow intelligent thermal regulation depending on the dynamic loading conditions. The trend to reduce the weight, volume, and power consumption of BTMS designs will be aided by developments in micro channel cooling interfaces, smart fluids and integrated energy recovery systems. On the whole, this review complements the importance of interdisciplinary studies, sustainability aspects, and the ongoing development of BTMS technologies to support the raising needs of contemporary energy systems.

Keywords: Advanced Battery Thermal, Comprehensive Review of Performance Optimization, Nano-Enhanced Phase Change Material

1. Research Background

The exponential growth in electric vehicle (EV) and portable electronic equipment demand has made lithium-ion (Li-ion) battery the mainstay of contemporary energy storage systems because of their high energy density, long life cycle, and thin lightweight design. Nonetheless, rapid charging/discharging as well as exposure to hostile environments in the form of thermal instability is a major risk to performance and safety. Unresolved, such thermal issues can result in poor temperature distribution, rapid aging, or disastrous systemic breakdown such as

thermal runaway [1] The thermal management of these systems, such as air cooling and liquid cooling systems, is typically less effective at managing high thermal loads, creating a necessity to develop alternative methods of management [2]

Researchers have actively sought the inclusion of phase change materials (PCMs) in BTMS to overcome these shortcomings because of their properties to absorb the excess heat in the form of latent heat transitions. However, the low thermal conductivity of pure PCMs limits their ability to be used in real-time thermal regulation [3]. As a reaction, nano-enhanced phase change materials (NePCMs), which largely focus on the addition of high-thermal-conductivity nanoparticles (e.g., graphene, Al_2O_3 , CuO), have exhibited much-enhanced thermal conductivity and heat storage capability (Saeed et al., 2021). This development has proven a good way to maintain battery temperature, efficiency of the system, and ultimately battery life. PCMs with other hybrid cooling strategies along with computational fluid dynamics (CFD) simulations, are thus emerging as a center of interest in creating next-generation lithium-ion batteries with high-performance BTMS designs. [4].

A fundamental aspect of designing any Battery Thermal Management System (BTMS) is a thorough understanding of the thermal behavior of the battery system. Figure 1 schematically presents the thermal dynamics involved within a battery. Heat generation in batteries stems from multiple sources, including ion intercalation phase transitions, electrochemical over potentials, and mixing-related heat release. Among these, the latter three processes contribute to **irreversible heat generation**, which accumulates and raises the internal temperature. In contrast, **entropic heat**, associated with the reversible isothermal reactions during battery operation, is categorized as **reversible heat**, as it depends on the state of charge and the thermodynamic properties of the system [5] The principal contributors to thermal generation under over potentials include (i) electrochemical reactions at the electrode-electrolyte interfaces, (ii) electron transport resulting in Joule heating due to internal resistance, and (iii) ionic conduction losses within the electrolyte. These heat sources collectively determine the thermal load on BTMS and underscore the importance of precise thermal modeling for effective thermal regulation.

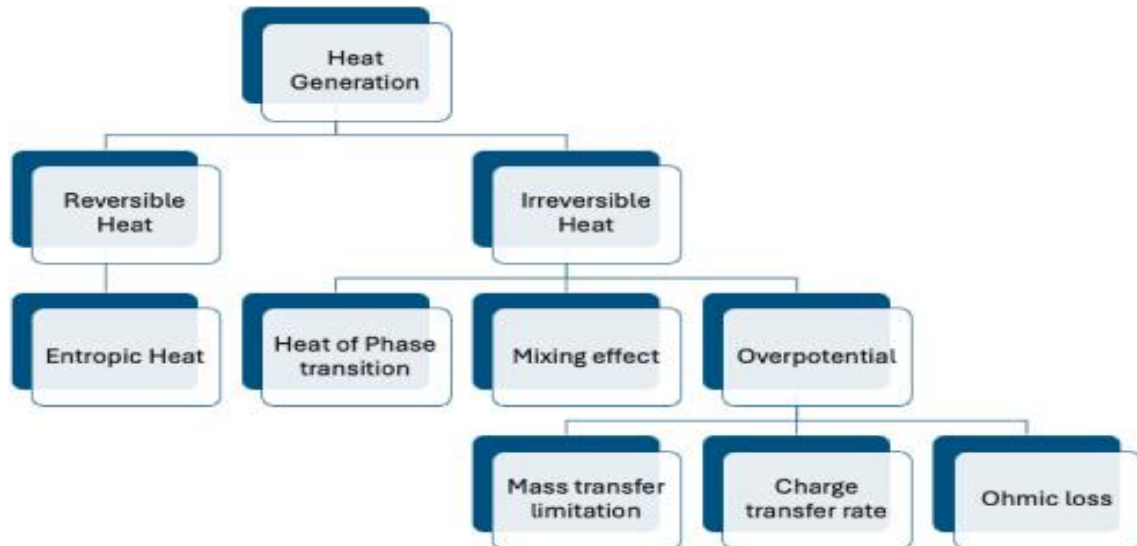


Fig 1: Thermal behavior of battery system and heat flow chart

1.1 The Need for Efficient Battery Thermal Regulation

These batteries are very sensitive to temperatures which can affect their performance, safety and their lifecycle greatly with high temperatures, batteries are subjected to the risks of thermal runaway, loss of charge capacity and even faster degradation of electrode materials [7]. On the other hand, charge acceptance is blocked by very cold temperatures, which inhibit electrochemistry. This has necessitated the use of battery thermal management systems (BTMS) to maintain the stable performance of the modern battery technologies.

1.2 Types of Battery Thermal Management Systems (BTMS)

Battery Thermal Management Systems (BTMS) are imperative in keeping battery packs within the recommended temperature levels so as to guarantee safety, maximize life, and improve overall functionality. Such systems are particularly relevant in high power applications in electric vehicles (EVs), hybrid electric vehicles (HEVs), and grid-scale storage systems where the batteries are often charged and discharged frequently in a wide range of environmental conditions. Generally, there are two major categories of BTMS, the active and passive systems [8].

Active systems rely on the use of outside power to drive elements like pumps, rather than to passively dissipate heat, but to actively remove it in a desired direction either away or towards the battery pack, depending on the thermal

management need. They are air-cooling, liquid-cooling, and refrigeration types. Air-cooling systems can use natural or forced convection to circulate air across battery modules; they are simple and cost-effective but generally insufficient for high-power batteries due to low heat transfer coefficients. In contrast, liquid-cooling systems are significantly more efficient because liquids have higher thermal conductivities and specific heat capacities than air. These systems employ coolant channels or cold plates integrated within or around the battery structure to uniformly manage heat. For even more stringent thermal control, especially under high ambient temperatures or in high-performance vehicles, vapor compression-based refrigeration systems are used, offering precise and powerful cooling but at the cost of added complexity, size, and energy consumption [9].

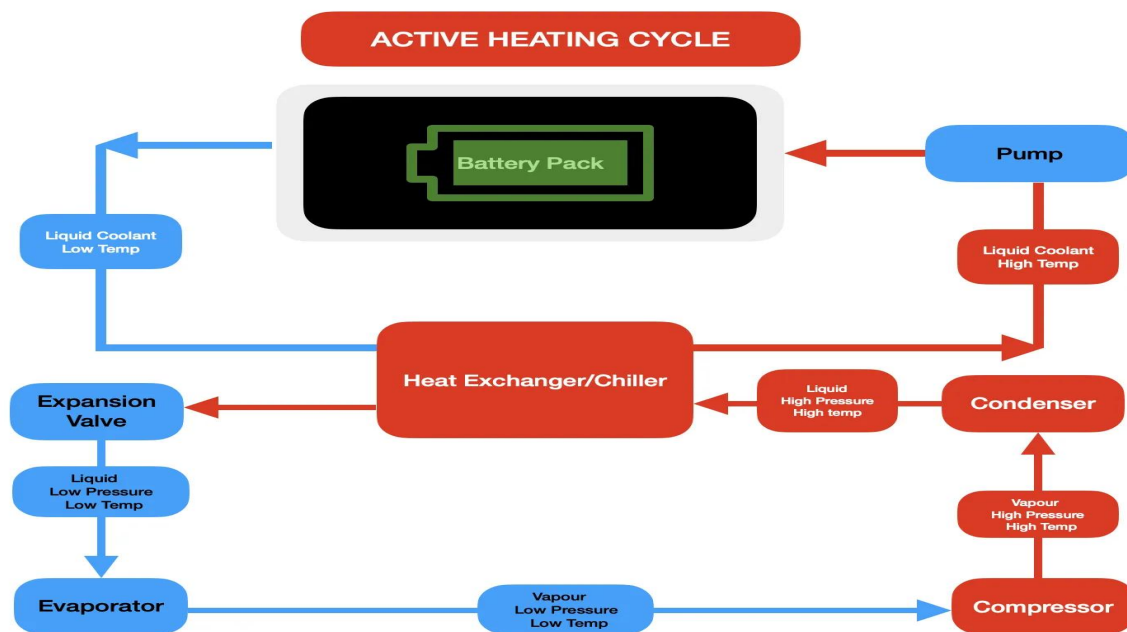


Fig 2: Types of thermal battery management system

Thermoelectric cooling (TEC), based on the Peltier effect, is another form of active BTMS where solid-state thermoelectric devices are placed directly onto battery modules to regulate localized temperatures. These systems allow rapid and targeted heat absorption or rejection without moving parts, making them compact and reliable. However, they are often limited by relatively low coefficient of performance (COP) values and high energy consumption, making them suitable mostly for

auxiliary or niche applications. Despite the superior thermal control offered by active BTMS, their main drawbacks include greater system complexity, higher cost, and parasitic energy losses that reduce overall energy efficiency—especially in mobile or electric vehicle applications where energy conservation is a top priority. In the past years, students have been conducting research on how to ensure that these systems are optimally designed by focusing on optimizing coolant flow channels and the geometrical shape of the heat exchangers and incorporation of smart control algorithms that changes cooling performance with the battery operating conditions. In addition, smaller and lighter weight modules and mini-channels and micro-channel cooling structures are under development to provide rapid heat transfer rates at minimal weight and volume increase [10].

Conversely, passive BTMS are created to control the heat loads using the natural thermal characteristics of materials and system design without using any external energy resource to achieve it. They are most suitable where efficiency in using power and simplicity of the system is paramount. Phase change materials (PCMs) are the well-researched passive materials with a high capacity to absorb latent heat of phase transitions (generally solid-to-liquid) to counter temperature increases on peak load times. This is useful in maintaining the cell temperature when charging/discharging. Nonetheless, PCMs have other associated problems of poor thermo conductivity, a characteristic that restricts their heating or cooling rates. To remedy this, scientists or researchers have offered hybrids PCM composites, with high-conductivity additives, like graphite, carbon nanotubes, or metal foams. Other passive methods are heat pipes and vapor chambers, which can achieve fast lateral heat transfer by virtue of the evaporation and condensation of a working fluid in an enclosed system. These materials possess a high practical thermal conductivity which serves them well in ensuring an even distribution of temperature within the batteries. Also, optimizations related to design (cell spacing, thermal insulation layers, high-conductivity structure materials) provide some assistance in minimizing the thermal gradients present in battery packs. Although passive BTMS are lightweight, requiring no maintenance, and energy-efficient, the lower capacity to deal with a high heat load limits their application to high-performance EVs or systems with aggressive fast-changing regimes [11]. To fill the gap numerous

contemporary designs are experimenting with hybrid systems that synergistically integrate passive and active components to provide excellent thermal performance with minimal energy overload

1.3 Challenges in Current BTMS Designs

In spite of substantial technological advancement of the Battery Thermal Management Systems (BTMS), there exist major obstacles that continue to hinder the utilization of the best battery thermo-management performance, safety and durability. The main problem is the low thermal conductivity of most of the materials in BTMS, particularly in passive cooling systems. Commercially available BTMS materials (e.g., paraffin-based phase change materials (PCMs) or polymeric insulators) have unacceptable heat transfer capabilities, which limits the rate at which heat may be dumped upon high-rate charging or discharging. This makes not only local temperature hotspots occur inside the battery modules but also causes thermal gradients which can spur research cell degradation and diminish battery uniformity with time [12].

The other common problem is the lack of efficiencies in how the thermal management parts are integrated into battery pack design. Some systems also depend on large or externally positioned cooling devices which constrain the design freedom and add to the net weight and volumetric bulk of the energy storage system. This poses particular trouble in the area of electric vehicles (EVs) and aerospace uses, where space, weight, and efficiency are critical. Improper spatial integration may also lead to non-uniform cooling, with parts of the total pack under-cooled and some parts overcooled which introduces an imbalance in thermal conditions and stability of performance of that battery pack [13].

Passive BTMS performance bottlenecks are brought about by the selection of PCMs. Although PCMs are preferred because of their latent heat storage capability in phase transitions, they can have very low thermal diffusivity and even slower melting/solidification cycles, and are thus slow to react to dynamic thermal loads. Also, PCMs alone are not able to help regulate sudden temperature fluctuations, which often happen during rapid charging processes or potentially intense driving [14] unless supported by potent thermal conductivity sprinklers such as graphite, carbon nanotubes, or metal foams.

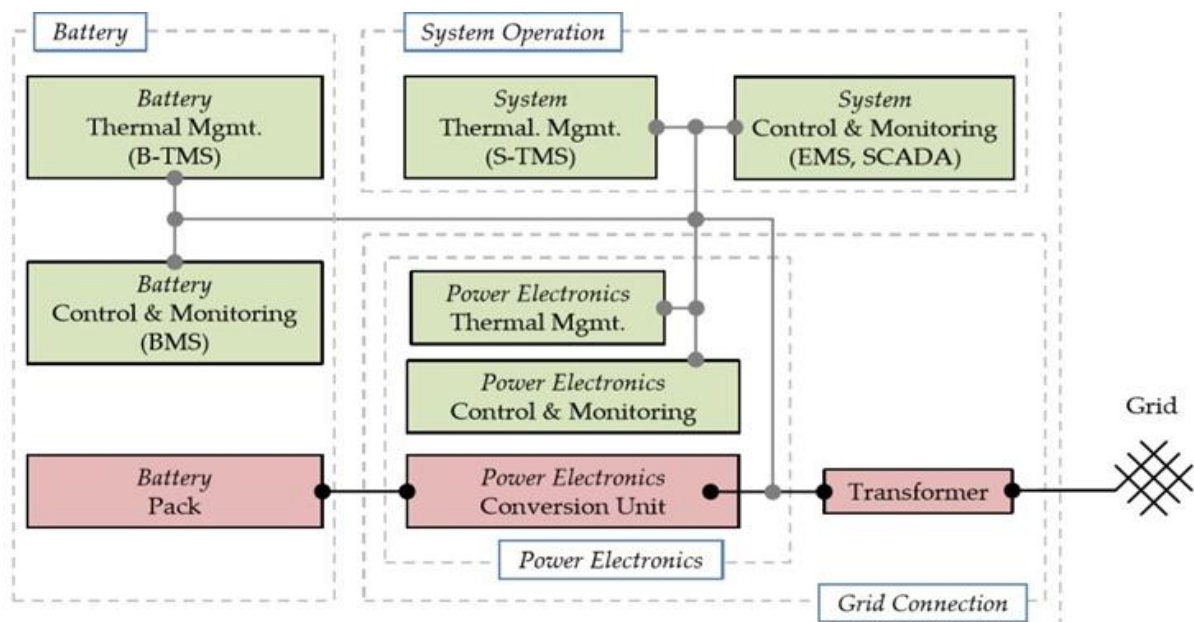


Fig 3: BTMS Challenges

As energy densities and power capacities of modern lithium-ion batteries especially in high-performance EVs grow, there is a rising need to support more responsive and adaptive BTMS architectures. When a transient increase in thermal energy occurs as can be seen in extreme acceleration or regenerative braking the existing systems fail to manage the temporary increase in heat efficiently enough and the rate of heat generation in the system may go beyond the dissipation capacity of the system. When this becomes the case, the risks of thermal runaway increases and can present severe safety hazards such as fire and explosion [15].

Moreover, poor insulation, as well as low-quality materials, causes poor frictional losses, heat escape and parasitic power usage. Such losses lower the two-way battery system performance and limit the usable working life. As an example, cold modules without strong insulation might need active cooling during extended periods of time, which adds power consumption on auxiliary systems and dilutes the amount of energy left to drive the propulsion or the loads [16].

To conclude, recent advances in BTMS have several fold problems including materials science constraints, system integration difficulties, and lack of dynamism when given multifaceted thermal demands. To make battery systems safer, more efficient, and longer-lasting, BTMS development in the future has to be oriented on using advanced composite materials, compact geometrical configurations, hybrid

cooling procedures, and smart thermal control processes.

1.4 Need for Innovative BTMS Approaches

The constraints around current Battery Thermal Management Systems (BTMS) get even more evident as energy storage technologies become progressively more demanding to keep up in areas like Electric Vehicles (EVs), Aerospace, and grid-scale storage. More innovative and adaptive BTMS solutions are much needed to be able to manage the increased thermal loads, more restrictive packaging requirements, and accelerated charging rates that next-generation batteries would have. Such innovations should focus on solving material-level applications and enhance system-level inefficiencies that thermal management needs to be as up to date with battery chemistry and design advancements [17].

Among the most promising paths, there can be found the integration of hybrid BTMS which are synergistically composed of both passive (e.g., phase change materials, heat pipes) and active (e.g., liquid cooling, air flow systems, thermoelectric modules) approaches. Such a two-pronged strategy can enable systems to take advantage of the high energy efficiency of passive cooling at low-to-moderate levels of thermal loading, but turn to active cooling in the face of peak operating loads. This type of hybrid system may offer dynamic transient thermal management and keep the temperature uniform within a battery and avoid localized hotspots, which is a common cause of thermal runaway or accelerated battery degradation [18].

The second frontier in BTMS innovation concerns the use of high-performance thermal interface materials (TIMs). The role of TIMs is to reduce the thermal resistance at the interface between cooling components and the battery cells. Convention TIMs are ultimately being substituted by superiorized materials such as grapheme-reinforced composites, carbon nanotubes, boron nitride Nano sheets and metal nanoparticle-reinforced polymers. These materials present outstanding thermal conductivity and mechanical flexibility and chemical stability, enabling better heat transfer even during cyclic loading and long-term endurance [19].

Moreover, battery module structural redesigns are also appearing as an important enabler to improved thermal management. New ways of arranging cells (e.g. staggered, hexagonal, or cross-flow shapes), built-in cooling channels, modular designs enable optimizing fluid flows and airflow within small battery enclosures. As

an example, the structural layers of battery packs can have micro channel liquid cooling to substantially enhance heat dissipation without overweighting or overcomplicating battery packs [20].

Nanomaterial invention has brought with it another revolutionizing possibility when it comes to BTMS design. Nanostructured PCMs containing an embedded conductive additive (e.g., nano metals oxides, Nano carbons) address the historical limitations of low thermal conductivity and slow phase transition reaction rates with faster and more homogenous absorption and release of heat. In the same manner, Nano fluids, i.e. base fluids with nanoparticles such as Al_2O_3 , TiO_2 or CuO , have provided increased convective heat transfer capabilities in active liquid-cooling loops [21]. Not only do these materials enhance thermal responsiveness but are the open door to lightweight and compact system development.

In addition to the materials and the architecture, the usage of intelligent control algorithms and real-time monitoring systems is becoming essential. Machine learning (ML) models, artificial neural networks (ANNs), and model predictive control (MPC) technology that can predict temperature increases and preemptively change the cooling strategy are becoming incorporated in modern BTMS designs. Such intelligent systems provide an optimal thermo performance under multiple environmental and operational regimes and the chances of losing energy due to thermal fatigue are minimal. Predictive BTMS may be applied in electric vehicles where the heat may be manipulated depending on driving habits, ambient temperature, and battery state-of-health [22], thereby enhancing efficiency and safety.

The necessity of the advancement is further tenable with the utilization of batteries in harsh conditions cover high altitude drones, deep sea robots and solar storage systems in extreme temperatures. At these environments, conventional BTMS would not work well because of the high ambient conditions not within the design range. In this case, new materials advanced insulation, phase tunable Nano coating, and adaptive radioactive cooling could be possible solutions [23].

To summarize, it is clear that there is a need to focus on shortcomings of current BTMS designs using a multidisciplinary approach with breakthroughs happening in materials science, thermal engineering, and data and systems

architecture. The future of BTMS can implement hybrid designs, a superior nanomaterial, and smart control systems that provide the desired balance in the efficiency-scale, reliability, and safety concerns of the system. This paradigm change will be vital in realizing the full possibility of high-performance energy storage systems and mainstream its use in various fields.

2. Introduction to Battery Thermal Management Systems

Battery Thermal Management Systems (BTMS) play a central role in the safety, efficiency and life of batteries, mostly lithium-ion batteries in electric vehicles (EVs), renewable energy storage systems, and electronic devices. Variations in temperatures have a strong impact on the performance of a battery. Being run at a temperature higher than optimal (usually in the interval 20-40 °C) may increase the rate of chemical degradation and cause thermal runaway, whereas below the optimal temperature energy harvesting is slowed down and electrochemical activity is diminished [24]. Therefore, BTMS play a significant role in the regulation of internal temperatures in terms of homogenous heat delivery, overheating, and operating conditions stabilization.

2.1 Classification of BTMS: Active vs. Passive Systems

Based on the type of energy and process going on when heat is transferred BTMS might therefore be categorized into two main groups; active and passive systems. This category helps in separating the systems that require an external power source to function and the systems that have an operating system using the material properties or thermodynamics of the natural process in temperature management. The active systems involve the utilization of mechanical or electrical equipment and off battery energy in order to move or remove heat actively into the battery system. They offer excellent temperature control and response rates, which is why they prove useful to power up high-performance devices such as electric vehicles (EVs), aerospace, and energy storage in huge quantity. Passive systems, in turn, do not depend on any outside source of power or use of heat-absorbing/heat-spreading materials and design features, but instead on the inherent modulation of the heat signature of the battery. Compared with active systems, passive systems can be less energy-intensive, less costly to run and build, more energy-efficient, and easier but this might not suffice in places where there is so much heat to be run into and/or

rapid temperature changes [25].

2.1.1 Active Systems

Active thermal management introduces into physical systems the utilization of external energy sources typically electrical energy to perform mechanical actions that manage battery-temperature. Active systems of this kind are more complex than the corresponding passive systems and offer far superior thermal management, but are necessary where thermal stability and the integrity of performance are critical factors. Among the most prominent types of active BTMS, one can single out Air cooling, Liquid cooling, Thermoelectric cooling and Vapor compression based each type being characterized by its peculiarities and working principles [26].

2.1.1.1 Air Cooling

This is the most straightforward and low-cost method of active cooling, commonly used in small-scale or low-power battery systems. It uses forced convection, where fans or blowers direct airflow across the surface of battery cells or through specially designed ducts and channels. The moving air absorbs heat from the batteries and carries it away. While air cooling systems are simple to design and maintain, their thermal conductivity is relatively low, limiting their effectiveness in applications that generate significant heat, such as fast-charging electric vehicles or heavy-duty machinery [27].

2.1.1.2 Liquid Cooling:

Liquid cooling offers a more efficient heat transfer method than air due to the higher thermal conductivity and specific heat capacity of liquids. Coolants such as water, ethylene glycol, or advanced nanofluids are circulated through cooling plates, serpentine tubes, or jackets that are closely coupled with battery cells. The heat absorbed by the coolant is then transferred to a heat exchanger or external radiator, where it is released to the ambient environment. Liquid-cooled BTMS provide excellent temperature uniformity and are well-suited for high-energy-density battery packs, though they are more complex, heavier, and may pose leakage risks if not properly sealed [28].

2.1.1.3 Thermoelectric Cooling (TEC)

This system operates using thermoelectric modules that exploit the Peltier effect, where an electric current drives heat from one side of the module to the other. TEC

systems are compact, reliable, and free of moving parts, making them attractive for localized or supplementary cooling. They are often used in conjunction with other cooling systems or in environments where space and noise constraints exist. However, their overall efficiency is lower compared to liquid cooling systems, and they are typically better suited for applications with moderate cooling demands [29].

2.1.1.4 Vapor Compression Cooling

These systems function similarly to household refrigerators and air conditioners. A refrigerant circulates through a closed loop consisting of a compressor, condenser, expansion valve, and evaporator. As the refrigerant evaporates, it absorbs heat from the battery system, and as it condenses, it releases that heat to the surroundings. Vapor compression systems are capable of delivering powerful and consistent cooling even under extreme operating conditions, making them ideal for high-performance EVs or aerospace applications. However, they are mechanically complex, energy-intensive, and often require regular maintenance and safety considerations due to refrigerant handling [30].

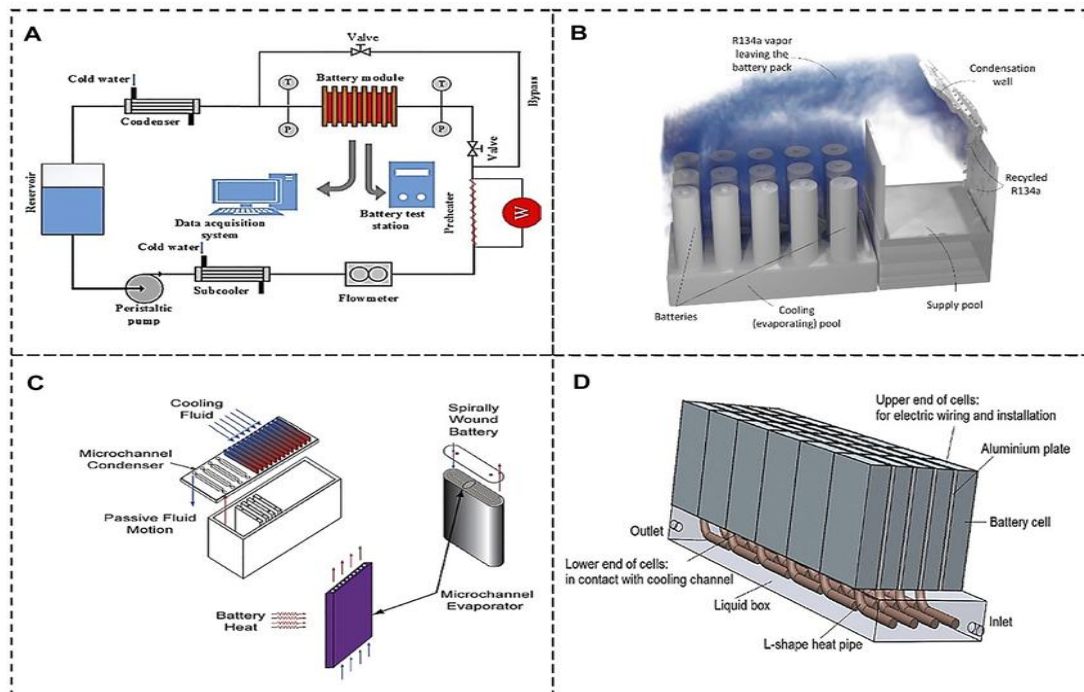


Fig 4: Active BTMS with liquid-cooled circuit and external heat exchanger

2.2 Liquid Cooling System of Batteries

2.2.1 Passive Systems

Passive thermal management systems operate without external energy input, instead utilizing the inherent thermal properties of specialized materials or structural design elements to regulate battery temperature. These systems are favored for their simplicity, reliability, low maintenance, and energy efficiency. By eliminating the need for mechanical or electrical components, passive BTMS reduce the risk of mechanical failure and parasitic energy loss, making them especially suitable for low-power applications, consumer electronics, and compact energy storage devices. However, their cooling capacity is inherently limited, which can make them insufficient for high-performance or fast-charging applications unless combined with active systems. Passive BTMS typically utilize **phase change materials (PCMs)**, **heat pipes**, **thermal insulation**, and **natural convection** as their primary modes of heat control [31].

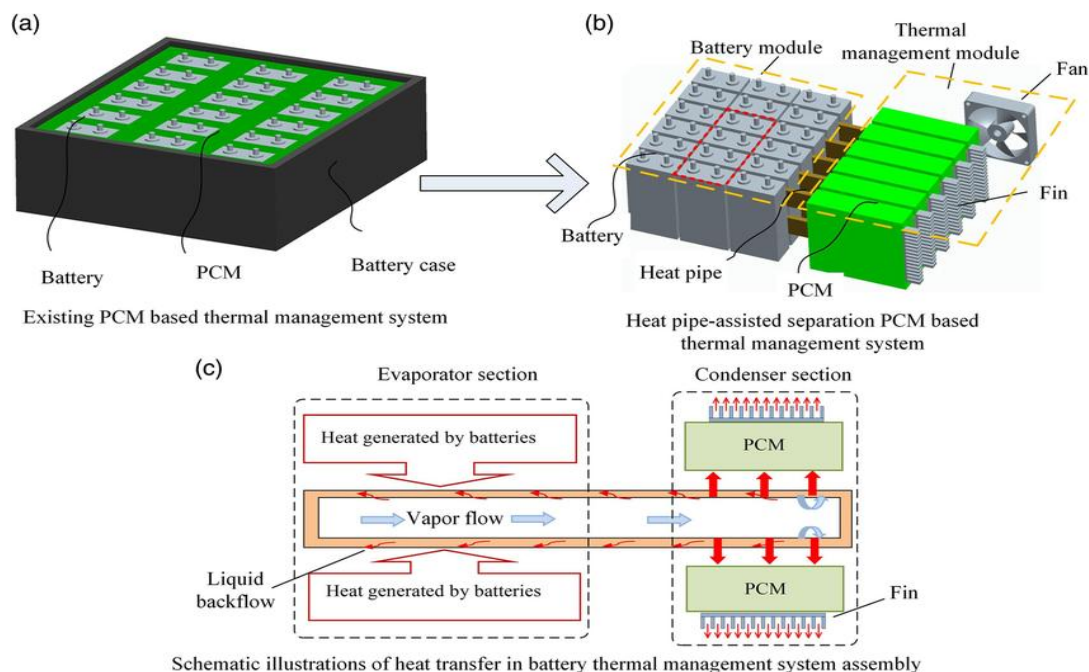


Fig 5: PCM-integrated battery module with natural convection airflow

2.2.1.1 Phase Change Materials (PCMs)

PCMs may store or release a lot of heat during phase changes, usually from solid to liquid or back again, making them a very attractive passive thermal control solution. To protect the battery from sudden increases in temperature, the PCM absorbs heat

until it melts, which happens when the battery's internal temperature hits its melting point. On the flip side, as battery that is cools, the PCM solidifies, releasing the heat it had held. This system prevents the battery from overheating and keeps its temperature more consistent. On the other hand, traditional PCMs aren't very responsive because of their poor thermal conductivity. To get around this, scientists are improving heat transfer performance by adding high-conductivity materials like graphene, carbon nanotubes, or metal foams [32].

2.2.1.2 Heat Pipes:

Heat pipes are passive the transmission of heat devices that use phase change and capillary contraction to transmit heat from one place to another. They are highly efficient at this. A metal tube that has been partly filled with something that works and sealed is the standard component of a heat pipe. The battery fluid does its evaporation while moving between the warmer evaporator exit and cooler condenser exit wherein it becomes liquid once again after giving up its heat. Then, by capillary force, the liquid can be re-drawn back to the hot end using a wick structure. Through this mechanism of recursion, heat could be easily carried over long distances with minimal temperature loss. Heat pipes are ideal to use in battery module to prevent thermal runaway and preserve capacity due to their small size, lack of noise and even spread of heat [33].

2.2.1.3 Thermal Insulation:

The battery fluid does its evaporation while moving between the warmer evaporator exit and cooler condenser exit wherein it becomes liquid once again after giving up its heat. Then, by capillary force, the liquid can be re-drawn back to the hot end using a wick structure. Through this mechanism of recursion, heat could be easily carried over long distances with minimal temperature loss. Heat pipes are ideal to use in battery module to prevent thermal runaway and preserve capacity due to their small size, lack of noise and even spread of heat [33].

2.2.1.4 Natural Convection:

Natural convection is a completely passive method of heat dissipation driven by buoyancy forces that arise from density differences in air due to temperature gradients. As the battery heats up, the surrounding air becomes less dense and rises, allowing cooler, denser air to flow in and replace it. This creates a continuous cycle

of air movement that facilitates gradual heat removal. While natural convection is inherently low in heat transfer capacity compared to forced convection systems, it can be effective in small battery enclosures or when combined with thermal enhancement structures like fins or vents to maximize surface area. It is best suited for low-power or standby applications where slow, consistent heat dissipation is sufficient [35].

2.3 Liquid Cooling system of batteries

2.3.1 Thermal Performance and Design Principles of Liquid Cooling Systems

Electric cars and trucks and high-performance batteries for electricity rely on liquid cooling since it is one of the most effective active thermal management solutions for lithium-ion battery systems. Battery modules are brought into close proximity to a coolant, which is usually water, glycol, or a combination of the two. The coolant is circulated through channels or plates. To keep battery cells in the ideal temperature range (usually 20-40 °C) [36], liquid cooling systems are preferable to air ones because liquids have a higher specific heat capacity and thermal conductivity.

The effectiveness of these systems is significantly influenced by parameters such as flow rate, channel geometry, coolant properties, and contact surface area. Researchers have explored various configurations, including serpentine, U-type, and pin-fin channel designs, to improve coolant distribution and thermal uniformity. Computational fluid dynamics (CFD) simulations and experimental validations have demonstrated that optimized liquid cooling architectures can maintain minimal temperature gradients (<5 °C) across battery packs, which is crucial for extending battery life and ensuring safety [37].

2.2.2 Advancements and Challenges in Liquid Cooling Technologies

Recent research in liquid cooling systems has focused on enhancing performance while reducing energy consumption and structural complexity. One major area of development involves the integration of mini-channel and micro-channel heat exchangers, which provide large heat transfer surface areas with compact designs. Hybrid cooling approaches, such as combining liquid cooling with phase change materials (PCM) or heat pipes, have also shown promise in improving transient thermal control. However, liquid cooling systems present challenges such as

increased weight, complexity, cost, and the need for robust sealing to prevent coolant leakage [38].

Additionally, pumping power requirements and thermal interface resistance must be minimized to maintain system efficiency. Advanced materials for cooling plates (e.g., graphene-enhanced composites or aluminum alloys) and intelligent control systems that dynamically regulate flow rates based on thermal load are being developed to address these challenges. Overall, liquid cooling remains a leading solution for high-demand battery applications, and ongoing innovations aim to further optimize its reliability, compactness, and thermal uniformity [39].

The coolant is in direct contact with the battery or flows coolant in the cooling jacket

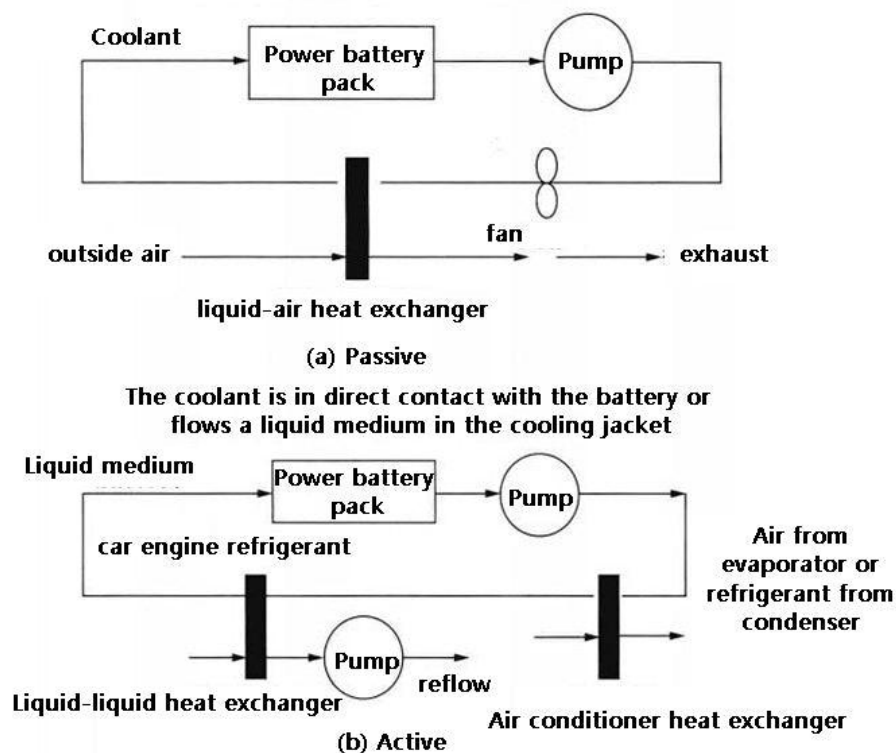


Fig 6: Liquid cooling system of battery

2.3 Energetic, Exergetic and heat transfer assessment of PCM

2.3.1 Energetic and Heat Transfer Assessment of PCM-Based Systems

Phase Change Materials (PCMs) are widely utilized in thermal management systems due to their high latent heat capacity and ability to maintain nearly constant temperature during phase transitions. In energy systems such as battery thermal management, building energy storage, and solar thermal collectors, PCMs

significantly enhance thermal regulation by absorbing excess heat during charging cycles and releasing it during discharge periods [40].

From an energetic perspective, the use of PCM improves the overall heat storage capacity and temperature stability of the system, especially under fluctuating thermal loads. Heat transfer in PCM systems, however, is often limited by the inherently low thermal conductivity of most PCMs, which necessitates the incorporation of thermal conductivity enhancers (e.g., metal foams, fins, or nanoparticles). Accurate modeling of heat transfer processes—typically involving melting and solidification governed by enthalpy-porosity or effective heat capacity methods—is essential for predicting PCM performance and optimizing thermal system design [41].

2.3.2 Exergetic Evaluation and System Efficiency

Energy analysis complements energy-based evaluation by accounting for the quality and usability of energy within a PCM-based thermal system. While energy analysis measures quantity, energy analysis reveals the actual potential of the PCM to do useful work, thus providing insight into irreversibility and thermodynamic losses. During charging and discharging of PCMs, irreversibility arise due to temperature gradients, imperfect insulation, and non-uniform melting fronts, which lead to energy destruction [42].

Integrating PCMs in systems like solar collectors or batteries can improve energy efficiency by reducing peak thermal loads and enabling smoother energy utilization. Recent studies employ detailed energy balance equations to evaluate performance metrics such as energy efficiency, destruction ratio, and enhancement factor, offering a more comprehensive understanding of system behavior. This dual approach—coupling energy and energy analysis with detailed heat transfer modeling—enables optimal design of PCM-integrated systems with enhanced thermal performance and minimized entropy generation [43].

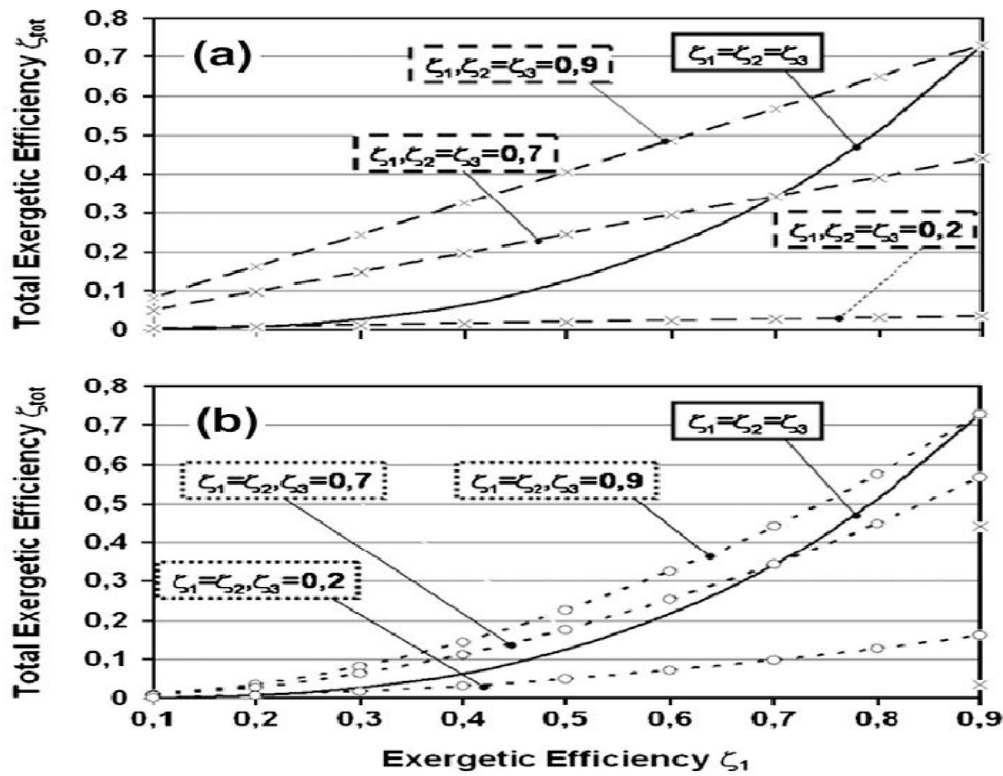


Fig 7: Exergetic Evaluation and System Efficiency

2.4 Materials Used in BTMS

The overall performance of the battery is also affected by the effects of its design architecture as well as the material used to participate in heat absorption, transfer and dissipation in a bid to meet the efficient thermal management demands of the system. The selected materials should have a high thermal conductivity, chemical stability, electrical insulation (no short-circuiting), and resistance to the battery materials. Combinations of coolants and heat transfer fluids used are of special concern in active BTMS because they directly affect the thermal performance, reliability, and safety of the system. The thermo physical properties of the fluids such as specific heat capacity, thermal conductivity, viscosity, and boiling point define how good they are in taking away the excess heat in the battery modules with regard to the operating conditions [44].

2.4.1 Coolants and Fluids

Coolants are core in active cooling systems where they pull heat out of the battery cells, and abduct it towards a heat exchanger or radiator. The coolant selection influences performance of the system in regard to the capability of the system in

ensuring uniform and safe operating temperature, system longevity, maintenance costs and environmental compatibility. Many kinds of fluids have been in common use with advantages and trade-offs [45].

2.4.1.1 Water

One of the most commonly used base fluids in the liquid cooling system is water because of its high specific heat capacity and good thermal conductivity enabling it to handle a lot of heat without a significant increase in temperature. Its boiling point (100 °C at normal pressures) and freezing point (0 °C) restrict its application in high and low temperature conditions. To address these limitations, water is often blended with antifreeze agents such as ethylene glycol to lower the freezing point and increase boiling temperature. Nevertheless, water also poses corrosion risks if not treated properly, requiring additives for pH buffering, anti-corrosion, and biocide control [46].

2.4.1.2 Ethylene Glycol and Propylene Glycol

These are widely used in automotive and industrial thermal systems as water-based coolant additives. Ethylene glycol (EG) improves low-temperature performance by preventing freezing, while also raising the boiling point of the coolant mixture. It is favored in closed-loop cooling systems for its chemical stability and ability to reduce scaling and corrosion. Propylene glycol (PG), while having slightly lower thermal performance than EG, is less toxic and more environmentally friendly, making it suitable for applications with stricter safety or environmental regulations. Both fluids, however, exhibit higher viscosity than water, which can increase pumping power and reduce convective heat transfer efficiency [47].

2.4.1.3 Nano fluids

These are emerging as highly efficient coolants in advanced BTMS due to their enhanced thermal properties. Nano fluids consist of a base fluid (such as water, ethylene glycol, or oil) in which high thermal conductivity nanoparticles—such as aluminum oxide (Al₂O₃), copper oxide (CuO), silicon carbide (SiC), carbon nanotubes (CNTs), or graphene—are dispersed in small concentrations. These nanoparticles significantly increase the effective thermal conductivity and convective heat transfer coefficient of the fluid without a substantial rise in viscosity. Nano fluids also

promote more uniform temperature distribution across the battery pack. However, their long-term stability, potential for sedimentation, and compatibility with system materials remain key challenges that are under active research. Additionally, careful formulation is required to prevent clogging or abrasion within micro channels [48].

Table 1: Properties of Common Coolants commonly used in battery thermal management systems (BTMS), electronics cooling, or automotive applications:

Coolant	Thermal Conductivity (W/m·K)	Specific Heat Capacity (J/kg·K)	Viscosity (mPa·s)	Boiling Point (°C)	Freezing Point (°C)	Density (kg/m³)
Water	0.60	4180	0.89	100	0	997
Ethylene Glycol	0.25	2415	16.1	197.6	-12.9	1113
Propylene Glycol	0.21	2400	52.0	188.2	-59	1036
Engine Coolant (50/50 EG-Water mix)	~0.40	~3400	~3.0	~108	~-36	~1060
Mineral Oil	0.13	1670	30–70	>300	-30 to -60	870–900
Fluorinated Liquids (e.g., 3M™ Novec™)	0.07–0.08	1100–1400	0.6–1.5	61–96	-80 to -135	1500–1700
Silicone Oil	0.15	1460	20–100	>200	-50 to -100	960–970

2.5 Thermal Storage Materials (PCMs)

PCMs store thermal energy by undergoing phase changes. Despite their energy buffering potential, their low thermal conductivity remains a challenge. Researchers

are exploring additives like carbon nanotubes or metal foams to enhance their performance [49].

2.6 Recent Developments in BTMS Research

2.6.1. Air-Cooling Strategies for Battery Thermal Management Systems

Some of the published studies have conducted experiments, numerical studies to extensively examine various forms of battery pack (BTMS) thermal management systems. Operation of battery at various temperature conditions has been an area of numerous studies that have been carried out at various levels, including cell, module and package. Moreover, in mathematical modelling, Computational Fluid Dynamics (CFD) has also been used by many researchers. Experimental study is essential in determining the effects of parameters as well as the interaction between the independent and the dependent variables. In this section, the research done by scientists to enhance the thermo-entrant control of different types of lithium-ion batteries using experimental and computational techniques is noted. [50].

Thermal control through air is one of the most well-understood ways to cope with the temperature of lithium-ion battery packs and cheaper and more applicable in electric vehicles (EVs) and energy storage systems. This process works out with either natural convection or forced air circulation where ambient air or guided air is applied to absorb and remove heat and take it out of cell. Although air cooling is intrinsically simple, it is not suited well to high-power applications without considerable design optimizations because its cooling capacity reduces at elevated thermal loads or when ambient temperatures are high [51].

In order to overcome these performance constraints, scholars have put forth a number of engineering solutions, such as optimal airflow channels, intelligently placed fins and battery cell geometries. These developments strive to realize the even heat distribution, lessened thermals, and diminished high operating temperatures all necessary attributes of battery security, stamina, and efficiency.

2.6.2 Airflow Design Optimization

New channel geometries have become a critical research area as far as the optimization of the air flow efficiency of battery modules is concerned. As an example, Luo et al. projected a dual-inlet, X-shaped air distribution framework that was neutral to the aerodynamics and reduced thermal spikes by 4.33 K with the

elimination of temperature gradients by 74%. The symmetrical air passage will guarantee that cool air is evenly spread across the battery pack that will give localized overheating. Furthermore, Yang et al. incorporated **bionic-inspired heat sinks and perforated distribution plates** to guide airflow more effectively through cylindrical cell arrays. Their system successfully restricted temperature differences to below 2 K, highlighting the impact of nature-inspired design in modern BTMS development [52].

2.6.3 Structural Cell Layouts and Orientation

In addition to airflow manipulation, **cell arrangement** within the battery pack plays a critical role in thermal behavior. Shen et al. explored a **non-vertical, Z-pattern configuration**, which realigns airflow to sweep across a larger surface area. Their tests showed a decrease in the maximum cell temperature by approximately 4 °C and a more uniform internal temperature profile. Similarly, optimization through **staggered or asymmetric cell placement**, as investigated by [53] has shown promise in balancing the trade-off between thermal uniformity and airflow resistance. While such layouts slightly increase pressure drop, they provide considerable gains in thermal control.

2.6.4 Finned Enhancements and Extended Surfaces

Another prominent method involves the use of **extended surfaces or finned structures** attached to the battery casing. These metallic appendages significantly **increase convective surface area**, accelerating heat dissipation under forced airflow conditions. [54] Demonstrated that **radial fin designs**, when paired with active air circulation, can reduce peak battery temperatures by nearly 39%, illustrating a substantial improvement over natural convection alone. Additionally, hybrid approaches—such as direct airflow systems coupled with structural baffles and low-viscosity coolants. Offering efficient heat removal at minimal energy cost.

2.6.5 Air-Cooling BTMS Strategies

Below is a conceptual diagram illustrating three core improvements in air-cooled BTMS:

1. **Modified Air Channels** – Symmetrical inlet/outlet geometries (e.g., X-type, Z-type).

2. **Advanced Cell Arrangements** – Staggered or bionic layouts.
3. **Finned Structures** – Radial, axial, or cross-flow fins for surface extension.

2.6.6 Equation: Heat Transfer in Air-Cooled BTMS

The general heat transfer from the battery surface via air cooling can be approximated as:

$$Q = hA(T_s - T_{\infty})$$

Where:

- Q = heat transfer rate (W)
- h = convective heat transfer coefficient ($\text{W}/\text{m}^2 \cdot \text{K}$)
- A = surface area for heat transfer (m^2)
- T_s = surface temperature of battery ($^{\circ}\text{C}$ or K)
- T_{∞} = temperature of surrounding air ($^{\circ}\text{C}$ or K)

Increasing the area A via fins, or the coefficient h via faster airflow, improves the system's cooling capacity.

Table 2: Additional Geometrical/Design Modifications in BTMS Air Channels

Modification Type	Description	Thermal/Flow Benefits
Extended Fins	Addition of longitudinal, louvered, or pin fins on channel walls	Increased surface area for heat transfer, enhanced turbulence
Wavy/Serpentine Channels	Air channels shaped with sinusoidal or serpentine paths	Induces mixing, disrupts boundary layers, improves heat transfer
Obstacles/Baffles	Placement of inserts or ribs in the flow path	Breaks laminar flow, increases turbulence and local convection
Variable Cross-Section Ducts	Channels with expanding or contracting areas	Controls velocity and pressure distribution, improves local cooling
Jet Impingement Zones	Targeted air jets aimed directly at battery surfaces	Localized high convective heat transfer rates

Modification Type	Description	Thermal/Flow Benefits
Porous Inserts	Media Use of foam metal or porous carbon materials in channels	Enhanced mixing, high thermal conductivity, reduced hotspots
Twisted Inserts	Tape Helical or twisted elements inside channels	Promotes swirl flow, delays thermal boundary layer development
Dual-Channel Configurations	Separate inlet and outlet paths or multiple parallel flow channels	Improved flow distribution and uniform cooling

2.7 Liquid-Cooled Battery Thermal Management Systems (LC-BTMS): A Comprehensive Review of Mechanisms, Modifications, and Modern Applications

In recent years, with the accelerated adoption of electric vehicles (EVs), hybrid electric vehicles (HEVs), energy storage systems, and advanced aerospace applications, the demand for highly efficient and scalable battery thermal management systems (BTMS) has intensified. The thermal management of lithium-ion batteries is a pivotal factor in ensuring battery safety, performance, and cycle life. Among all cooling approaches, **liquid-cooled battery thermal management systems (LC-BTMS)** have gained prominence as the most effective solution, particularly for high-energy-density and high-discharge-rate applications [55].

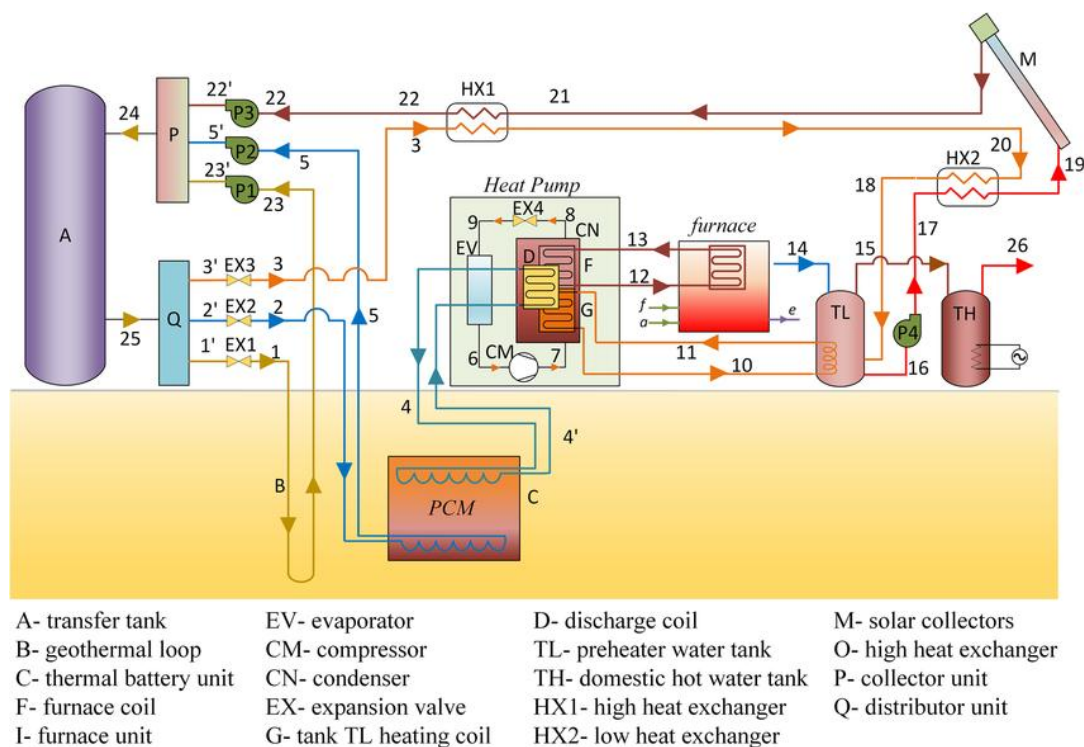
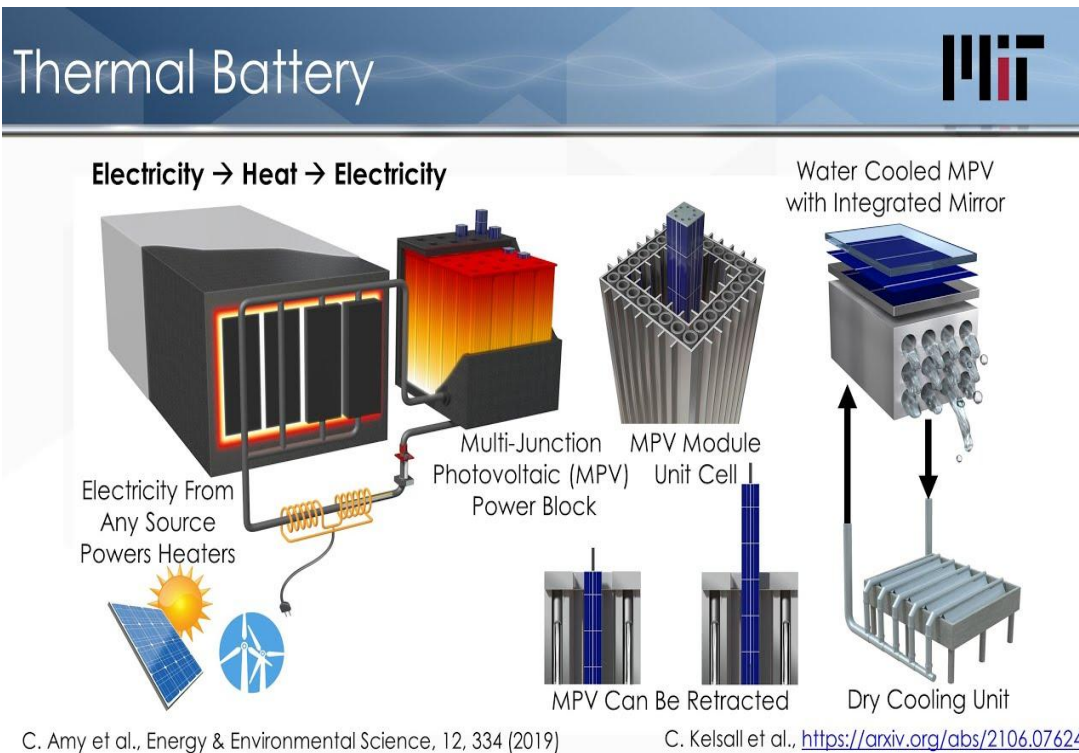


Fig 8: New Thermal Battery System

Liquid cooling systems surpass air-cooled BTMS in terms of **heat transfer efficiency, thermal uniformity, and compactness**, making them ideal for dense battery configurations where space is limited, and heat generation is significant. By utilizing coolant fluids that exhibit high thermal conductivity and specific heat capacity, liquid-cooled systems can rapidly extract and transport heat away from battery modules, preventing the risks associated with thermal runaway, overheating, and uneven temperature gradients across cells [56].



2.7.1. Evolution and Classification of LC-BTMS

The development of liquid cooling in BTMS has undergone several stages of innovation. Initially introduced in high-performance laptops and servers, liquid cooling was later adapted to electric and hybrid vehicles due to its ability to manage intense heat fluxes. **Liquid cooling systems** are typically classified into two broad categories based on the nature of contact between the coolant and battery cells [57].

2.7.1.1 Indirect Liquid Cooling (ILC-BTMS)

In ILC systems, the coolant is **mechanically separated** from the battery cells. It circulates through **cold plates, serpentine tubes, or jackets**, which are thermally interfaced with the battery modules via conductive materials and thermal interface materials (TIMs). The coolant absorbs heat from the plate surface and transfers it to an external radiator or heat exchanger.

- **Advantages:**
 - Safer from chemical or electrical leakage.
 - Uses well-established components and industrial-grade fluids.
 - Compatible with modular and scalable designs.

- **Limitations:**

- Efficiency is reduced by **thermal contact resistance** between the cell and cold plate.
- Requires high-performance TIMs to bridge thermal gaps.

2.7.1.2 Direct Immersion Cooling (DIC-BTMS)

In DIC systems, battery cells are **fully or partially immersed** in a dielectric fluid (such as mineral oil, esters, or engineered synthetic liquids) that directly contacts the surfaces of the battery cells. The coolant removes heat through direct convective contact and provides **extremely low thermal resistance**, making it ideal for ultra-compact and high-performance energy systems.

- **Advantages:**

- Near-uniform temperature distribution across the battery pack.
- Eliminates need for interface materials and complex channel structures.
- Excellent in managing **hot spots and rapid transients**.

- **Challenges:**

- High fluid cost and containment complexity.
- Requires non-reactive, non-conductive, and stable coolant.
- Concerns about long-term chemical compatibility with seals and packaging.

2.7.2. Liquid Cooling in Electric Vehicles and Industrial Applications

Today's electric vehicles leverage highly customized LC-BTMS designs. **Tesla**, for instance, uses a **patented serpentine cold plate layout** that weaves between battery cells, ensuring localized and consistent cooling. Vehicles such as the **Chevrolet Bolt EV, Jaguar I-PACE, Nissan Ariya, BMW i4, and Rivian R1T** incorporate multi-layer cold plates with **embedded microchannels** for rapid heat dissipation.

Industrial battery storage systems—used in **solar farms, wind energy backup, and data centers**—also employ liquid cooling due to the high density and critical thermal thresholds. In aerospace applications, where passive and air systems fall short, liquid BTMS solutions are adapted with lightweight materials and low-

viscosity coolants [58].

2.7.3 Research-Driven Modifications and Engineering Enhancements

In the past five years, LC-BTMS research has primarily focused on enhancing the efficiency, reliability, and modularity of cooling components. The most significant improvements have been made in the cold plate design, channel architecture, coolant flow path optimization, and integrated thermal material systems.

2.7.4 Cold Plate Geometry and Material Innovations

The **cold plate** serves as the heart of an indirect cooling system. It is responsible for transferring heat from battery cells to the flowing coolant. Traditional cold plates consisted of flat aluminum or copper plates with simple serpentine channels. Modern designs integrate **complex geometries**, **turbulence inducers**, and **multi-layer heat spreading surfaces**. A cold plate design incorporating **Phase Change Material (PCM)** along with a **spider-web channel pattern**. The PCM absorbs peak thermal loads, while the web layout enhances coolant spread, keeping battery temperatures below 40°C under 3C discharge. A **diamond-shaped channel network**, optimizing both the contact area and flow disturbance to improve convective heat transfer. Results indicated a **17–20% increase in thermal performance** compared to baseline designs. A 3D-printed cold plates with **vortex generators**, producing localized turbulence to break thermal boundary layers. Despite increased flow resistance, they achieved **35% enhancement in heat flux** removal [59].

B. Advanced Channel Configuration and Flow Control

The geometry and internal layout of coolant channels greatly influence cooling effectiveness. Research in this area explores **spiral**, **bifurcated**, **fractal**, and **microchannel networks**, targeting optimized flow rates and pressure distribution [60].

- **A Mini Channel Cylinders (MCC) and Channel-Cooled Heat Sinks (CCHS)**. MCCs provided localized cooling benefits but suffered from complex manufacturing. CCHS, with linear flow paths, offered better thermal uniformity across large modules.
- The inspiration from **spirulina algae** to create **bionic spiral fin structures**, increasing flow disturbance and improving battery temperature uniformity

by 30%. These designs are particularly suited for pre-conditioning and thermal recovery in cold climates.

2.8 Fluid Selection and Thermo physical Considerations

The choice of coolant plays a critical role in thermal system efficiency. Ideal fluids must possess a combination of the following attributes:

- High **thermal conductivity** and **specific heat capacity**.
- Low **dynamic viscosity** to reduce pumping losses.
- High **boiling point** and **thermal stability**.
- Electrical **non-conductivity** (for immersion systems).
- Chemical compatibility with casing, electrodes, and sealants.

Common coolants include:

- **Water-glycol blends** (widely used in ILC systems for EVs).
- **Mineral oils, fluorinated ethers, and synthetic esters** (used in DIC systems).
- **Nano fluids:** Water/oil-based fluids doped with nanoparticles (Al_2O_3 , CuO, graphene) to enhance thermal properties.

Emerging research suggests that Nano fluids can offer up to **35–50% higher thermal conductivity**, but their long-term stability, dispersion, and safety must be validated under real-world conditions.

2.9 Analytical Modeling and Governing Equations

The effectiveness of LC-BTMS can be evaluated using thermodynamic and heat transfer models. A fundamental equation governing heat removal is:

$$Q = \dot{m} c_p (T_{\text{out}} - T_{\text{in}})$$

Where:

- Q = Heat transfer rate (W)
- $\dot{m}$ = Coolant mass flow rate (kg/s)
- c_p = Specific heat capacity of coolant (J/kg·K)
- $T_{\text{in}}, T_{\text{out}}$ = Coolant inlet and outlet temperatures (K)

To evaluate convective performance, the **Nusselt number (Nu)** is commonly calculated using empirical correlations for turbulent or laminar flow regimes:

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$$Nu=C \cdot Re^m \cdot Pr^n$$

Where:

- Re = Reynolds number (flow inertia vs. viscosity)
- Pr = Prandtl number (momentum diffusivity vs. thermal diffusivity)
- C, m, n = empirical constants based on geometry and flow

Advanced modeling also incorporates **Computational Fluid Dynamics (CFD)** and **Finite Element Analysis (FEA)** for simulating transient thermal behavior, pressure drops, and hotspot formation under varying electrical load profiles.

Table 3: Comparative Table of Key Innovations in LC-BTMS (2023–2024)

Study / Year	Innovation Configuration	Coolant Used	Key Advantages	Limitations / Notes
Zhang et al., 2023	Multi-channel cold plate with variable fin geometry	Water-EG mixture	Enhanced cooling, thermal gradient	Increased local pressure drop
Chen et al., 2023	Micro-channel plate with pin-fin array	Nanofluid (Al ₂ O ₃ -Water)	Improved heat transfer coefficient by ~25%	Nanofluid stability & maintenance concerns
Kumar & Singh, 2024	Serpentine flow plate with phase separator	Pure Water	Uniform temperature distribution across battery module	Complex fabrication
Li et al., 2023	Dual-layered channels interleaved design	liquid Propylene Glycol-Water	Increased surface contact, lower cell temp	Slightly increased max system weight
Wang et al., 2024	Hybrid LC PCM-embedded plates	with Water cold PCM (Paraffin)	+ Delayed temperature rise, improved shaving	Requires PCM re-solidification cycle

Rahman et al., 2023	Liquid cooling with Deionized Water jet impingement nozzles	Very high local requirement, cooling performance	High flow rate complex control
Yuan et al., 2024	Integrated cooling-heating loop with thermoelectric element	Both active cooling and pre-heating in cold climates	High cost and power consumption
Alam & Hu, 2023	Flexible cold plates with graphene-enhanced coolant	Graphene Nanofluid	Excellent thermal conductivity, lightweight, adaptable
Sun et al., 2024	Modular LC system with smart flow distribution valves	Adaptive cooling based on heat load distribution	Requires real-time sensing and flow control logic

2.10 Future Research Directions and Challenges

While LC-BTMS systems are currently the most efficient thermal solution for batteries, several research frontiers remain:

- **Adaptive flow regulation:** Integration of thermal sensors and AI to control coolant flow based on real-time thermal loads.
- **Modular BTMS for battery swapping:** Quick-connect cooling systems for future EV battery exchange models.
- **Environmentally friendly and biodegradable coolants:** Reducing ecological impact of dielectric fluids.
- **Cost-effective nanofluids:** Scaling nanoparticle-enhanced coolants with stable, low-toxicity properties.
- **Multifunctional plates:** Combining cooling, structural support, and electrical sensing in one unit.

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<http://amresearchreview.com/index.php/Journal/about>**Table 4: Summary of Research on Liquid-Cooled Battery Thermal Management System (LC-BTMS) Innovations**

Research Focus Area	Key Approaches/Technologies	Performance Achievements	Challenges/Limitations
Channel Design Optimization	Serpentine, U-type, Z-type, multi-channel, interleaved, micro-channel	Up to 30–45% reduction in temperature gradients	Pressure loss and flow imbalance
Cold Plate Enhancement	Pin fins, wavy structures, porous inserts, hybrid geometries	Enhanced heat transfer by 20–35%, lower peak cell temperature	Manufacturing complexity, increased system mass
Coolant Innovation	Nanofluids (Al ₂ O ₃ , CuO, graphene), deionized water, phase-change slurries	Improved thermal conductivity (10–40%), better transient response	Stability, clogging, and long-term performance
Hybrid Cooling Techniques	LC + PCM, LC + TEC (thermoelectric), LC + air	Smoother temperature profiles, redundancy, and extended efficiency	System complexity, cost, integration challenges
Flow Management	Smart valves, jet impingement, flow diverters, flow field optimization	More uniform temperature across battery modules	Requires real-time sensors and control systems
Simulation & AI-Based Design	CFD optimization, machine learning, genetic algorithms	Reduced design iteration, energy-efficient	Computational cost, model validation issues

layouts

Integration & Scalability Modular LC designs, Adaptability for Cost of scalable cold plate units, EV/ESS applications, redesign, space pack-level integration maintainability constraints

2.11 PCM-Based Thermal Management: Principles and Practical Benefits

The core advantage of PCM-based BTMS lies in **latent heat storage**. When a PCM reaches its melting point, it absorbs a large quantity of thermal energy without a corresponding rise in temperature. This thermal inertia can delay or reduce the temperature rise in lithium-ion battery packs. After the load is reduced, the PCM can slowly release this stored heat as it solidifies, thus maintaining a more consistent thermal profile over time [61].

From a practical standpoint, PCM systems:

- **Improve thermal stability** by reducing temperature swings within the battery pack.
- **Enhance safety** by preventing hot spots and thermal runaway initiation.
- **Increase lifespan and cycle performance** by keeping cells within optimal temperature thresholds.
- **Reduce system complexity and maintenance** by eliminating pumps, compressors, and moving parts found in active systems.

However, standalone PCM systems do face certain limitations. Once the entire PCM volume has transitioned to liquid, its capacity to absorb additional heat diminishes. This “thermal saturation” can lead to sharp temperature increases if cooling is not actively restored. Therefore, many researchers advocate for **hybrid configurations**—combining PCM with either forced air or liquid flow systems—to ensure continuous thermal regulation.

2.12 Hybrid PCM-Air BTMS: Enhancing Passive-Active Synergy

Integrating **PCM with air cooling systems** has been shown to yield significant improvements in both energy efficiency and thermal management precision. In these hybrid systems, the **PCM acts as the first line of defense**, absorbing rapid heat spikes during high loads, while the air cooling mechanism gradually removes the stored thermal energy over time.

Such synergy allows for:

- **Reduced fan power consumption**, as air cooling can be delayed until PCM nears saturation.
- **Lower system weight and complexity**, compared to liquid-cooled hybrids.
- **Improved temperature uniformity**, as the PCM mitigates localized heat spikes while air flow distributes the excess heat evenly.

In a notable study, [50] designed a biomimetic BTMS using PCM and **variable-section fins** that mimic biological cooling structures. This system employed a **delayed air-cooling strategy**, resulting in a **59% reduction in power consumption** without compromising safety thresholds—the system maintained a maximum cell temperature under 40 °C and a temperature differential below 3 °C. Similarly, [51] explored a **honeycomb-inspired design** to enhance PCM thermal conductivity and structural integration, leading to better overall heat absorption and discharge characteristics.

[52] Extended this concept by incorporating **Z-type airflow channels** and direct PCM contact with battery tabs. Their comparative analysis revealed that the most thermally efficient configuration—where PCM directly touches the battery casing—resulted in a **3.48% reduction in the battery box volume** while also improving thermal homogeneity and space utilization.

2.13 Hybrid PCM-Liquid BTMS: Optimizing for High-Intensity Thermal Loads

While air-based PCM systems offer benefits in lightweight and low-power settings, **liquid cooling remains unmatched in terms of raw heat dissipation capacity**, particularly for high-performance applications like EVs. When paired with PCM, liquid-cooled systems benefit from both **fast convective cooling** and **passive thermal buffering**—a combination that allows for excellent performance under dynamic thermal conditions.

This hybrid architecture provides:

- **High instantaneous thermal buffering** during power surges, where PCM absorbs excess energy.
- **Sustained active cooling** through coolant circulation, especially valuable

after PCM saturation.

- **Smaller liquid cooling system requirements**, as PCM reduces the peak thermal load.

[54] Introduced a highly efficient hybrid BTMS that combined **wavy micro channel cold plates** with PCM blocks. Their simulations and experiments demonstrated **significant reductions in maximum battery temperature** and effective distribution of thermal gradients across cylindrical lithium-ion cells. The wavy design enhanced turbulence in coolant flow, boosting convective heat transfer without increasing pump power.

In another pioneering design, [55-57] developed a **self-regulating PCM system** that utilized the volumetric expansion during phase change to modulate liquid flow through a flexible valve mechanism. This “smart PCM regulator” successfully reduced the max temperature by **7.94%** under high ambient stress, maintaining the system below 39 °C. Furthermore, the system provided **real-time adaptability** without additional sensors or controllers.

2.14 Phase change materials (PCMs) and nano-enhancements

It is only very recently that PCM-based BTMS have been acknowledged for their better performance in temperature control. Using PCM in BTMS was initially proposed [31,34]. Compared to the uncooled battery, the PCM-cooled battery had a smaller heating range, as demonstrated experimentally. One common PCM, paraffin (PA), has some serious problems that may use some fixing. It leaks a lot and doesn't transfer heat very well. The low thermal conductivity of PA prompted the researchers to develop a composite PCM containing graphene as a filler [35,36]. Adding 1 weight percent graphene infill to regular PA enhanced the heat conductivity by a factor of sixty. They settled on copper mesh (CM) as a composite PCM for BTMS to protect PA/expanded charcoal (EG) composite materials [37]. The module's heat conductivity and toughness are enhanced by the CM structure, while the porous EG absorbs the liquid phase PA without leaking.

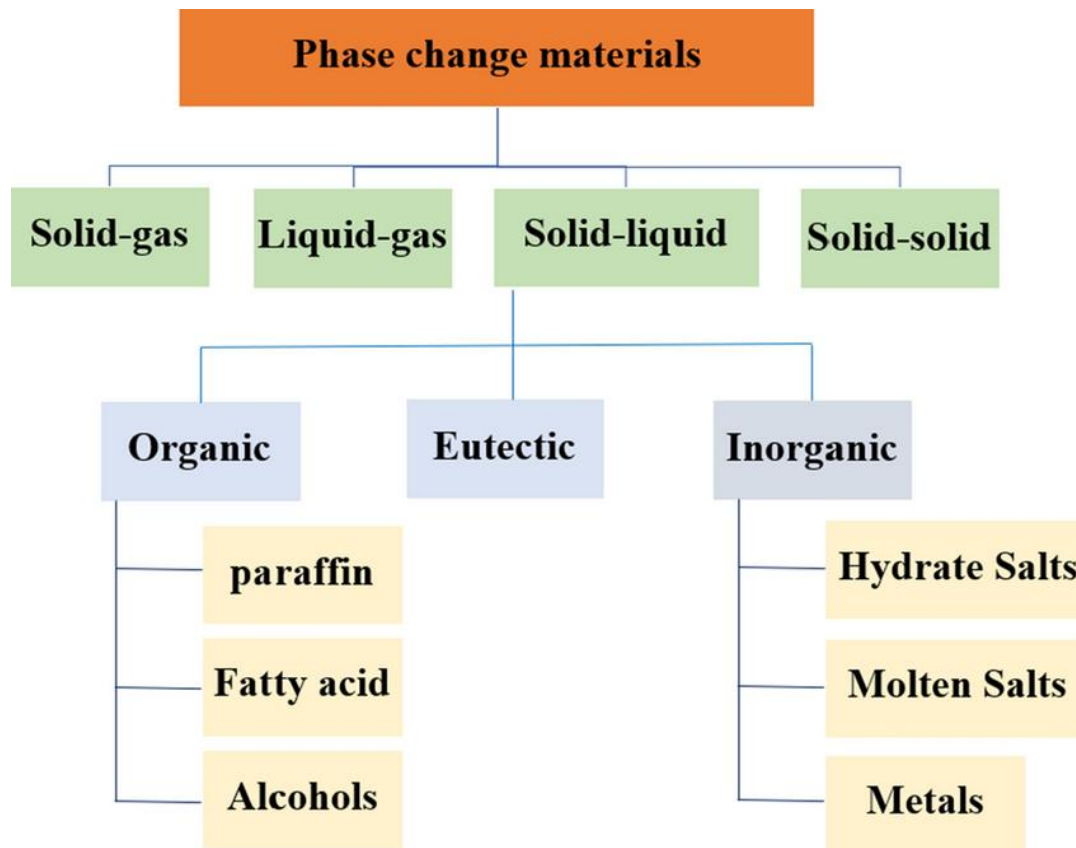


Fig 9: Phase Change materials frame

The results of the tests showed that CM/PA/EG outperformed PCM without CM in terms of heat dissipation and temperature uniformity. In addition to playing a vital role in heat dissipation, the CM heat sink integrated into the composite PCM enhanced heat transfer capabilities by interfering with airflow under the particular conditions of forced convection. EG/Kaolin/PA was used as the PCM in BTMS by [38]. They found that the best PCM for sustaining a steady temperature was a composite composed of 80% PA, 10% EG, and 10% Kaolin. A single cell's peak temperature could be effectively measured below 45 degrees Celsius with a discharges rate of 4 degrees Celsius. Even in the extreme cases of a greater releasing rate, the temperature disparity between each cell could be controlled within 5 degrees Celsius. After 30 minutes at 60°C, the temperature control test revealed no signs of leakage. The battery pack's temperature can be significantly lowered by 2.57 °C thanks to the composite material. Following phase shift by PCM, battery pack & cell heat may be significantly reduced. Fig. 8 (a and b) illustrates the clear

scenario where PCMs play a part in battering stacking and the resulting temperature regulation. PCM retains latent heat through changes in phase over a limited temperature range, which could be utilized to reduce internal battery heat accumulation. Modifications to PCM's chemical makeup enable the material's melting point and range of temperatures of performance as a heat absorber to be precisely adjusted. Common PCMs have specific thermal conductivity (K) values between 0.17 and 0.35 WmK⁻¹ at room temperature (RT). Copper has an RT temperature conductivity of about 381 WmK⁻¹, while silicon has an RT thermal conductance of about 145 WmK⁻¹. PCMs store heat rather than transferring it away from the power source pack. PCM serves as a temperature buffer in battery cells and keeps the lithium-ion cell from overheating. methods [9].

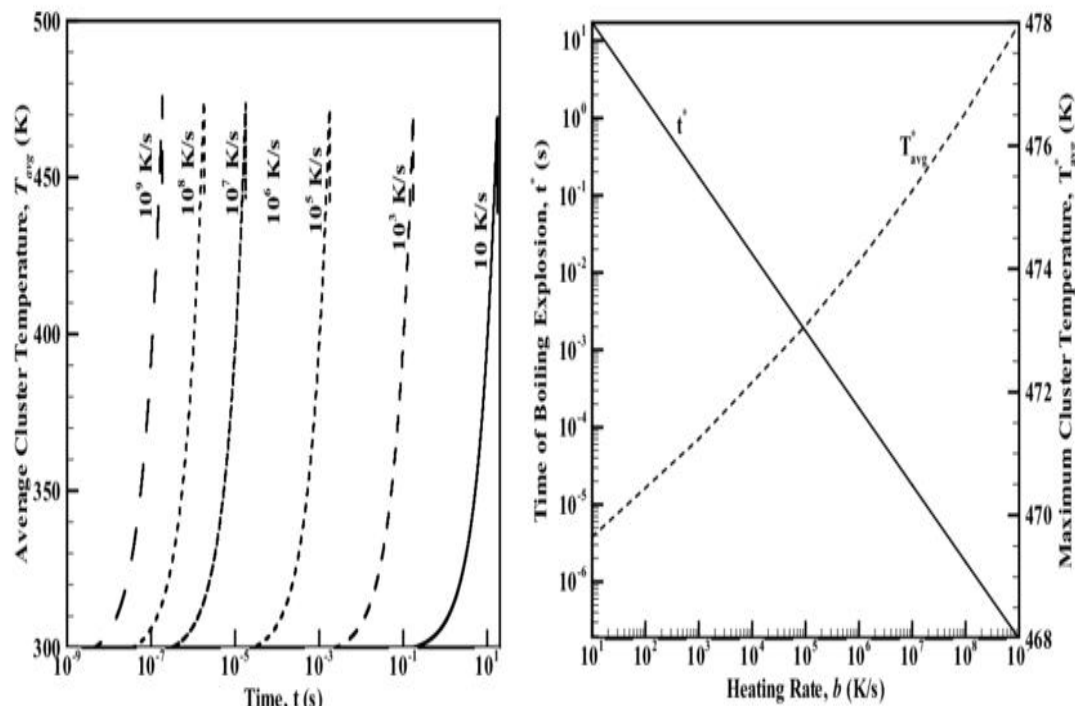


Fig 10: (a–b): Numerical modeling of temperature escalation inside the Li-ion battery packs (Reproduced with permission from Journal of Journal of Power Sources 248, Feb 2014, Pages 37–43. Copyright © 2014 Elsevier Ltd [36]).

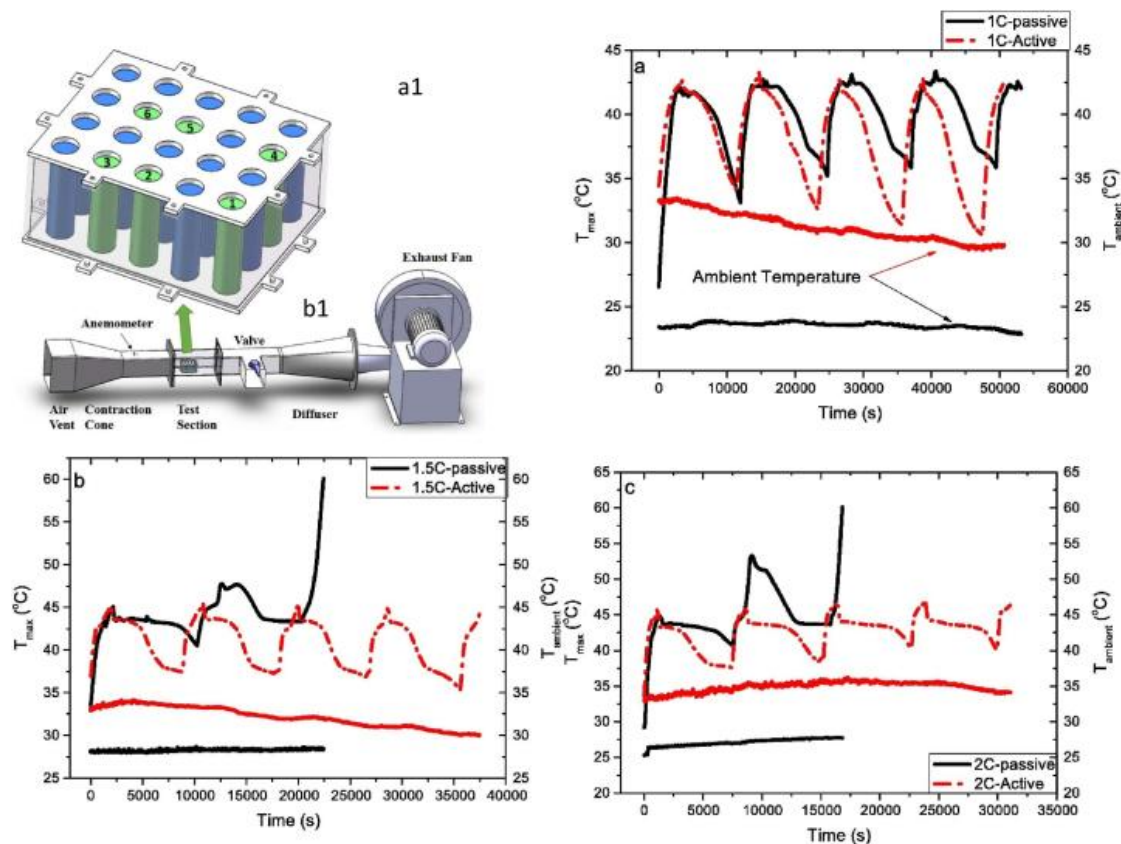


Fig 11: (a1) Battery pack 5S4P schematic; (b1) air channel construction. (a–c) Maximum battery temperature under entirely passive thermal management and hybrid systems (PCMs & forced air convection/discharge rate) (Reproduced from Applied Resources Volume 148, fifteenth of June 2015, Pages 403–409, with permission). [40] Elsevier Ltd., 2015. All rights reserved. This approach is different from how computer chips are typically cooled. Heat is transferred from computer chips to heat dissipation and external packaging using thin layers of Infrared Interface Materials (TIMs).

While solid graphite-based heat spreading devices may have an electrical conductivity of over 10^3 WmK^{-1} , TIMs have a conductivity of roughly 1 to 25 WmK^{-1} . In their efforts to enhance PCM, some researchers concentrated on factors unrelated to its core characteristics. The limited heat conductivity of the purest Cmp material remains a significant barrier to any future usage. J [39] looked on how PCM breadth affected the temperature for PCM-wrapped batteries. The findings showed that the PCM that was thinner than 3 mm produced a more

uniform distribution of temperature when the battery was indicted and discharged at various power densities at 21 °C, whereas the PCM thickness was 12 mm caused the peak temperature to drop by 3.04 degrees Celsius. PCM's presence would be crucial in reducing the battery's temperature increase during the first seven minutes, and PCM that is thicker surrounding the battery might provide better cooling. [40]

The efficiency of forced air cooling for PCM-based composite BTMS and contrasted its results with those of PCM-based hybrid BTMS using natural air cooling. The findings showed that inadequate natural air conditioning caused PCM to heat up in extreme situations, such as hyper thermal settings, and that it was difficult to export heat away from it effectively. In the subsequent test, PCM was combined with a forced air-convection technique, and it was demonstrated that the corresponding BTMS could keep the battery's internal temperature below 50 C, or at least below 2 C, even when the outside temperature was 7 C higher than the battery's internal temperature. PCM and air conditioning convection had different functions in BTMS.

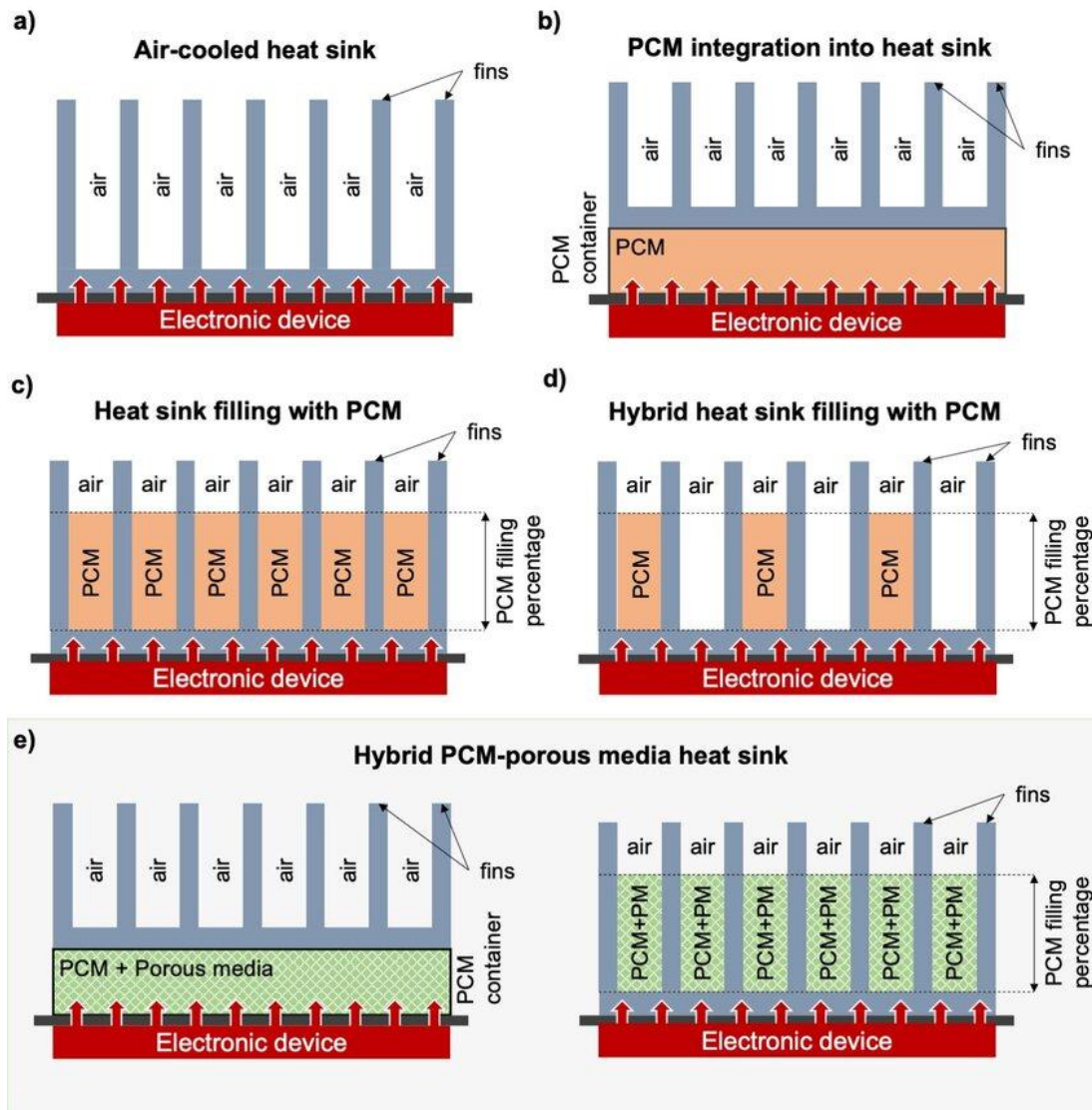


Fig. 11 displays some of the results; PCM was cooled using air conditioner convection and maintained within the ceiling and divergence temperature range. The thermal management, safety, and general performance of batteries can be greatly improved by combining a liquid cooling system with Nano-enhanced phase-change substances (NEPCMs) for battery modules. The high heat the coefficient of transfer offered by liquid cooling systems makes it possible to remove heat from battery cells effectively. The system can more efficiently manage large thermal loads when paired with NEPCMs. Heat is absorbed and transferred to an auxiliary heat exchanger by the liquid coolant as it circulates throughout the battery pack. Temperature spikes are avoided using NEPCMs, which absorb surplus heat under

peak loads & release it gradually [41].

For optimal performance and longevity, all battery cells must have a consistent temperature distribution. This is more successfully accomplished when NEPCMs are used in conjunction with liquid cooling systems. By absorbing and spreading thermal energy, NEPCMs reduce local hot patches, while the liquid coolant keeps the temperature constant [42].

Longer battery life results from efficient thermal stress management. Thermal deterioration is decreased when NEPCMs and liquid cooling are used together. While transitory heat spikes are absorbed and mitigated by NEPCMs, which lower overall stress for the battery cells, excessive thermal cycling is prevented by the liquid system's continual cooling action [43].

One major safety issue with battery systems is thermal runaway, which may be prevented with effective thermal management. By efficiently controlling high temperatures, liquid cooling in conjunction with NEPCMs improves safety. While NEPCMs serve as a thermal buffer, collecting excess heat during unusual conditions and keeping temperatures from rising to harmful levels, the liquid a cooling system continually removes heat [44, 45].

Consistent battery performance and increased energy efficiency are guaranteed by maintaining ideal temperature ranges. Overall energy management is improved by the combined system. By maintaining ideal operating temperatures, liquid cooling systems lower internal resistance and increase charge/discharge efficiency. By offering extra thermal control, NEPCMs lessen the liquid system's cooling burden [46].

Therefore, combining liquid-based cooling systems with phase change materials strengthened by nanotechnology offers a reliable way to manage heat in battery modules. Regarding heat dissipation, temperature homogeneity, battery lifespan, safety, & energy efficiency, this hybrid approach has several benefits. This solution solves the significant thermal issues that contemporary high-power battery applications confront by utilising the high heat transfer capacities of liquid coolants and the heating and cooling properties of NEPCMs.

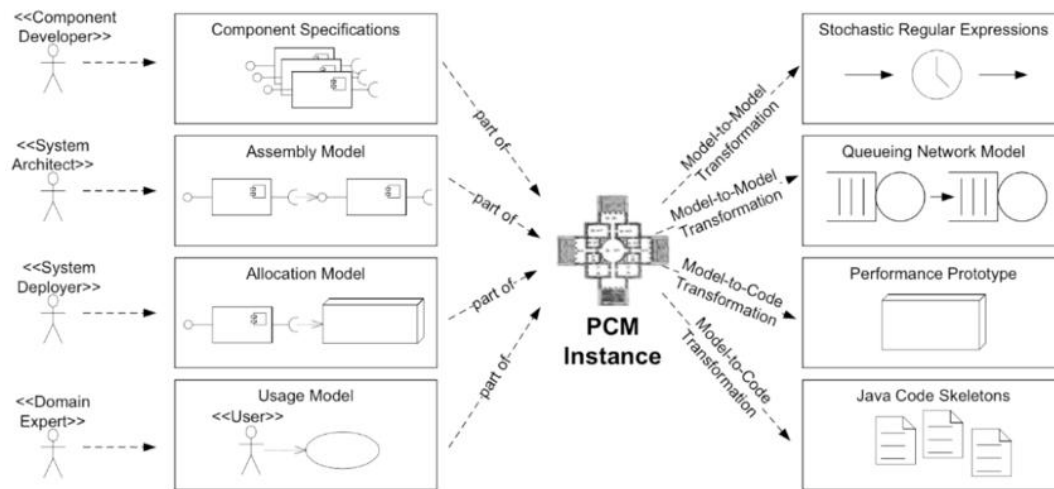


Fig 12: PCM system management

The slow heat transfer rate between PCMs and their surroundings is likely to blame for a passive TMS's ineffectiveness. Power conversion materials (PCMs) store the vast majority of the negligible heat generated by banks during discharge as sensible heat. Due to low-efficiency air natural convection, this type of heat can be dissipated into the surrounding environment. In contrast, PCM is able to retain a significant portion of the latent heat generated by high-current discharge due to the increased heat production. The complete release of latent heat is delayed until the subsequent discharge begins due to inefficient air natural convection. This reduces the potential heat storage capacity and raises the temperature at which the next discharge begins, for a net negative impact. As a result of rapid loss of latent heat and an increase in battery temperature over the maximum allowable value, thermal energy storage capacity becomes inadequate after multiple discharge cycles to handle the increased heat flow from batteries. [47–59].

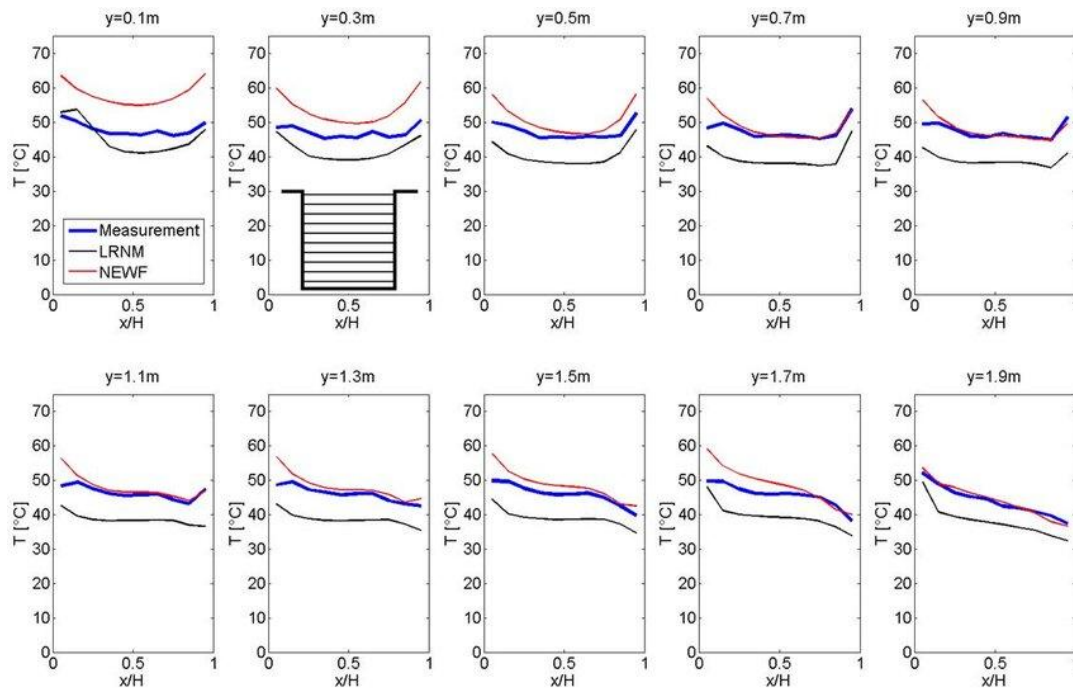


Fig. 13 (a–d): Various cases of temperature profiles (Reproduced with permission from Case Studies in Thermal

All things considered, NEPCMs provide a number of advantages over conventional PCMs when it comes to thermal management in batteries. These include higher heat capacity, faster transitions in phases, more mechanical stability, and the flexibility to tailor the material's properties to specific needs. These advancements make NEPCMs a state-of-the-art answer to the current problems with thermal management in battery systems, as they increase temperature regulation, lead to longer battery life, and absorb and dissipate heat more efficiently

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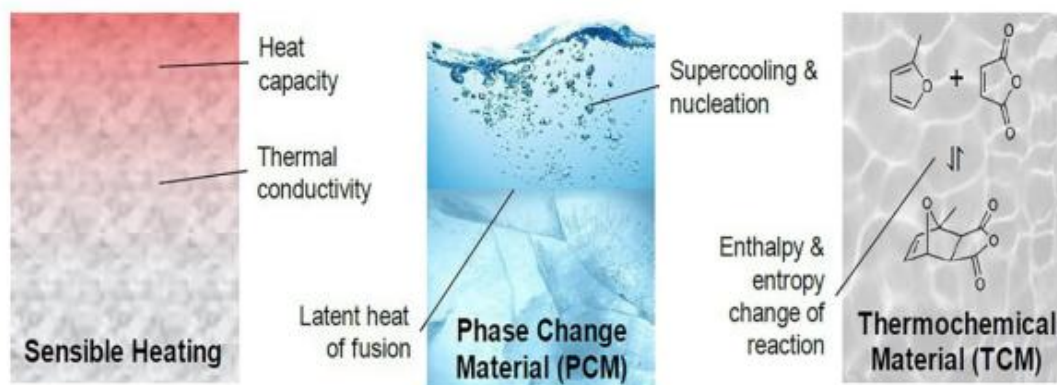
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Fig 14: Phase change material elements

2.15 Challenges and Considerations for PCM Integration

Despite their promise, PCM-based BTMS still face technical challenges that must be addressed for widespread commercial implementation [60].

1. **Limited thermal conductivity** of most PCM materials necessitates the addition of conductive fillers (e.g., graphite, copper foam, carbon nanotubes) to accelerate heat diffusion.
2. **Encapsulation issues**, where leakage during phase change or material degradation over time can affect reliability.
3. **Design complexity** in hybrid systems, particularly regarding the spatial layout of PCM blocks and fluidic pathways.
4. **Thermal saturation risks** if PCM volume or melting range is not adequately matched with the battery's heat output profile.

Researchers are actively investigating **composite PCMs**, **nanostructured additives**, and **3D printing techniques** to overcome these limitations, ensuring higher thermal conductivity, stability, and shape conformity.

Table 5: Summary and Applications of PCM-Based BTMS Designs (2023–2024)

Study	PCM Configuration	Type	& Battery Type	Design Innovations	Key Findings	Applications
Li et al. (2023)	Paraffin high-conductivity graphite foam	with	18650 Li-ion	Encapsulated composite integrated aluminum fins	Improved thermal conductivity with 3.2×; max temp reduced by 12.5°C	EV battery modules

Zhang et al. (2023)	Lauric acid–stearic eutectic PCM	acid–Pouch cells	Micro-encapsulation + aluminum casing	Maintained temp < 45°C during discharge	UAVs and drones
Kumar et al. (2024)	Paraffin al. graphene nanoplatelets	+ Cylindrical cells	Hybrid PCM with heat pipe integration	Reduced peak temp by 30%; extended battery life	E-bikes, portable devices
Ahmed et al. (2024)	Bio-based PCM with expanded graphite	Prismatic Li-ion	Sustainable PCM improved diffusion	Enhanced with sustainability; heat stable under charging	eco-Renewable energy storage
Singh & Yadav (2023)	Salt hydrate PCM in configuration	LFP battery pack	Dual-stage PCM (low-high melting points)	Extended operational safety range; thermal stability improvement	Grid >35% storage systems
Wu et al. (2024)	Paraffin Al ₂ O ₃ nanoparticles	+ Cylindrical 21700 cells	Nanocomposite PCM; cartridge design	40% faster heat modular dissipation; easy maintenance	High-performance electric vehicles
El-Sayed et al. (2023)	RT-44HC PCM slabs	Li-ion battery pack	Passive PCM + liquid hybrid	Achieved 60% better thermal uniformity vs PCM-only	Data center UPS systems

2.16. Future Directions for PCM-Based Cooling

To further capitalize on the strengths of PCM cooling systems, future research is moving toward:

- **Integrating PCM with thermal sensors and AI-based controls** for dynamic hybrid switching.

- **Exploring bio-based or recyclable PCMs** to align with sustainability goals.
- **Advanced encapsulation methods** for leakage-free, long-term stability.
- **Thermal modularization**—designing swappable PCM units for flexible BTMS scaling.
- **Dual-function PCM structures** that also act as fire retardants or mechanical buffers.

These developments could position PCM-based thermal management not just as an alternative, but as a **mainstream strategy** for electric mobility and stationary energy storage systems.

Table 6: Recent Research Advances in PCM-Based Battery Thermal Management Systems (2023–2024)

2.17 Thermoelectric-Based Battery Thermal Management Systems (TE-BTMS)

In the evolving landscape of battery thermal regulation, **thermoelectric cooling systems (TECs)** have re-emerged as a viable alternative to conventional approaches such as air and liquid cooling. As batteries are increasingly deployed in high-demand applications like electric vehicles (EVs), drones, and aerospace electronics, thermal performance becomes a limiting factor for safety, reliability, and longevity. While traditional systems rely heavily on convective and conductive heat transfer, thermoelectric modules leverage the **Peltier and Seebeck effects** to actively manage thermal gradients in a more compact and efficient manner [61, 65].

2.17.1 Fundamentals and Benefits of Thermoelectric Cooling

Thermoelectric devices operate on two foundational phenomena:

- **The Seebeck effect**, which generates electrical energy from temperature gradients, enabling thermoelectric generators (TEGs) to recover waste heat.
- **The Peltier effect**, wherein an electric current induces heat absorption or release at the junction of two dissimilar materials, forming the basis for thermoelectric coolers (TECs) [65].

TECs offer a unique set of advantages for BTMS applications: they are **solid-state**, free from moving parts or refrigerants, **lightweight**, silent in operation, and **environmentally benign**. These features make them especially suitable for systems where spatial and energy efficiency are critical, such as **compact EV battery**

enclosures, satellite power modules, and medical implant devices.

2.17.2 Advancements in TEC-Based BTMS Designs

Recent developments have improved the integration of TECs within hybrid BTMS frameworks. For instance, modern designs couple TEC modules with **liquid-cooled plates**, **heat sinks**, or even **phase change materials (PCMs)** to compensate for TECs' inherently low coefficient of performance (COP). By strategically placing TECs at thermal hotspots and optimizing the direction of heat pumping, these systems can actively manage local overheating while maintaining battery pack uniformity [66].

[67] Pioneered one such integrated setup by embedding thermoelectric modules between copper plates and acrylic housing structures, supplemented with a forced liquid-air circulation system. Their results indicated a **temperature reduction of nearly 20 °C** under high-rate discharge conditions, which significantly outperformed conventional cooling systems. Similarly, [68] explored a **dual-mode BTMS** that combined TECs for cooling and TEGs for power generation using waste heat. Their hybrid configuration, coupled with air-assisted heat dissipation, achieved a **7 °C drop in peak cell temperature** and demonstrated improved thermal efficiency with minimal additional energy consumption.

Although thermoelectric modules are traditionally criticized for low efficiency compared to other active cooling systems, their **fast response time**, **compact form factor**, and **flexibility of deployment** make them ideal for **dynamic BTMS designs**, particularly those requiring **precise and localized cooling**.

Table 7: Recent Developments in Thermoelectric Cooler (TEC)-Based Battery Thermal Management Systems (2023–2024)

3. Discussion and Conclusion

3.1 Air Cooling Methods

Battery Thermal Management Software (BTMS) often use air-cooling systems because they are simple, cheap, and easy to maintain. Free convection and forced convection are two ways to classify these approaches. However, changes are needed to enhance thermal performance because their efficacy is greatly reduced at high ambient temperatures. Air channel adjustments are among the most effective

enhancements since they significantly affect cooling efficiency. Airflow distribution and thermal gradients can be greatly improved with designs like the X-type, honeycomb constructions, and multi-inlet/outlet air passageways. Staggered configurations and modified Z-shaped systems are two examples of how changes to battery cell arrangements can lead to better heat dissipation and a more equal distribution of temperature. Integrating fin features like radial fins and internal baffles further improves cooling performance by increasing the surface area available for heat transmission. To improve safety, performance, and service life, these design solutions work together to make sure that air-cooled BTMS can keep the battery temperature within the recommended operating ranges. This is especially important for electric vehicle applications where thermal stability is key.

3.2 Liquid Cooling Methods

The use of electric vehicles, as well as other applications that need high thermal performance saw the extensive use of LIDC-BTMS and LDC-BTMS liquid-cooling technologies respectively. Liquid cooling is ideal as a heat transfer medium in comparison to air cooling due to their high thermal conductivity and heat capacity by their solutions. They have been adapted with greatly improved cold plates minimizing the temperature control efficiency of these devices. New designs like the spider-web river, mini-channel plates with a circular or serpentine pathway and the flow-type triangular structures allow efficient transfer of heat and provide a high cooling performance at high-load operating temperatures. These capabilities are further enhanced by cooling channel fixes, which optimise fluid dynamics through incorporation of wavy micro channel, expanded surface, and enhanced working fluids such as dielectric fluids, and Nano fluids. These improvements increase the thermal energy removal rate and guarantee electricity and safety. Hybrid systems that combine the advantages of both active and even passive thermal control like the use of PCMs and liquid cooling to offer improved temperature control are also provided. Although in an extreme environment that may require a lot of exposure to serious temperatures and active discharge sessions, these hybrid setups can assist in limiting the battery to heat excessively and maintain its level of functionality regular. The high costs of operation and system complexity are overridden by the fact that liquid cooling is an organic thermal management solution to high-power lithium-ion

battery applications.

3.3 PCM-Based Cooling Methods

An application of passive thermal management is the use of phase change materials (PCM) to stabilise battery temperatures by the absorption of latent heat during phase transitions. Although it does not use any moving parts to operate at all, it can be hybridised and made even more efficient through innovative design. They have experimented with many geometrical designs to optimise the heat absorption and dispersion arrangements such as square, circular and triangular PCM modules. When encapsulated in conductive material such as copper or aluminium, battery cells and PCMs can pass on heat faster. The hybrid air conditioning systems which combine PCM with liquid or air cooling procedures are more efficient at high discharge rates, especially at great temperature control. The use of encapsulated PCM units, porous structures, or high-conducting fins increase thermal performance dramatically by allowing more rapid heat distribution and increased cooling time. PCM cooling does not suffice to support persistent high-power functions, however it works well as a peak-load buffer and to extend battery life. It is also very energy efficient, a low-cost producer to run and environmentally friendly, therefore, it is an ideal type of energy to implement in applications that focus on passive solutions and moderate heat-loads.

3.4 Thermoelectric Cooling (TEC) Methods

Thermoelectric cooling (TEC) systems connect the battery to a high-precision temperature management system based on the Peltier effect. These systems have various merits such as miniature size, low noise, long life span and the possibility of absence of any moving parts. TECs are especially applicable in situations where mild control of temperature and space limitations are necessary. A particularly encouraging trend in this direction lies in the extension of TECs to Thermoelectric Generators (TEGs), combining them into a hybrid TEC-TEG system. Such set-ups utilise both cooling and energy recovery effects, thus enhancing the global efficiency of the entire scheme. Also, active and passive system hybrids that provide TEC with PCM material or fin structures have demonstrated an excellent enhancement in thermal control and energy consumption. High performance TEC designs: By focusing on high performance TEC designs (e.g. using a dual active cooling system

or TECs mounted in cold plates) the battery temperature may be kept at its optimum level even in the most extreme operational conditions. ANSA however, TEC systems are high-powered and costly compared to the conventional ways of cooling, a limiting factor to its wide-scale application. However, they perform well in precision and high-demand applications where battery dependability and temperature homogeneity are of utmost priority.

3.5 Techno-Economic Comparative Analysis

In order to have a complete assessment of the four key BTMS cooling procedures; air, liquid, PCM, and TEC, a listing of technical and financial conditions is used. They are cooling efficiency (CE), temperature uniformity (TU), maximum temperature reduction (MTR), energy consumption (EC), system complexity (SC), response time (RT), cost-effectiveness (C-E), scalability (S), and safety and reliability (SR). The moderate cooling efficiency and high cost effectiveness of the air cooling systems are as a result of their low complexity and ease of operation. They are also good in terms of temperature uniformity, but inextensive when subjected to high thermal loads. The more elaborate and costly liquid cooling systems offer high cooling power, great temperature homogeneity and quick response time, which are desirable in high demand applications such as EVs. The PCM cooling has a reasonable compromise between cost-effectiveness and performance, low energy usage, and acceptable reliability. It is, however, slow in response and might need to be integrated with other approaches in order to work in an optimal manner. TEC systems offer the best performance in cooling efficiency and the precision of temperature control but it is limited due to excessive energy requirement and high cost which makes the technology suited to niche, premium applications.

3.6 Advantages and Disadvantages

All BTMS approaches have their benefits and demerits. Air cooling is economical, of low complexity and minimal maintenance but is not suitable at high thermal loading conditions. Liquid cooling systems with better thermal performance and consistency add more design complexity and operating costs. The PCM based cooling offers good temperature control at low energy consumption, and system cost at the expense of responsiveness of active systems. The thermoelectric cooling provides accurate temperature control and rapid response, however its price and power

limitation limit extensive use. These comparatives reveal the necessity to adjust the BTMS design to special application demands and constraints.

3.7 Future Directions and Recommendations

Future research around BTMS technologies is projected to be on development of hybrid systems, intelligent control strategies and researches on advanced thermal materials. Systems that incorporate multiple cooling forms such as hybrid cooling that integrates air, liquid, PCM, and TEC cooling systems will probably proliferate, where each system can be used to satisfy specific operational requirements. Addition of nanomaterial, PCMs of high performance and magneto caloric materials will further enhance the heat transfer rates and higher thermal efficiency. Adaptive thermal management will depend heavily on artificial intelligence and real-time control systems so that predictive diagnostics and autonomous optimization can be performed. Additionally, the studies of a compact micro channel design, Nano fluids, and the integrated energy recovery systems will facilitate the invention of lightweight, high efficiency designs of BTMS. The concerns of sustainability, cost effectiveness, and adherence to safety regulations will also stay at the core of innovation. To achieve commercially viable next-generation BTMS solutions able to provide safe, efficient and environmentally responsible battery thermal regular, multidisciplinary integration and long-term performance testing may be necessary in the translation of research to practical, viable solutions.

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